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A Smart Heritage System to Re-Generate New Zealand's 19th Century Timber Churches

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Abstract: This article describes a Smart Heritage computational system that automatically produces a wide range of design proposals for new timber Gothic churches based on an intelligent interpretation of an architectural database of historic churches. The system enlists the software 'Houdini' and a digitally archived dataset of 19th Century timber Gothic churches. The cases presented here focus primarily on timber churches built in Wellington, New Zealand. Through a process of analysis and deconstruction of these historic churches into their characteristic architectural components, spatial organisation and geometric relationships, the system assembles them into novel designs based on high-level design parameters. This paper details this computational system, its development, its operation and its outputs. The role of the system that has been developed is two-fold. One is designing in an architectural heritage context, and one is as an aid to historical architectural investigations, or what can be called digital forensics. The particular outputs are automatically generated hybrid churches that capture the historical design values and complexities of Gothic inspired churches in New Zealand. However, the broader applications are as an investigative tool for historians, and as an objective generative tool for those involved in heritage reconstruction.

Keywords: Smart Heritage; procedural modelling; reconstruction; heritage policy; digital forensics

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1. Introduction

The preservation, re-creation and understanding of architectural heritage has increasingly utilized more sophisticated computer-mediated design methods as computational design technology has advanced. The practice of reconstructing such cultural artifacts digitally has consequently developed alongside the advancement of software and digital tools that are made available to researchers. When looking at the literature within the field of digital heritage, digital recreations of both existing and lost designs have become increasingly common.

One of the early applications of computational analysis, applied to augment understanding and analysis of historic architecture, and referred to as digital forensics, is given by Brown [1]. A particular application using more sophisticated digital analysis techniques was reported by Webb and Brown [2]; the digital forensic analysis in this case, for instance, established that critics had misread the cross section of the unbuilt parts of the Liverpool Metropolitan Cathedral. In doing so spatial relationships had been misrepresented in reviews of the unbuilt design.

Other contemporary developments and applications as part of this evolutionary chain have recently been described extensively by Buchanan et.al. [3]. The research developments in this paper focus on the more complex analysis and modelling methods that have enabled the creation of adjustable and, therefore, responsive, parametric reconstructions. This brings additional power and potential to the analysis. Consequently, this can further the understanding of these buildings while also giving greater freedom and efficiency for speculative models of lost or unbuilt designs to be created. We detail in this paper, an example of an application as an analytical tool, applied to the specific case of churches in New Zealand.

Further, given the potential for the system that has been developed to propose many potential variants that satisfy the important geometries, forms and relationships present in an original heritage context, there is the potential for deployment of the technique in a Heritage policy setting. In situations of lost or deliberately destroyed heritage sites, the debate about how to retain the original 'stamp' (the word as used by ICOMOS) is often contentious. Frameworks are needed to enable a sustainable and resilient approach to policy application as noted by Alsalloum and Brown [4]. The technique described in this paper provides a computational tool that can provide both a range of objective outline proposals for reconstruction or an analysis of proposals derived by conventional design techniques. This can help reduce debate about matters of subjectivity in what are often difficult heritage decision-making processes.

The research described in this paper advances the employment of smart technologies that automate the adjustment of design parameters to realize forms that are generated computationally. In terms of intention, the broad scope of the computational work owes its roots to key developments in shape grammar approaches, particularly those of Stiny and Mitchell [5] and Stiny [6].

In our work described in this paper, the designs produced by the system are driven by a ruleset that is based on our analysis of a particular heritage architecture: the 19th century timber Gothic Churches built in the city of Wellington, New Zealand. The primary computational tool employed is SideFX's procedural modelling environment 'Houdini'. A key component in the method applied lies in the refinement of a computational ruleset that aims to define the common characteristics present within a loosely defined architectural style, and ideally also the style differences across different designers of a particular typology. The use of smart technologies is essential, as the labour-intensive task of design analysis, and consequent generation is automated, and can therefore produce an extremely wide range of potential design outcomes.

The application of algorithmic systems is becoming more common in digital heritage applications. The primary aim of the research was to develop a new tool to augment existing digital forensic techniques. A complementary aim was for this tool to be capable of usefully informing the application of heritage policy. We suggest that the outcome does establish a technique and technological application that we believe has important potential in both regards.

2. Background

2.1. Digital Heritage Reconstruction and Analysis

Creating a digital 3D model of a building is by today's standards quite a simple operation. Basic CAD software capable of modelling and visualizing these digital representations have been used extensively over recent decades, with early published examples beginning to appear frequently during the 1990s [6,7]. As time has passed and computational power increased, greater photorealism could be achieved with the utilization of more complex geometries and textures, even though the method of creation remained essentially the same, i.e. prescribing geometries and appearance. The use of more complex parametric software saw key developments for the field. Evolving alongside CAD methods, parametric software produces geometry that is defined by code that captures relational parameters. This allows greater adjustability for the refinement of the final geometric output, improving on the absolutely defined geometrical definitions typically at the core of basic CAD systems.

A seminal example of the application of parametric tools in a heritage setting can be seen in the efforts to reconstruct (both digitally and physically) Gaudi's Sagrada Familia [8]. Mark Burry responded to the complexity of Gaudi's geometry and the incomplete physical records of the church by employing parametric relationships originally via coding in AutoLisp. Using digital tools more frequently found in the design of aeronautics components, Burry reverse engineered the forms of the church by extracting, and then defining, the mathematical algorithms that produced the complex geometries.

This parametric approach to heritage reconstructions has been increasingly adopted in other research efforts in recent years, proving the versatility of the method and its applications. One such example details the reconstruction of traditional Indian pavilions as described in the text 'Mayamatam' [9]. Using a custom-made parametric add-on for AutoCAD, Garg and Das (2013) detail how 3D reconstructions were created from the descriptions and rules defined in the historic text. Users can input variables, from which the system can create an almost infinite number of pavilions.

A similar approach has also been employed by Li et al. [10]. This research project develops earlier investigations devised to capture and reproduce the characteristics and geometric relationships extracted from ancient Chinese building design guides. The research captures geometric and spatial relationships based on the ancient Chinese design rule book, Yingzao Fashi, and additionally captures cultural variations that modify those relationships. Data were also collected from extant historic buildings. This research had the Yingzao Fashi rule book as documented source of geometric and relationship data, in the same way that Palladian primary geometric relationships had been made explicit. In the work presented in this paper, the relationships had to be derived from examination of existing buildings or drawings of lost buildings.

Another more recent paper with closer parallels to our work highlights an additional approach to parametric reconstructions. Kramer's (2019) research undertakes the digital modelling of America's Second Empire houses [11]. Using the same core Houdini software that is used in our work, Kramer creates a parametric system that can generate many different examples of both lost and existing Second Empire houses. This was achieved by categorising and defining the common elements shared by the designs and creating a custom parametric system. The resulting system successfully generates outputs that align well with the various historic precedents. Such a process highlights how the efficient adjustability of the software can be used to create a compendium of valid digital heritage reconstructions. Our research takes a similar approach, but adds useful features such as the automation of parameter adjustment.

2.2. Algorithmic Modelling and Smart Heritage

The application of smart computational technologies to the field of digital heritage continues to provide important innovations in both how architectural heritage is helpfully recreated, interrogated and understood. Focusing on the wider context of cultural heritage, the research of Batchelor et al. defines this research field as 'Smart Heritage' [12]. Their definition notes that "Smart Heritage is the convergence between the smart city and heritage disciplines that entwines the autonomous and automatic capabilities and innovation of smart technologies with the contextual and subjective interpretation of the past." In their investigation of the existing body of literature within the smart heritage field, examples show how heritage preservation and education are enhanced by the application of algorithmic systems that interpret real-time data and user inputs. An example of this kind of work can be seen in the pilot of Mar et al. for their 'Smart Heritage City project' [13]. The researchers develop a comprehensive system and smartphone application that interprets both the real-time data relating to various heritage monuments such as population and wait times within the historic town of Avila, Spain, and the users preferred visit locations and how long they are visiting for. Interpreting this live data through rules derived by the researchers, the system then outputs the ideal itinerary and route specific around the monuments, conditioned to the demands of the user and their personal preferences.

Architectural heritage reconstruction policy advice and the field of digital forensics share similar conceptual motives to those embodied in Smart Heritage, where the technology curates, analyses, and then delivers a heritage output that is useful to the end-users. The application of algorithmic systems to the interpretation of a complex set of data has been applied to heritage reconstructions in the past, even if the terminology 'Smart

Heritage' is not used. Procedural modelling is the approach that we have used for our explorations, which allows stepping beyond more fundamental parametric modelling, via the automation of parameter adjustment using computational rulesets.

An example of this approach is detailed in the 2012 article 'Automatic Reconstruction of Roman Housing Architecture' by Muller et al. [14]. This paper details the process of generating a large set of typical house forms and layouts procedurally. These were houses that were present in the city of Pompeii before its destruction. Using Shape Grammar techniques, of the kind described comprehensively by Jowers et. al. [15] in their reflective overview, the established system takes GIS mapping of both geographical and socio-statistical data (such as population density, age and function of the various urban areas of the city) and converts them into predefined rules to generate a 3D approximation of the entire city. Such a process has many parallel aims to those in the 'Smart Heritage City project', mentioned earlier, except that, as in our case, the outputs considered most appropriate are adjustable 3D visualisations.

Another example that takes a different approach is the procedural reconstruction of a neo-Gothic Church in the region of Vojvodina, Serbia [16]. Here, Tepavčević and Stojaković also use a method of shape grammar procedural modelling, with their outputs being primarily driven by a statistical analysis methodology. The research interrogates 20 existing churches that share a familial resemblance to the church being reconstructed. Shape characteristics within the sample group were examined, and occurrence probabilities were calculated for each shape property. Alongside the use of fuzzy logic, procedural modelling algorithms were developed to drive shape grammar software. The result is a system that generates plausible iterations of the lost church. The 3D model with the highest probability of representing the lost church was consequently determined. This project illustrates how algorithmic modelling and analysis can help reduce the subjectivity in challenging heritage reconstructions. Such a process can contribute to implementation of a particular framework for reconstruction of a specific case under the broader guidance of generalised heritage policies [17].

The ground-breaking work by Stiny [6] developed ideas and potential for algorithmic approaches using shape grammar methods. The principles had been established two years earlier as reported in Mitchell and Stiny [5], where the example of Palladian floor plan replication had been shown to be possible using a computationally enabled approach. The characterisation that Mitchell and Stiny devised produced a shape grammar approach that was both analytical and generative.

However, Mitchell and Stiny noted that further sophistication and capability would be desirable to describe and generate a Palladian villa more fully; the proportions of the plans and the computational replication of facade characteristics were absent from their initial work. Hersey and Freedman's 1992 book 'Possible Palladian Villas' took on this challenge and devised a richer 2D floor plan capability and a façade generator [18]. It does this through the creation of a custom digital interface, where the relationships are translated into procedural rules that then generate the 2D representations. A dataset of around forty published designs was a primary data source, and these published designs were then broken down into component elements. Hersey and Freedman noted what others had found, that Palladio's declared rules were not followed religiously in practice. In addition, other rules had to be inferred for the system to produce viable outputs.

Our research shares similarities with the cases mentioned above. One important consideration is that our sample group of buildings does not have formally prescribed rules as a starting point. There is a loosely understood standard church floor plan language but there is no precise prescription in the geometric relationships that this might lead to. The second issue is that we are investigating a typology (the New Zealand church), with several designers contributing to that typology. The third is that the New Zealand church emulates styles and geometric relationships, such as Gothic, that were intended to be constructed as stone buildings. Like the timber churches of North America, forms are modified from the original stone forms in response to the different properties of the main structural material. The geometries taken from stone churches are therefore of limited use in trying to characterise a New Zealand timber church style and geometry. Finally, to represent the spatial relationships most effectively, the method of visualisation of the outcomes is most effective with 3D models rather than 2D representations.

2.3. 19th Century Timber Gothic Churches

The Gothic style is widely known as being one of the most prominent architectural styles to develop in mediaeval Europe. During the Gothic revival period in the 19th century, Britain was expanding its empire, and this led to the construction of new churches and cathedrals in colonised locations. Gothic design was a standard for church architecture, and new settlers sought to replicate this tradition in locally available materials.

The transformation to a material that was linear and lightweight, joined by mechanical fixings rather than a heavy brittle material held in place by gravity clearly led to debate and confusion about how the geometries should be re-imagined. In the article by William Scott titled 'Wooden Churches' and published in 'The Ecclesiologist', Scott suggested that "We do not think these churches are in any respects good models of construction" [19]. An important criticism in the article relates to the main motif in the adopted style, the tall, pointed external roof. Inside this, the arch was the most efficient form to attain the height and spans with stone as the structural material in the traditional European church. In New Zealand, these forms were often replicated visually, but with curved timber members that performed little or no useful structural function. In addition, it was difficult and wasteful to create such forms using straight solid timber members as the source material. However, such rejection of the inappropriate use of timber did little to stop settlers from building this way, leading to a particular regional style and form that is the focus of our interest – the New Zealand timber church.

In previously mentioned heritage reconstructions such as that of Kamer and Akelman [11], the researchers began with a collection of buildings that were already identified as belonging to a specific, architectural typology. In the work of Garg and Das [5], descriptions of the rules that were used to devise new forms were also explicit. However, in the case of Wellington's Timber Gothic churches, there has been significantly less reporting and analysis of these designs. This is in part due to the nature of church design in this period, as there was a lack of both precedent and expertise to form the basis of new designs. Such an environment enabled the interpretation of the Gothic style in New Zealand and in cities like Wellington in particular. The result appears to have been bespoke designs that refer to other designs in the area, but in a loosely defined and articulated way.

More than 20 designs identified in our research, therefore, have a family resemblance, and sometimes employ re-use of certain features, forms, and geometric relationships. Consequently, the goal of our research was to create a system that can investigate and extrapolate from the incompletely defined design rules that tie these churches together.

3. Methods

3.1. Creating the Initial Parametric System

The research started with a relatively straightforward parametric reconstruction of a single design: St Mary's Cathedral (Figure 1). In 1898 this church, like several in New Zealand, was destroyed by fire and no architectural construction plans could be sourced, so finding details for the building proved challenging. However, one line of thinking was that the parametric digital model could be enhanced later if evidence were uncovered as part of the forensic reconstruction process. A small selection of photos was located, and an 1867 article was traced [20]. The article was written for the re-opening of the cathedral and gave rudimentary dimensions. From this, a process of deconstructing the church into its constituent components began.

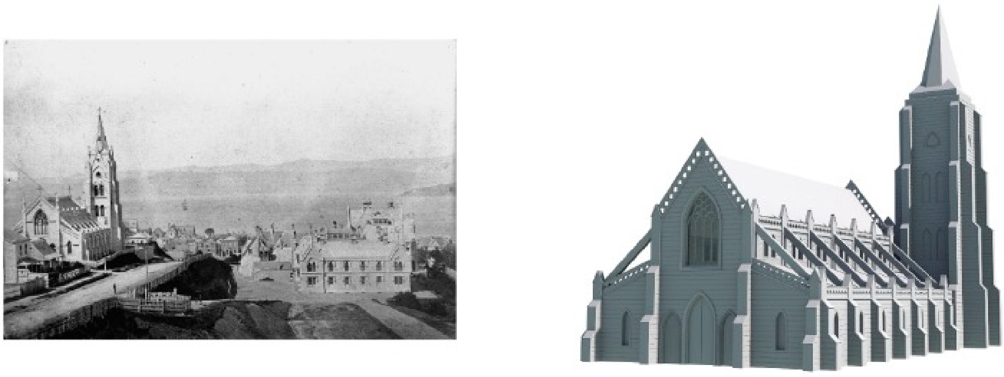

Figure 1. The initial reconstruction of St Mary's Cathedral that formed the basis of the church.generator (**right**). One of the few existing photos of the Cathedral (**left**) [20].

Firstly, the main spaces were analysed, with the distinct forms of the sanctuary, aisles and tower being identified. This allowed the shape of the central space of the nave to be delineated. Developing the representation from these main forms, the architectural elements in these areas were categorised into additive and subtractive forms. Additive components consisted of the various buttresses, parapets and eave details that are added to the basic core form; whereas subtractive components included elements that penetrate the main form, such as the windows and doors (Figure 2).

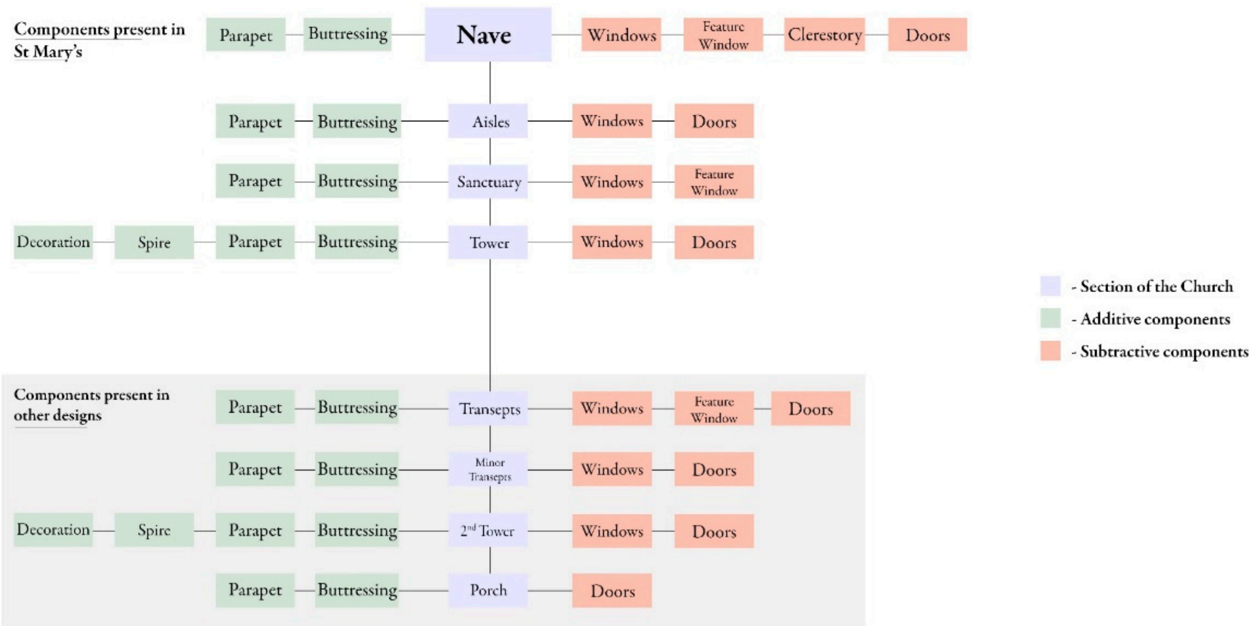

Figure 2. Breakdown of the spaces and detail components, comparing one design's makeup.(St Mary's Cathedral) to the other possible components in different church designs.

Deconstructing the spaces and forms in this way not only served to organise the forms of the design in order to understand them, but also provided the mechanism to organize these within the software computational design environment. Once these components are created in the software, they form a library that can be called upon for use in other church reconstructions. The visual code used to create the 3D geometry within the software Houdini is housed within subfolders, as illustrated in Figure 2. For each subfolder, parameters from the visual code within the folder can be promoted so that they are easily accessible. As shown in the simple case in Figure 3, parameters such as length, height and wall thickness can be promoted, and these variables then become adjustable by the user. The geometric outputs produced by these subfolders can then be accumulated and integrated to generate the final reconstruction.

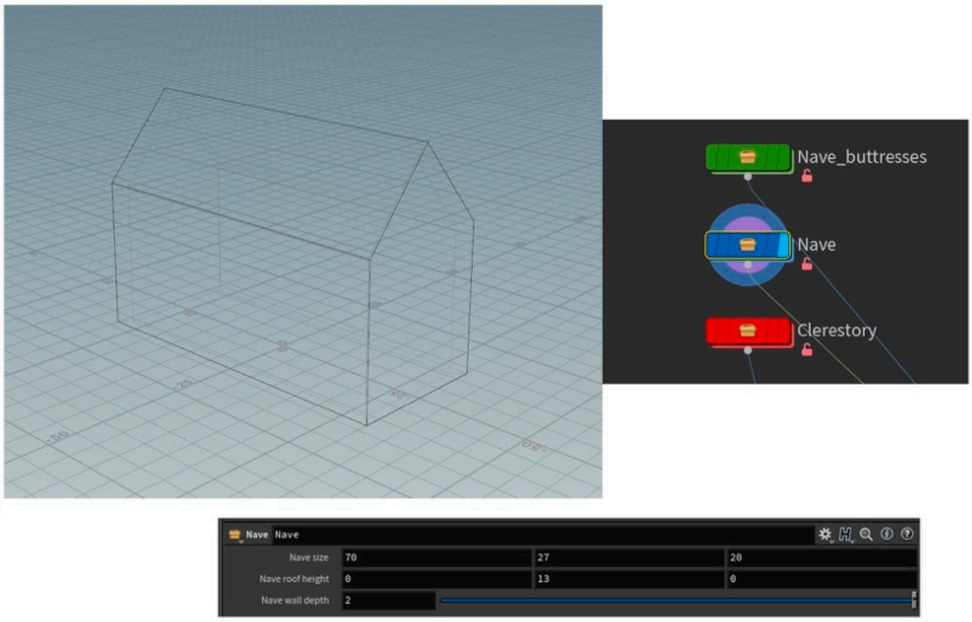

Figure 3. Diagram showing the parameters promoted for the Nave subfolder/component node.

This case was used to develop the techniques employed. One aspect of this experimental reconstruction that was successful and was carried through to all other reconstructions undertaken, was how the size and positions of all the supplementary spaces and components are linked to the defined relationship they have with the nave. For example, the aisle buttress component has adjustable parameters for its width, length, and projection into the aisle. The height and spacing however is determined by the dimensions of the aisle, with this in turn being linked to the dimensions of the nave. These rules defining interdependent relationships proved valuable later.

This process is shown more specifically in Figure 4, which illustrates how the initial form of the aisle is generated within the aisle subfolder/component node. The size parameters of the aisle are defined by the inputs it receives from its respective X, Y, and Z channels (ch("../size")). The X and Z channels are links from the promoted parameters that are thus accessible from the outside of the subfolder and are directly controlled by the user. The X channel on the other hand is simply a link from the X value of the Nave's initial form. The position is then determined by linking these size values and applying rules. This is shown within the software, as pasted/linked parameters are shown in dark blue, and active rules are shown in bright blue. The base of the aisle is made to sit flush with the ground plane by copying the size Y value (ch("sizey")) and dividing it by two, giving a positive value that shifts the form up. The Z value undertakes a similar process, as the side of the aisle is made to sit flush with the side of the nave. The size Z value is linked, divided by two, and then added to the nave length (ch("../Nave_Length/value1v1")) which is also divided by two. This gives a positive number that shifts the face of the aisle to the side of the nave.

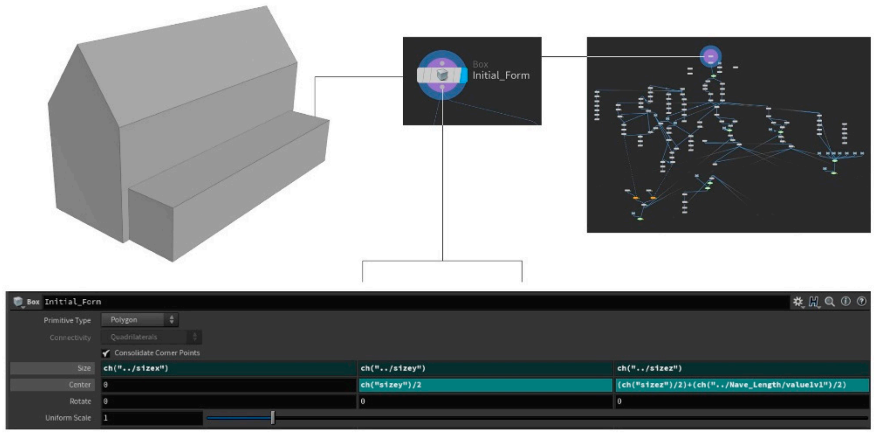

Figure 4. Diagram showing the computational expressions used within Houdini to create the basic form of the aisle. The expressions channel the dimensions of the nave and user inputs to give the initial 'box' node its size and position.

3.2. Expanding the System–Generating New Reconstructions

Once the basic parametric system was set up, this could then be used to create other designs; the accumulation of examples to extend the database was undertaken in a way that was partly strategic and partly pragmatic. Data for the next group of cases were readily available, either from measurement on site or from construction documents. The second church chosen for reconstruction was Old St Paul's, as it was of similar proportion and built at around the same time as St Mary's. The building also had a transept extension that was designed by the same architect as that of St Mary's, so it was expected that many design traits might be shared between the designs. Although this was true to a limited extent, many new components had to be created. The design was more elaborate than other designs reconstructed in this research, and many refinements and additions had to be made to the first set of components. This more complex case did, however, make the system much more powerful and robust. This was valuable when further reconstructions were enacted. Figure 5 illustrates the additional component categories that had to be created when reconstructing other design configurations (St John's was not fully reconstructed in this research).

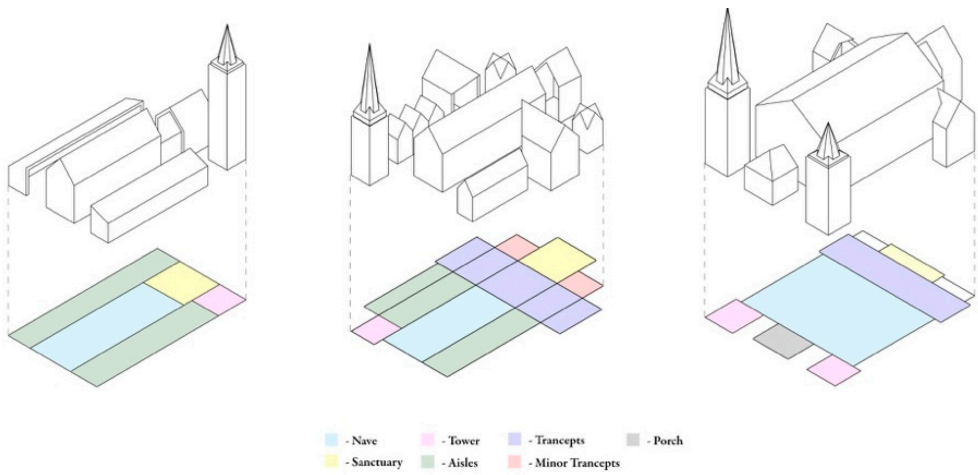

Figure 5. Spatial Composition of St Mary's Cathedral, Old St Paul's, and St John's.

To expand the system further, two designs were chosen that sat at either end of the spectrum in terms of size. These were Christ Church in Taita, having a capacity of around 100 people, and St Peter's, having a capacity of around 800 people. This pair of examples helped define the likely scope of the system in terms of scale. If the system functioned well within this range, that would act as reassurance in terms of verification. Very few components and adjustments had to be added to create these two examples, showing the reassuring capability of the initial system. The features and issues revealed in the second example church had clearly identified many variables and configurations that were found in less challenging cases. Figure 6 summarises the process of development and refinement of the system as the new cases were analysed and added to the vocabulary and spatial relationships. Figure 7 illustrates the significant range of outputs now possible at the end of this phase of additions to the component library and the associated rules.

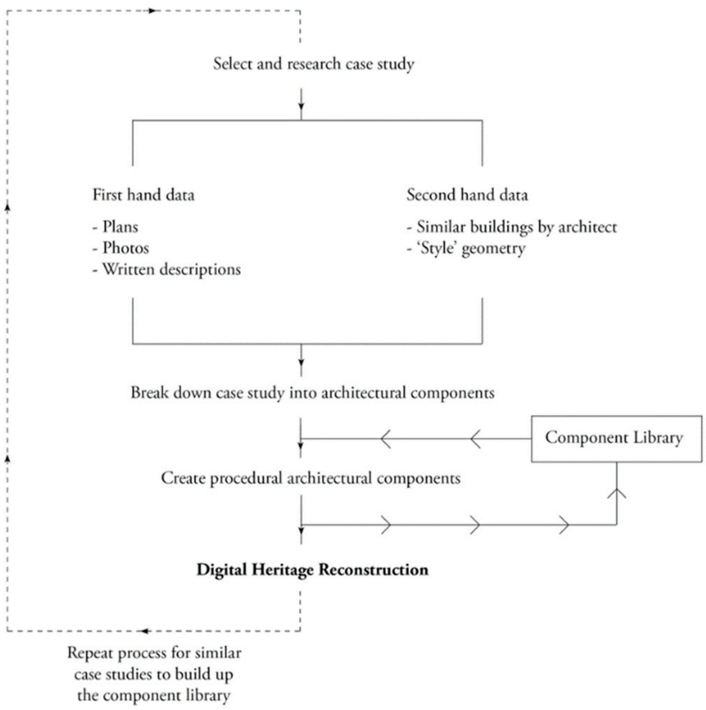

Figure 6. Diagram showing the process of expanding the parametric system, highlighting how a growing component library enables new designs to be created more efficiently.

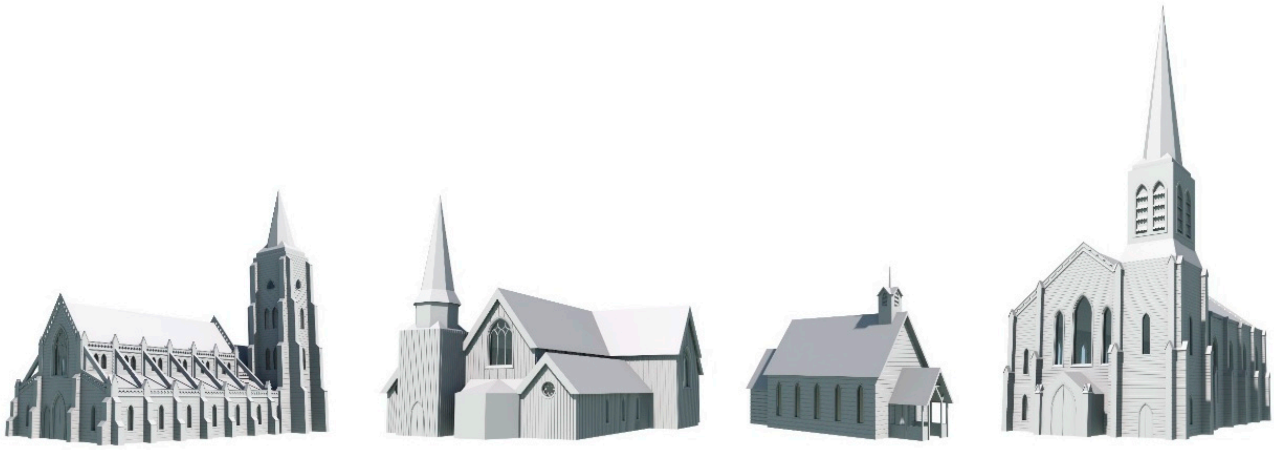

Figure 7. The outputs of the expanded system, St Mary's, Old St Paul's, Christ Church in Taita, and St Peter's.

At this point all the parameters from each component node were collected into a single 'control switch' node. This resulted in a single list of around 240 parameters that could be individually adjusted to create many unique designs. Here, pre-sets of the inputs could also be saved. This meant that each reconstruction could be characterized by a different arrangement of these 240 computational inputs.

3.3. Speculative Reconstructions

Once the system was able to produce a wider array of existing designs efficiently, the next stage was to test its capabilities when applied to other, less well-documented lost churches. As Wellington's timber Gothic churches are prone to material deterioration and fire, many have been lost over the years. Over 20 designs were researched for this paper, and fewer than half survive. As discussed, in the case of St Mary's, the age of these buildings often makes it difficult to retrieve accurate documentation, meaning that designs had to be extrapolated from what was known, based on the data and rule structure that had been accumulated in the system.

The Manners Street Wesleyan Church was built in 1869 by Architect Charles Tringham [21]. It burnt down in 1879 and just one close-up photo still survives. This photo shows only the front façade and gives little insight to the side and rear of the church. Despite this lack of information, a basic digital reconstruction could be postulated with the developed system (Figure 8). This is because of the strong similarities that this lost church shares with the existing design of St Peter's church. By comparison with the examples for which good data exists, a total of four have the enlarged nave design seen in this lost church, with Thomas Turnbull's St Peter's being one of them. Other aspects of the geometry also showed similarities. For this reconstruction, it appears that the later design of St Peter's is descended from the earlier Wesleyan Church. To complete the speculative proposition, the geometries of the main nave and accompanying sanctuary spaces of St Peter's were integrated into the lost church's reconstruction. The reconstruction therefore forms a basis for discussion and further research. As previously mentioned, this design can be modified as new, credible evidence is found.

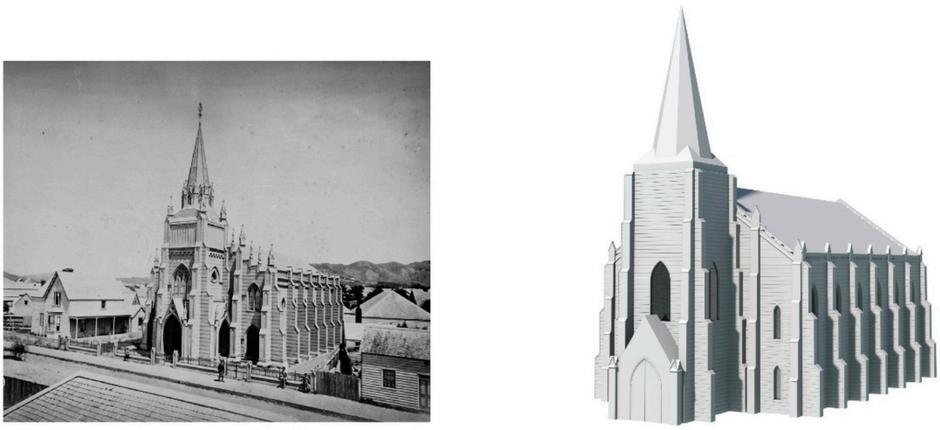

Figure 8. Photo of the Lost Manners St Wesleyan Church [21] and a basic reconstruction using the procedural system.

For some of these churches, the designers and builders were not recorded in sources that are generally available. We selected a small number of these for forensic investigation. One such design was the lost church of St James' in Lower Hutt. Comparing it to other timber gothic churches in the Wellington region, one of the most interesting details is the design of the tower, specifically its bell vents. This is seen prominently within Turnbull's church designs and an example was part of the reconstruction of St Peter's church. In investigating Turnbull's designs further, it was found that another church of his, St Patrick's in Masterton, also bore further resemblances to St James', having the same distinguishing bell vents and being of the same general size. By reconstructing the churches in our system, and comparing both designs (Figure 9), other similarities became evident, such as the same transept windows, sanctuary design and plan configuration. Consequently, it was speculated that St James's was either designed to resemble a church of Turnbull's or designed by Turnbull himself.

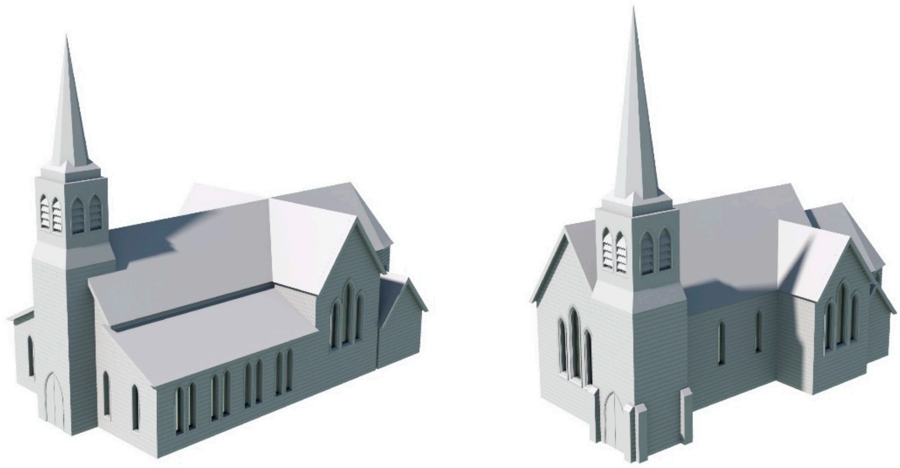

Figure 9. Reconstructions of the lost St James's and the highly similar design of St Patrick's in Masterton, by architect Thomas Turnbull.

With this information, subsequent investigation by a colleague based on our findings revealed that our deductions in relation to St James' Lower Hutt and St Patrick's Masterton were correct [22,23]. These church designs had previously not been attributed fully. It is gratifying and reassuring that the system can deliver a forensic analysis of a design that is automated and logical, and that can lead to helpful new discoveries, or direct conventional archive studies. The speculative designs of the Manners St Wesleyan Church and St James' shows how a semi-automated modelling system, when combined with other analyses, can lead to new findings.

3.4. Automated Church Generation

Although the research up until this point had employed procedural modelling software, a more fully procedural system was possible. For this, the user-controlled parameters could, instead, be directed by the computer. This was achieved by using the visual coding nodes within Houdini. The use of coding languages such as VEX or Python could have been a more efficient means of creating such a system, but we decided to exploit the existing developed environment. This environment also had an appealing visual structure.

As mentioned in Section 3.2, the 240 parameters that dictate the output of the system are channelled into a single list within the 'control switch' node. Initially, this was simply a central location that was linked to the parameters controlling the various components, serving only to redirect the user inputs. Further useful functionality was enabled by the addition of individual, interconnected switches, one for every parameter. As a result, the input that is sent to any individual component parameter is actioned by one of these switches (Figure 10). So, if the switch is not activated, user-controlled inputs are enabled, and, if it is activated, rule-controlled inputs are enabled. This is because the user-controlled inputs are now routed through the switch system, rather than directly to the component parameters as they were before. The rule-controlled inputs, on the other hand, are the result of computational rules that are defined for each parameter.

In our research, all these rules were based on the data accumulated from the church reconstructions already present in the system. For example, the length of the nave was defined as between 35 and 96 feet. As noted earlier, these were the values for the smallest (Christ Church in Taita) and largest naves (St Peter's) found in the reconstructed churches. For other parameters, such as the tower spire, simpler rules were applied. Only four different spire styles were reconstructed in this research, as the spire for St Mary's proved very adaptable and could be used as a generator for other designs. The procedural rule was defined to choose one of these four basic spire forms, with the height being determined in the same manner as discussed for the nave length, and the width being dependent on the size of the tower it is integrated with.

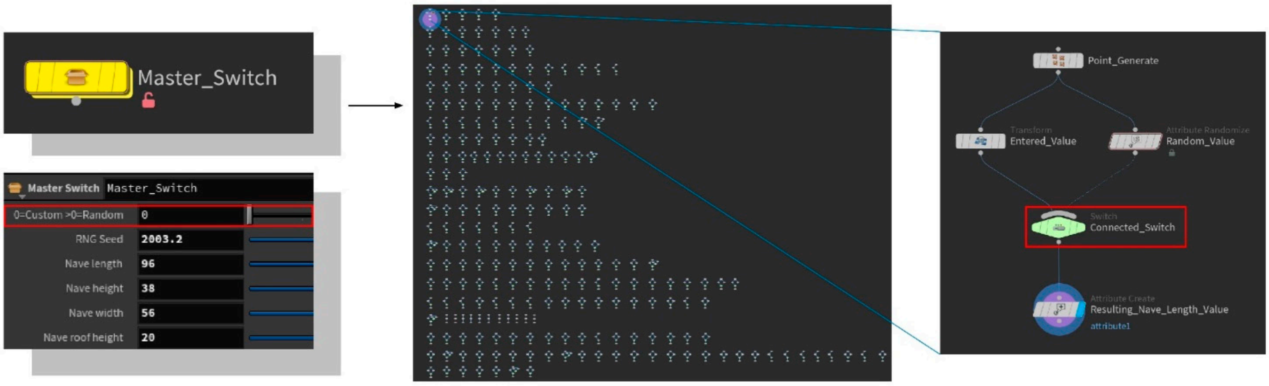

Figure 10. Diagram of the Houdini Interface, showing how the accumulated parameters were routed into individual, interconnected switches housed in the 'control switch' node. This allowed the inputs of the component parameters to be switched from user controlled to rule controlled.

The remaining components are then generated automatically by applying the linking of parameters and the rule system described in Section 3.1. The forms produced capture the important overall forms and geometric relationships that characterise a particular complete design. Further detailed elements could be added in future research. However, the focus of our research was to prove that such a system could generate designs that were consistent with the loose rules captured from documentation on, and measurement of, actual historic precedents.

The goal in creating the initial fully procedural system was for the system to produce a wide range of designs reliably. This process entailed an iterative process to arrive at a rule for each parameter, reviewing the outputs created, and then refining the rule or adjusting the component definition in response. During development, the system created designs that revealed bugs in the components' definitions, producing a distorted geometry. As the system was refined further, the outputs became more stable, gradually becoming closer to actual extant cases or plausible lost cases. An idea of the range possible can be seen in Figure 10.

Although these outputs would still require refinement to achieve a fully detailed representation of each particular style, the level of detail proved to be sufficient to capture the most important defining characteristics. In the forensic case that we quote, it was sufficient to suggest a strong family resemblance to the work of a particular designer. In the application in a Heritage policy setting, the most common case involves proposals for an urban area, or an overall massing and articulation of the form for a whole building. In either case, detail is likely to be secondary as a matter for consideration.

4. Discussion

4.1. Refinement of Rules

The outputs of the timber Gothic Church generator described above can be extraordinarily wide ranging. Valuable information can be drawn from these potential forms. The system created lays the framework for rules to be tested and refined in the future. The underlying iterative process is shown diagrammatically in Figure 11.

One potential area to refine and focus the pathway through the system (see Figure 12) would be to further categorise the churches into types, and filter using proportional rules. Further constraints could be applied to focus potential outcomes. Currently, the key starting values such as nave height, roof height and length are created individually.

As mentioned previously, starting values range from the small church of Christ Church in Taita to the large church of St Peter's. These two samples frame the extent of the current system. The result is that the system can create nave dimensions that are disproportionate to the overall massing. The system could be refined with further constraints that limit the potential for this.

Figure 11. Examples of the outputs from the fully automated system.

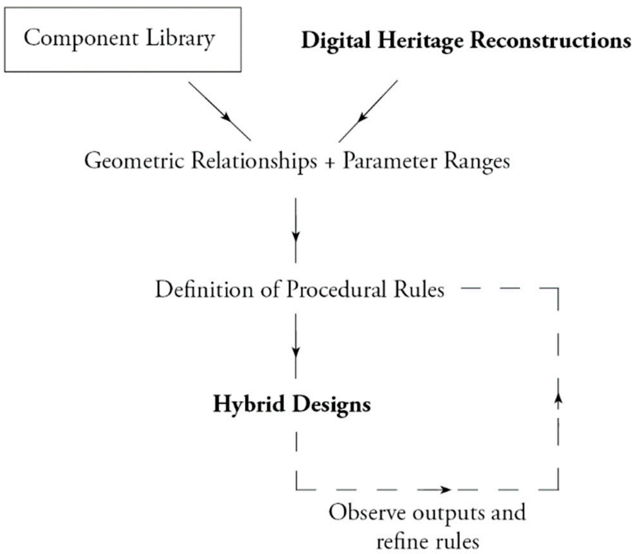

Figure 12. Diagram showing the process of rule refinement, based on the components and data used for the initial reconstructions.

In the examples of over 20 timber Gothic churches, in general, categorization in the system revealed three distinct sub types. There are the small, chapel-like churches such as that of Christ Church. Then there are mid-sized examples such as St Mary's and Old St Paul's. Finally, there are the large nave designs as can be seen in St Peter's and the Manners St Wesleyan Church. Therefore, a development plan could relate a particular instantiation to just one of these sub-groups, which would result in outputs that reflect the proportions of the historic churches that are appropriate to a particular site, since it is the site that often defines the scale. This would give a more constrained starting point and help narrow the definition of proportional rules to be established for each church type.

4.2. Opportunities for Further Automation

There are areas where the system could be automated further, and the capabilities of such a method could be expanded. One proposal of great interest is the further automation of rule creation. One flaw of the proposed method for rule refinement within the system (as shown in Figure 12), is that, even though the outputs are defined by unbiased computational rules, the decisions for what rules need to be created are still determined subjectively by the researcher. Although insights into the characteristic rules of a style can be investigated, any attempt to create a comprehensive definition using this method could still be prone to human bias. The human agent may indeed desire the control present in the current system, as this would be helpful as a design or research investigation aid; but, if human bias were to be averted, allowing the computer make these decisions could yield other interesting lines of investigation.

The research by Jia et al. [24] describes how an application using deep learning methods was developed that could replicate the painting style of any artist which it was trained to imitate. The system was fed both an image that gave the painting its subject matter, and a host of reference images of paintings that provided the style the system was set to imitate. Using a simulated brush and canvas, the system attempts to paint the subject matter, then checks it against the reference images. By computing a large amount of painting attempts, tracking their inputs, and checking against the reference images, the computer gradually learns what inputs result in the paintings that most resemble the reference paintings, effectively building its own computational rules.

Applying such an approach to the context of the research in this paper, a 3D view of the reconstructed churches would be used as reference points. The system and its parameters would then be controlled by the computational scripts in much the same way as the computer controls the digital brush and canvas in the work of Jia et al. If a large number of hybrid churches could be generated (with the output being a 3D view similar to that of the reference reconstructions), the system could check these against the references and gradually learn what inputs result in hybrids of the greatest likeness. The created rules would then give an unbiased estimate of the rules that tie the reference reconstructions together, while also being a much more efficient means of refinement than a human could be capable of.

How the buildings are broken down into component parts and relationships and entered into the system is also a key area where automation could provide many benefits. If reconstructions could be generated via image mining technology to interrogate photos and drawings of a given building, this would allow large quantities of historical data to be stored as a complex dataset. This would also help generate a wide-ranging component library where highly detailed hybrid churches could be created and explored. If this and the automation of the rule making process were to be achieved, it would vastly improve the potential of digital forensic investigations within the context of architectural heritage.

Although smart, automated technologies have been applied by application of a procedural approach in our work, there is the opportunity to achieve more powerful outcomes using technologies such as Generative Neural Networks [25,26]. In a project that has similar motives to ours, Zheng and Yuan [27] have exploited machine learning technology in an urban design context using an artificial neural network that is first trained with generated design data, and then tested by adjusting the feature parameters. In their work, the system examines a particular architectural design network and learns and then infers geometric design features. As the system can learn and then generate design characteristics of buildings, the technology, as with our system, clearly has the significant potential for application in heritage policy implementation.

5. Conclusions

The key outcome of the research in this paper is a methodology that demonstrates how smart, automated systems can be used to aid forensic investigation as part of architectural history examination, and to aid implementation of heritage policy.

The procedural system that we have developed has been achieved through the creation of a two-part system. One part provides a digital space for historic data to be stored for interrogation, and a second part a computational framework that allows investigations into the design characteristics present within these cultural artifacts. We noted above the two major application roles for the system as:

(i) a forensic aid to aid historical studies
(ii) to provide objective support to heritage policy delivery in practice.

In terms of being an objective aid to forensic examination we noted above that the deductions in relation to St James' Lower Hutt and St Patrick's Masterton were found to be correct [22,23]. It is reassuring that the system can deliver a forensic analysis that can helpfully support historic investigations but, like any forensic examination, such techniques should not be relied on in isolation. The system also suggested that St Peter's and St John's churches in Wellington were related to the Manner's St church in the same city, designed by Tringham. Further research established no link in this case.

The system can also, we believe, be applied in a heritage and reconstruction setting. Policies relating to heritage reconstruction can be difficult to interpret, often being a point of contention. Our computational system has the potential to be objective in both analysis and proposal of appropriate reconstruction. Such a tool provides the heritage designer with the basis for a more objective set of proposals, in which the qualities and characteristics of buildings that are initially situated in a heritage area, have been derived rationally. In fact, the richness of the data and competency of the system means that a desired range of alternative solutions can be generated as the basis for discussion.

So although this research focuses on the rules underpinning Wellington's timber Gothic Churches, such a method can be applied to any sub-genre of architecture. The process of rule investigation detailed in this article does have points worthy of note. As mentioned in the discussion, the system relies on a degree of human judgement to choose the most important overarching geometries and relationships that drive the rule refinement process; this could mean that there is some human bias. A repeated application of the system should, however, largely address this. The work shows that valuable conclusions can still be generated, and further automation of this aspect of the system is a key area for future development. Such a development would allow comprehensive rules for any chosen sample group of reconstructed buildings and building typologies to be defined. This article hints at how such a rich level of automation could be achieved, serving as a steppingstone to the complete application of smart technologies for the investigation and development of architectural heritage proposals.

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Abbreviations

CAD—Computer Aided Design.

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