

**Carnegie Mellon University**

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**The 3D Form Analysis of Regional Architecture Using Deep Learning:  
A Case Study of Wooden Churches from the Carpathian Mountains**

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## Abstract

Recent research into 3-D architectural and urban form analysis using deep learning (DL) methods has shown potential to extract and identify intrinsic features from large collections of building data and draw novel insights into how our built environment is configured and interrelated. In order to explore these new capabilities, this thesis offers a detailed case study of a critical engagement with building data and DL techniques for the purposes of architectural-historical form analysis. For a case study, it documents the creation of a custom dataset of 3-D meshes of 313 wooden churches located within and near the Carpathian Mountain regions of Ukraine using photographic data and 3-D reconstruction techniques. Though the subject of ongoing scholarly interest, the complex regional style variations of these churches has made it difficult to establish clear stylistic rules that govern both their differences and similarities. As a result, this lack of consensus has led to conflicting findings and ongoing contention amongst researchers. Given this challenge, this thesis attempts to demonstrate how recent statistic-based rather than traditional heuristic approaches might provide an alternate way to obtain new insight into this issue. For example, by offering a way to search for and identify both complex and nuanced form relationships and patterns among hundreds of churches at once within a single diagram. This includes detecting where stylistic overlap occurs, identifying groups of hybrid-styled churches, uncovering endemic micro styles, and revealing broad form patterns that illustrate how architectural features gradually morph across hundreds of buildings. The thesis thus offers a path for DL-based form analysis techniques to be put in conversation with traditional architectural studies, helping identify strengths and weaknesses, as well as opportunities for hybrid and cross-methodological architectural-historical analyses. Indirectly, this thesis also demonstrates an alternate method of architectural documentation through a combination of 3D building reconstruction from sparse imagery and architectural style encoding using DL-methods. Considering the threat to Ukrainian culture given the current war with Russia, digitally preserving both the individual churches themselves through 3D reconstruction and the rules that define their styles through DL-methods, has the potential to document and protect this important and distinctive part of Ukrainian architectural folk heritage.

**Keywords:** Artificial Intelligence, Deep Learning, Typology, Cultural Heritage, Digital Heritage, Morphometry, Architectural Distant Reading, Architectural Preservation, VAE, Architectural Analysis, Vernacular Architecture, Regional Architecture, 3D Reconstruction

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# Chapter 1 | Introduction

## 1.1 Background

The study and analysis of architectural form is an important area of research as it helps architects and researchers better identify spatial rules that influence a buildings appearance, such as proportion, geometric organization, symmetry, repetition, and texture. Analyzing these rules allows them to better understand the symbolic and cultural significance of architecture and its relationship to a wider ecosystem of built form and human creativity. However, architectural form, influenced also by external factors such as culture, climate, terrain, and politics, is often difficult to describe due to its complex three-dimensional state and incorporation of numerous interrelated physical and ephemeral features.

Given this challenging task, various techniques have been developed throughout history to quantitatively describe and compare architectural form in traditional manners. For example, through comparative architectural drawings [1], complex geometric rules used to define architectural styles [2], formulas purporting to describe the “essence” of architectural beauty [3], grammars that describe both interior and exterior architectural characteristics [4], and parametric based tools that computationally encode a buildings appearance [5]. These more traditional “close reading” [6,7] approaches can help to gain an extremely detailed understanding of an individual or relatively small collection of buildings. This is opposed to more contemporary “architectural distant reading” [6,7] approaches that leverage powerful computational techniques like Convolutional Neural Networks to encode and identify more general form rules across larger datasets of hundreds or thousands of buildings at a time. Though architectural form analysis in general, is often thought of as a fairly recent practice, it in fact, has a long and rich history stretching back for hundreds of years, and has been part of a larger and slowly evolving effort to discretize building form using mathematics and rule-based systems.

Within Classical architecture, some of the earliest records to encode and analyze building form was conducted by pioneers like Alberti and Palladio who attempted to understand the rules that governed architectural form by abstracting and reducing the complexity of architectural representation [8,9]. Once understood, these rules could also be used as prescriptions for similar designs [2]. Later architects like Durand began to use mathematics and geometry to define and create a taxonomy of architectural building types in order to "offer artists a general and inexpensive panorama of architecture" [2] as shown in figure 1-1.

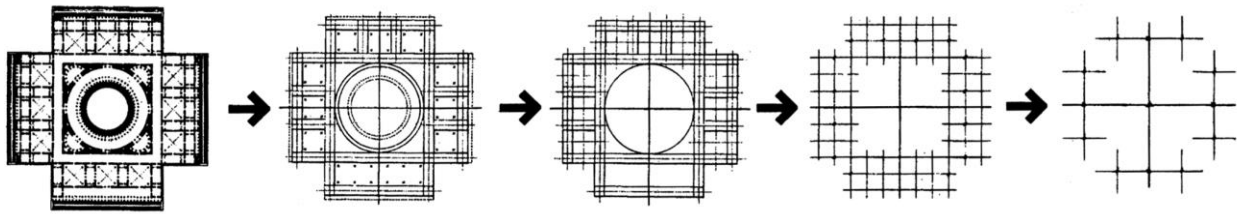


**Figure 1-1:** Durand illustrating how a building floorplan can be described through geometric abstraction [2]

As theories of evolution began to take hold from the mid-19<sup>th</sup> century onward, research was driven to explore and analyze the deeper underlying and interconnected rules that drove the form of not only particular typologies (hospitals, churches, schools), but relationships between typologies. Though not architecture related, early theories by D’Arcy Wentworth Thompson — on Growth and Form [10], Noam Chomsky — Syntactic Structures [11], and Fredrick Brooks—An Experiment in Musical Composition [12], began to define these deeper foundational rules as not only a means to break down form complexity into abstractions but as a means to create something new when these very abstractions are recombined in new ways. For example, the rules that define the form of certain species of fish according to Thompson [10], the sentence structure of the English language as described by Chomsky [11], or the musical composition of piano music proposed by Brooks [12]. Within architecture, these ideas were also explored by G. Stiny and W. Mitchell within their development of a parametric Shape Grammar that defined the general rules of ground plans of Palladio’s villas as a definition of the Palladian style [62] (Figure 1-2). This was based on G. Stiny and J. Gipps 1971 Shape Grammars paper which aims to produce a set of rules, or “grammars” that explain the patterning of design objects, and then generate new designs based on these rules. [13]

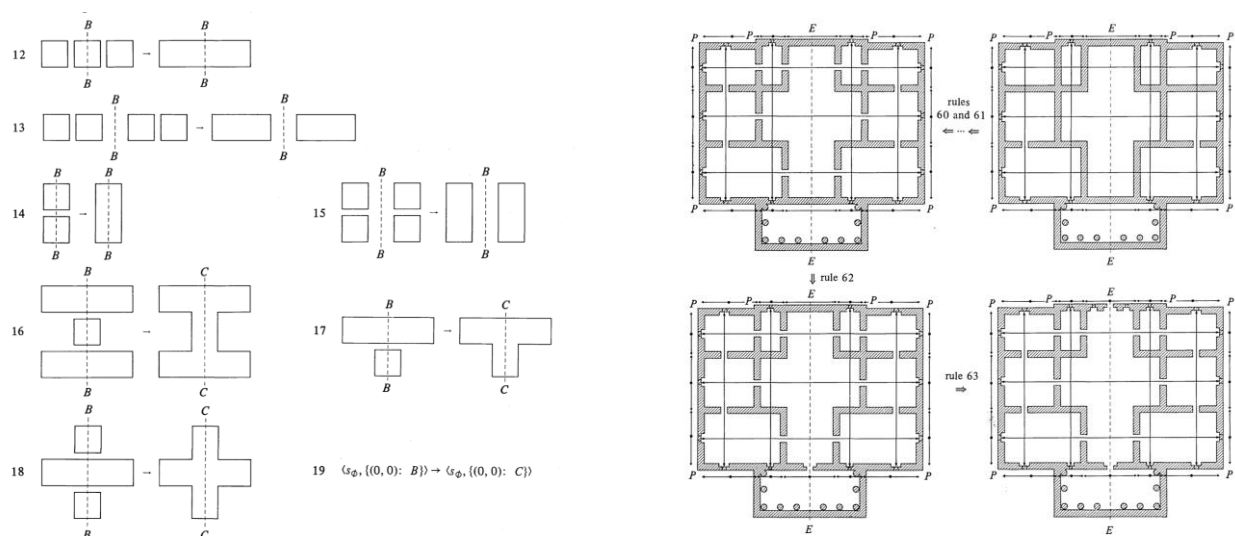


**Figure 1-2:** Rules for room layout (left) and rules to generate window and door openings (right) as described in Stiny and Gipps Shape Grammar for Palladian style villas [62].

Later advances within this area were made by U. Flemming in 1986 when he developed a shape grammar to describe and generate house designs in the Queen Anne Style typical to Pittsburgh's historic Shadyside district [14], and J.P. Duarte's Malagueira House grammar, which could generate similar style houses in 3D [15] (Figure 1-3). Much later, projects like Daniel Aliaga's 2007 "Style Grammars for Interactive Visualization of Architecture" [16] and P. Muller et Al.'s "Procedural Modeling of Buildings" [17] provided a means to better generate, access, and manipulate building grammars by leveraging advances made in parametric design, a powerful procedural method for generating and controlling complex 3D forms through manual computation-based rule-setting.

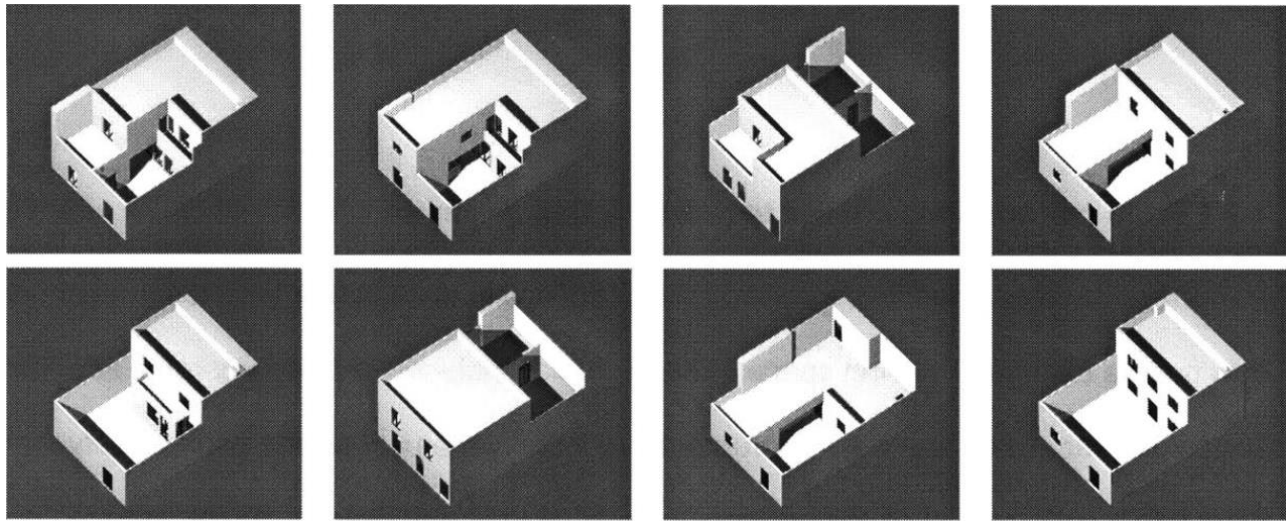


**Figure 1-3:** Generative results of Duarte's Malagueira House grammar. [15]

Recently, the study of architectural form has experienced a surge in interest, due in part, by the advancements in Deep Learning (DL) based visual pattern recognition tools using Convolutional Neural Networks (CNN) like Generative Adversarial Networks (GAN) [18] or Variational Autoencoders (VAE) [19]. Compared to more traditional methods, which often take time, are typically manual, and can analyze just a handful of buildings simultaneously, these new techniques can be applied to thousands or even millions of buildings at once. And after a relatively short processing period, provide the means to more easily and quickly explore the complex and difficult to detect morphological patterns that permeate through these very large collections of buildings. For example, in his 2019 paper "Context-Rich Urban Analysis Using Machine Learning: A case study in Pittsburgh, PA" [64], Jinmo Rhee uses these methods to identify the various types and locations of urban form patterns throughout the entire city of Pittsburgh, Pennsylvania. By leveraging the analytical power and capabilities of DL, he was able to obtain results that might have taken years to complete via manual survey and traditional form analysis methods.

## 1.2 Related Works

To better understand the landscape of current work, I will review three recent research projects that have investigated the potential to enhance the practice of architectural and urban form analysis with DL methods.

An early and ambitious proposal was demonstrated by V. Moosavi in his 2017 paper “Urban Morphology Meets Deep Learning” [20] where he used DL methods to identify, encode and organize the urban forms of one million cities around the world into distinct form categories. By representing urban forms as two-dimensional 256×256-pixel images of city road networks and encoding them as a 640-dimensional urban latent vector represented as 640 individual float point values using a deep-convolutional autoencoder, Moosavi was able to cluster them into 2000 groups. Then, he generated a type of “urban spectrum” that visually showcased the diversity of these clusters in an easy-to-understand diagram which organized urban form accordingly. By sampling from this spectrum, specific urban forms can be viewed as well as others that share similar organizations, with degree of similarity informed by the Euclidean distance between urban vectors. He then assigned a unique color to each cluster and mapped them back to geographic space, thus showing the geographic dispersion of these various urban form types around the world.

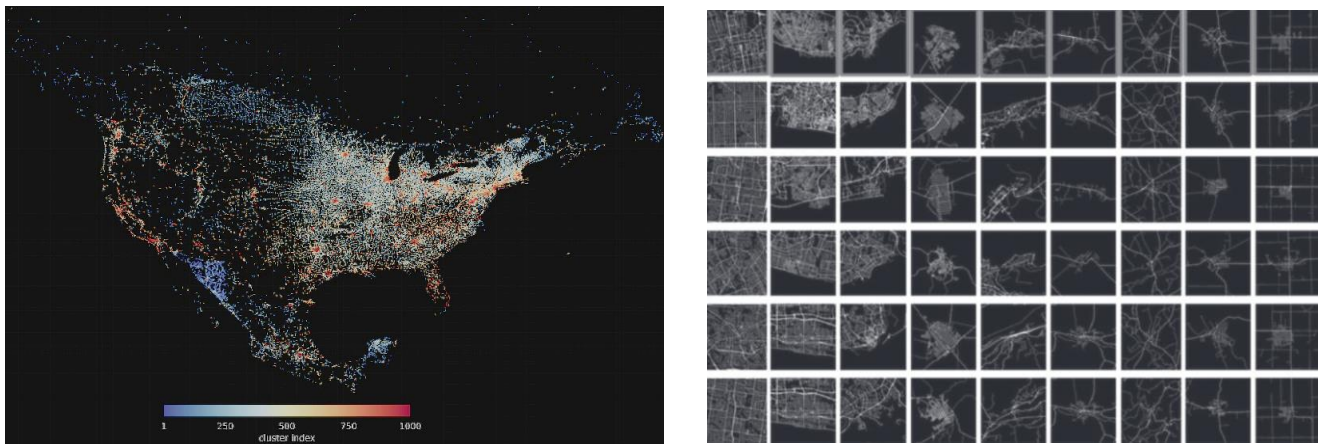


**Figure 1-4:** Moosavi showing the distribution of 33 of 875 urban forms in North America (left) and the five most similar urban forms shown below the top row (right). [20]

Another related project includes the 2021 study of urban blocks of Chinese cities by Chenyi Cai et al. [21]. In this study, Cai constructed and analyzed the form patterns within a custom dataset of 3817 urban residential plots or blocks in an attempt to classify them according to nuanced form similarities. Here, blocks were represented as two-dimensional images, where each image contained a gray shape that represents the area or footprint of

the urban block and smaller pink shapes that represent the footprints of buildings within the block. Each block within his dataset was then encoded as a 2048-dimensional latent vector using GoogLeNet, a deep convolutional neural network built specifically for image classification via feature mapping. Afterwards, each of the 3817 latent vector representations of city blocks were clustered according to similar spatial layouts. Similar to Moosavi, a diagram was created that showed all blocks organized according to these clusters and their relation to one another. Individual blocks that share “similar” form, which is determined according to Euclidean distance between each urban vector, can be visualized. In this case, urban vectors that are closer together suggest increased form similarity, while urban vectors further apart suggest decreased form similarity.

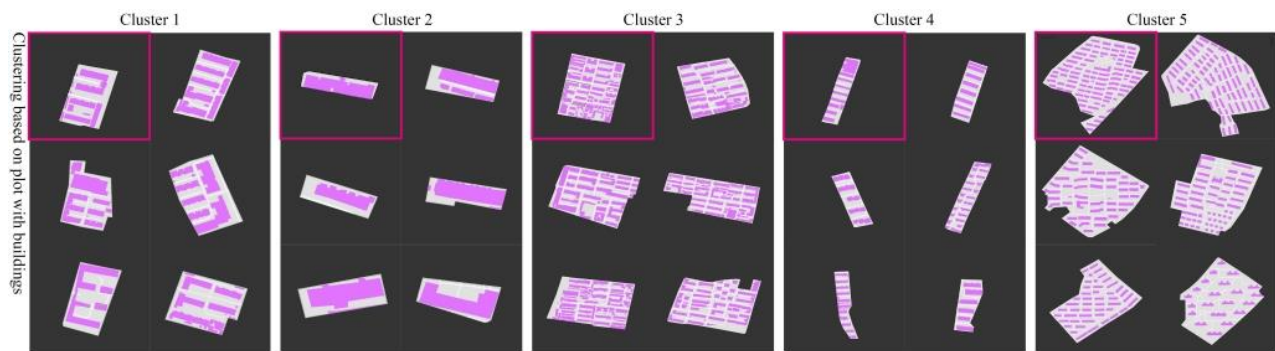


**Figure 1-5:** Cai illustrating 5 clusters of urban blocks that have been grouped together according to similar plot and building shape. [21]

When considering 3D architectural form, Jinmo Rhee and Pedro Veloso proposed a method to capture the 3D morphological features of 4,956 high-rise buildings sourced from 31 different cities around the world [22]. Each building was represented by a series of 256×256-pixel images representing horizontal slices of each high-rise taken at various height increments. By using an IntroVAE model [19], they were able to encode each image as a 10-dimensional latent vector representation and cluster by similar form. By doing this, they identified 14 different types of high-rise buildings by the different configuration of building components such as podiums and towers. They then proposed a typical form for each group, as shown in figure 1-6, to visualize and qualitatively evaluate the types. The typical forms were determined by taking the nearest building data point to the cluster’s centroid. Based on the typo-morphological investigation, they introduced an intriguing method of generating new forms of high-rise building by adjusting the latent space distribution learned by the model with impressive results. It must also be stated that this paper greatly inspired this research as it was one of the earliest and effective papers to describe the potential of DL-methods in the analysis and generation of 3D form.



**Figure 1-6:** Rhee and Veloso showing the typical form of the various types of high-rise buildings. [21]

Both Moosavi, Cai and Rhee & Veloso demonstrate powerful new methods for encoding and clustering urban and architectural form, which allowed them to parse through and better analyze and understand the range of diverse configurations that exist within our built environments. Additionally, Rhee & Veloso effectively demonstrate how this method can be used to generate novel 3D forms that share similar morphology. However, additional insight into the patterns of urban and architectural form may arise by investigating other domains and variables that affect a building form. This is further supported by Rhee who states that “by integrating geometric and other social, economic, cultural, and environmental data, form can be more broadly interpreted as a phenomenon of human activities. As a result, Deeprise will be one step closer to analyze morphological principles and features related to our society” [22], suggesting that there is much more to learn from form patterns.

### 1.3 Intended Contributions

This thesis intends to show that insightful morphological relationships among our dataset of 313 Carpathian wooden churches can be revealed using contemporary DL techniques and reflects on specific ways these analyses might enrich existing architectural scholarship and expert knowledge on the subject. However, to set itself apart from other work, this thesis argues that findings acquired from DL-based “distant reading” [6] techniques are more thoroughly understood when compared against the findings of traditional “close reading” [6] approaches. However, as other research has almost exclusively used extremely large datasets that have rarely been analyzed using traditional approaches due to their size, such a comparison has often been difficult or impossible to do. As a response, my thesis uses a *small* dataset of a *previously studied* building type in order to make this comparison and demonstrate how DL-based findings can enhance our understanding of architectural form most efficiently when taking into consideration the findings acquired through more traditional approaches.

To begin, I will compare DL-informed results with conventional studies that have utilized traditional analytical methods and demonstrate that there is correlation between the way in which these two differing approaches

have grouped churches in terms of similar form. I will then show how DL techniques can help to identify groups of churches that share similar forms according to more general or more specific architectural features by altering cluster size. This allows both primary, secondary, and tertiary style groups of churches to be identified. Additionally, I will provide evidence that DL-techniques can help to identify and located clusters of harder to recognize endemic micro-styles that have developed within isolated geographic regions, such as within certain valleys or along certain rivers. Finally, I will offer a path for DL-based form analysis techniques to be put in conversation with traditional architectural studies in order to help expand and enhance our understanding of architecture.

In addition, my thesis intends to offer a number of useful technical contributions to both the field of architectural form-analysis and to the research of Transcarpathian wooden churches. First, it will demonstrate a method to build a custom 3D dataset of a non-western, rural, and “niche” building type using the NeRS technique [23] that converts sparse imagery into three-dimensional models. Second, it will show how similarly small and custom datasets can be successfully augmented in size in order to sufficiently train DL-models. As a result, this research will likely be the first of its kind to apply DL-based form analysis approaches to a custom 3D dataset of vernacular architecture. Thirdly, it will present a multimodal approach for analyzing latent space distributions by incorporating both DL-oriented approaches, such as Rhee’s method of clustering and identifying typical and least-typical form [64], and traditional approaches such as reference to cultural-zoning maps, church style and sub-style diagrams, and other existing research material [24, 25].

Furthermore, as the author is of Western Ukrainian descent whose relatives originated from Bukovina, a cultural region that has its own distinct style of Carpathian wooden churches, this thesis is a means to bring awareness to the fragile and culturally significant folk architecture of his ancestral roots.

## Chapter 2 | Data

### 2.1 Overview

The dataset used in this paper consists of 331 3D building forms representing the 3D re-constructions of 331 existing and non-existing — i.e., dismantled or destroyed — historic wooden churches generally located in the Carpathian region of Eastern Europe. This one-of-a-kind dataset was custom made by the author and represents the first of its kind for this building type and likely the first of any building type to be reconstructed from sparse 2D imagery in this particular way. Rather than homogenous in appearance, the churches within this dataset represent the rich heterogeneous mixtures of styles that define the Carpathian wooden church building type.

The key advantages of the data used in this paper, includes the following: To begin, the architectural data, as shown in figure 2-1, is in the form of generally high-quality 3D models rather than more abstracted representations such as 2D building footprints or 3D extruded building footprints. For example, both Moosavi and Cai used datasets in the form of lower representation 2D images as shown in figure 1-4 and 1-5 [20, 21]. By using 3D forms, more complex and accurate building shape information can be encoded and learned by the DL model. For example, things like roof shape, subtle undulations in exterior envelopes, building overhangs, and other architectural extrusions, recesses, and geometric elements that may be more indicative of a particular architectural style.



**Figure 2-1:** Three 3D churches models from the dataset displaying high resolution geometry and texture. Models by author.

Secondly, the data represents a unique, generally rural, and rare building type with just a few hundred examples left standing today [26]. Due to the limited availability of high-resolution niche or even common 3D data of digital building models [27], comparable work typically has used pre-existing, urban architectural data sourced from large and readily available city models [20,21]. Therefore, to the best of my knowledge, there are very lim-

ited, and likely no other existing studies applying DL-form analysis methods to similar types of rural niche architectural datasets.

The reason for the under-representation of high quality rural, smaller urban, or niche 3D architectural data at scale is likely due to the cost associated with creating 3D models as it requires a huge investment of time, labor, and money for expensive equipment [28]. After surveying existing city models, it was observed that high quality architectural data was often only available for larger urban environments of wealthier countries. Though 3D models for other urban environments may exist, they are often low resolution, highly abstracted and typically represented as simple volumetric building extrusions [27], thus providing insufficient building form detail for this or similar types of DL-based research. As for generally rural, rare and niche, building types like the Carpathian wooden churches, it is unlikely that any more than a handful of models, likely constructed by different sources, may exist online. As a response, this thesis demonstrates how 3D datasets of non-urban, rare, and niche building types from any country can be built by anyone from scratch. We additionally demonstrate how to augment smaller datasets in order to be sufficiently large enough to train a DL networks.

## 2.2 Representation

The 3D buildings that make up our dataset are represented as a collection of vertices, vertexes, vertex normals, and faces in .obj format; a simple and widely used data-format that represents 3D geometry alone [29]. Each .obj file is also accompanied by two texture files, the first being an image of the building texture in .png format, and the second being a .mtl file that specifies the material properties. As most DL models were developed to encode imagery represented by pixels, I converted our 3D .obj files to voxels in order for it to be compatible to this underlying image-oriented architecture. This is because voxels are a format which represent 3D objects in a

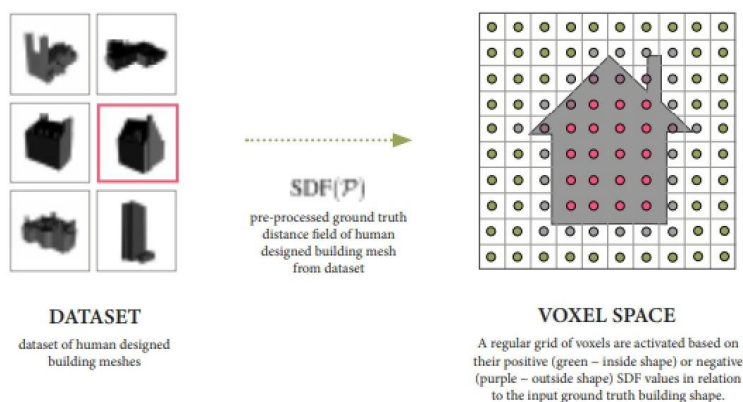


**Figure 2-2:** Illustration of 3D .obj building models (left) being converted into an SDF voxel representation (right). Diagram by author.

similar way that 2D images are represented by square pixels. Voxels, however, represent 3D forms as a collection of 3D pixels organized within a 3D grid of a user-specified size. For this paper, 3D church models were converted to  $32 \times 32 \times 32$  voxels using signed distance field (SDF) [30], for continuous representation within voxel space. With normal voxels, each voxel within the  $32 \times 32 \times 32$  grid, representing 32,768 individual voxels, is represented by a 0 or 1. 1 meaning that the voxel overlaps with the given geometry, and 0 if it does not. SDF however, assigns a float point (number with decimals) rather than binary point (0 or 1) to the voxel, thus not only indicating whether a voxel has intersected, or is within the given geometry (positive numbers indicate that the voxel is inside the 3d volume and negative numbers indicate that the voxel is outside), but also that voxel's distance to the surface of the given geometry [30] (fig. 2-2). This added information allows SDF voxels to achieve a much higher representational accuracy than typical voxels.[30]

## 2.3 Augmentation

In order to sufficiently train the DL network and extract a reasonable latent space distribution, where latent space is a representation of abstracted data where similar data points are clustered closer together, the dataset needed to be augmented from 313 buildings to 5,627 buildings. Data augmentation is common technique if the dataset is insufficiently large to train a DL-model and helps prevent overfitting [32]. Overfitting is when a model begins to memorize hyper-specific features of the data, rather than more useful general features of the data that

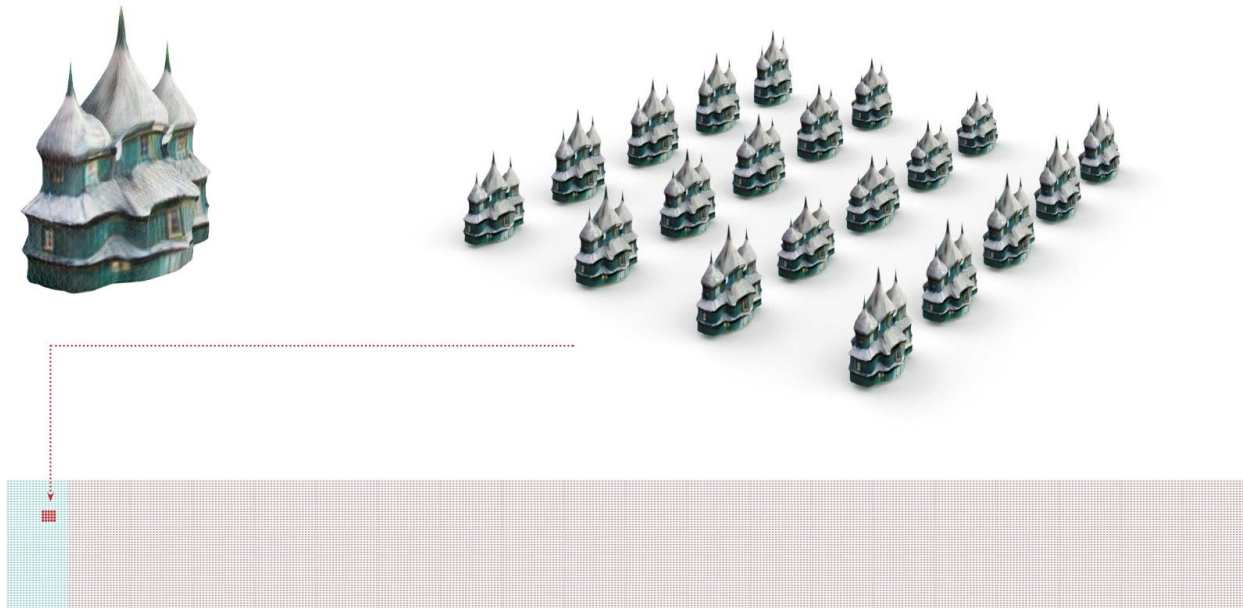


**Figure 2-3:** Augmenting our original dataset of 313 buildings (represented as blue dots on left) to 5,627 buildings (blue dots plus red dots) through random scaling and rotation (rotation not shown here). Diagram by author.

might help better describe it as a whole. To avoid overfitting, the dataset was augmented to be 17X its original size by making 17 copies of each building, with each copy being slightly different from the next through a series of transformations such as rotation and randomly scaling. To expedite this process, a custom script and data pipeline was created in Grasshopper, a parametric design software used to create and manipulate 3D geometry. The final augmented dataset for model training included 5627 voxel files, each being 129 kb, leading to a total dataset size of 725.88 MB

### **2.3 Additional Metadata**

A plain-text CSV file also accompanies each church .obj and .mtl files and contains church specific metadata, such as church name, construction date, latitude, longitude, address, google maps link, status (standing, not standing), links to descriptions, and image source providers. As this 3D dataset of Carpathian wooden churches is the first of its kind, the authors hope that providing both the 3D model and metadata might benefit others who are conducting related research related to the Transcarpathian wooden church typology.

## Chapter 3 | Church Description

### 3.1 Background

The wooden churches of the Carpathian Mountain region can be generally described as unique examples of a broader, yet long-lost wooden architectural heritage. Unlike their urban counterparts, the rural and historically remote Carpathian wooden churches were subjected to far fewer hazards. For example, risk from fire, vandalism, arson, and replacement with stone architecture [24] was much more common in more populated urban areas. As such, Carpathian wooden churches provide a unique glimpse into a wooden architectural heritage that has generally disappeared within the rest of Eastern, Central, and Western Europe [24].

Geographically, the majority of these churches are located within or nearby the Carpathian Mountains, an important range that has historically been a major divider between Eastern and Western cultures. Rising from the ground from its most Southeastern zone in Eastern Serbia and reaching a maximum elevation of 8,711 feet, the Carpathian Mountain range runs in a linear fashion first Eastwards into Romania, then Northward into Western Ukraine, and then suddenly back Westward while straddling the border between Northern Slovakia and Southern Poland. For centuries, Eastern and Western influence, such as Byzantine, Ottoman, Baroque and Gothic culture both entered and intermingled with local mountain traditions, providing fertile grounds for material and immaterial cultural synthesis [24, 33]. Such conditions gave rise to the unique and endemic clothing (Figure 3-2), culi-



**Figure 3-1:** The Church of the Epiphany in the village of Oryavchyk in Ukraine (right), and the Church of St. Basil in the village of Cherche, Ukraine. Images from [www.about-ukraine.com](http://www.about-ukraine.com).

nary, musical, and creative outputs that still popularly define many of these distinct cultural groups and geographic zones today. Similarly, the wooden architecture of this region reflects a rich blend of both Eastern and Western architectural motifs [33] as shown in figure 3-1 and is most pronounced within the sacred churches that still occupy and remain an important fixture within many of these communities.

Beyond their representation of a lost wooden architectural heritage, more importantly, these churches represent the distinct folk architecture cultures of the various ethnic groups of the region, with each having their own easily recognizable building style defined by their particular traditions, cultural, spiritual, and climactic needs [34, 35]. This study will focus on the central Carpathian region, within, and surrounding, Western Ukraine, and as a result, will include the primary cultural groups of the area, including the Lemko, Boyko, Hutsul and Transcarpathian cultures.

Endemic to the region, the churches of the Carpathian Mountains have become sacred and irreplaceable objects of cultural significance to both the cultural groups that built them and to the countries they are located within. As a result, efforts have been made to preserve, repair, and protect them for future generations. This was reflected globally in 2011 when 16 of these churches were designated as UNESCO world heritage sites [36]. Recognizing and preserving these churches is especially important given that the vast majority have been destroyed or dismantled due to both world wars, destructive ethnic and political agendas, arson, or periods of general neglect. From the thousands of churches that once existed only a small percentage survive today, with an estimate of 5-8 lost each year [37]. This loss becomes startlingly apparent when considering that out of the 689 wooden churches that existed in 1939 within the Eparchy of Przemyśl, a small historic region slightly smaller than Delaware, the second smallest state in the United States, nearly 350 were lost by 1989, with even less still standing today [38].



**Figure 3-2:** Girls from the village of Veliky Bychiv which is located within the Hutsul cultural region. 1920's (left) and the Church of the Protection of the Blessed Virgin (right), 1792, now located in the Pyrohiv National Museum of Folk Architecture and Rural Life of Ukraine, in Kyiv, Ukraine. Images from [www.localhisotry.org.ua](http://www.localhisotry.org.ua) and [www.derev.org.ua](http://www.derev.org.ua) respectively.

### 3.2 The Four Primary Church Styles

To better understand the complex landscape of Carpathian wooden church morphology, we can generally partition it into four primary styles, or what is commonly referred to as "Schools" of folk temple construction [24]. This include the Boyko, Lemko, Hutsul, and Transcarpathian schools, which are the result of the design inclinations of four distinct cultural groups located in the Carpathian region of Western Ukraine. In terms of construction date, the vast majority still standing were built between the 18<sup>th</sup> and 19<sup>th</sup> centuries, though some are as old as the 17<sup>th</sup> and even 16<sup>th</sup> century. Other schools of wooden folk temple construction are also included in the dataset such as Bukovina, Pokut, Podilia, Opilska, Przemsyl, Volhynia, Bessarabia. and Transylvanian school though lesser in number. However, the paper will only focus on the main four primary schools represented in our dataset, being the Boyko, Lemko, Hutsul, and Transcarpathian schools.

Carpathian wooden churches, though drastically ranging in form, do however, share several architectural similarities. This includes the use of timber as a primary building material, the integration of horizontal log construction, the application and showcase of masterful carpentry techniques, and the generally common use of Tripartite plans as a basis for overall geometric configuration. As shown in Figure 3-3, tripartite plans are composed of three quadrilateral or rectangular spaces linearly connected in a row beginning with the narthex, or small entry space, the nave where the congregation sits, and the private and smaller sanctuary space which is only accessed by the clergy and is traditionally located behind a wooden screen called an iconostas. Though 5 partite, 7 partite and 9 partite churches are prevalent, they are more common within the Hutsul cultural group.

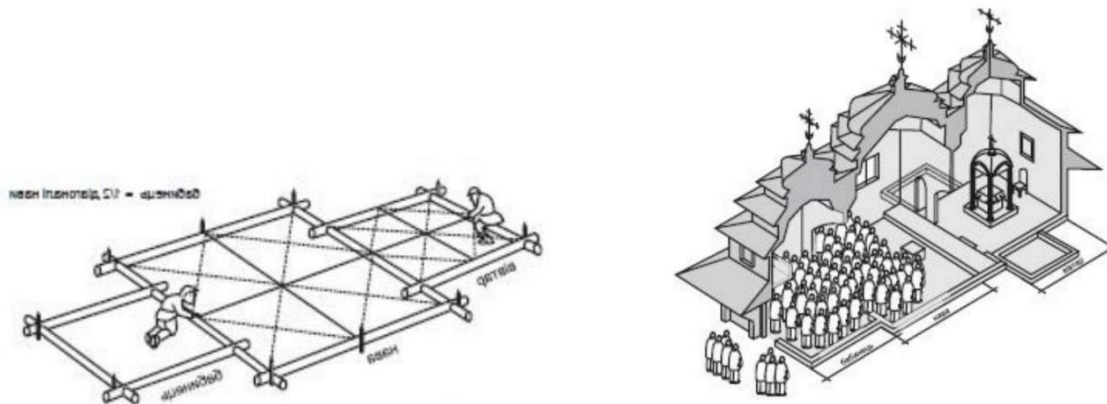


**Figure 3-3:** Diagrams showing the common tripartite (3 room) configuration, with narthex on the left, nave in the middle, and sanctuary on the right. From Yaroslav Taras's 2020 publication "Wooden Temple Architecture of the Ukrainian Carpathians" [25]

### ***Boyko Churches***

The Boyko school of folk architecture construction located in the North Carpathian region of Ukraine and Southern Poland [25] is defined by the use of a linear tripartite plan of stacked log construction, topped by three multi-tiered roofs that can either be in pyramid or dome like in shape [25, 36, 40]. Though the middle one is often the highest, dome height may slightly vary depending on the region, age, or sub-style of the church. The most noticeable characteristic of Boyko churches is often its multi-tiered towers, in an often stepped pyramid fashion, where each step, referred to as a "zalom" in the Ukrainian language, is angled upward to allow for water runoff (Figure 3-4). Boyko churches might incorporate a single zalom that breaks the dome into 2 stacked portions, or up to 7 or 8 in its most dramatic form reminiscent of multi-tiered Japanese pagodas. However, some Boyko churches may include just a middle, two, or even a dome-less condition depending on the needs or economic requirements of the community. As a result of this inconsistent dome configuration, Boyko style can often be difficult to identify. These churches can also vary in height, being either narrow and tall or short and squat. They also incorporate a lower skirt roof, called an "opasanya" that protects the exposed log walls and stone foundation from rain and snow damage. According to the 2011 UNESCO report, only 70 wooden churches of Boyko style are left [36].



**Figure 3-4:** An example of a typical Boyko church from "Wooden Temple Architecture of the Ukrainian Carpathians". [25]

### ***Lemko Churches***

Like the Boyko designs, churches built in the Lemko School in the Northwest Lemko cultural zone also incorporate the linear tripartite plan and three-tower configuration. However, rather than three multi-hipped pyramidal domes, Lemko designs replaces them with three tall domineering towers, with the tallest, widest and bulkiest over the narthex entry space, with the remaining two sequentially decreasing in size as they move to-

wards the rear of the church. The last two towers are significantly narrower, and all three are topped with a series of stacked onion-shaped volumes that decrease in size as they move towards the top [25, 36, 40]. This cascading tower configuration adds to the general elegance of Lemko churches and is often considered their main defining morphological feature (Figure 3-5). However, Lemko sub-style designs vary greatly in terms of number of roofs, tower heights, lengths, and roof shapes. This variation is so great in fact, that the three towers completely disappear, making it difficult to tell some Lemko churches apart from Transcarpathian ones. According to the 2011 UNESCO report, only 70 wooden churches of Lemko style are left in Ukraine & Poland [36].

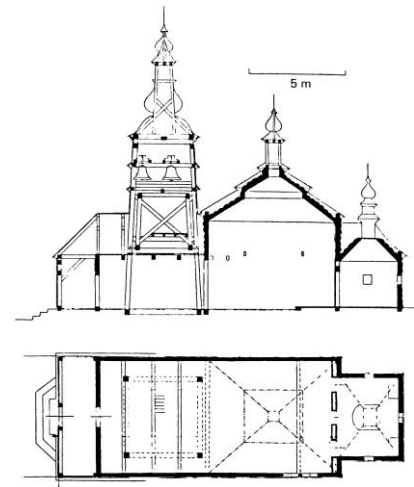


**Figure 3-5:** An example of a typical Lemko church. [40]

### ***Hutsul Churches***

Differing from all other styles, churches built in the Hutsul school, which are primarily located in the Southern Ivano-Frankivs'k of Ukraine, incorporate the Greek-style cruciform rather than tripartite plan configuration [25, 36, 40]. This is achieved by widening the nave or adding rooms on either side. In combination with an omnipresent central dome, flanked by pitched roofs or sometimes two or four smaller domes, Hutsul churches are often easy to differentiate from Boyko, Transcarpathian and Lemko styles (Figure 3-6). However, some sub-styles like within the Pokut school have shorter nave projections / more subtle cruciform plans [25], thus making them difficult to differentiate from single-domed Boyko churches found within the Bolehivsko-Dolynsk-Pereginsk, or Sambir-Dolynsk region [25]. According to the 2011 UNESCO report, only 150 wooden churches of Lemko style are left in Ukraine & Poland [36].

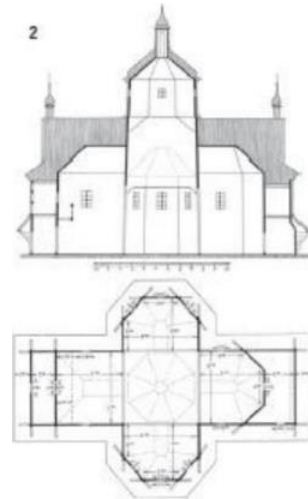


**Figure 3-6:** An example of a typical Hutsul church from "Wooden Temple Architecture of the Ukrainian Carpathians". [25]

### *Transcarpathian Churches*

The primary morphological features of Transcarpathian school churches can be distinguished by the emphasis of a single tower of varying heights over the narthex of the church. Followed by a single or two stepped gable roof that covers the remaining spaces of these tripartite-planned church [25, 36, 40] (Figure 3-7). However, due to the proximity and overlapping Boyko and Lemko region in the northern portion of Transcarpathia, certain sub-styles of Transcarpathian churches have adopted aspects of both, for example, churches within the Kraynia-Svalkyasko-Ploskiv region, which contain both Lemko and Boyko morphometric features [25]. Other variants incorporate baroque and gothic features and extremely tall towers and higher nave and sanctuary spaces with double roofs, most notably built in the Southern end of the Ukrainian Carpathian region and those within the Marmures region of Romania [25].

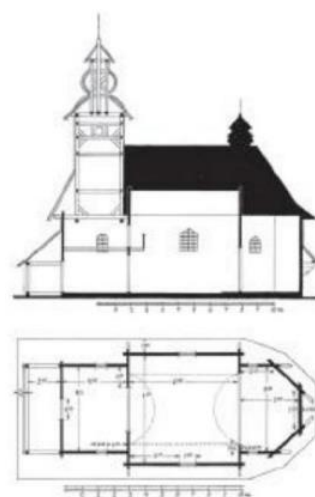
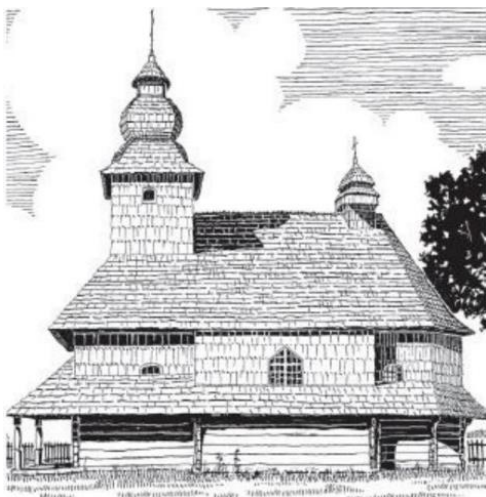


**Figure 3-6:** An example of a typical Hutsul church from "Wooden Temple Architecture of the Ukrainian Carpathians". [25]

### Church Sub-Styles

Furthermore, within each school, there are other sub-styles and sub-sub-styles that share both complex and subtle styles characteristics [25]. There are many reasons for this, but many sources suggest the following. First, Carpathian wooden churches were not designed according to pre-conceived technical plans or drawings of any sort. Rather, they were conceived verbally and locally by both the craftsmen who built them and the religious members and local congregation who would attend them. As books or drawings of existing churches were scarce or nonexistent, church designs were often based on the visual style of neighboring churches in nearby towns [25]. As a result, this gave rise to distinct style groups that tended to cluster among smaller communities that were relatively isolated together within smaller geographic regions such as within certain valleys, or along certain rivers or road networks [25]. Furthermore, as drastically changing traditional styles was generally avoided, church styles evolved at a very slow pace, suggesting perhaps why and how these unique sub and sub-sub styles are still present even within recent designs today [25].

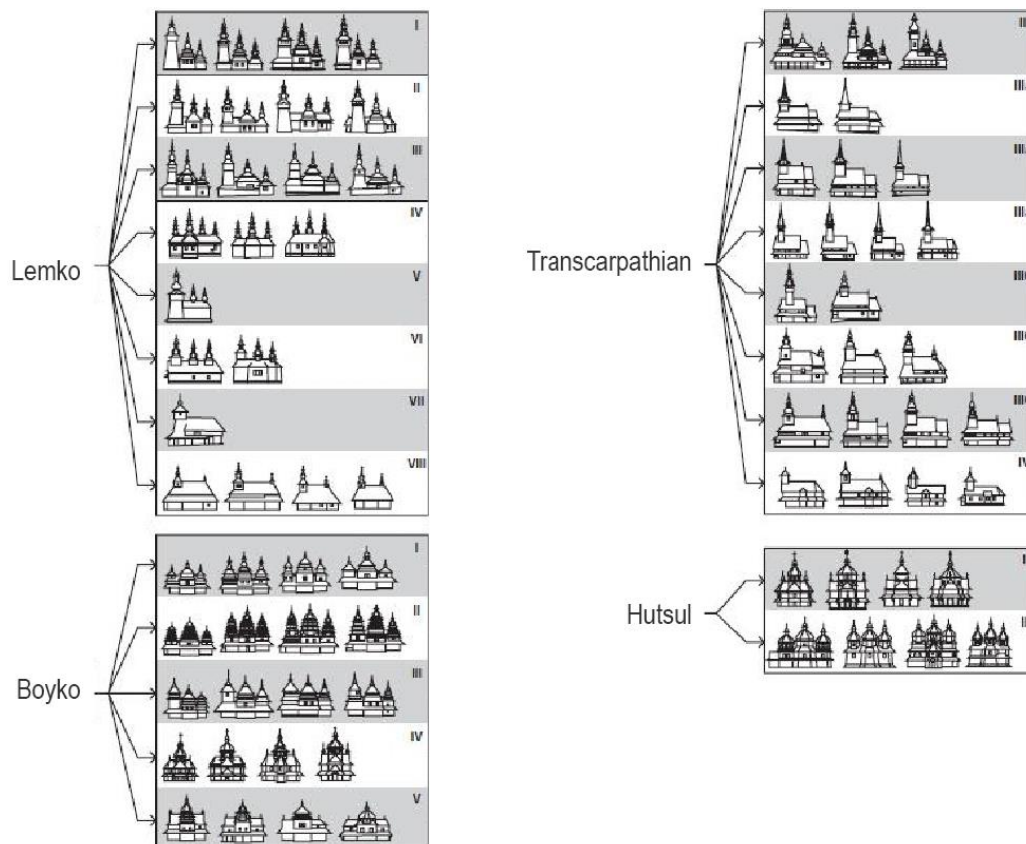


**Figure 3-7:** The various sub-styles of the four main Schools of folk temple construction according to Yaroslav Taras, one of Ukraine's leading expert on these churches from "Wooden Temple Architecture of the Ukrainian Carpathians" [25]

In addition to a locally inspired design process, craftsmen themselves also helped to develop regional and sub-regional styles of their own. As design and construction decisions were primarily carried out on site, the preferences, skills, tendencies and building styles of individual craftsmen led to further differentiations within the regions they worked within [25]. As a result, craftsmen, though their identities are often unknown [41], left a trail of unique churches that showcased their own architectural style variation and interpretations, therefore further enriching the overall typology with clusters of smaller sub-style groups where they worked. Overall, a rich architectural typology which has diverse variations based on certain styles are observed in Carpathian Wooden churches (Figure 3-7, 3-8, 3-9). The subtle taxonomy of the churches shows the potential of using Deep Learning to analyze their form. As the single typology is in fact, made up of a complex interconnection of smaller formal sub-styles defined by cultural regions and sub-sub-styles, defined by communities and craftspeople, DL might help us identify these overlapping and blurry boundaries, suggesting perhaps, new interconnections, relationships, and differences.

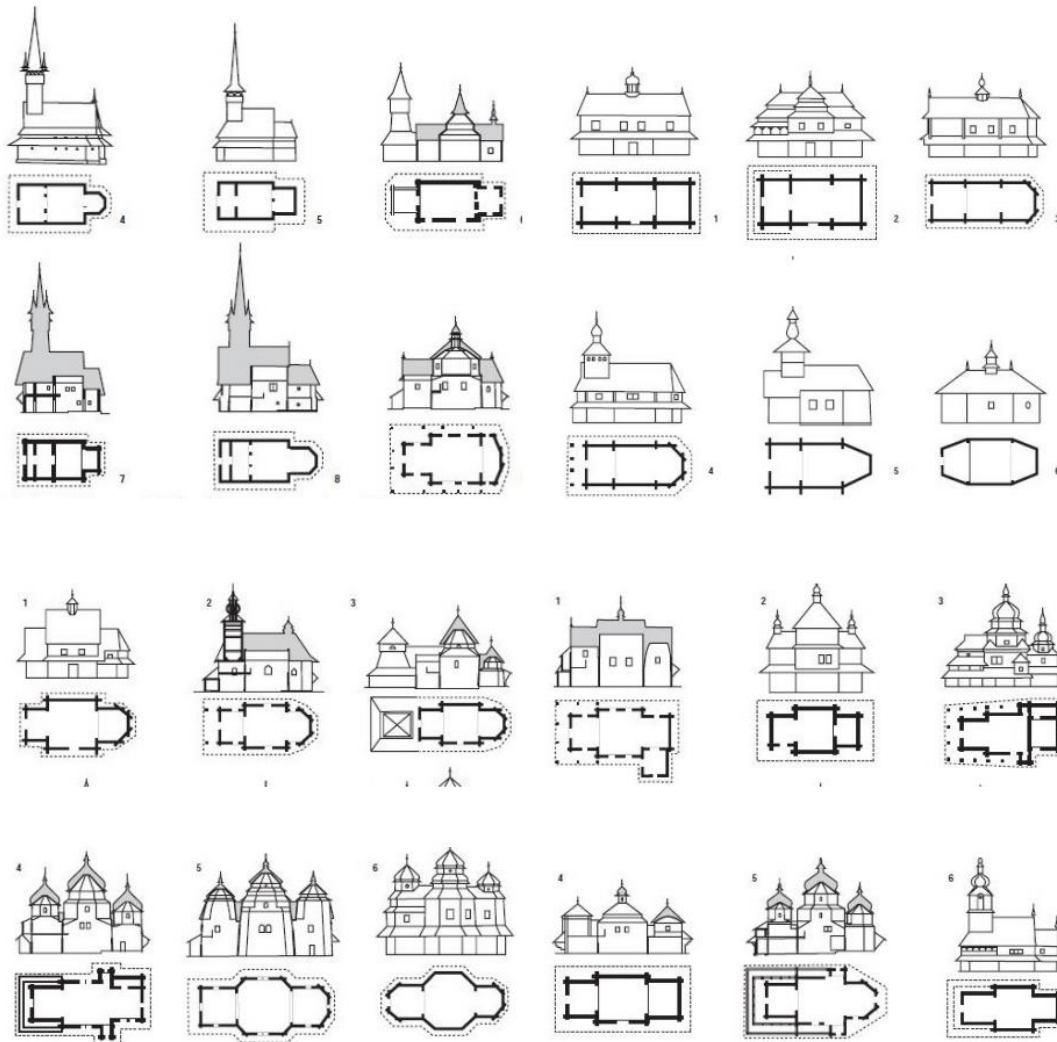


**Figure 3-8:** Additional sub-style variations from "Wooden Temple Architecture of the Ukrainian Carpathians" [2]



**Figure 3-9:** Clockwise from top-left: 1) Boykiv church, from village of Volosyanka, Ukraine. Boyko school. Image taken by Valery Tashchyshyn. 2) Church of St. Nicholas, village of Velyke Urmeziyevo, Ukraine, 17<sup>th</sup> century, dismantled in 1965. Transcarpathian school. Image from Mykhailo Syrokhman. 3) Church of St. Kosmy and Damian, Village of Kremna, Poland. Lemko school. Image from Google Maps. 4) Church of the Holy Trinity, village of Mykulychyn, Ukraine. 1868. Hutsul school. Photo by Maxim Gavrilyuk. 5) Church of mother of god. village of Rownia, Poland. Boyko School. Image from Google Maps 5) St. Michael's Church, village of Kutu, Ukraine. Image from Valeriy Taschishin.

### 3.3 Existing Research

In order to compare our DL form analysis results with existing research, it is important to briefly describe the existing landscape of Carpathian wooden church research and how their morphometric relationships have been described over time using traditional analytical tools and methods.

To begin, the formal study of Carpathian wooden churches has a long, yet sporadic history beginning in the middle of the 19th century and continuing to this day [25]. Although these churches were mentioned as far back as the 10th century by Arab traveler Al-Mas'udi in the survey "Notice of Houses Revered by the Slavs"[25], and sporadically throughout the 17th century, by historic figures such as the Patriarch Maraii and as objects of attention by famous Slavic painters Atahanasius Klyrik and Yosyp Hochemskyi [25], they remained a sidenote to serious academic inquiry. However, as the culmination of national liberation movements, the rise of European Romanticism and an interest in studying one's own history and culture arose during the mid-19th century [25], so did interest in these seemingly "exotic" and "folk-costumed" cultures and their peculiar looking churches that dotted the hillsides amongst the small and remote villages of the Carpathian Mountain region. As such, a host of scholars from all countries that bordered on these regions began the first surge in academic interest in the subject [42]. For example, "within merely two decades, a host of Czech scholars studied all aspects of Rusyn [Carpathian] culture and produced a remarkable number of publications, many of which continue to be of value today" [42]. The most significant publications of this period such as V. Miskovskii's "Wooden Churches in the Carpathians" [43] published in 1880, and in publications by researchers T. and K. Moklovsky began to describe the overwhelming variety of church forms that occupied this region through artistic drawings, paintings, mapping of style group boundaries and locations, and comparative technical illustration of plans, elevations, detail drawings of various church styles [25].

During the 20th century, scholars shifted their focus towards the identification, classification and organization of these churches into their primary groups according to morphological characteristics, as well as construction techniques, and other non-material cultural / cultural influences. Early work that laid the foundation of this

generalized understanding of church form patterns, includes publications by V. Scherbakivsky, who first described and defined the Boyko church style in 1913, V. Zalozetsky, who defined the four main church types and their general distribution in the Transcarpathian region in 1926 [25], and M. Dragan's 1937 publication "Ukrainian Wooden Churches: Genesis and Development of Form" [44].

After a lull in interest during and after the two world wars, lasting until the early 1960's, and again throughout the 1980's during Soviet rule, more recent academic work tended to focus on characteristics of even smaller sub-regions and sub-groups of churches such as M. Syrokhman's "Churches of Ukraine. Transcarpathia" [45] where he focused on churches that reside within that region, or R. Sulyk's "Wooden Church construction in Stryi Region" [46], R. Brykowski's "Wooden Church Architecture on the Crown Lands of the Polish-Lithuanian Commonwealth" [47] where he illustrated where church sub-types were clustered within a specific region and Alexandru Babos's more recent 2004 publication "Tracing a Sacred Building Tradition: Wooden Churches, Carpenters and Founder in Marmures until the turn of the Century" where he diligently described the various particularities and sub-types of Marmures (Southern Transcarpathia) church types through technical drawings and maps that delineated major style locations and boundaries [48].

Most recently, academics like Yaroslav Taras [24, 25, 34] and Galyna Shevtsova [33], have attempted to unite this complex and largely fragmented research landscape by developing broader and more encompassing theories and surveys regarding the entire landscape of churches variation, including their genesis and development. While others, such as Mykhailo Syrokhman focus on uncovering and remembering lost churches and their histories through recent book publications and research projects while promoting the protection of churches that still stand [63]. Nevertheless, Taras laments that research has also hit a roadblock due in part by the "lack of comprehensive studies of building types using the cartographic method[s], [for example], drawing hundreds of plans, facades and putting them on thematic maps in order to identify the geography of the spread of characteristic architectural solutions and the boundaries of architectural and cultural districts" [25]. However, as DL-learning techniques provide the means to potentially do this, I believe contemporary tools leveraging AI may help experts to continue this history of research, conduct new studies, make interesting discoveries, and gain new insight into the folk culture of Carpathian wooden churches.

## Chapter 4 | Methods

### 4.1 Custom 3D Dataset Construction

#### 4.1.1 Summary of Technique

As large high resolution 3D datasets of rural, non-western, and niche building types are largely non-existent, the author had to create his own custom dataset of Carpathian wooden churches. Rather than manually modeling each church in digital space from scratch, the authors chose to use a 3D reconstruction technique to convert 2D images of churches into 3D models. Though there are many other 2D image to 3D model conversion systems available such as Bentley System's "Context Capture" [49] or Epic Games "Reality Capture" [50], these and other similar systems require hundreds of images taken within highly controlled environments with consistent lighting conditions, precise camera localization in order to create a 3D model. As hundreds of photos of Carpathian wooden churches with such rigid imagery requirements simply do not exist, nor was it feasible to travel to Eastern Europe take them myself, I chose to construct our dataset using a novel 3D reconstruction technique called Neural Reflectance Surfaces (NeRS) [23], which can convert just a few images taken in various lighting condition, with different cameras, and with different optical settings into "geometrically and texturally accurate water-tight 3D reconstructions" [23]. NeRS achieves this feat by greatly reducing its reliance on these rigid photo requirements and building upon several existing methods for defining geometry and surface radiance developed for the computer graphics industry [23]. As a tradeoff, however, the NeRS process requires a significant degree of manual image pre-processing and parameter setting to produce high quality 3d objects. Requirements include choosing the final images for reconstruction, providing object masks for each image, defining the horizontal and vertical rotation camera angle of each image in relation to the target object to reconstruct, defining the estimated field of view (FOV) of the images, and defining a geometric template that is similar in shape and size to the target object.

#### 4.1.2 Geographic Search Boundary

The wooden churches used as data within this research reside within the mountainous, foothill and watershed region of the Carpathian Mountain region of Central Europe. As this region encompasses upwards of two-hundred thousand square kilometers it quickly became apparent that searching for a collecting all wooden churches within this area was not feasible. Thereby, I chose the smaller central region of the Carpathian Mountain region as the area in which to search for churches and source imagery from (Figure 4-1). This smaller geographic region encompasses several unique cultural regions and as a result, includes most of the primary wooden church style-

variations. Some churches from outside of this region, though relatively nearby were also included in order to add further form diversity to the dataset.

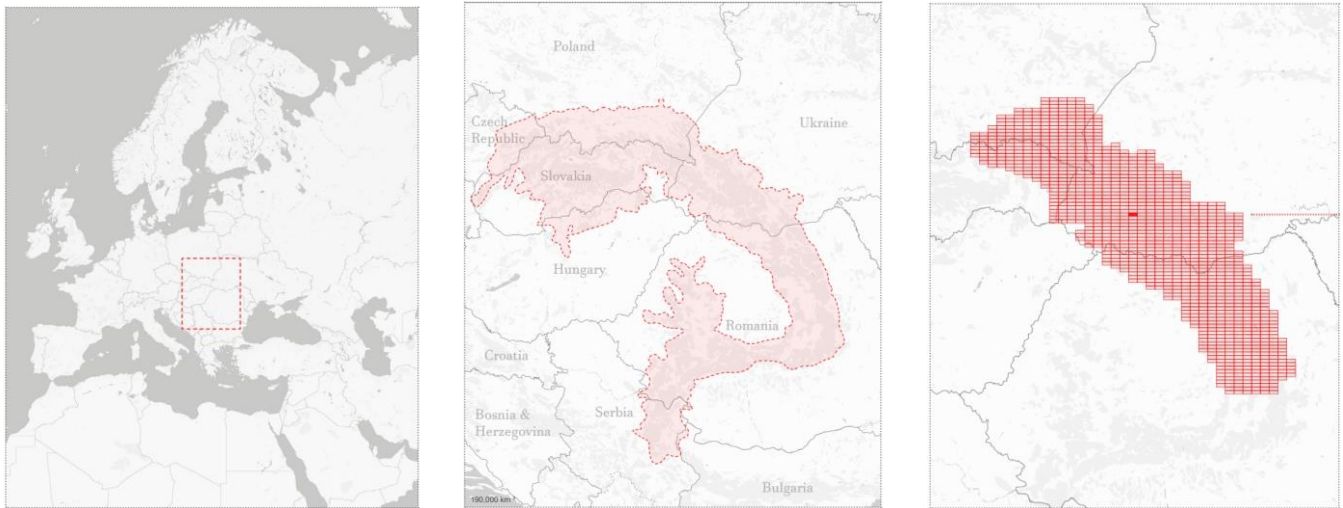


**Figure 4-1:** The search area to locate, collect and reconstruct churches. The location in respect to Europe as a whole (left), the boundaries of the Carpathian Mountain region (middle), the central Carpathian region overlaid with a search grid (right). Diagram by author.

#### 4.1.3 Image Sources

In order to build a 3D database of churches using NeRS, images covering all sides of the churches were located and collected. As no single source of images of all churches within this region exists, images were manually, and often painstakingly searched for and collected from a variety of sources. Sources included academics, independent researchers, online collections, repositories, news websites, social media platforms and search engines.

Academics who allowed me to use imagery from their own personal collections included Mykhailo Syrokhman and Olena Krushynska. Syrokhman, a professor at the Transcarpathian Arts Institute in Uzhorod, Ukraine and Ukraine’s leading expert on the Wood Churches of Transcarpathia provided images of churches that no longer exist, or have been inadequately documented, thus adding a unique dimension to the dataset that would have otherwise been impossible to obtain. Olena Krushynska, a Chemist at Kyiv National University, with a passion for wooden churches, had developed and continues to maintain a website for her project the “Wooden Temples of Ukraine” [51]; the most extensive catalog of wooden churches in all of Ukraine. On her website, she also meticulously documents each church location and provides a Google Map link, which was helpful as there were many churches within my dataset that were difficult to locate.



Church of Domashyn



Church of St. Nicholas



Church of the Nativity of the BVM

**Figure 4-1:** Examples of rare images of lost, or poorly documented churches graciously provided by Mykhailo Syrokhman.

Independent researchers include Maxim Ritus, who thoroughly documents the interiors and exteriors of hundreds of culturally significant buildings in Ukraine through technical land-based and drone photography (Figure 4-2). He records this ongoing project on a blog [52] which he continuously and frequently updates with both photographs and detailed descriptions of new buildings on nearly a weekly basis. He graciously gave me permission to use his photographs for this work.



**Figure 4-2:** An example of Maxim Ritus's technical and thorough photo documentation process which he carries out for each cultural building he surveys and posts to his blog [52].

The second source used to find and collect images of churches was Google maps, where a comprehensive search within the target region was carried out. In order to do this, a 16 mile by 9-mile search grid over the central Carpathian region was defined and allowed for systematic discovery, identification, and image collection. This

process, which took multiple weeks to complete, identified 275 churches, therefore being the most significant source for churches and church images. By scanning through satellite views of the landscape while searching for the term’s “church”, “wooden church”, and their Ukrainian, Polish, Slovakian, Hungarian translated equivalents depending on the search region, many churches not provided by previous sources were located. Once a church was found on Google Maps, and if available, crowd sourced images of the building could then be acquired as screenshots (Figure 4-3). However, as not all churches had imagery or had insufficient image coverage of all sides, supplemental images had to be searched for and collected from other sources.



**Figure 4-3:** An example of crowd sourced images found on Google maps for the Church of The Holy Spirit Shown here.

The third source used for acquiring images were independent websites that contained their own unique church image repositories. Images from this source were supplementary to the 3D reconstruction process that were not available via academics, independent researchers, or Google Maps. Some of the more helpful websites were “Castles and Churches of Ukraine” [53] a project that aims to catalog historic buildings in Western Ukraine run by Iryna Pustynnikova and “The Drymba Project” [54] which is a Ukrainian tourist and local history network. One of the most helpful independent website sources was the “Pslava” project website, which is a large database that includes images, drawings and detailed descriptions of over 70,000 historic and culturally significant monuments meticulously organized by region within various Central European countries developed by Mykola Zharkyykh [55].

The final source used for acquiring the most elusive church images were miscellaneous websites. These websites varied from news websites that may have published an online article on a particular issue surrounding a church, a community Facebook page where an image of religious event may have included a church in the background at the required missing angle, or a within a personal blog of someone who passed by the related building.

Finally, roof plan images of each church were acquired via satellite imagery sourced from the Google Earth application (Figure 4-4). Rather than acquiring images from Google Map's satellite view mode, the Google Earth app provides multiple satellite images of the same geographic locations taken at different time periods. This image variety is important as satellite views can often be low quality or negatively affected by long shadows during certain times of the day, or have objects covered by occlusions like leaves from trees or cloud cover. Having multiple image options provides a means to compare the images and select the one with the highest detail and the least occlusions.



**Figure 4-4:** An example of satellite images of roof plans sourced from Google Earth.

In total, over 10,000 individual images of 517 wooden churches were painstakingly collected in this manner (Figure 4-5). It is important to note that not all churches were able to be reconstructed in 3D do to insufficient or incompatible imagery.

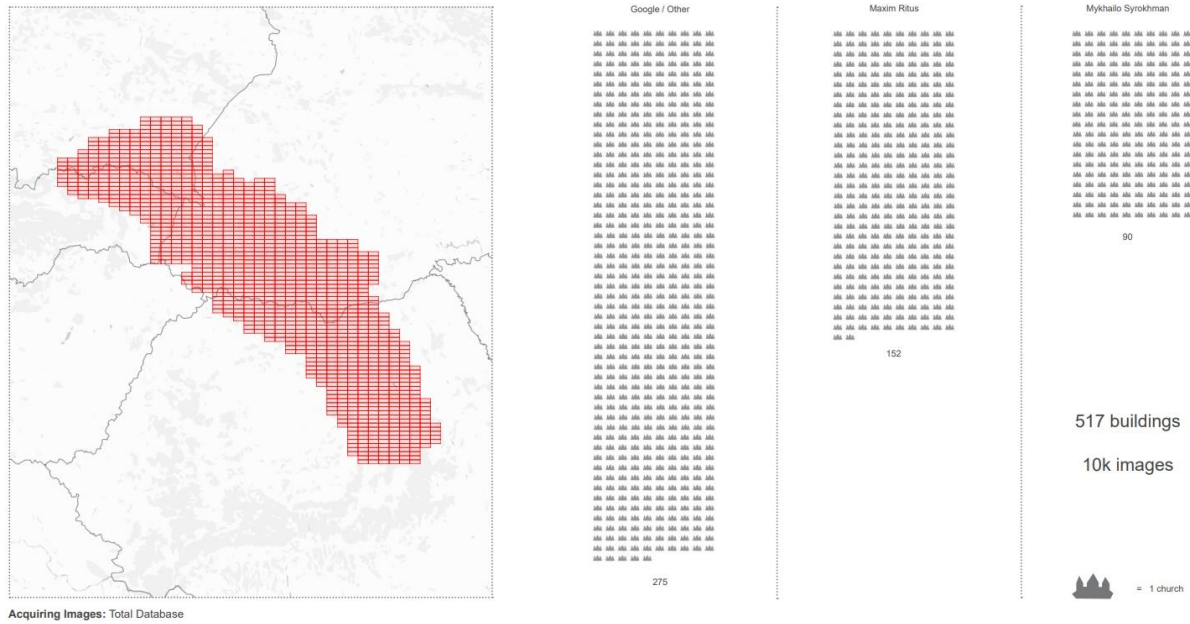


**Figure 4-5:** Breakdown of of image sources. 275 from Google / Other (miscellaneous websites, independent websites, Olena Krushynska’s collection), 152 from Maxim Ritus, and 90 from Mykhailo Syrokhman. Diagram by author.

#### 4.1.4 Image Pre-Processing

Next, the images for each church needed to be pre-processed and properly prepared in five stages. In the first stage, the final images required for the 3D reconstruction process need to be selected. Though many images of each church have been collected, not all of them will be used in the NeRS 3D reconstruction method. In general, images that share as similar field of views, lighting conditions, and vertical angles, as possible should be used as they produce the best reconstructions, though this is not required given the flexibility of the NeRS approach. In total, only 8-10 images need to be included. Included images should show the following sides of the building. front (0°), front left angle (45°), left side (90°), back left angle (135°), back (180°), back right angle (225°), right side (270°), front right angle (315°). However, as churches are almost always symmetrical, images for only half the church need to be acquired (Figure 4-6). These images will be later horizontally flipped to represent the other side of the building in step 5 of the image processing stage. In the second stage, a select number of images were required to be altered in order to ensure their associated church was accurately reconstructed in 3D. For example, images occasionally had to be manually editing or constructed to provide the front or rear elevations which, after much experimentation, was required by NeRS to create accurate 3D reconstructions. As images from directly in front or directly behind churches are not always guaranteed, “false” perspectives needed to be custom created to provide this angle through image warping or collaging multiple images together (Figure 4-7).

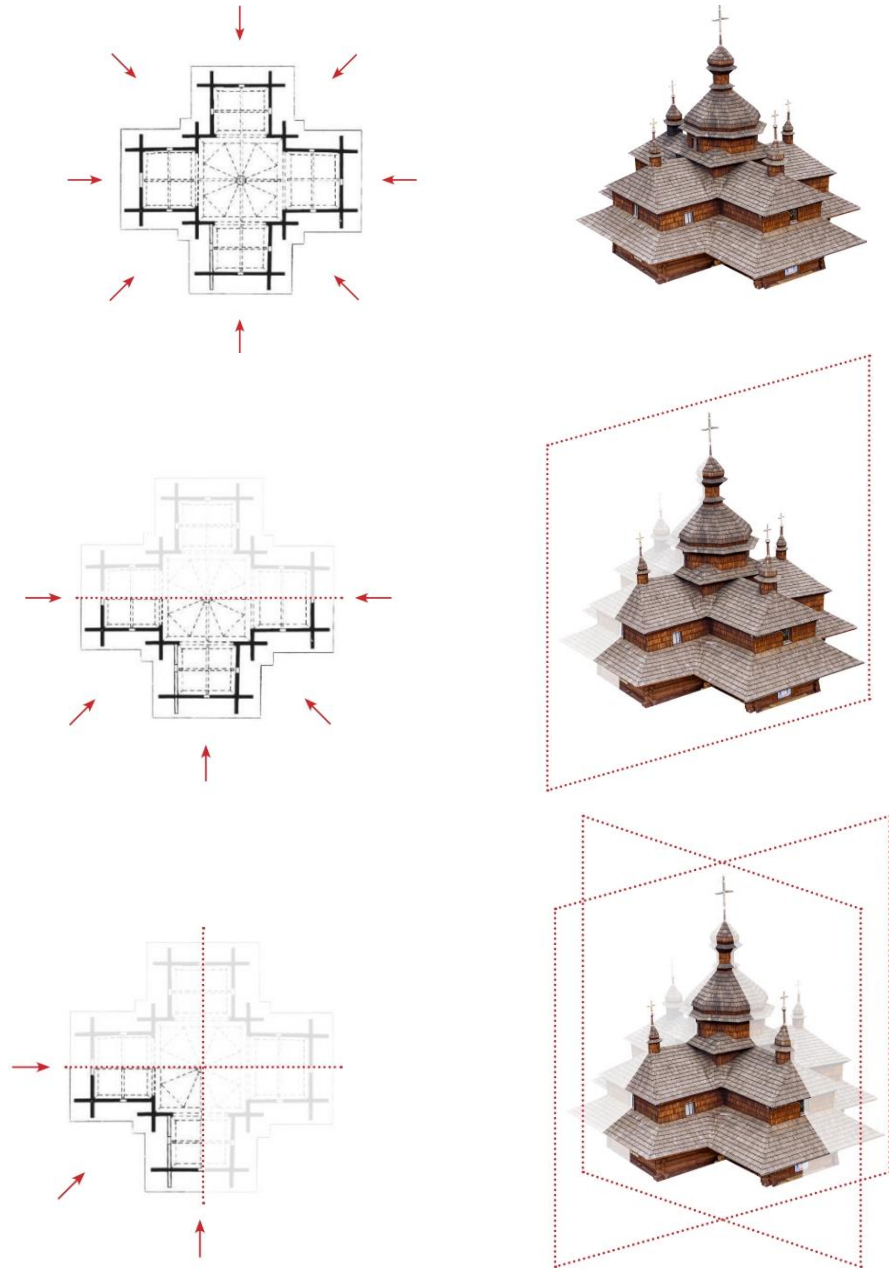


**Figure 4-6:** If churches are symmetrical lengthwise (middle), images of only half of the building are needed. If a church is symmetrical both lengthwise and widthwise, images of only one quarter of the building are needed. Diagram by author.

In addition, some images had major occlusions that needed to be removed manually, while others sometimes had FOVs that needed to be altered through image skewing techniques. All above edits were carried out in the photo editing software Adobe Photoshop. In the third stage, object masks needed to be provided for each individual image. As there are thousands of images, an object detection model was used to automatically detect the church and output an accurate image mask which represents the foreground volume of the church with white pixels and the background with black pixels. Providing these images ensures that NeRS only reconstructs the church, rather than its surroundings. However, image masks that included occlusions such as plants, people, and other objects in front

of the church had to be manually edited. In the fourth stage, both the horizontal and vertical camera angle between the camera and the church was manually recorded to a JSON file. These JSON files and their embedded angle information is necessary for the reconstruction process as it helps to determine how images correspond to the shape being reconstructed, and thus how images relate to one another. In the fifth stage, a custom script was created to automatically duplicate images and horizontally flip them to represent the other side of the building. Horizontal and vertical meta data recorded in the JSON file is also duplicated and modified to represent the newly created and flipped images. In the sixth and final stage, the dimensions of a shape template corresponding to the estimated approximate size of each church must be determined. A custom script was similarly produced to help expedite this process and save to the corresponding JSON file.

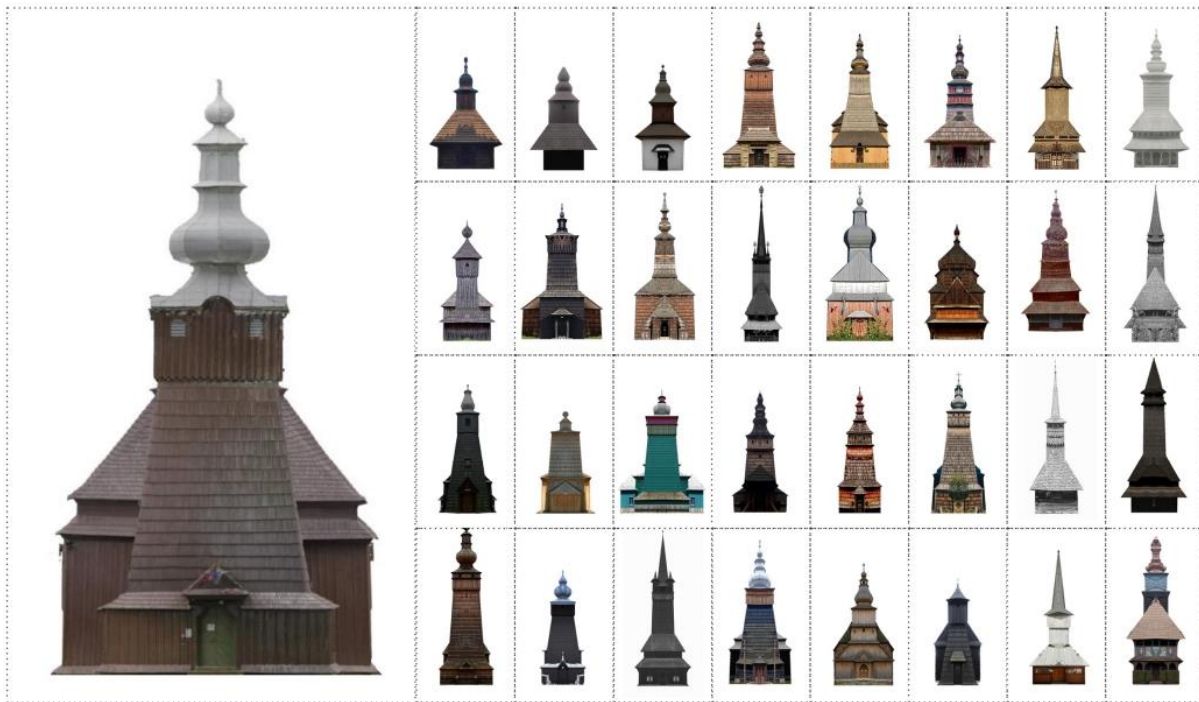


**Figure 4-7:** “False” front elevation images created manually by morphing existing images or collaging various images together. Images by author.

#### 4.1.5 3D Reconstruction using NeRS

Once all images have been preprocessed and their corresponding JSON files complete, the final stage of the reconstruction pipeline (Figure 4-8) was reached and each church was reconstructed from the images as a high-quality detailed mesh object using the NeRS algorithm. To reconstruct each church a remote computing cluster containing 4 GPUs (NVidia GeForce GTX Titan X with 12 GB of VRAM) was used to expedite this process. Once completed, the reconstruction quality of each church was manually inspected. Churches displaying unsatisfactory reconstructions were modified accordingly (image and image parameter modifications) and then

reconstructed again locally until satisfactory reconstruction results were achieved. Churches that could not achieve satisfactory reconstruction results were discarded. Out of the original 409 churches, 96 could not be reconstructed due to insufficient imagery. The final dataset of reconstructed churches includes 313 individual buildings (Figure 4-9).

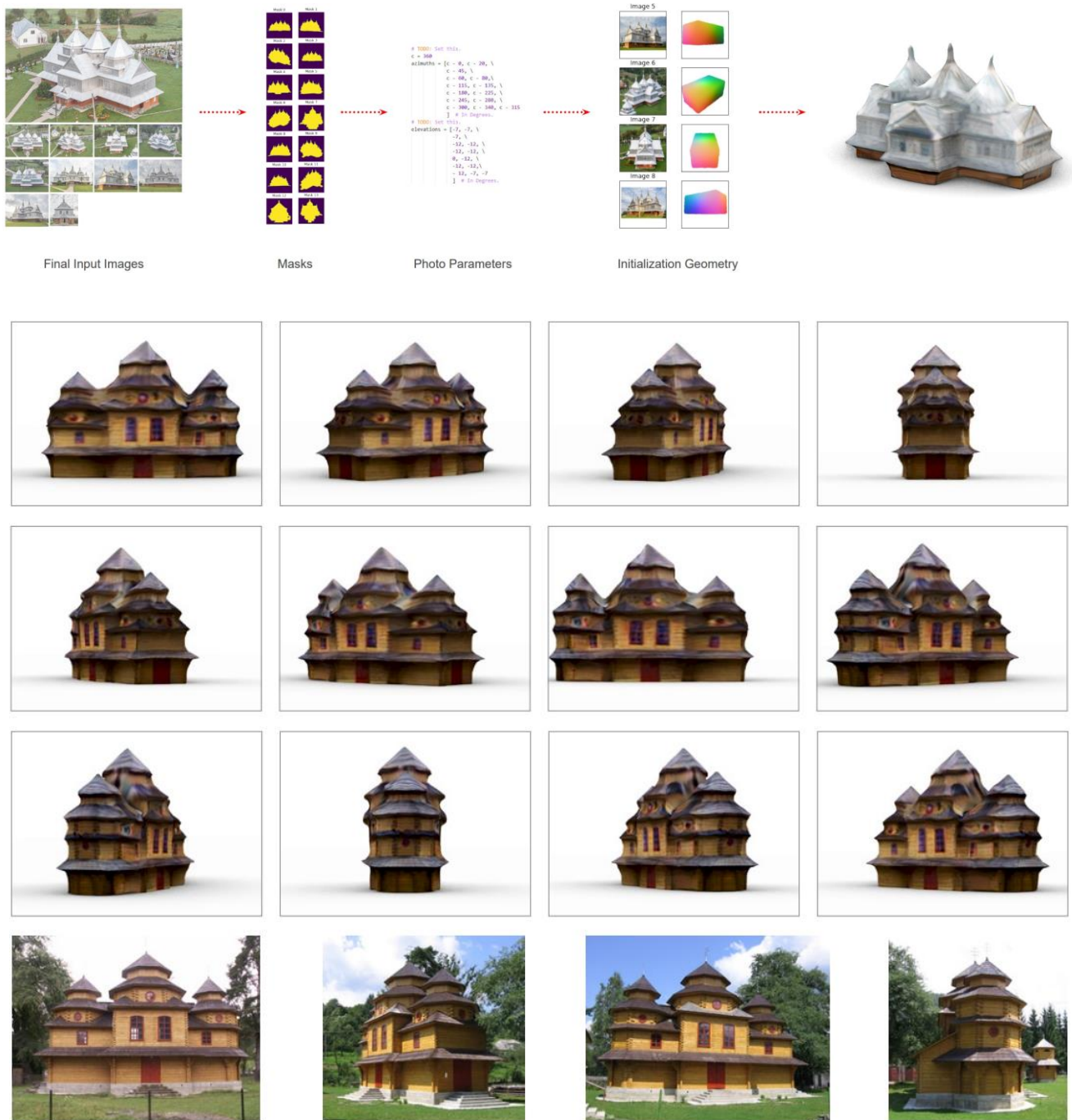


**Figure 4-8:** The NeRS pipeline [23] (top) and an example of a successful reconstruction (below). Diagrams by author.

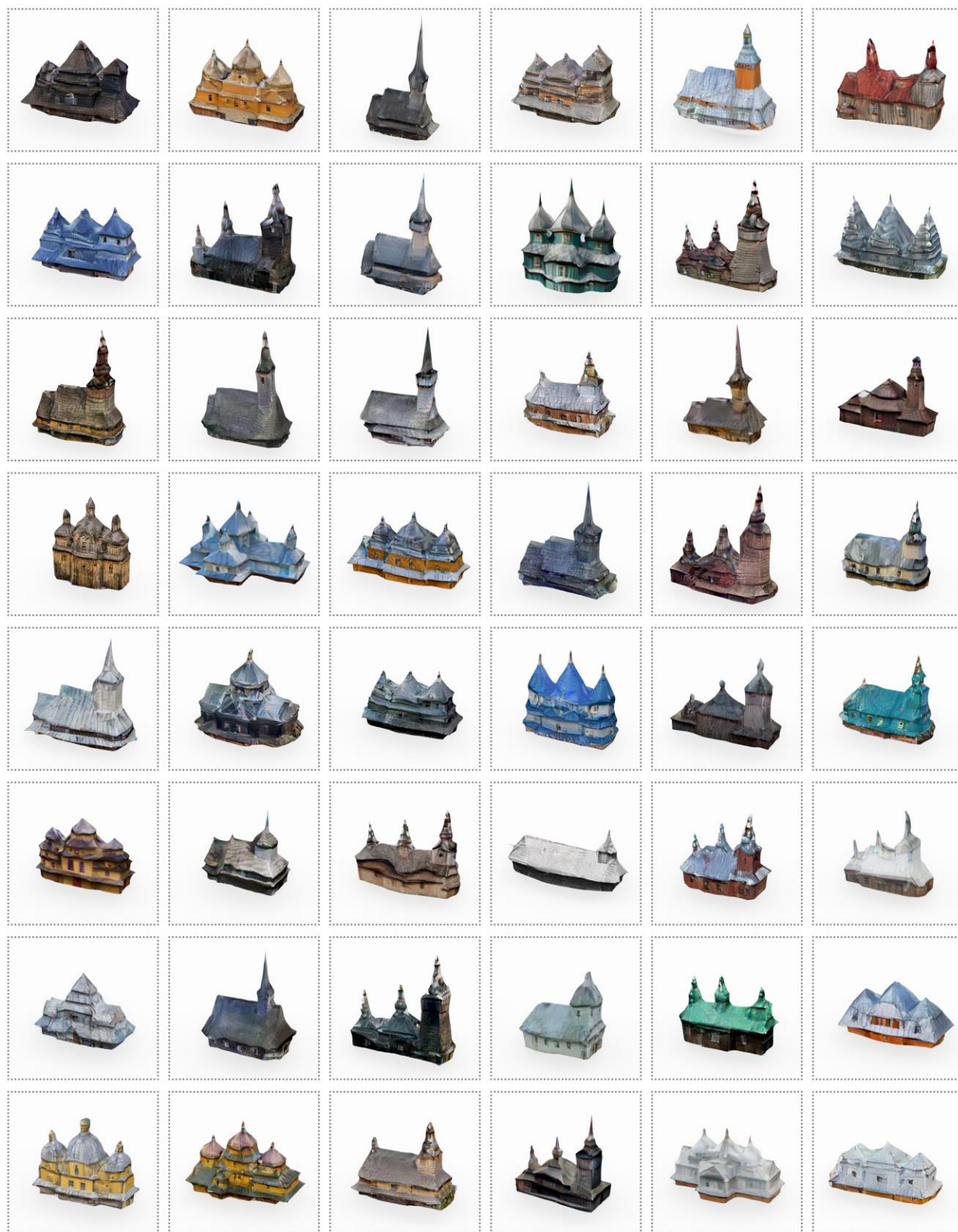


**Figure 4-9:** A sample of 48 3D church reconstructions displaying a wide variety of schools and sub-styles that are part of the dataset 3D models by author.

## 4.2 Model

The neural network architecture chosen for form analysis was a variational autoencoder (VAE) [19]. Similar to GANs [18], VAE are among the most widely studied and prominent generative models used within the field of deep learning for tasks like image synthesis [56] and novel 3D shape generation [44]. Though traditional VAE's do not achieve the sharpness and clarity in novel generations as compared to GANs [57], they can yield a robust manifold in a latent space through accurate encoding and robust mapping of visible variables ( $x$ ) to latent variables ( $z$ ) [19]. Here, a manifold can be understood as “groups or subsets of data that are ‘similar’ in some way. [58] While latent space can be thought of as “simply a representation of compressed data in which similar data points are closer together in space” [58]. As this thesis focuses on shape analysis, rather than novel generation, a VAE (Figure 4.10) model was selected due to its superior analysis operations such as pattern recognition, clustering, and various types of classification, all of which require robust manifolds in latent space.

Generally, VAE consists of two neural networks, the encoder (E), which converts input data into an encoded representation, and the decoder (D) which reconstructs the data from the encoded representation [19]. Together, VAE aims to "jointly [learn] deep latent-variable models and corresponding inference models using stochastic gradient descent" [58]. In other words, they aim to fit a probability distribution to the features of the data. When reconstructing these data features, there is a loss score which, in general, is the difference between the original and the reconstructed data. This loss score is then used to update the parameters of the distribution to better fit, or match the original data features, thus decreasing the loss.

To begin the process, the encoder abstracts high-dimensional data ( $x$ ), in this case a 3D church model, into a low-dimensional vector ( $z$ ), represented by numeric float values between 0 and 1 [19]. This data abstraction yields a distribution over a reduced dimensional latent space, with the number of dimensions determined by the number of numeric float values (also called latent vectors) chosen. For this project, I chose to use a 128-dimension latent space, thus our VAE attempts to accurately represent each church as a series of 128 individual float values, with each value representing a unique morphological characteristic identified by the model.

Next, the decoders job is to then reconstruct the original object as accurately as possible by sampling the original data from the latent space. If the encoder abstracts data poorly, a rough or inaccurate decoded output will result. This reconstruction loss ( $L$ ), or the difference between the original data and reconstructed data, is finally calculated by taking the sum of the expected log likelihood (E) (reconstruction loss) and the prior term (KL loss), which is then backpropagated through the network in order to update the networks weights and improve the encoder [19].

This iterative process of encoding, decoding then improving through backpropagation occurs over and over until the reconstruction error is reduced as much as possible and a satisfactory reconstruction output is achieved. However, unlike traditional Autoencoders which tend to overfit and produce irregular latent spaces that make data analysis or generation extremely challenging, VAEs address this by regularizing the encoder using a prior over the latent distribution  $p(z)$  [19]. Due to the stable and regular latent space and its advantages for analytical tasks, a VAE model was chosen to conduct all analytical experiments on our dataset. [19]

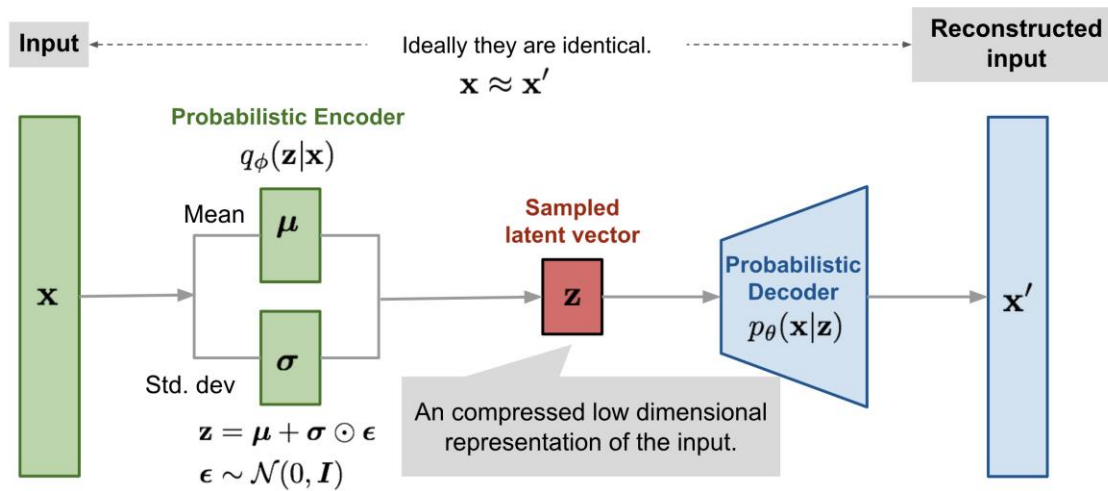


**Figure 4-10:** VAE Architecture. Image from <https://lilianweng.github.io/posts/2018-08-12-vae/>

### 4.3 Model Training

To train the VAE model on our 5,627-building dataset I used a computer custom built for deep learning operations which has the following specification: An Intel Core i9-10920X CPU @ 3.5 Ghz, a GIGABYTE X299X Aorus Master Motherboard, one NVidia GeForce RTX 3080 Ti GPU with 12 GB of RAM, and 128 GB of memory. Training was carried out using a VAE model for 1000 epochs over a period of just over 4 hours. To adequately tune the model for this task, the following hyper parameters were used: a batch size of 32, a single learning rate of 0.00005 with Adam optimizer, and a latent space size of 128. Data was split into a 5,065-object training set and 562 object test set using a standard 1:9 ratio. At approximately 330 epochs, the training and test errors intersected leading to slight overfitting and a final train - test error difference of 0.02. The final training loss was 0.34 and the final test loss was 0.32 suggesting only negligible overfitting (Figure 4-11). Convergence occurred just after 900 epochs. Reconstruction of the encoded data is show in Figure 4-12 and displays satisfactory results.

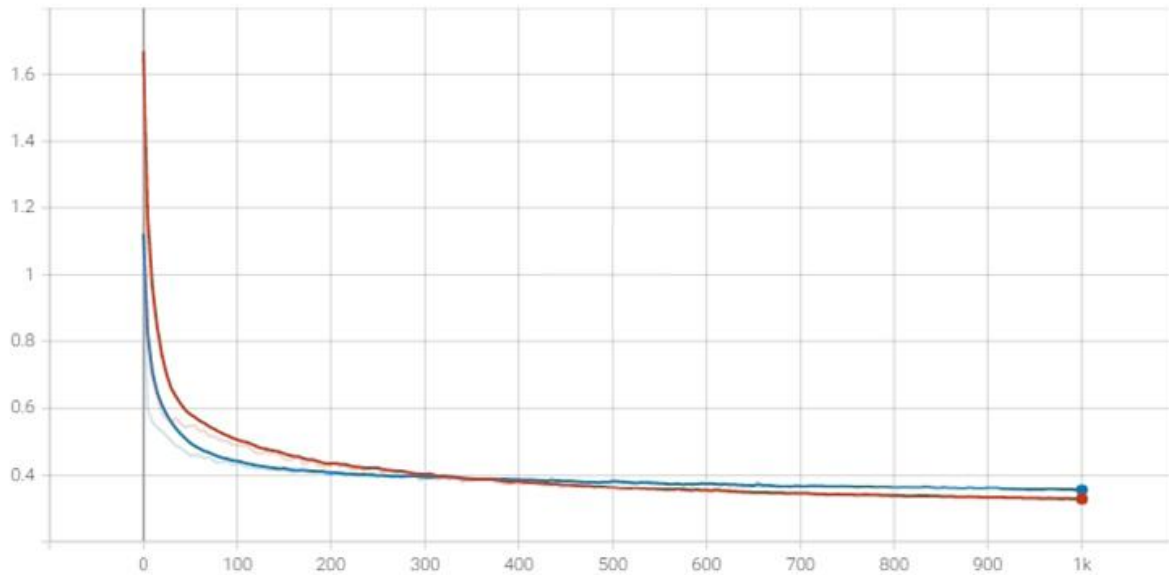


**Figure 4-11:** Losses during training process. Figure by author.

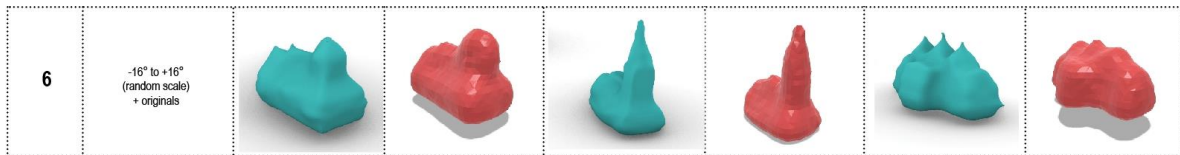


**Figure 4-12:** Ground truth models (green forms) being encoded and reconstructed by our model (red forms). Figure by Author.

## 4.4 Clustering

Once training was completed and the model could satisfactorily encode and decode the dataset, I was then able to cluster churches according to similar form and start searching for interesting groupings that might reveal unique church styles and sub-styles. The framework for architectural form clustering and investigation as described below was developed by Jinmo Rhee and demonstrated in his 2019 paper “Context-rich Urban Analysis and Type Investigation in the Form of High-rise Building Using Deep Neural Network” [64].

To begin this process, each original church needed to be individually transformed into its 128 latent-vector representation, or more commonly referred to as its “z-value”. However, as the dimensionality of these z-values is too high to visualize, they must be abstracted and reduced to just two dimensions. To do this, t-Distributed Stochastic Neighbor Embedding (t-SNE) [59] was used to reduce high-dimensional values, 128 in this case, to low dimensional representations, two in this case, while preserving as much of the original data distribution as possible. This is done to increase interpretability and allow us to visualize complex, multi-dimensional data. When

each of the 313 z-values are converted to just two dimensions (an x and y value) then displayed on a scatter plot, their position from one another within the plot represents their degree of morphological similarity. Thus, points that are closer together indicate church forms with increased similarity and ones that are far apart indicate church forms with less similarity. In this way, we can visually *see* and *understand* church's morphological relationship to all other churches within the dataset. Unlike traditional architectural diagrams, mapping and technical drawings that are often limited to describing a handful of buildings at a time, t-SNE dimensionality reduction provides an incredible amount of information and insight into data relationships by allowing us to visualize complex form patterns amongst hundreds or even tens of thousands of objects at once.

For this paper, I used the following t-SNE parameters to reduce the dimensionality of the datasets latent-vectors from 128 to 2. Number of components was set to 2, while perplexity, learning rate, and number of iterations remained at the default values of 30, 200 and 1000 respectively.

Identifying both complex and subtle clusters among hundreds or thousands of individual z-value points can be a challenging, if not impossible task dependent on the size and complexity of the dataset. To assist with this task, I used a technique called "Density-Based Spatial Clustering of Application with Noise" (DBSCAN) [60] which searches for and color codes clusters according to point density. Search parameters can be controlled by setting DBSCAN hyper-parameters such as the "minimum number of samples" (mns) in a neighborhood for a point to be considered a "Core point" of a cluster, and "epsilon" (eps) or the maximum distance between points to be considered as being within the same cluster neighborhood. In this way, clusters can be more easily discovered, explored and identified via color coding to reveal both large clusters representing broader church form similarities and smaller clusters that may indicate more niche or narrowly shared form characteristics.

By using DBSCAN, our church dataset was clustered in 3 different ways. First the data was partitioned into 6 large primary clusters according to broad church form characteristics, for example whether there is the presence of a single tower or not. Secondly, the data was grouped into 15 medium-sized secondary clusters suggesting the presence of various medium-sized sub-style groups. And finally, the data was separated into 49 small tertiary clusters suggesting the presence of numerous micro-styles. DBSCAN parameters used for the three clustering exercises are as follows. For the first primary clusters, eps was set to 1.936 and mns to 5. For the secondary clusters, eps was 1.7 and mns, 4. For the Tertiary group, eps was 1.23 and mns, 3. For all 3 clustering exercises, outlier samples that were within a maximum distance of 1.5 to a cluster and were not included in that cluster were automatically assigned to be included in that cluster.

## 4.4 Cluster Analysis

Once a cluster is established, it must be properly understood and represented. To recall, clusters, in this case, represent groups of churches that share similar morphological characteristics. To better understand what morphological characteristics are represented within an identified cluster and to allow for easier identification of form patterns, the following methods were established.

First, due to the small size of the dataset, it is possible to view an image of each church assigned to a particular cluster. Through subjective visual processes, such as church form comparisons to existing church style diagrams, reference to the original 3d models, domain knowledge gained from discussion with experts like Mykhailo Syrokhman, I was able to speculate which particular church styles or architectural characteristics were being grouped together. For example, churches with a single tall tower, or churches with three low towers of equal height that may indicate a Boyko style church. However, as clusters are formed based on 128 unknown characteristics, determining what primary shared characteristics define a particular is not always easy.

A second method learned from, and developed by Rhee [29], assists with this by sampling the nearest church point to the centroid of the cluster. As clusters are identified by t-SNE and propagated outwards from a central dense core cluster, it can be understood that the centroid represents the "typical" or "average" church form of that cluster. This provided me with the means to retrieve the "typical form" of each cluster, thus identifying the general morphology represented within the given cluster. Equivalently, defining the furthest church from the centroid and interpolating (morphing) between the two in 3D model space helps to visually see the range of morphological variation within the cluster.

Finally, we can also map each point within the cluster back to its real geographic coordinates and compare their distribution to existing research [25] that has defined the architectural-ethnic boundaries of the various styles and sub-styles of these churches. In this way, we can deduce which regional style(s) or sub-style(s) the cluster might represent. However, as regional boundaries overlap, and church styles can be found deep within other regions, resultant observations using this final method should be considered suggestive rather than prescriptive.

## Chapter 5 | Results

### 5.1 Existing Research Benchmarks

In order to evaluate our cluster results against existing research findings, I chose to use Yaroslav Taras's 2020 publication "Wooden Temple Architecture of the Ukrainian Carpathians" [25] as a ground truth benchmark for comparison and reflection. This was decided as the publication, to the best of the authors knowledge, represents the most current, extensive, and detailed description of the Carpathian wooden churches, their complex and interrelated styles and sub-styles and their geographic distribution within and around Western Ukraine.

In his publication, Taras paints a clear and definitive picture of the distribution, regional boundaries, and form relationships between the numerable styles and sub-styles of Carpathian wooden churches. He does this by defining clear geographic architectural style boundaries of Carpathian wooden churches according to both primary style-groupings (Lemko, Hutsul, Boyko, Transcarpathian, etc.) and secondary sub-style groups via detailed maps and diagrams. In addition to geographic boundaries, Taras also attempts to explain and illustrate how the entire landscape of various church styles are related to one another in terms of their morphological features, evolutionary roots, and ethnic origins (Figure 5-1).

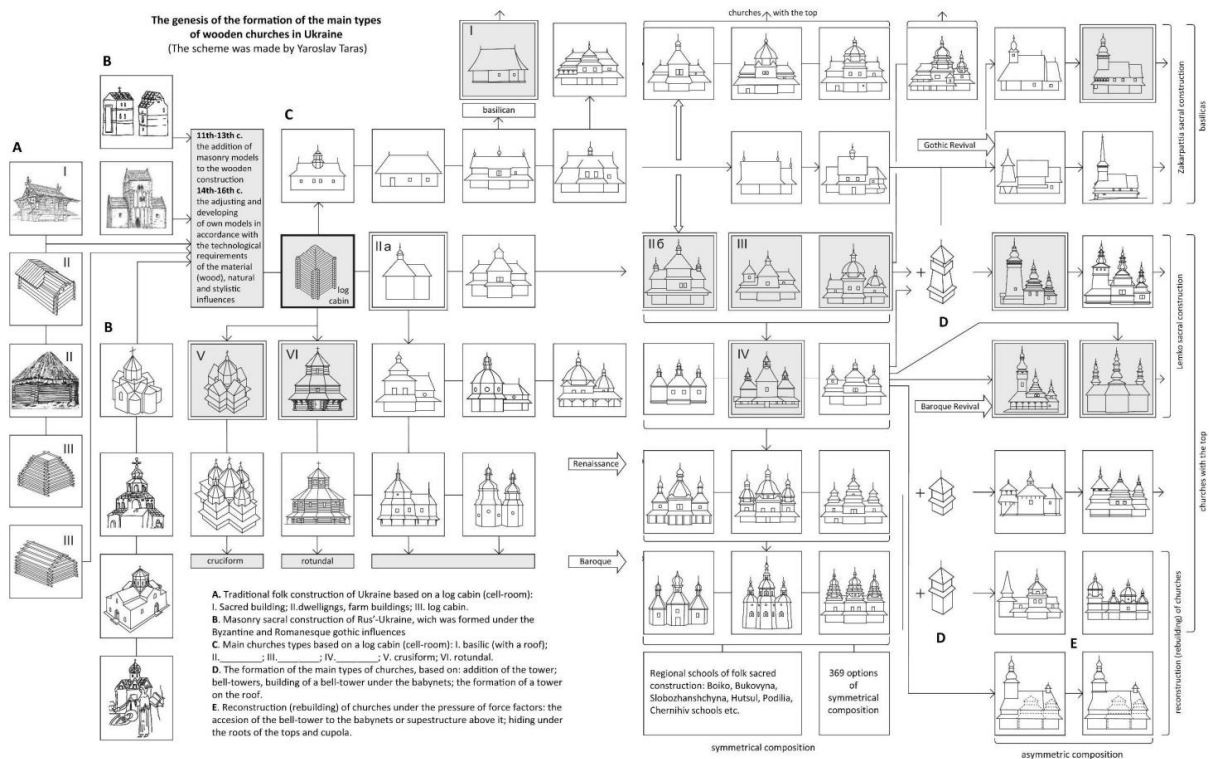


**Figure 5-1:** Taras's diagram showing "The Genesis of the Formation of the Main Types of Wooden Churches in Ukraine". [24]

The following diagrams from his book were the most helpful. First, his cultural architecture regions map (Figure 5-2), which defined geographic boundaries for the various schools of folk architecture construction. Here, boundaries were decided upon by not only the latest agreed upon cultural regions, but also through the acknowledgement of various historic, political, religious, geomorphological, climatic, and transportation-related factors that may have affected the distribution of the various architectural styles throughout the region [25]. By overlaying the clusters of similar style churches defined by the DL-model with Taras's church style maps, I was able to determine if there any style related correlations exist. Secondly, his architectural sub-style maps (figure 5-3) which suggest the geographic boundaries of the various sub-styles of the four primary schools of church architecture (Boyko, Hutsul, Lemko, and Transcarpathian). Similarly, by overlaying the DL-defined clusters of similar styled churches with these diagrams, I was able to determine whether any of the architectural characteristics within the smaller secondary or smallest tertiary clusters defined by our model correlated with any of the architectural styles associated with the overlapping cultural regions as defined by Taras. This allowed me to determine if the

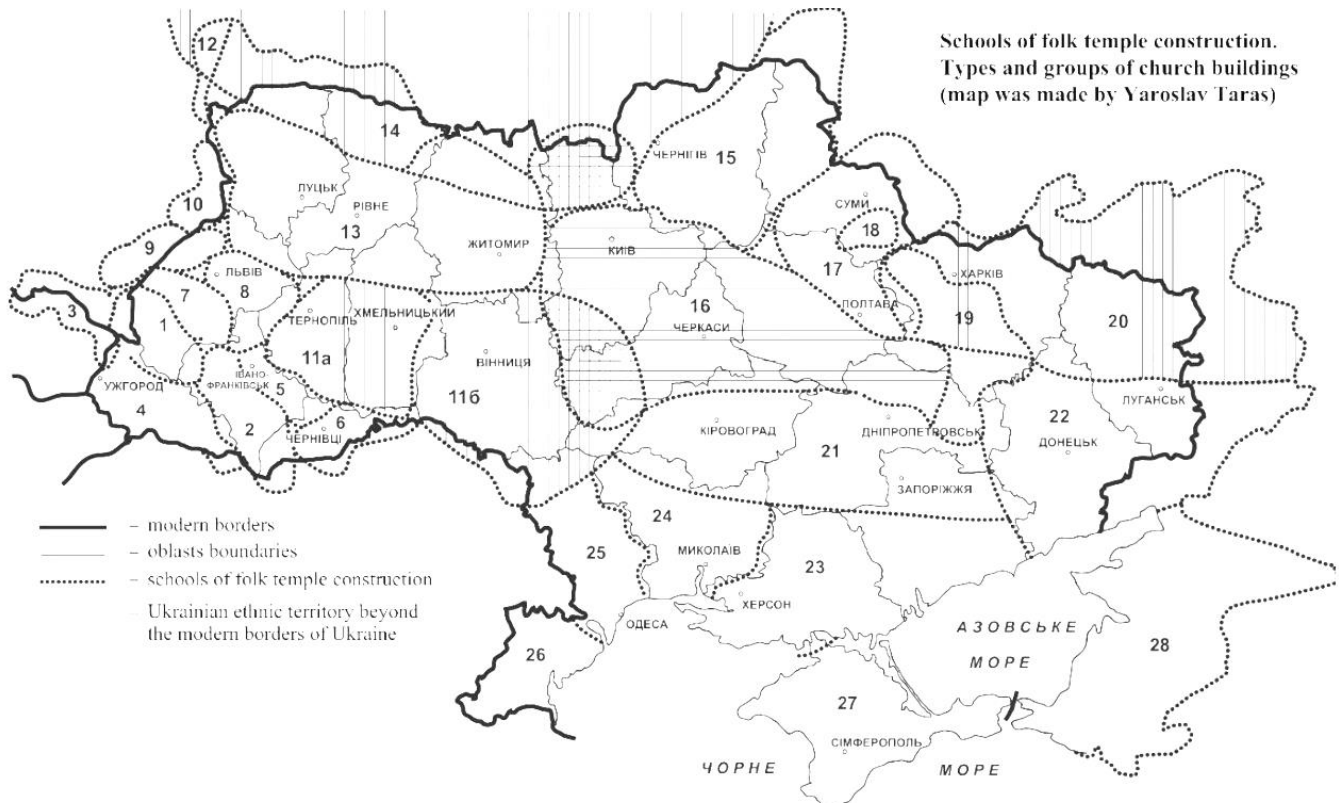


**Figure 5-2:** Taras's School of folk temple construction, types and groups of church buildings map. The following is the English translation for the regions indicated on the map which are most pertinent to this work. 1) Boyko, 2) Hutsul, 3) Lemko, 4) Transcarpathian, 5) Pokut, 6) Bukovina, 7) Pre-Carpathian Podnistrovska, 8) Opilska, 9) Przemsyl, 11a) East Podilia, 13) Volhynia [24]



## 5.2 Latent Space Configuration

After extracting and plotting the z-values of all 313 original non-augmented churches to an x-y grid, the result latent space distribution (Figure 5-4) appeared noticeably partitioned into large clusters. This initial observation suggested that the model was able to identify repeating and similar morphological patterns amongst the varying church forms within our dataset.

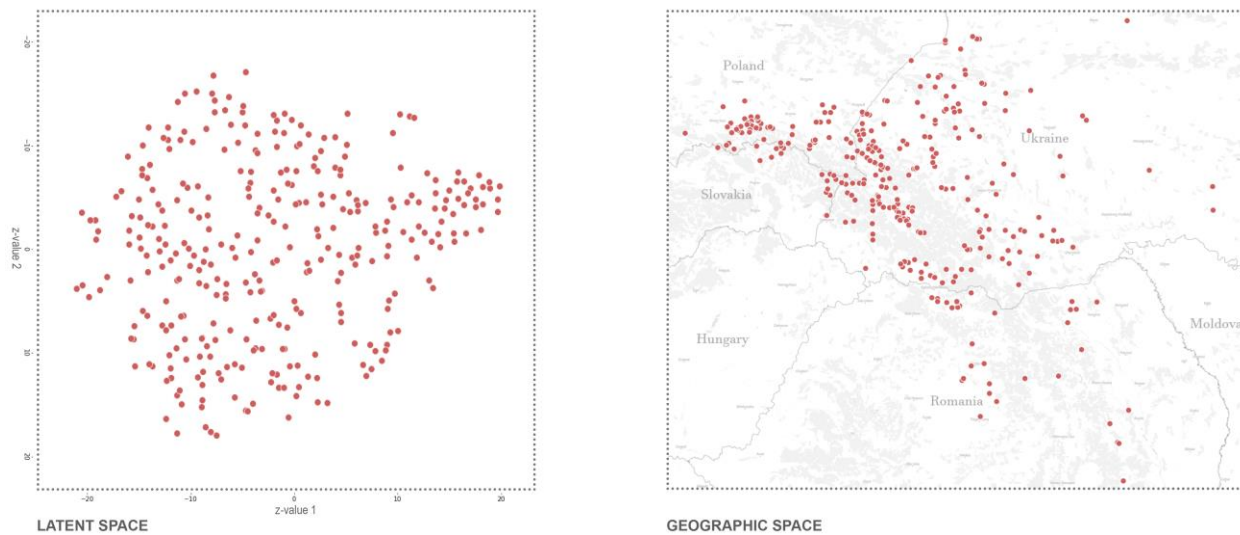


**Figure 5-4:** Latent space distribution of church dataset (left), geographic distribution of church dataset (right). Diagram by author.

## 5.3 Primary Clusters

With the help of DBSCAN, I was then able to objectively establish the size and range of these clusters and others and color code them into 7 primary groupings as shown in Figure 5-5, labeled Group 0, 1,2,3,4,5, and 6. See Section 5.5 *Data Clustering* for DBSCAN parameters used to identify clusters. By using the three methods of cluster analysis, I was then able to determine the general morphological characteristics and general church styles represented within each cluster.

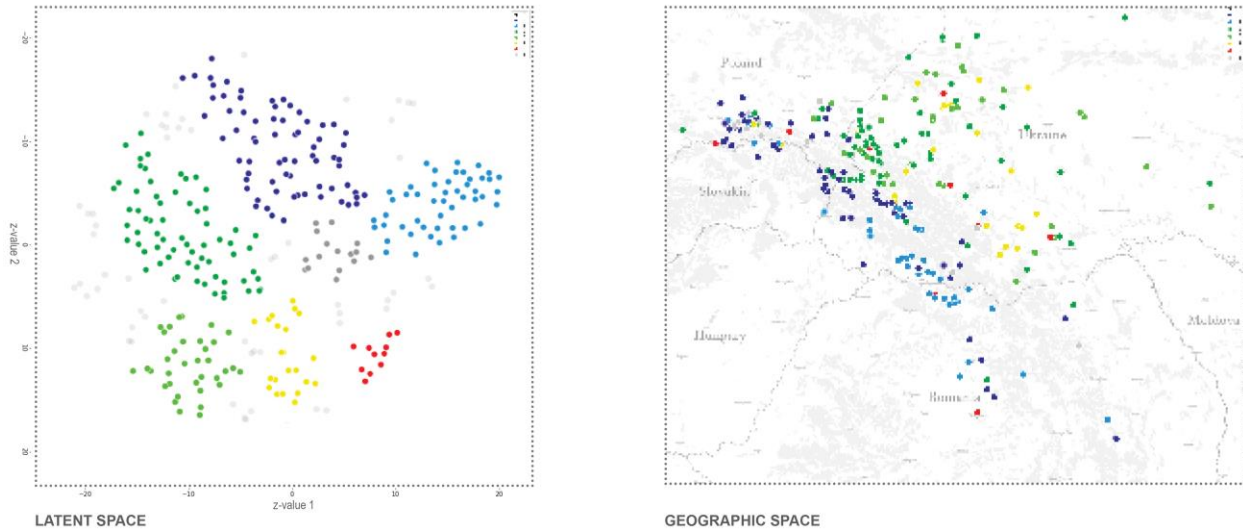


**Figure 5-5:** Primary clusters of churches that share similar form in latent space (left), and their location in geographic distribution of church dataset (right). Diagram by author.

### *Cluster 0*

Cluster 0 contained 70 churches that were spread out with moderate density (Figure 5-6). By referring to images and 3D models of each church within cluster 0 as well as existing research material, it quickly became apparent that all churches shared very similar morphological characteristics. The most noticeably dominant architectural characteristic was a single tower that emerges from the roof of the narthex, or entry space of the church. While 22.9% of these towers could be considered tall, the vast majority (77.1%) of them were short. In addition, 32.8% of churches had two or three towers in total, while 67.2% did not suggesting that this cluster possibly contained at-least two primary style groups. As a note, single tower churches sometimes had a small onion-shaped dome at the opposite end of the roofline, however, these domes were not considered “towers”. Secondly, nearly all the churches were organized around a linear tripartite plan, with no or very minimal side projecting spaces extending outwards from the nave space. While some Styles contain large extensions, creating cruciform like floor plans, such as the Hutsul School, these churches did not. Most of these churches incorporated a single or double stepped hip roof that extended backwards from the tower over the nave and then again over the smaller sanctuary space at the opposite end. Churches with and without single or double hip roofs make up 67.2% and 32.8% of the cluster respectively.

By finding the centroid of this cluster and viewing the closest church point to it, represented as the clusters “typical form” [64], our subjective observations were confirmed as this church contained all the morphological characteristics previously mentioned. Interestingly, the furthest church point from the centroid appeared to be

very morphologically similar to the central point. For example, having a single short tower over the narthex, a single hip roof from front to back, and a relatively small size with likely partite plan. However, after interpolating between the two churches in three dimensions, it was noticed that the further one had a much higher roofline, and a tower that did not stop at the roof above the nave but continued downwards and appeared to be nearly disconnected from the rest of the church. This interesting attribute suggested that there perhaps were multiple variations of this morphological type that needed to be explored.

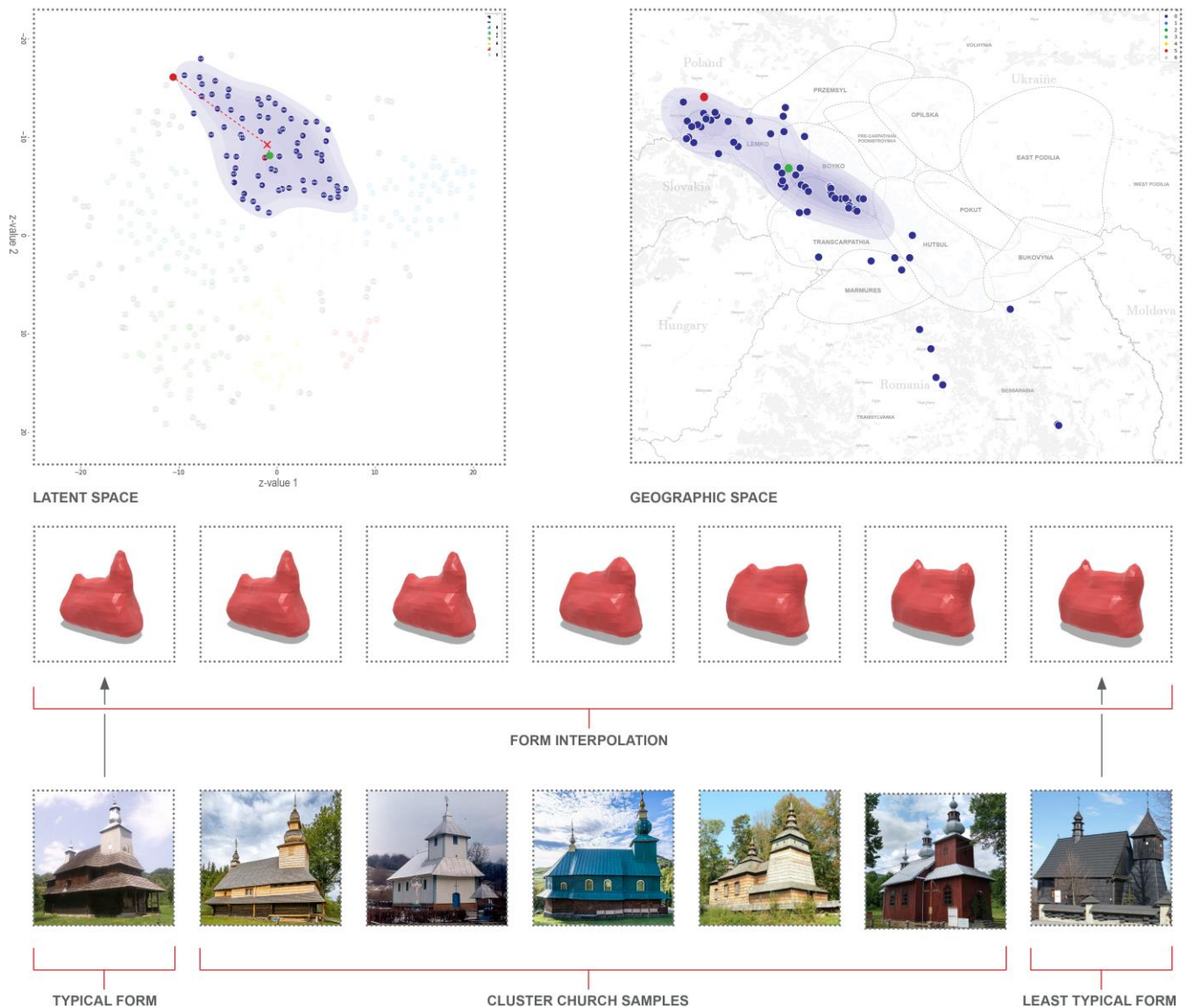


**Figure 5-6:** Primary cluster 0 in latent space (upper left), and its location in geographic distribution of church dataset (upper right), as well as the typical form (image lower left) and least typical form (lower right), and the interpolation between them (middle red forms). Finally samples of addition churches from that cluster (lower middle). Diagram by author.

Finally, by plotting the churches back to their geographic position, I was able to observe which architectural-cultural zones they fell into, as defined by Y. Taras style boundary diagrams, thus suggesting their possible primary style. Interestingly, though many of the churches appear to be morphologically similar, thus suggesting a single style, the churches in fact are clustered within two very different primary cultural regions, Transcarpathia and the Lemko region thus suggesting that the majority of churches within this cluster are of those corresponding schools of design. In addition, there is another cluster located within the overlapping area between these two zones. Closer inspection of churches within this overlapping area reveals a transitional zone, where Lemko style churches begin to look like Transcarpathian churches and vice versa, thus making it difficult to tell them apart by morphological characteristics alone. The typical form as indicated by the green dot is in this zone and is of Lemko style of the East (Snynskyi region) sub-type [25]. This also suggests that further clustering must be done if we hope to determine the various church style sub-groups, or other previously unknown / undescribed sub-group morphological relationships or patterns within this primary cluster. Churches with similar morphology exist in the Transylvania and Bessarabia region as well [25], indicating that morphology can be shared and blended across multiple cultural regions.

### ***Cluster 1***

Cluster 1 contained 65 churches that were densely located within a single area (Figure 5-7). Like Group one, a single tower that emerges from the roof of the narthex, or entry space of the church was the most noticeable morphological trait. This was the case for 77.7% of the churches located in this group. Like cluster 0, this group also had several churches that contained 1-2 additional towers making up 25.4% of the dataset, again suggesting that this cluster possibly contained at least two primary style groups. As in cluster 1, this group also showcase a narrow linear tripartite plan without significant side projections from the nave. Similarly, the dominant roof type is a single or double stepped hip roof which was present in 73% of the churches.

The typical form centroid of this cluster revealed that this cluster represents a similar style of church as cluster one, however with a much larger and taller tower, often with a dramatically tall, pointed roof above the narthex. In addition, the single or double roof lines are higher than cluster 1 as are the exterior side walls from the ground to the bottom side of the roofline. In general, the roof also appears to be at a steeper angle, as does the roof which caps the tower and rises much higher in elevation. Overall, the form is tall and narrow, showcasing the hallmark indicators of a linear tripartite plan which is often slightly wider in the middle, and slighter shorter and narrower at the rear where the sanctuary is located [25]. By finding the furthest point, we can see that the tower is

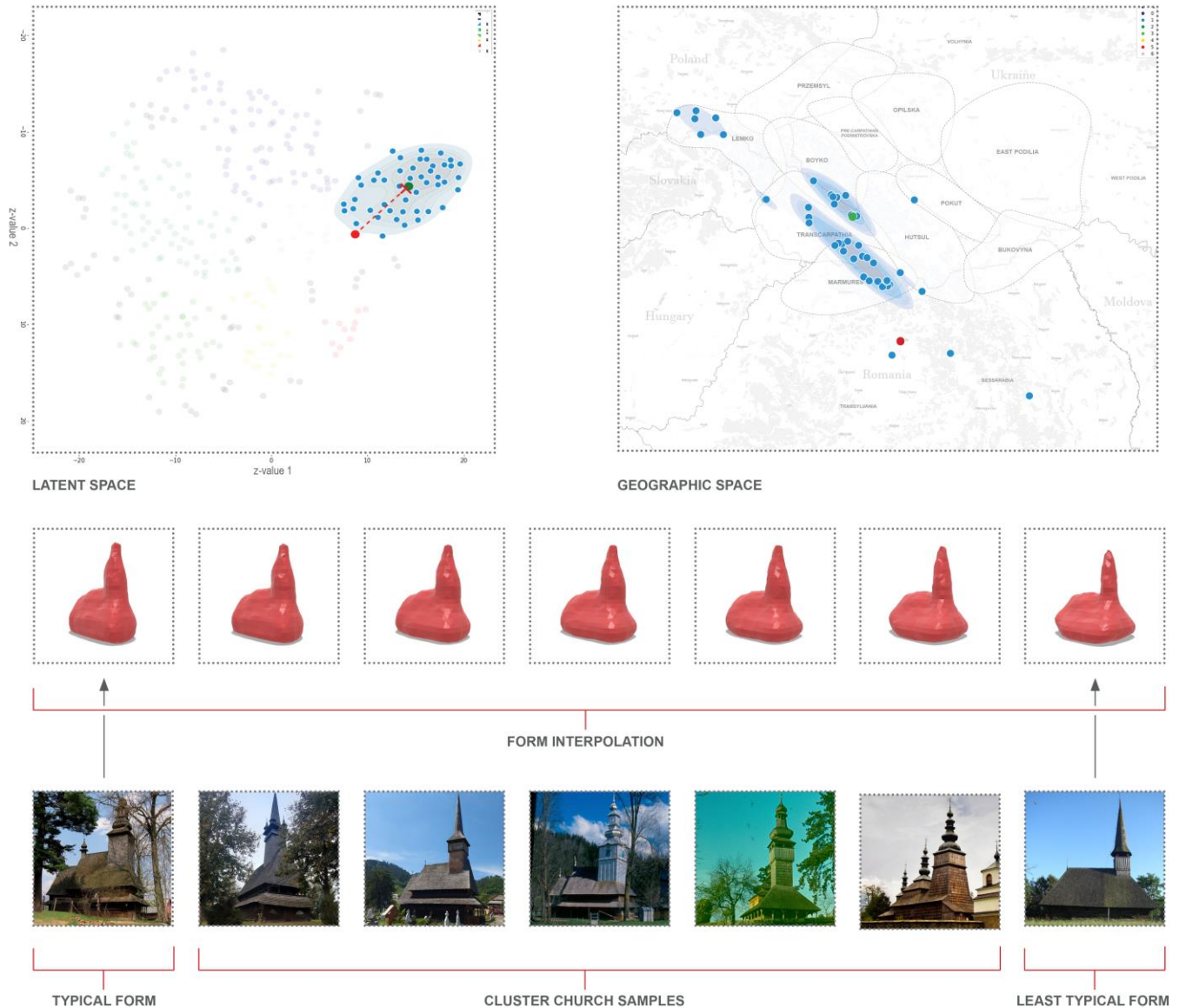


**Figure 5-7:** Primary cluster 1 in latent space (upper left), and its location in geographic distribution of church dataset (upper right), as well as the typical form (image lower left) and least typical form (lower right), and the interpolation between them (middle red forms). Finally samples of addition churches from that cluster (lower middle). ). Diagram by author.

much narrower and is set slightly back from the front. The roof height is also lower and is in the form of a wider single roof that covers both the nave and sanctuary and sides of the narthex. The roof is also at a shallower angle and less dramatic than the typical form. This suggests the inclusion of alternate, potentially outlier style groups.

Finally, by plotting the churches back to their geographic position, we can observe that the churches fall into three general zones. In the Northern section, they fall into the Lemko region, as some churches within the cluster contain the hallmark morphological characteristics of that style (three towers plus pyramidal roof shapes

below). Though they are clustered with the other churches, they are quite unique and less related to the rest. The second group is clustered in Transcarpathia and within an area of overlap with the Boyko region. However, these churches represent the hallmark signs of the Transcarpathian school, being a single tall tower, single or double hipped roof, and a linear tripartite plan. Finally, the southern cluster represents churches within the Transcarpathia Marmures area, which are quite similar to the middle group but contain much taller pointed towers in the Gothic style of that region.

## ***Cluster 2***

Cluster 2 contained 63 churches that were with medium density located within a single area within latent space (Figure 5-8). The most noticeable architecture element shared by 61.5% of the churches within this group is the presence of 3 pyramidal or sometimes dome towers with the middle one the highest, strongly indicative of the Boyko school of folk architecture. Of the remaining 38.5% of churches, 27.7% have a dominant central dome in the middle of the church with the remaining 10.8% having none or some other configuration indicating that perhaps the cluster is too large. Beyond the presence of a central pyramidal or dome tower, what ties all churches together is the presence of the narrow, linear tripartite plan and generally tall, narrow and long configuration of the 3 main volumes capped with one or three pyramids' roofs or domes.

The typical form centroid of this cluster reveals a classic-style Boyko church with three tall towers surrounded by multiple tiers of decreasing sized zaloms, or rings of narrow roof overhangs that continue up the height of the tower. Though not indicative in the 3D model, which is abstracted, one can easily see the three towers and the generally long and narrow plan that makes up the tripartite configuration. The central tower is also noticeably taller than the other two, thus indicating the typical Boyko church configuration. With the furthest or "least-typical" point, we can see that only a small central tower remains flanked by two hip roofs of equal height. However, the lower volume of the church equally indicates the same tripartite plan with almost the exact same proportions as the typical form, thus indicating that the proportion of plan may be more influential on the formal characteristics of this cluster than previously considered.

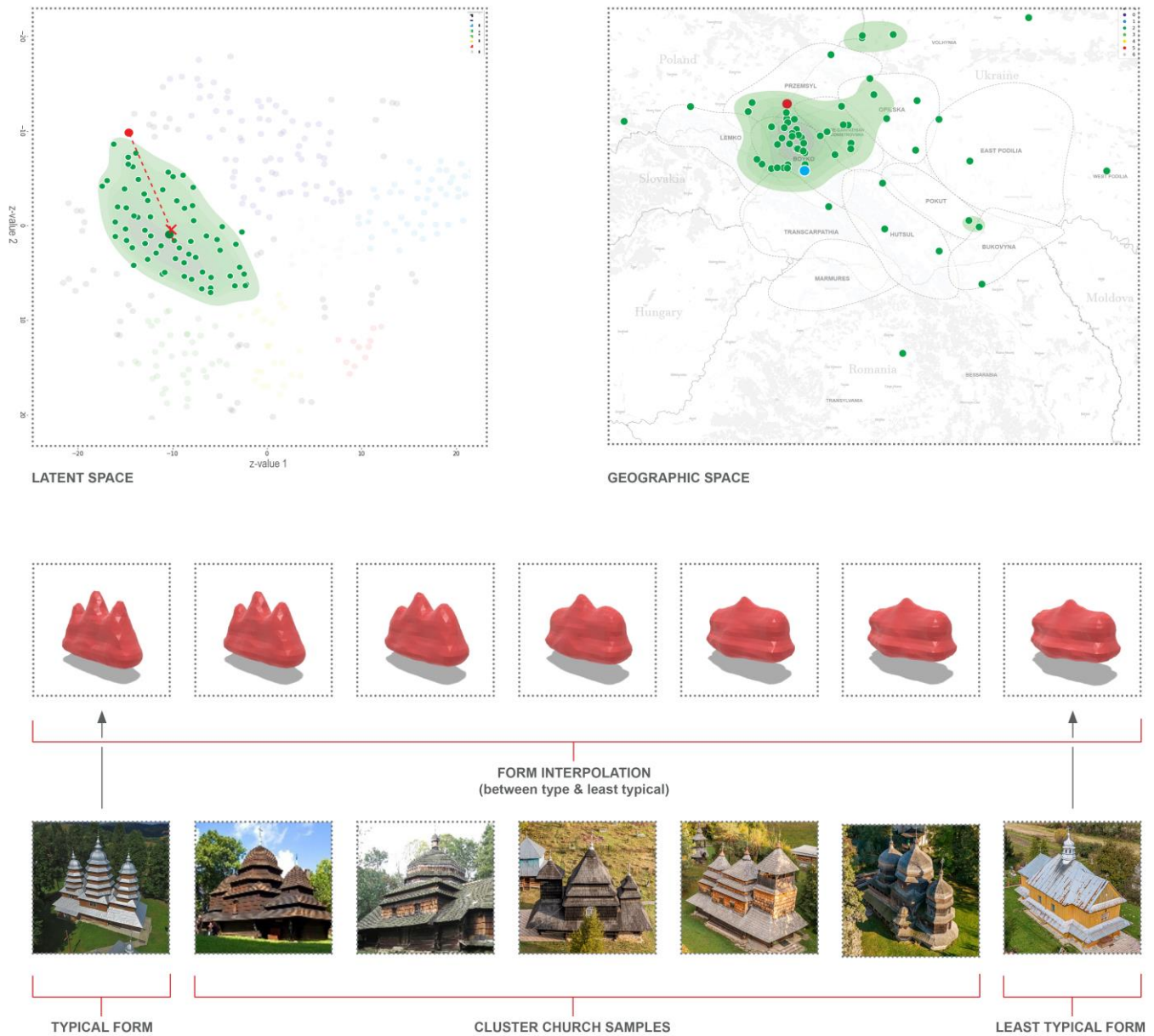


**Figure 5-8:** Primary cluster 2 in latent space (upper left), and its location in geographic distribution of church dataset (upper right), as well as the typical form (image lower left) and least typical form (lower right), and the interpolation between them (middle red forms). Finally, samples of addition churches from that cluster (lower middle). ). Diagram by author.

Finally, by plotting the churches back to their geographic position, we can observe that the churches are in highest concentrations within the Boyko region as well as neighboring regions such as the Przemsyl, Lemko, and Pre-Carpathian Podnistrovska regions. There are also noticeable numbers of churches located in other, more distant regions such as within Volhynia, Opilska, Podilia, Pokut and Hutsul zones, indicating that churches with similar Boyko-like morphology can be found in other regions as well. As Boyko churches do not always have three towers, and often just one, it becomes challenging to differentiate other single central tower churches with

tripartite plans from other cultural regions such as Opilska or Volhynia. In addition, similar churches in these other regions can also have three-tower churches, therefore further complicating classification beyond pure morphology.

### ***Cluster 3***

This cluster contains 39 churches that are located with medium density just below cluster 2 (Figure 5-9). The churches within this cluster share many morphological similarities as the previous cluster which contained mostly Boyko style churches. However, what can immediately be noticed is the vertically stretched volumes of the tripartite plan before they transition into towers. This feature seems to tie these churches together, in addition to the presence of a dominant central tower (48.7% of churches) which in some churches flanked by two slightly shorter towers in Boyko-like style (51.3%). This nearly 50/50 split separates the cluster into two distinct groups, however, similar to the previous group they all share the same tripartite plan, though 23% of churches show noticeable widening of the central nave space, thus indicating possible influence from the Hutsul School which is the only primary style which has nave extensions and cruciform-like plans.

The typical form of this cluster appears quite like the typical form of cluster 2, however, in a side-by-side comparison, it shows significant vertical stretching of the main church volume below the start of the towers. This vertical emphasis reaches its maximum in the least-similar form which has pronounced vertical elongation capped by three domes that narrow and terminate at a sharper point. Additionally, the widening of the central volume which holds the tallest dome can easily be seen, thus suggesting that the morphometric characteristics of cruciform plans are being included within this cluster

By plotting the churches back to their geographic position, we can see that the churches within the cluster primarily fall within two cultural regions, being the Boyko and Opilska regions, however, are also overlapping in the neighboring region of Przemsyl. This indicates the presence of similar morphological characteristics within these three zones. Another smaller cluster is in the Pokut zone, which, to the best of the authors knowledge, can have church styles characterized by slightly cruciform plan and vertically stretched volume and a small cluster in Podilia. We can also see how the least-typical church form is located far outside of these groups, indicating its outlier state given its lack of geographic neighbors. However, its form does begin to come close to a number of churches located in the Pokut zone. Given this mixture, Cluster 3 clearly contains numerous styles that although are the result of the unique communities within these different cultural regions, do share several interesting overlapping morphological traits.

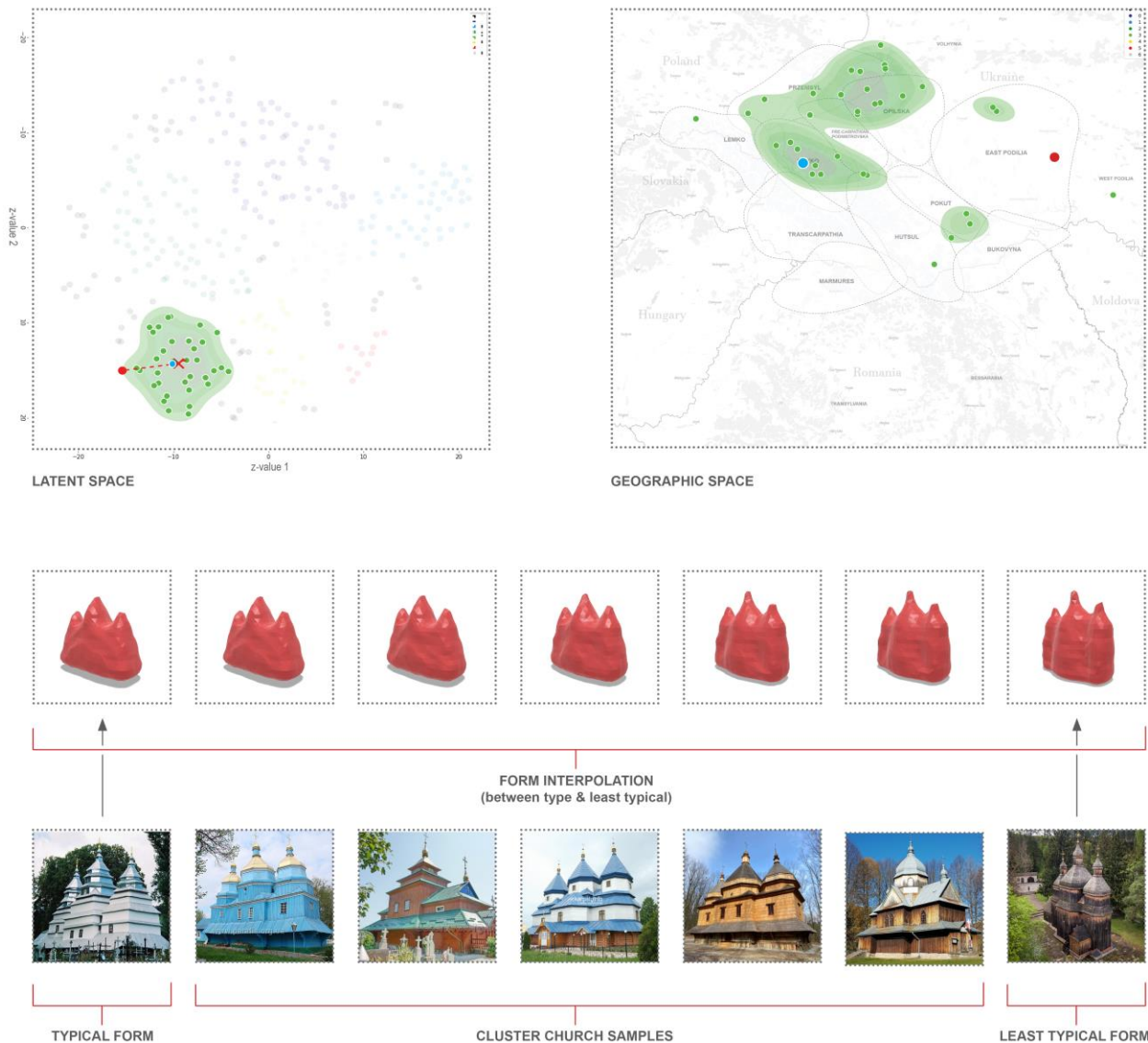


**Figure 5-9:** Primary cluster 3 in latent space (upper left), and its location in geographic distribution of church dataset (upper right), as well as the typical form (image lower left) and least typical form (lower right), and the interpolation between them (middle red forms). Finally, samples of addition churches from that cluster (lower middle). ). Diagram by author.

### Cluster 4

This cluster contains 22 churches that are located with medium density to the right of cluster 3 (Figure 5-10). The churches within this cluster seem to fall into two general categories. First, 45.4% of them that have a dominant cruciform plan organization while 54.6% have are organized volumetrically according to a linear tripartite plan. Those with cruciform plans typically have a single central tower (80%) with the remaining 20% having three towers with the middle tower being the tallest. Those with a linear tripartite plan are split into two primary

groups, with the first (41.6%) having a single central tower, and the remaining ones having three pyramidal or dome like towers with the central one being the tallest. Thus, tower count was not the primary trait of this group. By comparing churches within this group to existing studies and domain knowledge, this cluster was determined to contain the morphological characteristics that suggest that both the Hutsul school, which here is represented with a cruciform plan with one or three central towers, and Boyko style, which here is represented by the churches with linear tripartite plans with one central or three towers. However, some churches which appear to be Boyko suggest the Opilska school which are in some cases can be morphologically similar.

This mixture of Schools can be seen more clearly when plotting the churches back to their geographic position as they tend to fall into three primary cultural regions. First, the Hutsul zone which is characterized by cruciform plan including the neighboring Pokut school can include similar morphological features, the Boyko School and the Opilska School. This cluster is perhaps too broad and accounts for too many morphological categories (cruciform plans and tripartite plans), suggesting that further secondary clustering should be done

Interestingly, interpolating between the typical and least-typical form of this cluster does not showcase these two groups (5-11). Rather, it shows two churches that both have linear tripartite plans, with the least-typical form being a very extended and long version of the typical form. If we refer to latent space, we can see how the typical form is taken from between two smaller vertically stacked clusters, and the least-typical form is taken from the top cluster. From this observation and through other analytical means, we can deduce that the top small cluster represents churches with linear cruciform clusters incorporating the hallmark Boyko and Opilska architectural characteristics, and the lower one tends to represent churches with Cruciform organizations indicative of them belonging to the Hutsul or Pokut style. By interpolating between the typical form of these two groups, we can see

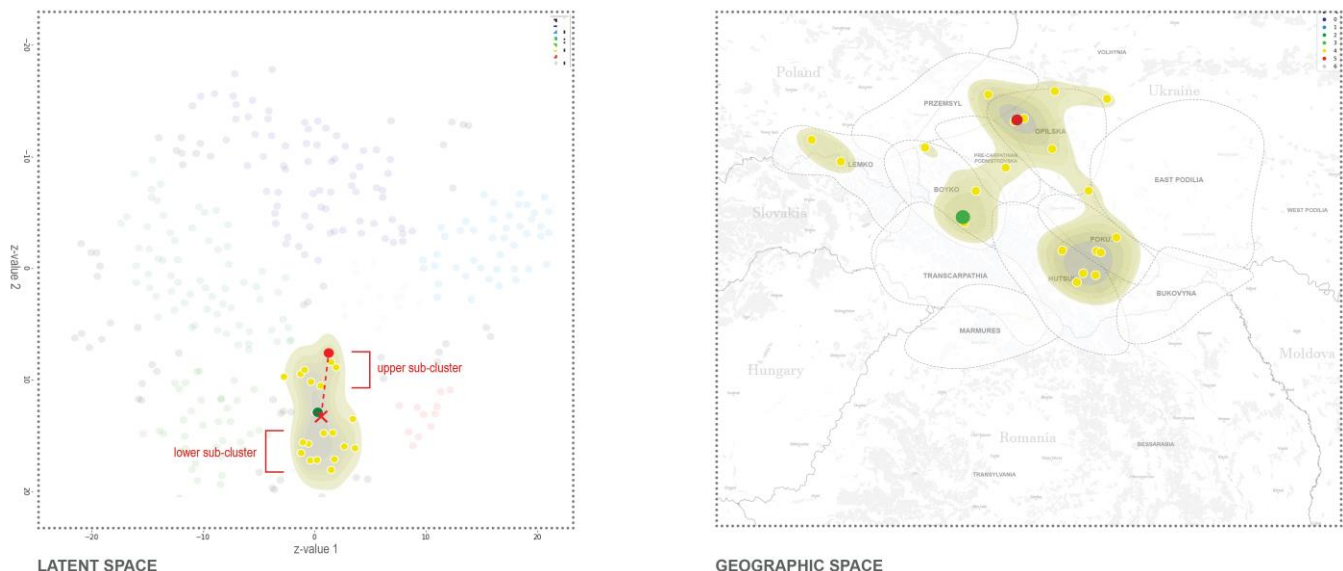


**Figure 5-10:** Primary cluster 4 in latent space (upper left), and its location in geographic distribution of church dataset (upper right)

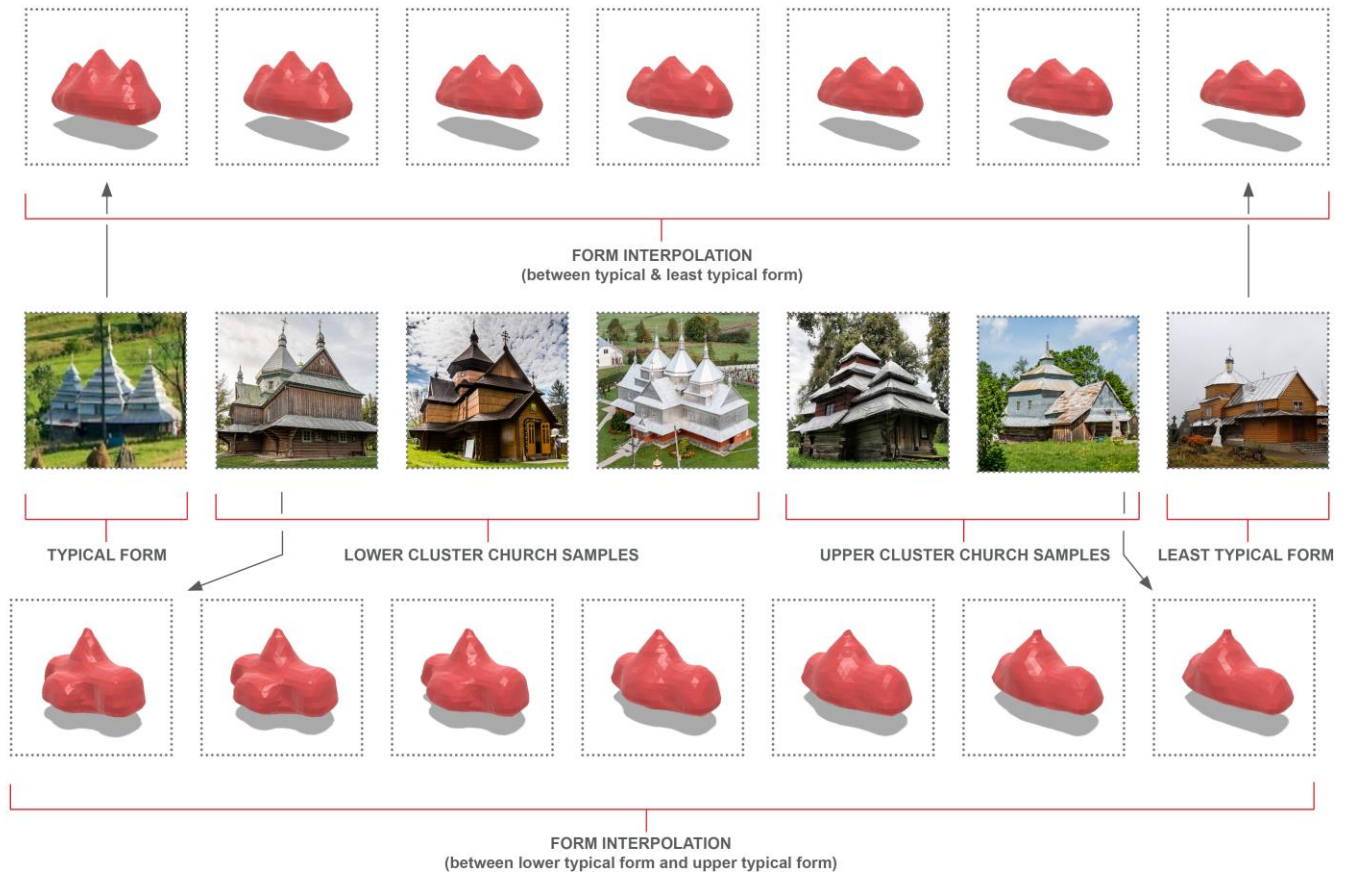


**Figure 5-11:** Cluster 4 typical form (image - middle left) and least typical form (middle - middle right), and the interpolation between them (upper red forms). Finally, samples of addition churches from that cluster (middle). In addition, interpolation between upper cluster typical form (image - middle second from right), and lower cluster typical form (image – middle second from left), and interpolation between the two (bottom row). ). Diagram by author.

that in fact, they both share the similar formal qualities of a central large tower with two long hip roofs extending from either end with somewhat similar proportions. However, the lower cluster has two additional perpendicular roofs extending from the central tower to satisfy the cruciform configuration pattern. This may explain both their proximity and separation from one another.

### Cluster 5

This small cluster contains just 11 churches that are located with high density nearby and to the right of cluster 4 (Figure 5-12) and includes both cruciform and linear tripartite morphology traits with one central or two or three towers. It is also in medium proximity to cluster 1 which represents single tall tower morphological traits. As a result, cluster 5 seems to contain churches with characteristics of both clusters including both cruciform lay-

out churches (54.5%), tripartite plans with one central or two or three towers (18.2%) similar to cluster 4, and churches with a single medium to tall tower over the narthex (27.3%) in the style of cluster 1. The low number of churches within this cluster and geographic dispersal suggest that perhaps all of them are morphological outliers. For example, one of the churches in this group has features of both the Hutsul-dominant cruciform plan, while simultaneously showing the typical three tall tower forms ribbed with zaloms of the classic Boyko style (second church photograph from left in below figure). Thus, perhaps explaining the churches position in latent near areas that represent both the cruciform style and three tall tower style suggestive of the Boyko School. Referring to existing studies and research regarding these churches, it becomes apparent that this small cluster does not represent a single dominant morphological characteristic that describes the entire cluster, but rather an interesting mixture of geographically scattered churches from the dataset which contain less represented smaller sub-style forms, of which half contain cruciform plans.

Interpolating between the typical and least-typical form of this cluster reveals this diversity as the morphological differences between a cruciform church with three towers is quite different than a linear-tripartite-plan church with a single tall tower over its narthex. This suggests that this cluster, though dominated by churches with cruciform plan suggesting a strong presence of Hutsul-style churches, should not be assumed to have a single dominant morphological characteristic, but rather, a mixture representing different morphological styles.

This is further reinforced by the dispersed nature of the cluster in geographic space. Again, there is a higher concentration around Hutsul cultural region, but again churches are still dispersed, suggesting that they may reflect a variety of sub-styles, which could be misinterpreted if referring to the latent space diagram alone.

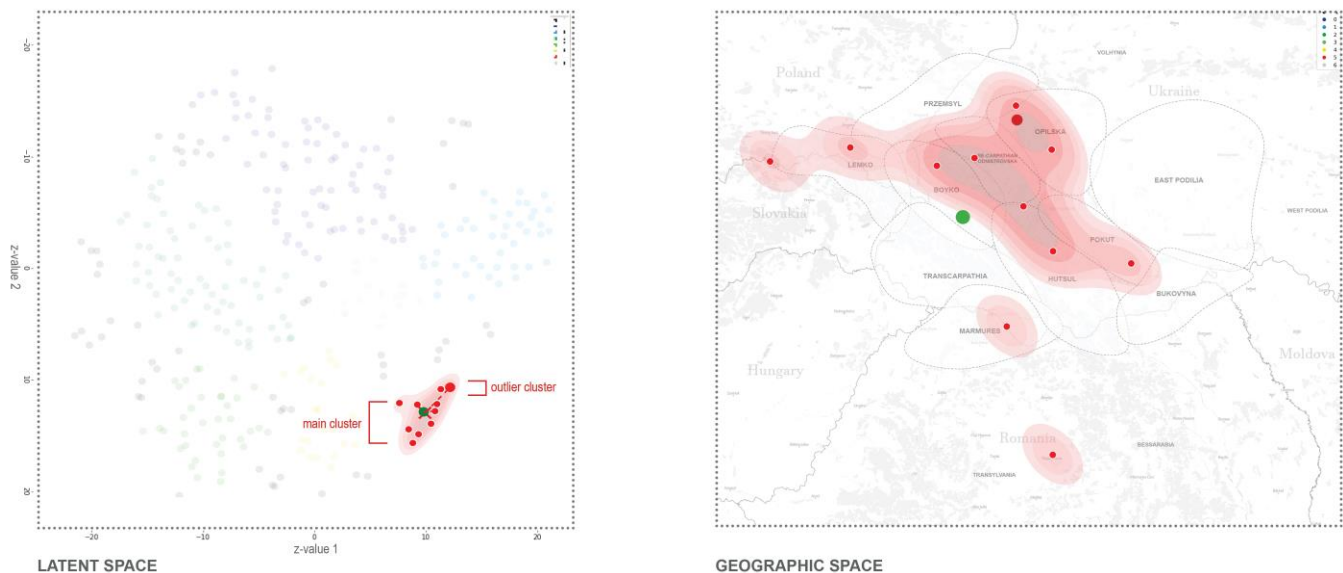


**Figure 5-12:** Primary cluster 5 in latent space (upper left), and its location in geographic distribution of church dataset (upper right)

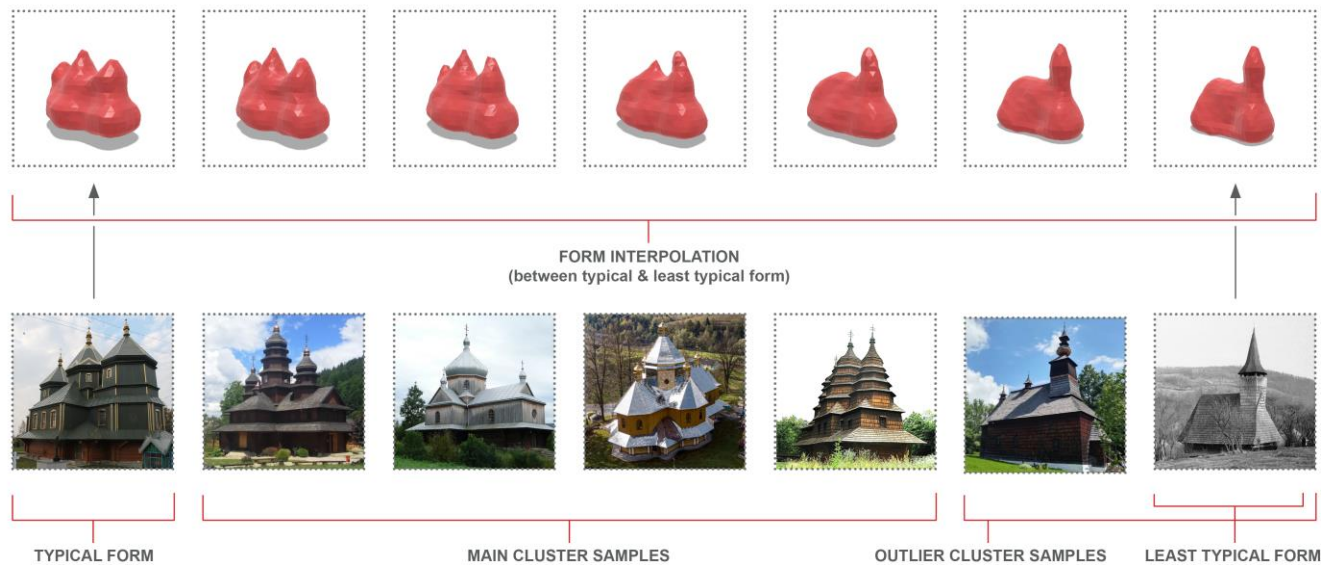


**Figure 5-13:** Primary cluster 5 typical form (image lower left) and least typical form (lower right), and the interpolation between them (top row). Finally, samples of addition churches from that cluster (lower middle). ). Diagram by author.

### Cluster 6

The final cluster contains 16 churches that are located with medium density directly beside cluster 0 and cluster 1 and is characterized by the presence of three narrow towers (62.5% of churches within the cluster) located along a long and narrow volume characterized by a slightly wider middle section likely indicating a tripartite plan (81.3%). For churches with 3 towers, 80% of them reduce in height from front to back with the first tower being the largest and most prominent. The roof structure below the second and lowest tower in the rear are also broken up and step downward in height. This feature is hallmark of the classic Lemko style. The other 20% have towers that are of the same height, with 66.6% of them having a single hip roof of consistent height. By referring to existing form studies, this also suggests the Northeast sub-style of the Lemko School of design [25]. Also present is a group of churches with very long and narrow volumes containing a single hip roof broken by a single low projecting tower. These geographically concentrated churches, though similar in morphology do not appear to satisfy any of the defined style-guidelines laid out in previous research and may be variations or outliers within their class.

Identifying the typical form centroid of this cluster helps me establish the dominant presence of churches with three-tower configuration that gradually lowers in height from front to back, sitting upon a long rectangular

volume, thus indicating a linear tripartite plan. The least typical form located furthest from the centroid was not well encoded, thus does not adequately represent the original structure. The encoded form looks more like the centroid form, which perhaps explains why it can be found within close proximity in latent space.

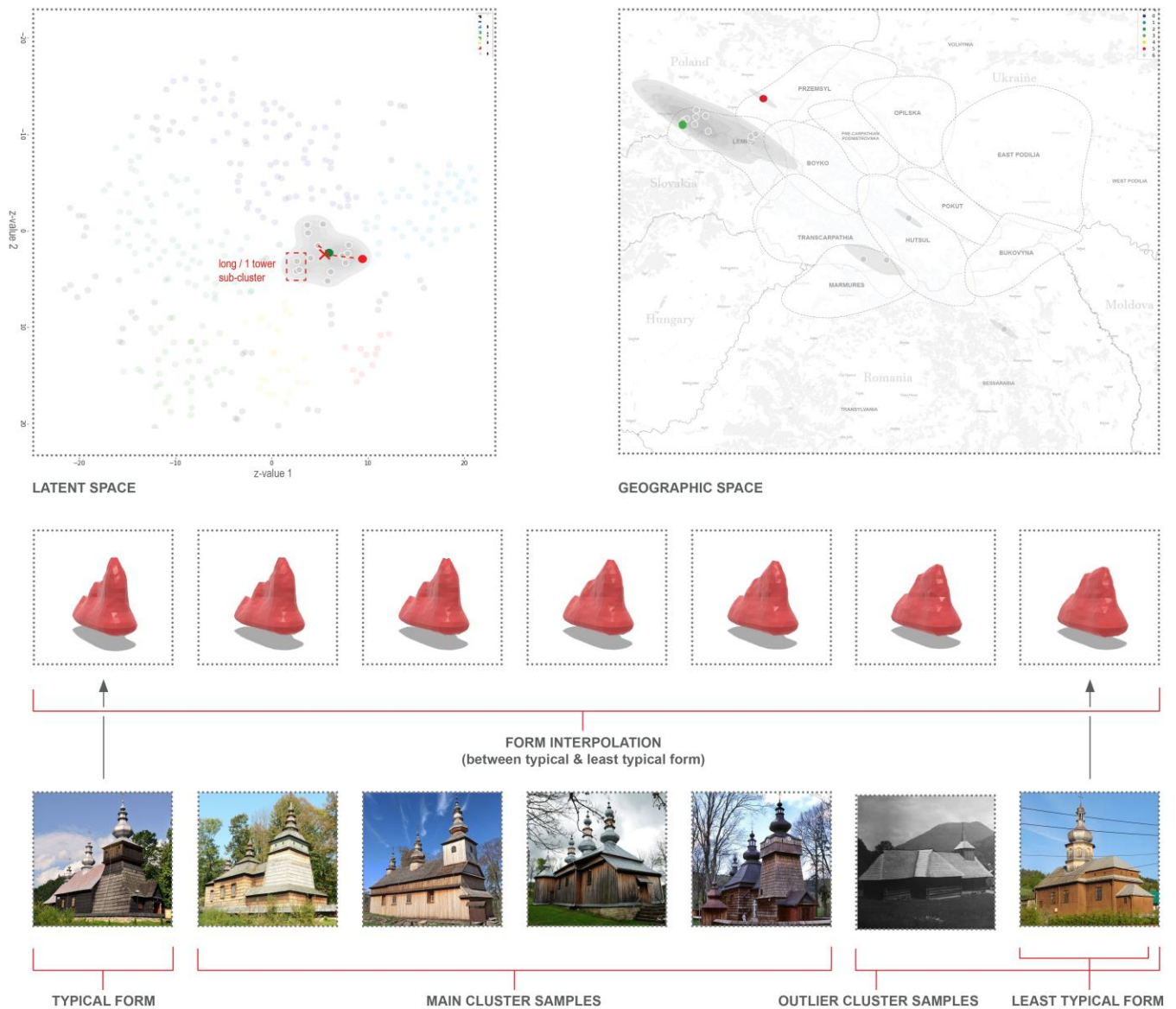


**Figure 5-14:** Primary cluster 6 in latent space (upper left), and its location in geographic distribution of church dataset (upper right), as well as the typical form (image lower left) and least typical form (lower right), and the interpolation between them (middle red forms). Finally, samples of addition churches from that cluster (lower middle). Diagram by author.

## 5.4 Evaluating Primary Clusters Against Ground Truth Labels

By referring existing research [24, 25, 35, 36, 38, 39, 40], I was able to assign ground truth (G.T.) style labels to each church point in our 2D latent space scatter plot. These labels indicate which School of folk temple construction they belong to according to existing research. This includes the primary four schools including; Boyko (1), Hutsul (2), Lemko (3), and Transcarpathian (4), in addition to other schools such as Pokut (5), Bukovina (6), Pre-Carpathian Podnistrovska (7), Opilska (8), Przemsyl (9), Kholmshchyna (10), Podilia (11), Volyn (12), Transylvanian (13), Bessarabian (14), and Southern Malopolska Gothic (15), all of which are represented in lesser volumes within the dataset. Part of the Transcarpathian School labelled as the Marmures (16) style given the unique style of that area and overlapping style names, “Transcarpathian style” or “Marmures style”, used by various researchers [25, 61]. By having these labels, I was able to better evaluate how well our model was able to cluster capture the primary morphological traits of these schools of folk architecture construction. However, it is important to note that church morphology does not always indicate what architectural-cultural school it belongs too due to the morphological overlap that exists between these primary styles [25]. Thus, it is expected that churches with the same label may appear in multiple clusters at once due to these ranges in form within primary style groups. For example, the morphology of the Lemko East Snynskyi region sub-style does not look like a “typical” Lemko church but looks startlingly like the Transcarpathian inter-mountain region sub-style and vice versa [25]. Previously identified overlaps and interesting new ones discovered in this work is what will be discussed in the remainder of this chapter.

When referring to the latent space diagrams, it is clear that there is correlation between the G.T. labels and the original clusters predicted by the model. As each predicted cluster represents a dominant and primary morphological characteristic, for example, churches with only one tall tower above the narthex, we can see how two or more dominant traits can fall within the latent space specified as a single primary style by the G.T. labels.

### ***Boyko G.T. labels***

The Boyko G.T. labels appear to overlap both cluster 2 and 3 predicted by our model (Figure 5-15). This suggests that Boyko churches may have two primary morphological forms. The first, being churches with vertically *shorter* or more squat tripartite volumes below the towers as discovered when analyzing the typical morphology cluster 2, and churches with vertically *taller* tripartite volumes below the towers as learned from cluster 3. When comparing the geographic space diagrams, we can see that group 2 and 3 contain other churches that share similar morphological traits that are not labelled as “Boyko” by the G.T. labels. When taking a closer look

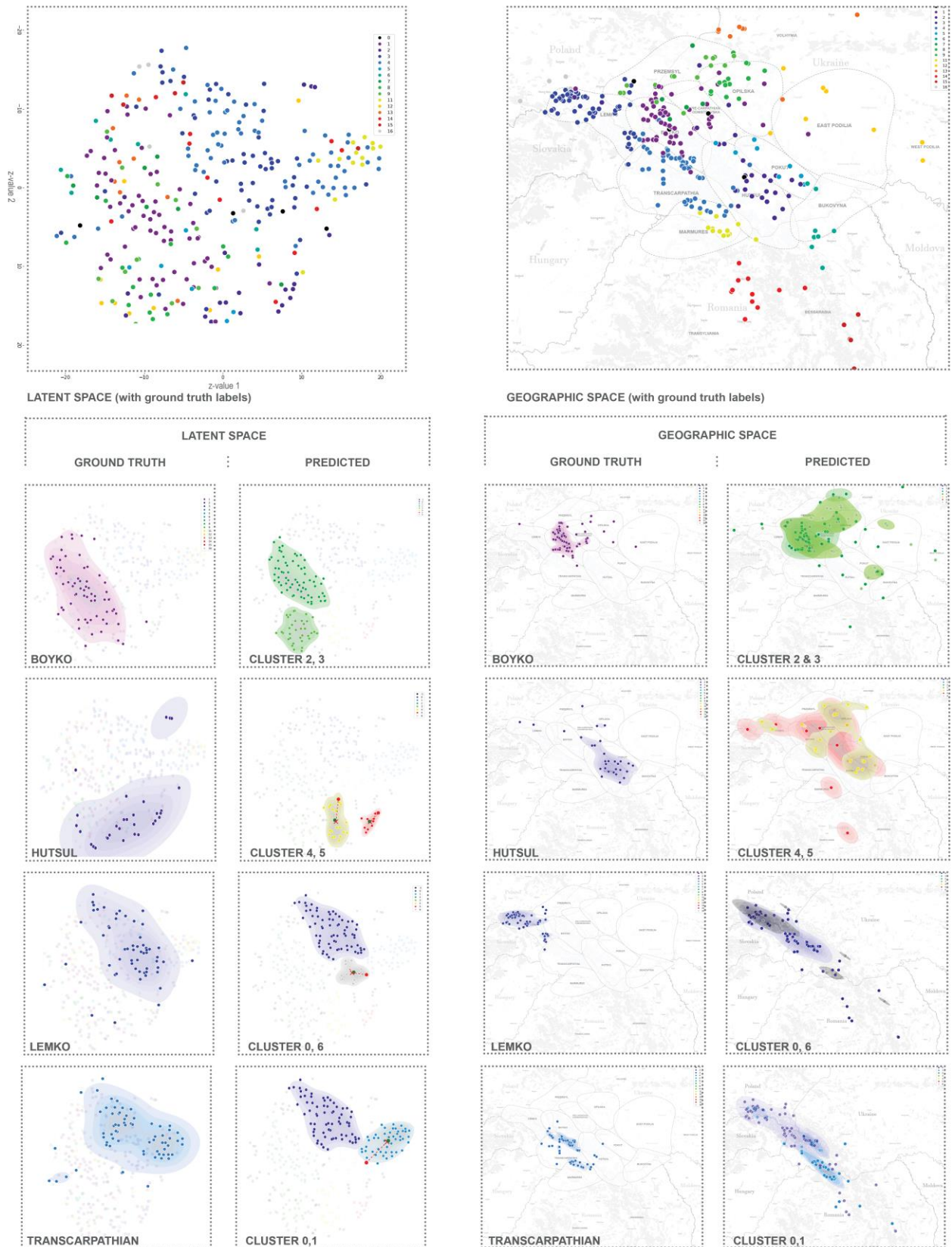


**Figure 5-15:** Ground Truth labels and their associated churches in latent space (upper left), and their location in geographic distribution (upper right). This is also broken up by primary clusters (small diagrams below). Diagram by author.

at the data as well as the geographic space, it becomes clear that churches within the Opilska, Przemsyl Pokut and Podilia, all regions that contain churches which share similar morphological traits to Boyko-style churches, thus suggesting further sub-clustering and inquiry to uncover additional sub-style clusters.

### ***Hutsul G.T. labels***

The Hutsul G.T. labels appear to loosely collect around the bottom perimeter of the latent space distribution and does not seem to be represented strongly by any single predicted cluster (Figure 5-15). To begin, there are far less Hutsul churches represented in the dataset, so perhaps the model did not have enough volume to properly learn and cluster the style accordingly. Nevertheless, the position of this style according to the G.T. labels is robustly designated around the bottom.

The two clusters that best represent the Hutsul morphological style and overlap the G.T. labels include clusters 4 and 5. Cluster 4 contains morphological elements that represent the classic Hutsul form, including a cruciform plan and geometric organization and a single or triple tower configuration with the central tower being the tallest. Cluster 5 represents morphological traits that are undoubtedly cruciform in plan, but representative of schools that are not necessarily located or related to the architectural-cultural Hutsul zone. It also contains churches that contain both Hutsul and Boyko elements simultaneously, indicating an interesting stylistic mixture of two major schools of folk temple construction.

By referring to the geographic space diagrams, we can see that churches with cruciform plans and tall central towers exist in zones like Lemko, Przemsyl, Podilia, Pokut, Boyko, etc. Y. Taras notes that the Hutsul school has spread much further than the others, which may explain why it is so prevalent within other regions [25]. Further combinations of sub-clustering, geographic space mapping, and references to existing research may reveal other interesting sub-styles and morphometric correlations between these interesting cruciform style churches.

### ***Lemko G.T. labels***

The Lemko G.T. labels appear to overlap cluster 0 and 6 predicted by our model (Figure 5-15). The first and larger cluster is more concentrated in the middle, while the second cluster which is much looser is located just above and to the left. This suggests that there are at minimum, two different primary morphological forms repre-

sented within Lemko-style churches. First, Lemko G.T. labelled churches that fall within predicted cluster 0 may contain dominant towers over the narthex and a tripartite plan, while the ones that fall within cluster 6 are represented by the classic Lemko morphology but may also include a number of Lemko sub-styles such as the Northeast and Northwest sub-style.

By referring to the geographic space diagrams, we can see that cluster 0 covers a broad range including the Lemko zone, thus suggesting that this cluster needs to be broken down into sub-clusters to obtain a more detailed understanding of the morphological sub-styles within this group. Due to our domain knowledge, we know for a fact that Transcarpathian and Lemko churches have distinct morphological characteristics and will likely fall into separate predicted clusters if further investigation is taken. Given this, we also learn that these two styles are related and may likely overlap in form given their close proximity to each other in latent space.

### ***Transcarpathia G.T. labels***

Take, for example, the area designated by the “Transcarpathia” G.T. labels which encompass the area of two clusters predicted by our model (Figure 5-15). From this, we can presume that Transcarpathian churches have two primary morphological forms. The first, being churches with a single *short* tower over the narthex with a tripartite plan and hip roof as designated by cluster 0, and churches with a single *tall* tower with a tripartite plan and a typically steeper roof and higher exterior side walls. However, in geographic space it becomes apparent that churches with similar morphological characteristics as the Transcarpathian school exist in other schools of folk temple construction. For example, within the Lemko architectural-cultural zone, which as we have learned contains many churches with tall towers over the narthex as well as linear tripartite plans. This suggests that the morphology of churches from the Lemko and Transcarpathia zones are related

## **5.5 Secondary Clusters**

As primary clusters only provided a general understanding of the primary morphological style groups represented within our dataset, I re-clustered our latent space distribution in order to reveal more nuanced form similarities and patterns that were not yet identified. See Section 5.5 *Data Clustering* for DBSCAN parameters used to identify these secondary clusters. From initial observations we can see that many of our primary clusters could be broken into three to four smaller clusters (Figure 5-16). After re-clustering, I identified fourteen sub-clusters that could potentially help describe more specific sub-styles. Due to the number of clusters identified, the remainder of the section will only briefly describe the sub-clusters identified within primary cluster 0.

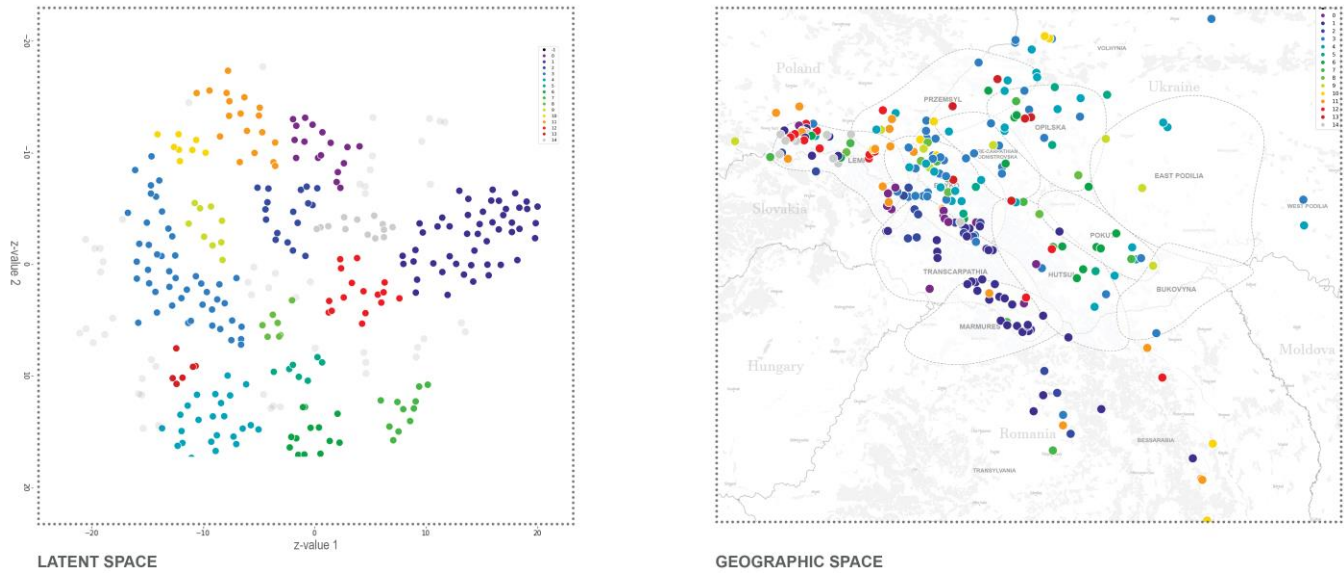


**Figure 5-16:** Secondary clusters of churches that share similar form in latent space (left), and their location in geographic distribution of church dataset (right). Diagram by author.

### *The Sub-clusters Within Primary Cluster 0*

Primary cluster 0 was partitioned into four secondary clusters named sub-cluster 0 (purple), 2 (dark blue), 11 (orange) and 14 (red) by re-clustering the data into smaller groups (Figure 5-17). To recall, primary cluster 0 contained smaller volume churches with linear tripartite plans with a single short tower above the narthex and minimal side projections from the nave. Initial observations suggests that secondary clusters can better define particular regional sub-styles, evidenced by the reduced number of geographic outliers present when mapping clusters back to geographic space.

#### *sub-cluster 0*

Sub-cluster 0 is located on the right side of cluster primary cluster 0 and contains 17 churches which are reflective of the typical morphological characteristics of its parent cluster (Figure 5-17). All churches share nearly identical formal characteristics and are difficult to tell apart if referring to morphology alone. The centroid church represented in the cluster seems to be slightly larger than the other churches within the cluster and contains a two stepped hip roof configuration where the smaller rear roof over the sanctuary is smaller. The least similar church is remarkably similar except that it has a single hip roof at the same height. Interpolating between these two

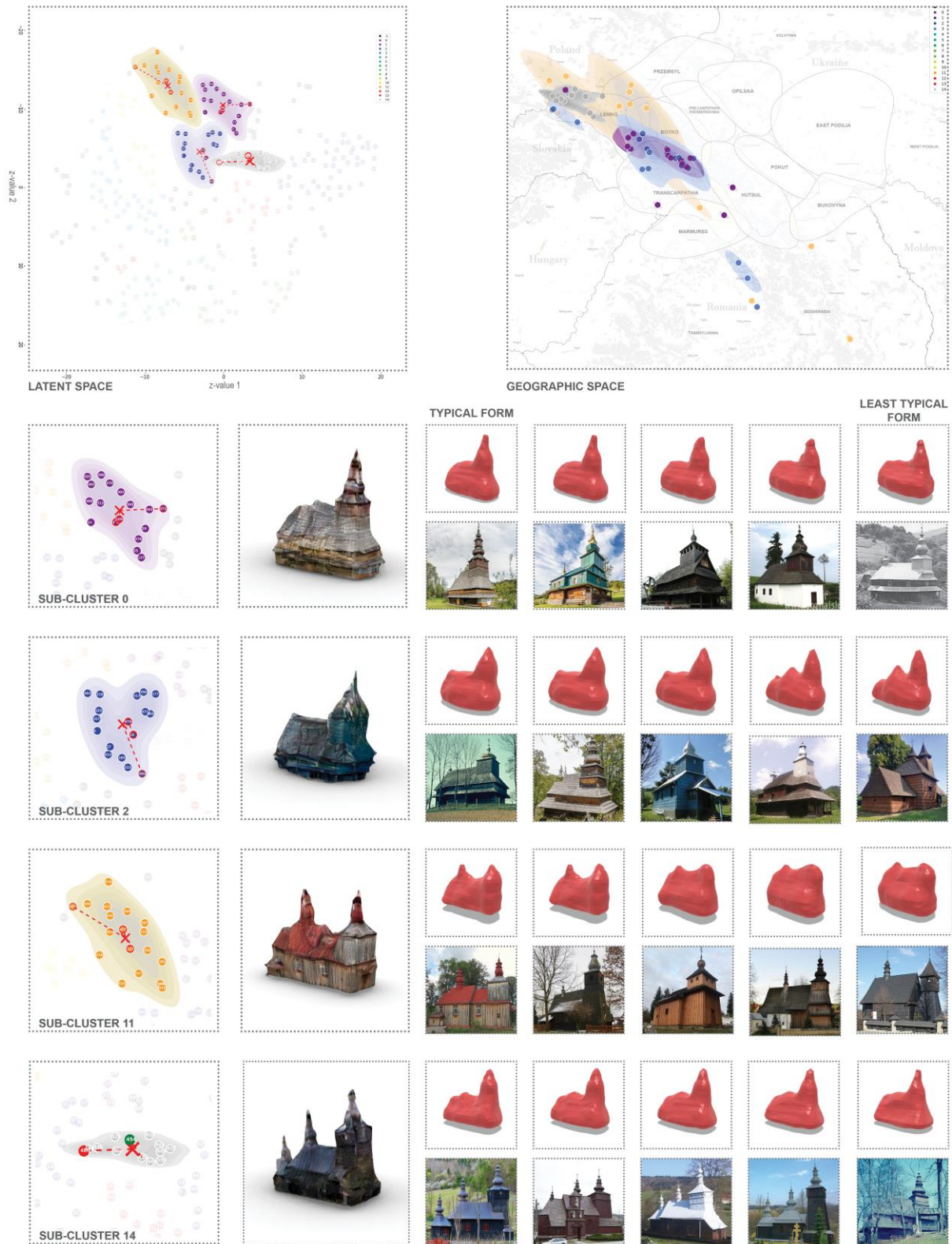


**Figure 5-17:** Secondary clusters of churches that share similar form in latent space and their location in geographic distribution of church dataset. Typical (second and third column) and least typical forms (far right column) of each cluster are shown. As well as interpolations between them (red forms). Additional images of churches within each cluster are shown (images – fourth to sixth column). Diagram by author.

reveals little difference and confirms the robust and consistent formal characteristics of this sub-cluster. Plotting these churches back to geographic space, however, reveals that they fall within both the Lemko and Transcarpathian zones, suggesting that these two regions may share sub-styles with quite similar morphology. Interestingly, the Lemko churches that share this typical Transcarpathian style are located in the most Southern reach of the Lemko region, which is right beside Transcarpathia, thus suggesting that morphological overlap may occur around these cultural border areas leading to a blur and endemic synthesis between styles.

### ***sub-cluster 2***

Sub-cluster 2 is located at the bottom of primary cluster 0 and also contains 17 churches which are also reflective of the typical morphological characteristics of its parent cluster (Figure 5-17). The majority of churches share nearly identical formal characteristics and are difficult to tell apart if referring to morphology alone. The centroid church represented in the cluster represents the typical form of the cluster and contains a single hip roof configuration and stubby short tower. The least similar church is quite different and represents the Slovakian Lemko sub-style [25], characteristic of significantly shorter towers, a lower and a more vertically compressed tripartite volume, often the lack of a rear tower, and an overall more simplified, spartan geometric form. Interpolating between the two reveals this. It may be noticed however, that the differences between this sub-style of Lemko church and the typical form is not as drastic as it would have been expected and only includes an additional tower in the center and a lower roof over the nave. If comparing the typical form of this group to a classic Lemko church with three massive towers, the morphological difference may be different. This may explain why this particular sub-style church is located within this cluster. When plotting back to geographic space, we can see that these churches fall within the Northern area of the Transcarpathian zone and the Southern part of the Lemko Zone, again suggesting a location of potential architectural-cultural overlap and influence between styles.

### ***sub-cluster 11***

Sub-cluster 11 is located at upper left corner of primary cluster 0 and also contains 18 churches which are somewhat different than the typical morphological characteristics of its parent cluster (Figure 5-17). Within this group, the front tower of these churches seems to be pulled away from the body of the church and sits proud to the main volume of the building. This can be noted by the tower walls continuing to the ground in almost all examples shown, compared to towers that terminate at the roof, in a way that is typical of the majority of churches within parent cluster 0. This indicates that these churches are likely from another architectural-cultural zone.

However, the cluster also contains churches that appear different from one another, with some looking like those in sub-cluster 2. After finding the typical form we can see that indeed, the average morphology of this cluster includes a tower that sits proud to the main body of the church. The least-typical example also shares this configuration, but with the tower completely separated from the rest of the church except for a low connecting hall at ground level. After plotting to geographic space, we can see how churches within this cluster are located within 3 different zones, Przemyśl, Lemko and Boyko regions. However, most are located within the North ends of these groups in Poland, which may indicate a unique style of church within that area which has not been studied in this work.

#### ***sub-cluster 14***

Sub-cluster 14 is located at the bottom of primary cluster 0 and also contains 13 churches which showcase the classic three stepped tower configuration with linear tripartite plan configuration of the Classic lemko style (Figure 5-17). After reference to existing research [25], it was discovered that this sub-cluster seemed to contain morphological elements characteristics of multiple Lemko sub-styles including the Late and North (low towers) sub-styles. After plotting this cluster to geographic space, we can see that indeed, these churches all come from the Lemko zone and seem to be located in the North central and Northeast areas, which is where these sub-styles are located. Though I found the typical form of this group, it did not seem to be well encoded as I had hoped and thus was only a low-resolution representation of the ground truth building volume. We believe this may be because these particular sub-styles of Lemko churches have much lower towers than their tall counterparts and may have been more difficult to encode due to their similarity with other styles such as the Transcarpathian style. As we can see, the least-similar form is a Transcarpathian style church which other than the lack of middle and rear small towers like the other churches in this group, is in fact quite similar, that is, having a single tall tower over the narthex, and a double height roof dropping in height from the nave to the sanctuary. The interpolation between the two churches, though at low resolution, shows that other than the two additional towers, the overall morphology between the two church forms is quite similar.

## **5.6 Tertiary Clusters**

Tertiary clustering revealed a whole host of small clusters which suggested a number of more nuanced sub-styles within the larger secondary clusters. See Section 5.5 *Data Clustering* for DBSCAN parameters used to identify these secondary clusters. There were 49 sub-clusters identified that ranged in size from 4 to up to 20 churches. This high prevalence of tertiary clusters makes a great deal of sense given the range of existing church-

sub-styles and even small micro-styles which are noted to also exist but have not yet been rigorously categorized compared to their parent sub-styles. For this chapter, the tertiary clusters from sub-cluster 14 will be described.

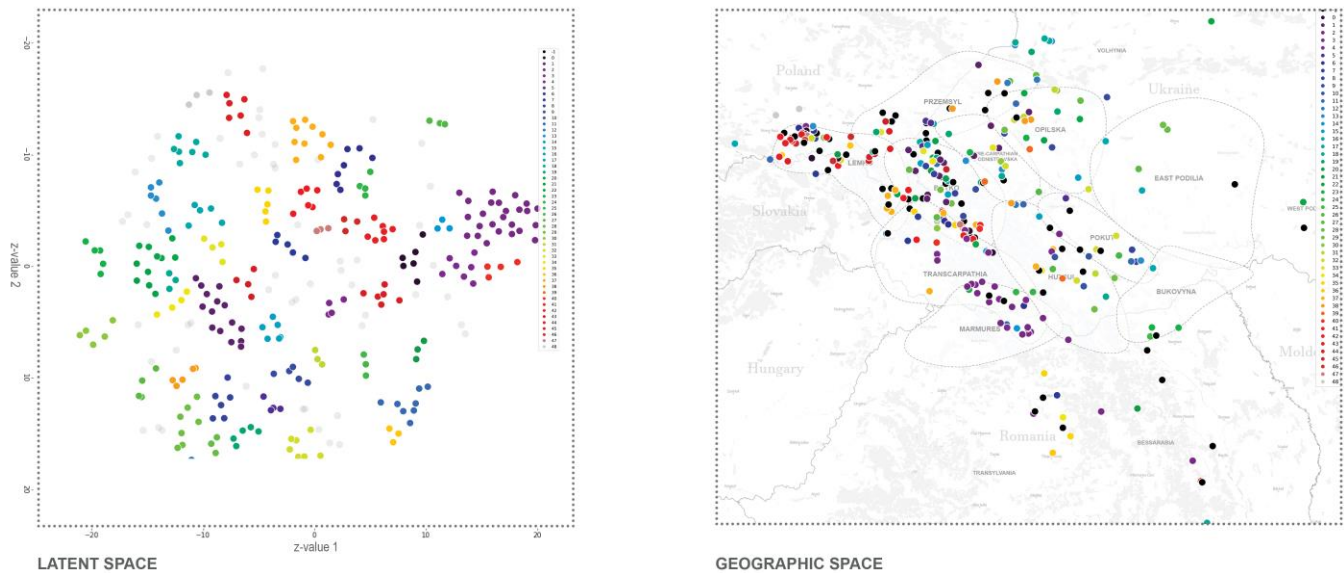


**Figure 5-18:** Tertiary clusters of churches that share similar form in latent space (left), and their location in geographic distribution of church dataset (right). Diagram by author.

### *Micro-Clusters Within Sub Cluster 14*

Sub-cluster 14 was re-clustered into three micro-clusters 47 (green), 46 (blue), and 42 (red) (Figure 18). To recall, sub cluster 14 is represented by churches with the following morphology: three medium sized towers that reduce in height from front to back indicating potential Lemko style, and a linear tripartite plan with minimal side projections from the nave. Overall, these micro-clusters each contain a unique morphology suggestive of a particular Lemko sub-cluster.

#### *Micro-cluster 47*

Micro-cluster 47 is on the far left of the parent cluster and represents Lemko-style churches with low towers (Figure 5-19). This style, which is very similar to the Transcarpathian style is the start of a micro-trend found within the overall latent space distribution. This micro-trend goes from left to right starting with micro-cluster 47 and ending with micro-cluster 42 and represents an increase in tower height within this particular style

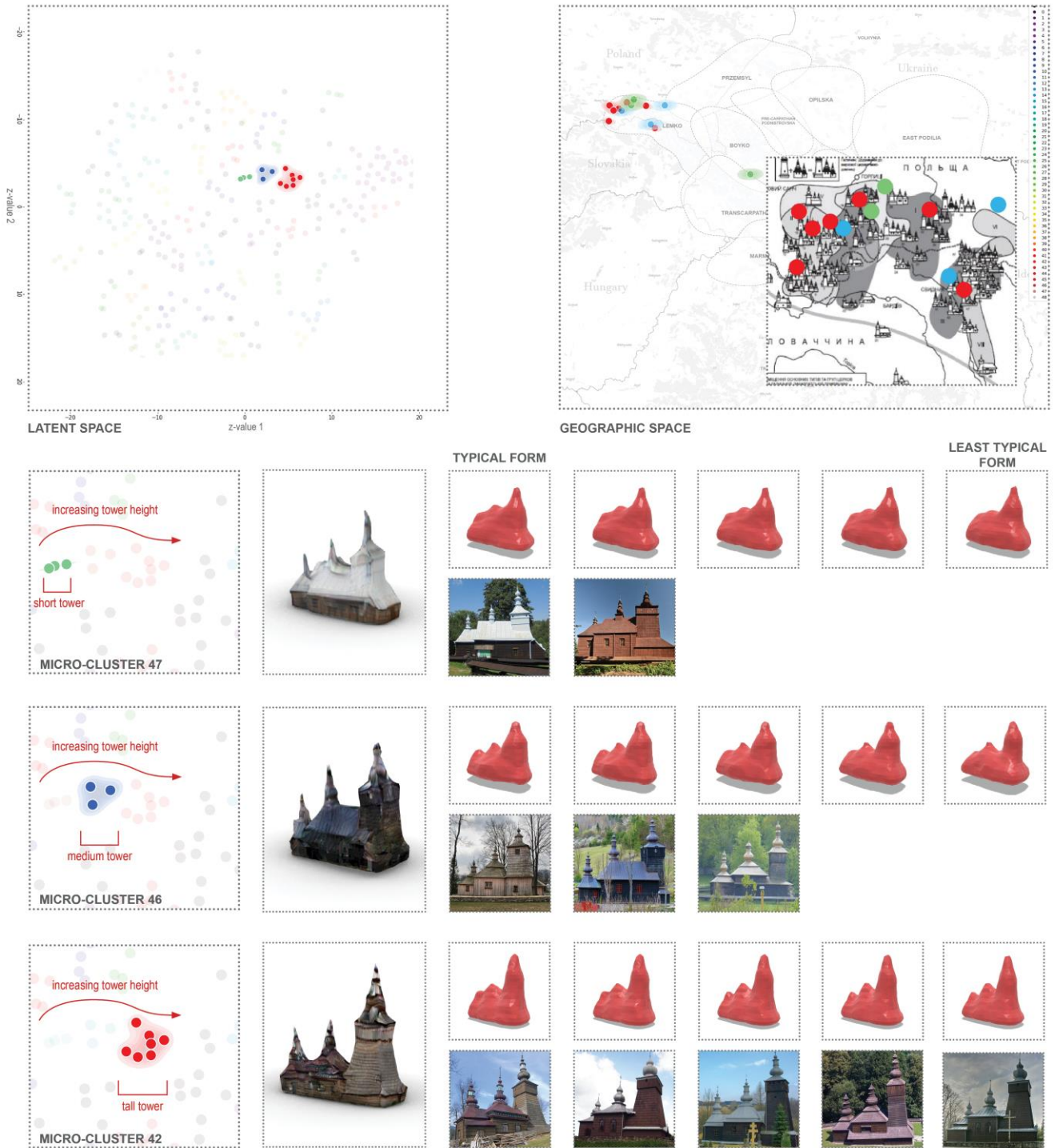


**Figure 5-19:** Micro-clusters showing three different groupings of Lemko churches where tower height increases from left to right. Diagram by author.

of church. Cluster 47 represents churches with the smallest towers which was discovered when finding the typical form of this church as shown below. When interpolating between the least typical form, we can see how the over-

all morphology does not change, thus suggesting the consistent clustering of a single particular sub-style. When referring to existing research [25], it was observed that this cluster likely represents the “North (with Towers)” Lemko sub-style, a style which can easily be confused with as a Transcarpathian style. Though there are morphological differences between the two, they are very nuanced. Plotting this church back to geographic space falls within the sub-styles ground-truth geographic zones as indicated within Y. Tara’s map of Lemko sub-styles [25].

#### ***Micro-cluster 46***

Micro-cluster 46 is in the middle of the parent cluster and represents Lemko-style churches with medium height towers and two separated pyramidal roof structures over the nave and sanctuary with the rear one being the lowest (Figure 5-19). Being between micro-cluster 47 with short towers to its left and micro-cluster 42 to its right with the tallest towers, this micro-cluster represents the middle stage of the tower height micro-trend identified and is accordingly represented by churches with medium sized towers. By interpolating between two churches within this micro-cluster, we can see how the form does not change much and maintains the formal characteristics of this group. This again, suggests that the churches morphology is extremely similar. When referring to existing research [25], it was determined that the typical morphology of this cluster is suggestive of the “Northeast Late” sub-cluster as identified by Y. Taras. This is further suggested when plotting the cluster to its geographic locations as they all fall within the ground-truth boundaries of this sub-cluster’s boundaries.

#### ***Micro-cluster 42***

Micro-cluster 42 is at the far-right end of the parent cluster and represents Lemko-style churches with tall towers and 2 separated pyramidal roof structures over the nave and sanctuary with the rear one being the lowest (Figure 5-19). Located at the end stage of the tower height micro-trend it represents the churches with the tallest towers within parent sub-cluster 14. By interpolating between two churches within this micro-cluster, we can see how the form does not change much and maintains the formal characteristics of this group. This again, suggests that the churches morphology is extremely similar. When referring to existing research [25], it was determined that the typical morphology of this cluster is suggestive of a combination of “Northeast Early (Classic)”, and the “Northeast Late” sub-clusters as identified by Y. Taras. This is suggested when plotting the cluster to its geographic locations as the churches fall within the ground-truth boundaries of these sub-cluster’s boundaries.

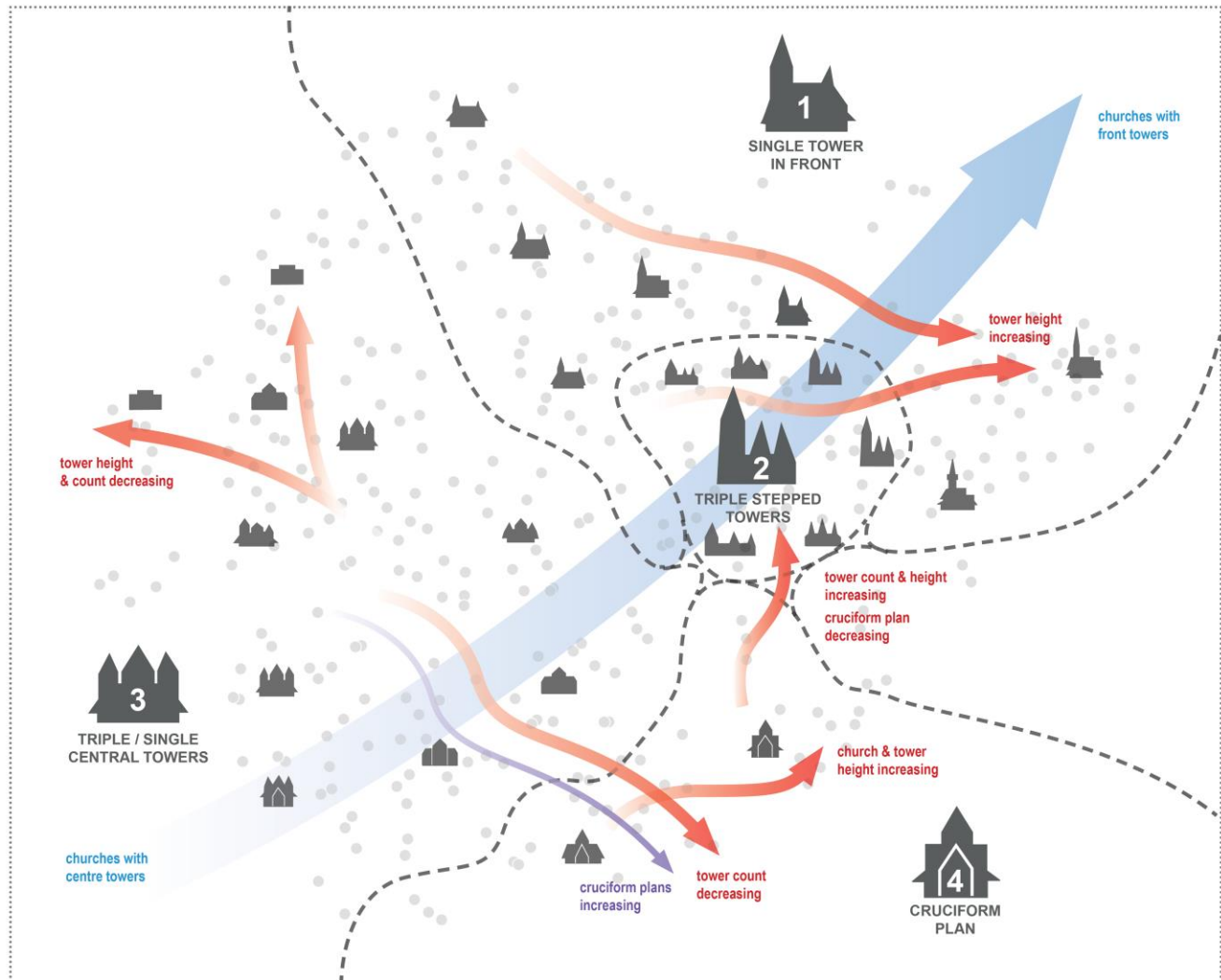
## Chapter 6 | Observations

### 6.1 Examining Latent Space Manifolds

By observing relationships and repeating trends between clusters, sub-clusters, and tertiary cluster through a combination of typical and least typical form finding, reference to existing research and expert domain knowledge, easy dataset accessibility, and geographic space observations, larger morphological-based patterns could be found discovered and tracked within the overall latent space data distribution. These groupings of similar data within latent space are also referred to as “manifolds”. In this way, I could decipher micro and macro-organization of the latent space by observing relationships between its various manifolds, thus providing novel insight into the unique morphological patterns of this architectural type.

#### *Primary Church Form Distribution*

One the most noticeable patterns was the distribution of the four primary church form configurations which help describe in broad strokes, the larger form configurations of the majority of churches within our dataset (Figure 6-1). However, this just reinforces that our model was able to generally differentiate the four main schools of folk architecture that were primarily represented within the dataset: Hutsul, Lemko, Boyko and Transcarpathian. These four configurations, “single tower in front”, “triple stepped towers”, “triple / single central towers”, and “cruciform plan” are located in 4 zones as indicated by the black dotted lines in the diagram with typical church form and zone number indicated by the large dark grey church silhouettes. The first configuration located in zone 1, has a single dominant tower at the front is located from the middle to the upper right-hand portion of the latent data distribution. This configuration is often, but not always associated with the Carpathian School. The second configuration located in zone 2, has three towers that step down in height from front to back is located in a small central cluster just below the first. This proximity is likely due to both having a tall tower at the front above the narthex, as well as the shared linear tripartite plan. This configuration is often, but not always associated with the Lemko School. The third configuration located in zone 3 has either a single central or three towers that sit over a linear tripartite form with the central tower being the tallest. This configuration is often, but not always associated with the Boyko School. The final configuration located in zone 4 and also has a single, three or even five towers with the central tower being the tallest but incorporates a cruciform plan. This configuration is located at the bottom of the distribution, and beside the previous configuration due to their overlapping morphological features of having a central tower. This configuration is often, but not always associated with the Hutsul School.



OBSERVATIONS - tower counts, heights, and cruciform plans

Figure 6-1: Macro and micro form trends identified by this research across the latent space distribution. Diagram by author.

### ***Central Tower to Single Tower Pattern***

Zones 3 and 4 are on the opposite side of zone 1 given the fact that the churches within these areas never have just a single tower above the narthex (Figure 6-1). Likewise, churches in zone 1 never have a tower in the middle above the nave, but rather a single tower at the front above the narthex. Zone 2 is placed between zones 3 and 4 and zone 1 because they contain elements of both. That is, they have both a tall central tower over the narthex, *and* a central tower over the nave. This represents the largest and most general trend that influences all churches within the latent space distribution with its direction represented by the large blue arrow.

### ***Tower Height and Count Pattern***

Another noticeable pattern is the change in tower height and count across the latent space distribution (Figure 6-1). The directionality of these patterns is indicated by the red arrows in the diagram. Specific information regarding the direction of increase or decrease is indicated by the red text. By finding and illustrating this trend, I obtained a deeper understanding of the dataset by providing a means to compare the tower height and count of one church to the next. It is also clear that this pattern does not occur in a single linear direction, but rather in a complex multi-directional manner across the latent distribution diagram. This complexity makes it difficult to both detect and track without careful study of each cluster and an intimate knowledge of the subject through domain knowledge and experts and reference to existing research and geographic space.

As indicated, this trend has 6 main “arteries” of direction. Within zone 1, tower height drastically increases from left to right as shown by the churches with small towers in the upper left portion of the zone and the churches with extremely tall and narrow towers at the far right of the group. This left to right configuration continues within zone 2 where not only the front tower increases in height but also the rear two within this three-tower configuration. This trend within zone 2 is illustrated within 6. *Results. 6.5 Tertiary Clusters*. Within zone 3, the direction of tower height change rotates 90 degrees to a vertical orientation travelling from the middle up where tower height decreases and middle down where tower height decreases again. Decreasing tower height is also accompanied with a decrease in tower count, typically from 3 to a single central tower. Within zone four, both tower height and count increase from vertically from the upper portion of zone 4 into zone 2 which is occupied by the Lemko-style triple stepped tower configuration. Along all of these arteries, we typically find churches that more or less follow these patterns. Though this is not guaranteed, it does represent the majority of cases, especially within zone 1 and 2 where it is almost universally followed.

### ***Tripartite to Cruciform Plan Pattern***

Another noticeable form pattern indicated by the purple arrow is the transition from tripartite to cruciform plan which occurs between the bottom of zone 3 and zone 4 (Figure 6-2). Though the typical form of zone 3 is mainly represented by a linear-tripartite plan, it does start to transition towards a cruciform plan at the bottom as it nears zone 4 (church 1). This is marked by churches that have increasingly wider nave spaces which in turn, begin to give the church a cruciform shape (church 2). With churches nearer to zone 4, these projections tend to get larger, hence increasing this cruciform effect. Once in zone four, the clear cruciform shape emerges (church 3).



**Figure 6-2:** Identified latent space trend, where church form transitions from tripartite to cruciform configuration. Diagram by author.

## 6.2 Unusual Clusters and Surprising Findings

### *Towerless Church Cluster*

When looking for clusters of buildings that are likely to share very similar forms, a good method is to search for small, dense groups of points in small clusters of three to four points. One such cluster was found in the far-left corner of the latent distribution, and through further investigation, was found to express churches with the unusual morphological condition of having no towers (Figure 6-3). This characteristic was featured among all churches within the cluster, thus indicating a potential sub-style of church. However, when referring to previous research and specific information related to the individual churches [25], it was quickly discovered that almost none of these churches belonged to the same sub-style or even primary School of folk temple construction. Rather, they were a hodgepodge of different church styles, created by very different cultural communities and scattered around various different regions. Furthermore, the size of these churches varied greatly from a small church to a large almost cathedral-like form. In another case, it was discovered that one of the churches originally had a tower, but it had since burned down, leaving it in its current sad towerless state. As history, cultural origins, geographic distances and unhappy events were not considered when creating this cluster, it is easy to see how other unusual groupings might easily occur. With this in mind, no real knowledge could be gained through this cluster, thus putting into question the validity of all other clusters unless closely examined.



**Figure 6-3:** Identified latent cluster that includes churches without towers. Diagram by author.

### ***“T” Churches***

Another unusual cluster identified was a large grouping of churches that at first glance only seemed tangentially related by their hip roof configurations and minimal planar exterior walls. More noticeable were their differences, being a seemingly random collection of churches from different schools of folk architecture construction (Figure 6-4). Nevertheless, latent space suggested they were very similar given their points in latent space were densely packed together. After investigating, it was suspected that the clustering may have been caused by the presence of noticeable building additions added to both sides of the backs of these churches. These later additions gave the churches a “T” configuration, which for all schools of temple is highly unusual. However, to the model, this T configuration was likely the very thing that was considered an important “defining” feature, when in reality it would be considered an afterthought to those familiar with this building type. Given this, with a lack of domain knowledge of contents of a dataset, we run the risk of missing these unusual, and potentially misleading correlations.

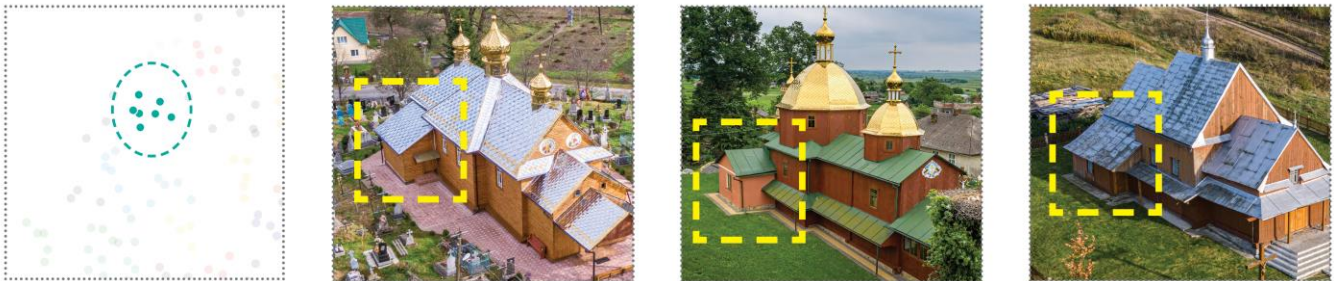


**Figure 6-4:** Identified latent cluster that includes churches without rear additions on both sides. Diagram by author.

### ***Similar Forms Yet Different Cultural Roots***

It was observed that two sub-styles of churches from different schools of folk temple architecture construction, being the Lemko Snynskyi regional style and the Transcarpathian Velikoberezhnyansky-Chornogolovska regional style, appeared to have nearly identical morphological characteristics (Figure 6-5). Even after careful study and reference to existing research, these two churches were hard to distinguish apart from each other due to both of them including a single squat tower above the narthex, a single hip roof from front to back and fairly consistent roof overhangs and overall geometric proportions. Shown below are two examples (1,2) from the Lemko Snynskyi sub-style and one in the Transcarpathian Velikoberezhnyansky-Chornogolovska sub-style (3). When referring to latent space, we can see that these three churches are in quite close proximity to one another, hence suggesting similar form and possible architectural-cultural relationship. When plotting them to geographic space, we can see that they are also all within relatively close proximity as well, therefore further reinforcing this presump-

tion of shared cultural origin. However, when classified by experts [25], they all fall within very different schools, first, the Lemko School (1,2) and then the Transcarpathian School (3).

Though morphologically similar closer inspection revealed subtle differences, for example, the front face church 3 as opposed to the front angled roof in 1 and 2 is more in line with Transcarpathian school. While the onion domes on top of the tower of 1 and 2 is more in line with the Lemko style. Though subtle, these are still morphological characteristics that are important, especially to ethnographers, architectural researchers and the communities that built them. However, these differences may easily be lost by either the abstraction that takes place during the data processing stages, modeling, or encoding process, or if captured just left unnoticed if the domain knowledge doesn't exist to understand these subtle differences. However, it is also important to acknowledge the benefits of clustering these two styles within the same group as it recognizes and identifies an interesting overlap between two styles. In geographic space, we can see how these overlapping styles occur at the border of three cultural regions: Transcarpathia, Boyko, and Lemko. Thus, acknowledging the complicated cultural overlap and blurring of boundaries that exists in the real world, perhaps even suggesting that they be classified in new ways, or the introduction of “border style” Schools of folk construction.

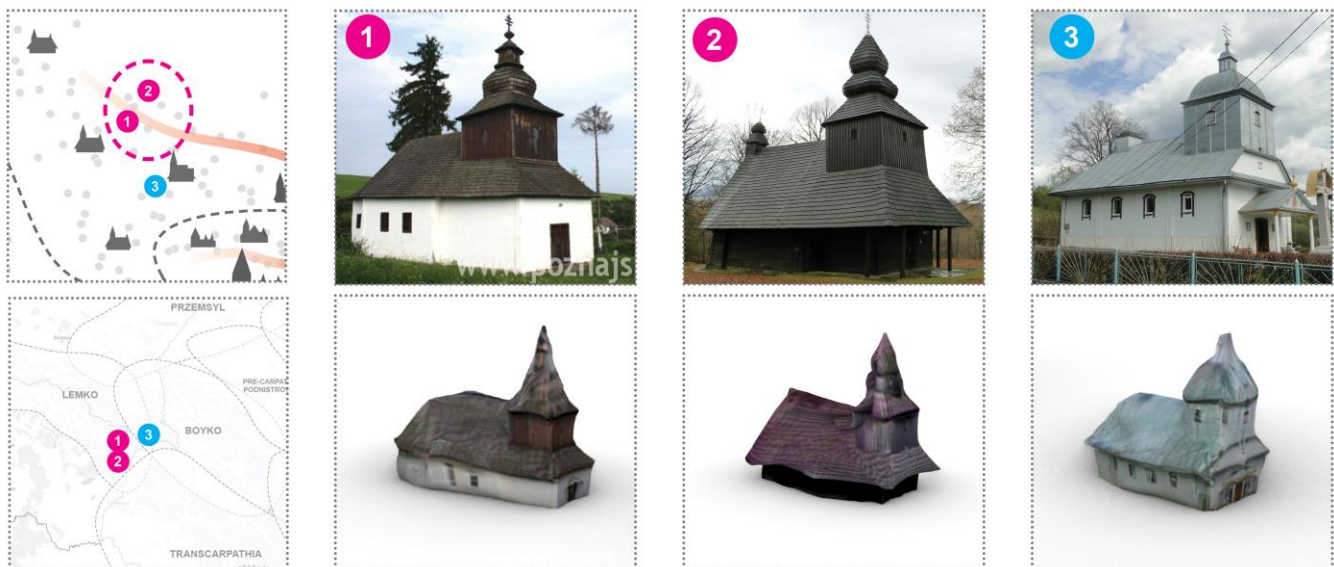


**Figure 6-5:** Identified latent cluster that contains churches that share very similar form but are from different schools of Folk Architecture constructions (Lemko and Carpathian). Diagram by author.

### ***River & Valley Micro-Styles***

A conversation with Mykhailo Syrokhman, one of Ukraine's leading experts on the wooden churches of Transcarpathia revealed that certain church sub-styles could only be found within certain valleys or along short

stretches of rivers. He mentioned that the general isolation of these areas limited the spread and influence of these styles into more distant towns and regions. In addition, church designs were not based on pre-existing drawings or blueprints, but rather through observation of other churches in nearby towns, with any additions or differences being the result of a combination between a particular master craftsman's personal style and the spiritual, functional needs and aesthetic preferences of the community [25, 41]. In this way, churches designs were often influenced by the style of existing churches in nearby towns [25]. As church styles spread slowly from one town to the next, the isolated nature of these areas provided the right conditions for these endemic styles to develop over time [25].

In order to determine if our DL-methodology could help detect these regional micro-styles, I began plotting the smaller and tightly grouped tertiary church clusters to geographic space to see if any of the churches fell along the same river or within the same valley. Two clusters containing churches that met these criteria were detected. First, a small cluster of two Boyko churches within a single valley (Figure 6-6) and second, a then a group of three Transcarpathian School churches along the same river.



**Figure 6-6:** Identified latent cluster that includes two Boyko churches that are extremely similar to each other, unique from other styles and located within the same remote valley. Diagram by author.

The first group of two Boyko churches were found within the same latent space micro-cluster and were detected within the same valley within the central Boyko architectural-cultural zone. Built during the mid to late 18<sup>th</sup> century and located just four kilometers apart in geographic space, these two churches appear almost identical in form to one another, showcasing a simple three pyramidal tower configuration with the middle one being the tallest, and the one over the narthex being only slightly lower, with the one over the sanctuary the smallest. Both have a single zalom (a narrow roof overhang that encircles a tower) encircling the two end towers, with the middle tower having two. There is also a noticeably gap over the zalom of the front tower over the narthex, which helps to emphasis its height. Finally, a continuous roof overhang, called an opesanya surrounds both churches at about mid-way up the main volume of the church below the pyramidal roof structures. Window placement also

seems to be about the same for both churches. Though there are many Boyko churches in the dataset, these two represent a unique sub-style different from the rest.

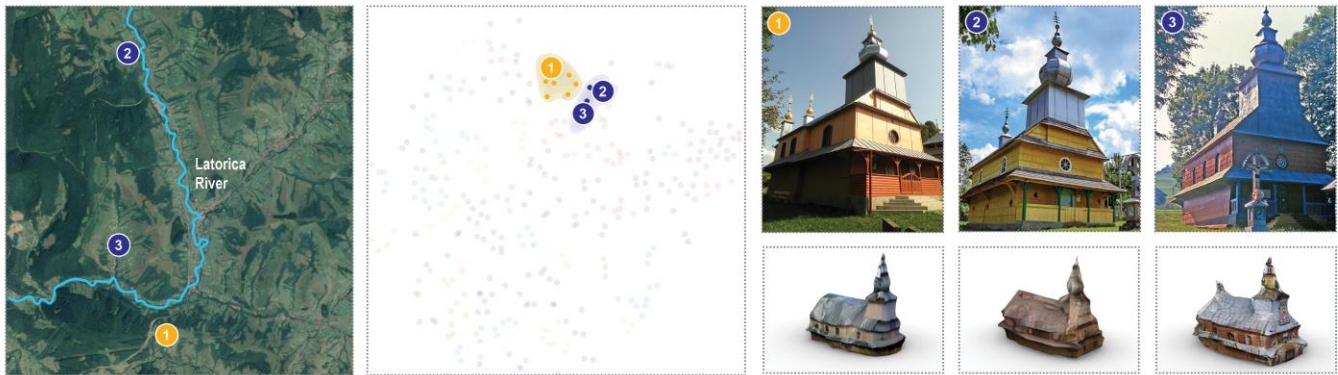


**Figure 6-7:** Identified latent cluster that includes two Transcarpathian churches that are extremely similar to each other, unique from other styles and located along the same section of a river. Diagram by author.

The second group of three Transcarpathian churches were found within two neighboring latent space tertiary-clusters and are located within three villages in close proximity along the Latorica river within the northern Transcarpathian architectural-cultural zone. Built in the early 19<sup>th</sup> century, with one being built in the mid-18<sup>th</sup> century, the morphology of all three appear nearly identical with a flat and prominent front building façade that contains the entryway, a circle window above the main entryway and a barn-like roof line that meets a squat tower topped with a circle Baroque influenced dome. Out of the three, only one has a slightly wider nave space that projects from the side walls. All three have a hip roof with a small projecting mini tower topped with a smaller dome at the rear above the sanctuary space. All three also have a narrow roof overhang that surrounds the building at about halfway up the main building volume below the roof.

Interestingly, only the Boyko cluster can be categorized within Y. Tara’s detailed list of church sub-clusters. According to his research [25], these two Boyko churches fall within the boundaries of the “Classic Boyko” sub-style geographic zone. However, as many churches in our dataset also fall within this zone but do not look like these two churches, we can conclude that these two do in-fact reflect an under-represented micro-style. The three Transcarpathian wooden churches, do not fall within a sub-style category, and thus, also suggest, to the best of the authors ability, the existence of a generally less-recognized endemic micro-style.

### *Messy Clusters & Geographic Distributions*

In many of the above examples, I demonstrated how churches with similar forms may be found within tertiary clusters, or by looking for churches in close geographic proximity to one another. However, this is typically not as straightforward as clusters can still contain messy mixtures of styles and geographic distribution of churches can be confusing.

Though general form trends may be identified within a cluster, it does not mean that all churches within that group contain the morphological characteristics expressed by the typical form determined to best represent it. When considering that our DL model uses 128 different form characteristics in order to describe their individual forms, identifying which architectural characteristics are shared across a cluster is not always easy. Though a main morphological trait for the group may be identified, it may in fact be the second or third most important defining feature, while the primary one may be something more difficult to observe at first glance. For example, building proportion, height to length ratios or overall volume which are more difficult to identify with the naked eye. In addition, churches may not be thoroughly “learned” or encoded accurately due to not having enough examples of that type, insufficient training time, overly abstracted data, and so on. In the example below (Figure 6-8), we can see the wide range of three tower churches found within a tertiary micro-cluster. This messy collection of churches with only loosely shared similarities makes it difficult to understand and identify formal patterns by indiscriminately looking at form alone and even finding things like typical and least typical form. However, identifying what morphological traits were shared amongst these messy groups was much easier to do when gaining domain knowledge of the subject matter, and access to existing building style descriptions and past research.



**Figure 6-8:** Identified latent cluster that includes a messy collection of various church sub-styles, though primary Boyko. Diagram by author.

When referring to the geographic distribution of churches, it also cannot be assumed that churches within close proximity of each other necessarily have similar morphological traits. Take for example, the three Transcarpathian churches described in the previous section. Though they have nearly identical forms and are clustered

along the same stretch of river valley, other nearby churches just one valley over (Figure 6-9), are defined by drastically different forms in Boyko style, an entirely different School of folk architecture construction. Given these discrepancies, proper interpretation of churches within both latent space and their geographic distribution must be supplemented with existing domain and expert knowledge and reference to existing research in order to avoid any misunderstandings or misinterpretations.

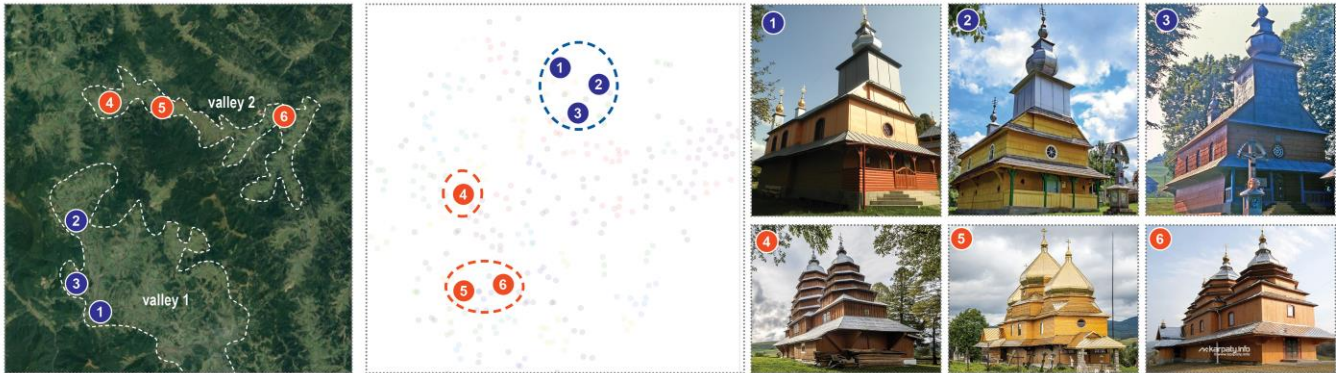


**Figure 6-9:** A visually identified geographic cluster of churches, that may suggest similar style due to their close proximity, but are in-fact quite different styles located at opposite ends of the latent distribution. Diagram by author.

## Chapter 7 | Conclusion

### 7.1 Summary

This research presents a detailed case study of a critical engagement with building data and Deep Learning techniques for the purposes of architectural-historical form analysis. This thesis argues that insightful morphological relationships among our dataset of 313 Carpathian wooden churches might be revealed using contemporary DL methods and reflects upon specific ways these analyses might enrich existing architectural scholarship and expert knowledge on the subject.

To begin, I compare DL-informed results with conventional studies [25], that have utilized traditional analytical methods and demonstrate that there is correlation between the way in which these two differing approaches have grouped churches in terms of similar form. I then show how DL techniques can help to identify groups of churches that share similar forms according to both general and specific architectural features by altering cluster size. This allows both primary, sub-style, and micro-style groups of churches to be identified. Additionally, I provide evidence that DL-techniques can help to identify and located clusters of harder to recognize endemic micro-styles that have developed within isolated geographic regions, such as within certain valleys or along certain rivers. I also highlight how DL-based findings can potentially be misleading if not properly interpreted and supplemented with domain knowledge and existing research. Finally, I offer a path for DL-based form analysis techniques to be put in conversation with traditional architectural studies in order to help expand and enhance our understanding of architecture.

Finally, my thesis offers a number of useful technical contributions to both the field of architectural form-analysis and to the research of Transcarpathian wooden churches. First, it demonstrates a method to build a custom 3D dataset of a non-western, generally rural, and “niche” building type using the NeRS technique [23] that converts sparse imagery into three-dimensional models. Second, it demonstrates how similarly small and custom datasets can be successfully augmented in size in order to sufficiently train DL-models. Thirdly, it presents a multimodal approach for analyzing latent space distributions by incorporating both DL-oriented approaches, such as Rhee’s method of clustering and identifying typical and least-typical form, and traditional approaches such as reference to Taras’s cultural-zoning map, church style and sub-style diagrams.

## 7.2 Findings

By having access to existing research, domain expert, geographic mapping, and a comprehensible small dataset, I was able to obtain a deep and rich understanding of our data, evaluate the findings of our work and discover novel insight, through the following observations:

- How morphology indicative of the four main schools of folk temple buildings (Boyko, Lemko, Transcarpathian, and Hutsul) was dispersed among the latent space distribution using primary clustering.
- How secondary clustering of smaller groups of churches generally provided better identification of church sub-styles within more defined geographic areas.
- How micro-clustering of even smaller church groupings helped to identify both endemic micro-styles that could only be found in certain valleys or along specific rivers and also interesting border styles that contained a synthesis of two or more schools of folk architecture construction.

In addition, this rigorous understanding allowed me to then identify and establish broader patterns across the data including:

- The multi-directional manner in which tower height and count changes across the latent space distribution.
- The degree and direction building forms change from tripartite to cruciform across the latent space distribution.
- How the dispersion of church datapoints within our latent space distribution diagram is generally organized into two overarching master groups being churches with single towers over the front entry space, and churches with towers over the middle nave space

A thorough understanding of the building data also allowed me to identify subtle micro form patterns within the latent distribution that indicated:

- A unique and nuanced condition where tower height over the narthex space changes amongst various Lemko sub-style church categories
- A rare instance when the church form of two opposing Schools of folk architecture completely overlaps and are almost indistinguishable from one another

Lastly, various potential misleading clusters were identified within the latent distribution including:

- A cluster containing a hodgepodge collection of different style churches that did not have towers.
- A cluster containing stylistically unrelated churches defined by building additions that resulted in the churches having a “T” formation

- A number of outlier styles that tended to cluster together regardless of major style differences.

### 7.3 Discussion

The use of DL-based techniques for architectural form analysis has clear strengths but should not be used as a stand-alone tool in its current state. Alone and without prior knowledge of the dataset, we run the risk of misinterpreting results, making assumptions, and drawing inaccurate conclusions. Rather, by complimenting DL-methods with findings from existing research, domain knowledge, and geographic reference, we can more accurately interpret its findings and draw more meaningful conclusions. This became quite clear during study as I had to continually shift my attention between latent space, map space, and existing research in order to accurately evaluate, question and investigate what was learned by our model and whether new and meaningful knowledge could be gained.

This is especially relevant to the Carpathian wooden churches of Eastern Europe as there still is “no unanimous opinion about types of churches and criteria they should be attributed to the schools of the national temple building” [25], due in part to the “lack of comprehensive studies of building types using the cartographic method[s], [for example, by] drawing hundreds of plans, facades and putting them on thematic maps in order to identify the geography of the spread of characteristic architectural solutions and the boundaries of architectural and cultural districts” [25]. However, as DL-learning techniques provide a means of doing just this, I believe researchers of this building type and others could greatly benefit from this new and informative method of DL-based analysis.

In this research, I also demonstrated how a custom 3D dataset of a specific architectural type can be created using the NeRS technique. This is important as 3D architecture data in general, is mostly unavailable online, especially of a niche, rural and rare building type like Carpathian wooden churches. By building this dataset, I hope to have demonstrated how creating custom 3D data for DL-based research is not impossible and does not require on-site scanning but can be created through sparse photographs alone. This is especially relevant when buildings are not accessible, for example during times of conflict, such as the ongoing war in Ukraine with Russia, are difficult or impossible to reach, are too dispersed or are too numerous to document by hand. In addition, buildings are often temporary or even ephemeral objects that do not permanently exist. This is quite apparent with the Carpathian wooden churches which have disappeared drastically over the past 100 (Figure 7-1) years and continue to do so today due to neglect, arson, political reasons, or destruction during times of war. However, creating a dataset using NeRS was tedious and time consuming given the amount of manual work required for each one of the thousands of images. This was reflected in the multiple months it took to build the Carpathian wooden church dataset.

In addition to 3D reconstruction, by encoding the style of these churches using DL-techniques like VAE I was able to preserve both the individual and overall styles present within the dataset. As the morphology of the dataset is represented as a distribution of latent vectors, both existing churches and novel churches in similar styles can be generated, thus providing a means to capture and provide access to the stylistic “essence” of Carpathian wooden churches far beyond their potential physical lifespan. When considering the threat to Ukrainian material culture given the current war with Russia, digitally preserving and protecting both the churches themselves and their stylistic “essence” becomes increasingly important if we hope to preserve this important and irrefutably distinct part of Ukrainian architectural folk heritage.

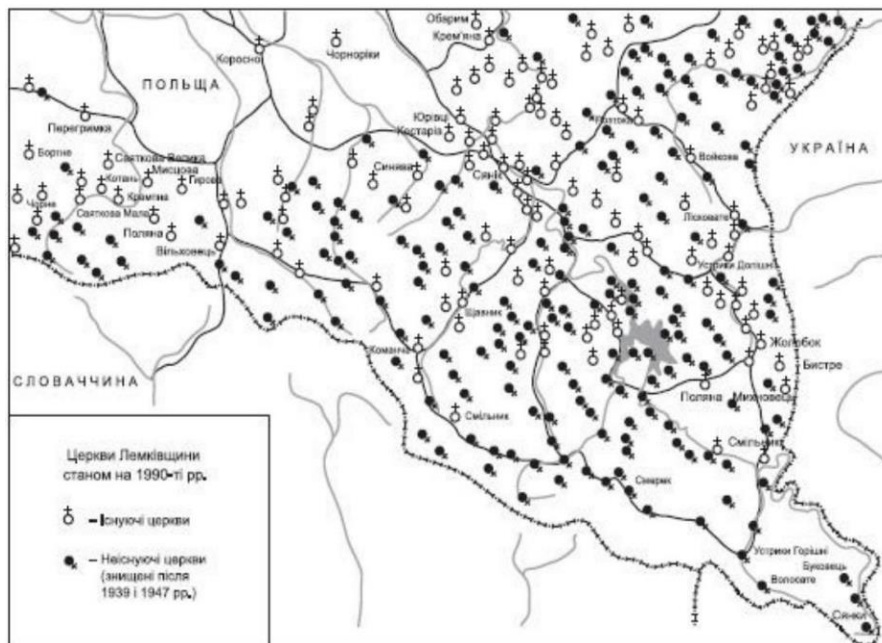


**Figure 7-1:** Churches lost between 1939 and 1947 (black circles) and churches still standing (white circles) in the historic Przemyśl region in what is now Southern Poland. [25, 38] from "Wooden Temple Architecture of the Ukrainian Carpathians".

## Chapter 7 | Limitations and Future Work

The demonstrated study only encoded a single primary style of wooden church, being the Carpathian style and closely related surrounding styles. It may be interesting to include other wooden church styles from more distant territories, for example Norwegian wooden churches, in order to observe their place within latent space in comparison to Carpathian wooden church. This would be a fruitful way to understand formal relationships and reveal interesting patterns across the broader building styles of more contrasting ethnographic zones.

During the data preparation stage, the 3D data was also highly abstracted when being converted into a 32x32x32 voxel. As a result, the VAE model did not have the opportunity to capture and encode more subtle form characteristics. As a result, buildings that may have had subtly different forms were clustered too closely together due to this lack in resolution. In addition, ground truth building dimensions were likely distorted during the 3D reconstruction process due to its reliance on sparse imagery. As a result, buildings encodings were not only based on abstracted representation but also slightly distorted one too. In future studies, I could address this by supplying more images in the 3D reconstruction process to reduce distortion and by converting our data to 64x64x64 voxels to decrease abstraction.

Selecting churches to include in the dataset was also done early on in the study, prior to gaining a more informed understanding of the range of Carpathian wooden church styles that exist. In that regard, I may have included within or left out churches from our dataset that shouldn't have been. One result of this was that a number of churches from the Opilska cultural region were mistakenly added to the dataset thinking that they were Boyko style due to their similar morphology. Interestingly however, the model was seemingly able to tell the difference between the two, with Opilska churches being more clustered near the bottom left while Boyko churches tended to be clustered above at middle left. However, it is unknown how much this mistakenly included style had affected the overall organization of the dataset. In the future, more expert knowledge could be accessed earlier on to ensure the data is as refined as possible.

The model used in this research also had trouble adequately encoding the less represented church styles within in the dataset due to the lack in volume of similar styled examples. As a result, these particular churches were placed within small clusters of other outlier churches at the perimeter of the latent space distribution. In addition, when decoding their z-values, their resultant decoded forms were often inaccurate and were more reflective of other styles that were more represented in the dataset. This suggested that these churches were inaccurately represented by the model, which in turn, may have affected results through their inclusion in incorrect clusters. This may explain why clusters contained churches that seemingly didn't match any of the typical morphological

characteristics dominant within the group. To address this in future work, I could increase the size of our dataset with more churches to reduce outlier cases or better augment our data to compensate for them.

Data augmentation could also be improved by introducing more randomness and distortion. Within the study, I only used random building scaling in the x, y, and z direction and continuous rotation from -16 degrees to +16 degrees in 2-degree increments. Future studies could introduce more varied kinds of distortion such as slight building warping, scaling of certain parts of buildings, or introduction of geometric noise. This may help improve model training by reducing reconstruction error, increase reconstruction accuracy, and create a better partitioned and distributed latent space.

Next, the results of this experiment were only explored and evaluated by members of this team, thus the number of morphological patterns across the latent space distribution that could be investigated was limited. In future studies, I could share results with others, such as domain experts or even members of the community where the churches are located. This may reveal novel relationships that may have not been missed or gone unnoticed. This could be done through an online website that allows for simple and straightforward means to explore the latent space and its relation to, geographic space and 3D models. Metadata and existing research could also be made easily available. By providing an interactive interface with easy-to-use controls, it is suspected that many interesting findings could be obtained through this type of community involvement.

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