9th International Conference on New Trends in Architecture and Interior Design - 9th ICNTAD'23
May 19-21, 2023
PROCEEDINGS BOOK

Digital Conservation in Tai O Village: Point Cloud Space and Architecture Conservation Legibility

Daniel Keith ELKIN[1], Chi-Yuen LUENG[2], Norah Wang XIAOLU[3]

[1]Core V, v1002c, The Hong Kong Polytechnic University School of Design. dkelkin@polyu.edu.hk
[2] Core H, HK426, The Hong Kong Polytechnic University Department of Applied Social Sciences. leung.chi.yuen@polyu.edu.hk
[3] Unit C, 8/F, King Palace Plaza, No. 55 King Yip Street, Kwun Tong, Hong Kong. norahxdwang@impactanalytics.com.hk

---

Abstract

This paper presents the results of digital documentation and conservation work conducted in Tai O Village, Hong Kong. The premise of the paper is to explore digital LiDAR and photogrammetry scanning workflow and viability for architectural documentation, analysis, and conservation. Tai O is famous for stilt houses, some of which remain from the 1800's. Despite their architectural and cultural value, depopulation and policy constraints threaten their future. This situation prompted a research initiative to digitally document and conserve a sample of houses using 3D scanning. The objectives of the project include to digitally conserve the stilt house conditions with 3D scans; to develop and advance techniques for using 3D scans in digital architectural conservation; and to develop and advance techniques for extracting descriptive and analytical information from 3D scans.

Just over three hundred stilt houses remain in Tai O, and this project samples twenty selected through snowball sampling. Where possible, researchers sampled stilt houses across the four types remaining in the Village. Researchers assigned house cases a random number and scheduled initial and follow-up meetings to complete data collection in the field. For each case, researchers conducted 1-hour semi-structured interviews with residents before completing a 3D scan of the house interior using a Leica BLK2Go handheld photogrammetry and LiDAR environment scanner. This renders a "point cloud" file of stilt house conditions, which researchers exported to .e57 file types for manipulation in Rhinoceros 3D. The primary contributions presented are workflow for conversion of point clouds to simplified volumetric non-rational b-spline (NURBs) geometry and traditional orthographic architectural drawings; the presentation of a volumetric analysis algorithm based on incremental contouring; and the extraction of meaningful programmatic and physical condition data from resulting architectural drawings.

The results find that, for conservation purposes, the legibility of 3D point cloud data gathered using these techniques is adequate for effective, though labor-intensive, translation of orthographic drawings; that the meaning of the volumetric analysis algorithm remains unclear, and that 3D point cloud data allows researchers to extract information required for more traditional typological analysis. Researchers extract cloud data using proprietary software which does not support detailed architectural drafting. File size and compatibility demands necessitate decimation reduction of original point clouds for use in drafting software. This reduces cloud detail and could hypothetically make interpretation into orthographic drawings more difficult. Researchers found, however, that they could produce architectural drawings from decimated point clouds with only occasional field verification. Researchers also drafted simplified volumetric NURBs models of each house and subjected them to a technique termed Volumetric Development Analysis (VDA). This algorithm constructs a volumetric estimation of house geometry using increasing numbers of orthographic contours, which quantifies relative geometric complexity between house cases, and allows comparison between actual volumetric models and estimated volumetric models requiring gradually increasing geometry and computing power. Researchers propose this may provide insight on relative geometric complexity between houses, but results are yet unclear. Lastly, the project yields comparable descriptions of stilt house floor areas and programmatic composition for traditional typological analysis. © 2023

***Key Words**: stilt houses; Tai O Village; 3D Modelling; 3D Scanning; spatial analysis.*

---

1. Introduction

This paper discusses the results of a digital documentation and conservation project conducted in Tai O Village, Lantau Island, Hong Kong. The purpose of the paper is to explore LiDAR and photogrammetry scanning workflow and viability for architectural documentation, analysis, and conservation through presentation of a recent project. The paper's contributions to scholarship include the production of data digitally conserving stilt house conditions through 3D scanning and orthographic drawing; developments and advancements to 3D scanning techniques and their conversion into more usable formats and orthographic drawings for conservation purposes; and techniques for extracting analytical information from 3D scanning geometry. The paper also contributes the theory and technique for Volumetric Development Analysis (VDA), a digital algorithm-driven technique designed to describe relative geometric complexity between cases of sampled buildings. The paper is divided into six sections below. Section two explains the context of the project, and the urgent need for digital conservation of stilt houses in Tai O Village through 3D scanning. Section three provides a brief literature review of 3D scanning technologies and conservation precedent. Section four describes the digital conservation objectives and workflow for the present project. Section five describes the theory and method of VDA in detail. Section six presents data results extracted from the project sampling. Lastly, section seven includes conclusions from the project and discussion of the project's implications and future work.

2. Tai O Village and the Context of Conservation Work

This section describes the current and recent situation in Tai O Village to contextualize the digital conservation work. Tai O Village's situation is distinct due to vernacular *pang uk* (棚屋) or stilt house architecture remaining in the Village, and a combination of environmental threats and legacy policies that make digital documentation and conservation of these houses an important undertaking. Tai O is a small village on the western coast of Lantau Island, a large, western-lying island within the Hong Kong Special Administrative Region (Hong Kong). The present population of Tai O is approximately two thousand people [1], but the Village was much larger in the past and was, in fact, the largest Village on Lantau Island and a major commercial centre [2-3]. Recently, Tai O has drawn local and international attention due to its concentration of pang uk, which supports a distinct fishing culture and intangible cultural heritage. Despite their inherent cultural value and economic value to tourism, pang uk face threats from fire, flooding, and storms, as well as degradation from abandonment [4]. This degradation is unlikely to see long-term mitigation, as legacy policies from the colonial period that prohibit improvement and redevelopment of stilt houses are still enforced [5-6], and there does not seem to be political will to change this situation. As such, stilt houses in Tai O are arguably an instance of significant tangible cultural heritage that is threatened and likely to disappear. Digital conservation, in the form of 3D scanning of stilt house physical conditions is, arguably, a worthwhile initiative given that their physical conservation is uncertain at best. What follow are the results of a project designed to digitally conserve a sample of stilt houses in Tai O using 3D digital environment scanning technology. As described further in section four, the project samples twenty stilt houses, about three hundred of which remain in Tai O Village at the time of writing. Before describing the project's workflow, the following section provides a brief literature review of 3D scanning technology and digital conservation precedent to explain the principal technologies and methods involved, choices made in the design of the project, and contributions to digital conservation methods emerging from the project.

3. 3D Environment Scanning Technologies and Digital Conservation Precedents

This section briefly summarizes literature on 3D environment scanning technologies and digital conservation precedents to contextualize our work in comparison to other research. We reviewed four articles chosen for their recent publication and implementation of 3D environment scanning for heritage conservation. For brevity, we provide a summary of each article's content, and a table describing key aspects of each in relationship to our work. Li et al.'s article is a broad review of LiDAR and 3D scanning preservation of build heritage in China [7]. The second, third, and fourth articles are case studies: M Gloria Gomes' and A. Tomé's description of heritage mapping of a castle in Sintra [8], and Pervolarakis et al.'s digitization of the Palace of Knossos, and their implementation of augmented and virtual reality (AR and VR) technologies for education and tourism [9-10]. The table below describes the research objectives; technology employed of scanning platform type and technology for describing geometry (NURBs, mesh, point cloud, etc.); the building type surveyed; and the type or types of output emerging from each study. The table also includes our study for comparison. In summary, the typological approach of our project and the constraints of working in Tai O distinguish our work from this literature. Unlike these precedents, our study aims to extract data for architectural typological study from point clouds as described below. As such, extraction of orthographic architectural drawings from point clouds is a major part of our workflow and contribution, unlike many other studies which focus on displaying 3D scanning geometry through AR, VR, or conventional 2D visualization. Second, these precedents and many others depend on aerial or tripod-mounted 3D scanning technologies, which are not feasible for our project. Aerial scanning in Hong Kong requires special permissions which, at the time we conducted our research, were time-cost prohibitive. Tripod scanning equipment offers special challenges in stilt houses in Tai O, as they are often cramped, feature shared spaces, and, most critical for comparison with other works, are occupied by residents. As the table describes, our research has several distinctions from other work that constrain its objectives and workflow, as detailed in section four.

Table 1. Summary of 3D Digital Conservation Precedents/Literature

		Technology			
Reference	Objectives	Platform Type	Modelling Tech.	Building Type	Outputs
[7], Li. Et al.	Overview of 3D scanning and heritage preservation literature in China.	(By Others) Aerial; terrestrial vehicle- and tripod-based.	(By Others) LiDAR and photogrammetry point clouds; Mesh models.	(By Others) Heritage conservation sites; monuments; unoccupied.	Varied across sources cited.
[8] Gomes and Tomés	Heritage site digitalization; deterioration mapping.	Aerial; terrestrial tripod-based (Faro Focus 3D)	Photogrammetry, LiDAR, and infrared thermography point clouds, thermograms.	Historic defensive site (Castle); unoccupied.	Digitalization of heritage site. Inspection and deterioration mapping techniques.
[9-10] Pervolarakis et al. 1 and 2.	Heritage site digitalization; survey technique development [9]; visualization in AR/VR [10].	Aerial; Terrestrial tripod-based. (Faro Focus 3D)	Photogrammetry and LiDAR point clouds; Mesh models.	Historic palace/archaeological site; unoccupied.	Surveying and digitalization techniques; AR/VR visualization techniques.
Presented Research	Heritage site digitalization; NURBs model translation technique development; architectural typological study.	Terrestrial hand-held (Leica BLK2Go).	LiDAR and photogrammetry point clouds; NURBs models; orthographic projections.	Historic single-family residences, occupied.	Digitalization of heritage sites; NURBs models and plan drawings; typological/spatial programming data.

4. 4. Digital Conservation Objectives and Workflow

4.1. Objectives

This section describes the objectives of our project in detail and our workflow for digital conservation of twenty stilt houses in Tai O Village. It provides the methodology for the project in comparison to digital conservation works discussed above, the justification for that methodology based on theory and the project's research objectives, and the steps taken to execute the project given Tai O Village's unique circumstances.

The objectives of this project are, broadly, to accurately document and conserve housing conditions in stilt houses in Tai O, given threats to their continued existence discussed in section two. This entailed combined data collection and analysis techniques connecting the project to both architectural and sociological theories of housing, and dividing data gathering into physical condition and socio-cultural condition description categories. The basis for gathering data on physical conditions in stilt houses are architectural typological theory and comparison methods, which depend on a combination of geometric description and behavioral description through orthographic drawing. Typological analysis entails description of how spaces are physically constructed and articulated, but also how they are behaviorally separated through spatial programming. Spatial programming is typically divided into categories of related behaviors and scripts to separate spaces by function: kitchens, bathrooms, bedrooms, and so on. Where possible it is preferable to extract quantitative data to describe spatial programming according to separated floor areas and calculation of floor area totals. This allows for case-wise and variable-wise comparison of housing conditions in higher levels of detail [11] [12]. Variables extracted from 3D scanning data for each case in the project are as follows in Table 2. These are a selective list of data recorded on sampled stilt houses, focused on those that require generation of orthographic plan drawings:

Table 2. Summary of Typological Comparison Variables.

Variable Name	Variable Description
GFA	Gross Floor Area describing the total area of the house per floor level to the outer boundary of the wall/enclosure in meters squared (m2).
NFA	Net Floor Area describing GFA less un-occupiable areas of the plan, i.e., solid material shown as hatching in floor plans. Given in m2.
NFA/GFA Ratio	NFA for each house divided by GFA, providing an approximation of occupiable area of the house compared to its total area as a percentage.
BeR GFA	GFA sum of all bedrooms in a house case in m2.
BeR Count	Whole-number count of all bedrooms in a house case.
BaR GFA	GFA sum of all bathrooms in a house case in m2.
BaR Count	Whole-number count of all bathrooms in a house case.
LiR GFA	GFA sum of spaces dedicated to living room behaviors, including meeting with family members, entertaining, relaxing, etc. Given in m2.
DiR GFA	GFA sum of spaces dedicated to formal or semi-formal dining and related behavior given in m2.
W Area	Total area of exterior windows in a house case in m2.
W/GFA Ratio	Window Area divided by GFA for the house case, providing a comparison of daylight entry in each house and overall house size given as a percentage.

Additional attributes extracted from each 3D scan entail volumetric descriptions of house geometry, which are treated in section five within the VDA description. Digital point cloud data and/or mesh geometry do not lend themselves directly to extracting numeric data to describe spatial programming on their own. Most software required to import 3D scanning data from scanning equipment is proprietary to the scanner manufacture and includes minimal or no drafting and measurement tools. Extracting clear orthographic projects is often possible, but time consuming and offering few analysis capabilities. We therefore developed a workflow to convert point cloud geometry into conventional orthographic plans and sections to allow drafting and extraction of area calculation geometry.

In terms of socio-cultural data, the basis of this project began with John F.C. Turner's writing on housing architecture and satisfaction. Turner describes a multi-factor model for housing development, satisfaction, and decision-making, suggesting that occupants choose and design housing according to diverse and complex responses to their, "household accounts," [13]. Our study sought to explore Turner's hypotheses in Tai O by gathering socio-cultural data through semi-structured interview. Interview data are not considered in this paper, but an important part of the larger project's methodology. Lastly, we wanted to explore whether there were relationships between Turner's theories of complexity in housing decision-making, and geometric complexity in housing architecture at the volumetric level, which we explore through the VDA technique described below. The objectives of the project are, therefore:

- To complete 3D scanning of each stilt house, including interior conditions of all accessible spaces.
- To complete scanning house exterior conditions where feasible.
- To construct accurate simplified volumetric NURBs models of each stilt house for comparison using the VDA technique.
- To construct accurate plan drawings of each stilt house from point clouds with spatial programming divisions.
- To extract spatial programming area data from plan drawings according to variables listed above.
- To confirm plan drawing and spatial programming accuracy via field confirmation.

These objectives, along with exigencies of working in Tai O, precipitated the following project workflow.

4.2. Workflow

The workflow for digitally conserving each stilt house began with eliciting participants for the project through community liaisons. The Tai O Village YWCA Community Work Office (YWCA) project leader connected us with a Tai O resident we hired onto the project as a long-term field researcher (FR) tasked with eliciting participants and completing field work. Research in Tai O depends heavily on personal connections due to, in our collaborators' estimation, the close-knit nature of the community, threats of squatter policy enforcement, and generally advanced age and low literacy levels among Tai O residents. We therefore relied on snowball sampling methods to elicit a target of twenty participating households, depending on our field researcher's personal connections and ability to secure commitment. In this regard, the BLK2Go's ease of use was a distinct advantage: researchers trained FR to use the scanner and could rely on his personal relationship with stilt house residents to make them comfortable and complete scanning in the field. Upon securing agreement to participate, the FR scheduled initial meetings and interviews at houses to be sampled.

Initial meetings entailed explanation of the project and a semi-structured interview lasting roughly one hour, followed by 3D scanning of the stilt house interior. We originally intended to elicit responses to structured, survey questionnaire-type interviews with stilt house residents. We found stilt house residents averse to structured discussion, and more likely to provide details of their experience following a more ethnographic model. The subject of interviews was stilt house residents' housing conditions, satisfaction, history, outlook, and decision-making. Interview results are pending publication.

After interviews, researchers scanned each stilt house with the Leica BLK2Go, walking the scanner through the interior of the house and around the exterior where possible. Scans lasted approximately ten to fifteen minutes. The FR scheduled follow-up meetings with each participant and concluded the first meeting. We imported scans into Leica's Cyclone 360 Register BLK2Go Edition software (Cyclone 360), confirming the completeness and quality of each scan. There were occasional issues with scan quality and completion: in three cases, initial scans experienced a failure of the LiDAR connection to global positioning (GPS). This resulted in abnormal scans as shown in Figure 1 below. In these cases, researchers returned to the follow-up meeting with stilt house residents to re-scan. Otherwise, follow-up meetings entailed securing publication permission, compensating stilt house residents, and closure of each field work case.

Fig. 1. An aerial view of a LiDAR scanning error model. The stilt house scanned is visible in the lower left and is considerably smaller than the error geometry proceeding upward and to the right.

Upon case field work completion, researchers assigned each house and interviewee a pseudo-random case number using an online number generator to anonymize data and protect residents' privacy [14]. Researchers imported each 3D scan into Cyclone 360 and exported point cloud geometry into .e57 files for software compatibility through the program's "Publish" dialog. We used McNeel Rhinoceros 3D (Rhino) to develop NURBs geometry and orthographic drawings from point clouds and found that full-resolution versions of point clouds were difficult to import and manipulate. We therefore used the "Decimate Point Clouds" command in Cyclone 360 to reduce point cloud file size. This command overlays a cubic voxel grid of a designated size on the original point cloud and averages points within each voxel to a single point at each voxel centroid. We decimated clouds to a 5 mm voxel. Visual differences between original point clouds are illustrated in Figure 2, and file size differences before and after decimation are given in Table 3. With a mean file size reduction of 76% this reduction in detail makes point cloud files significantly more manageable and transferable with, arguably, marginal reduction in legibility. For review and data reproduction, all decimated point cloud files are publicly available on Mendeley archive via the first author's website after a one-year embargo extending from the time of upload [15].

Fig. 2. A point cloud at original resolution in Cyclone 360 (left) and after decimation in Rhinoceros 3D (right).

Table 3. File Size Comparison before and after decimation by House Case

House Case Number	Original Cloud File Size (kB)	Decimated Cloud File Size (kB)	Percent Reduction
023157	822,509	205,442	75%
069817	1,051,720	321,710	69%
128590	653,715	180,869	72%
169032	620,692	204,645	67%
241590	904,623	245,112	73%
261094	1,097,831	340,871	69%
326789	929,273	218,409	76%
328954	1,255,539	113,154	91%
478523	703,570	185,272	74%
539775	2,219,043	302,368	86%
583904	650,646	172,923	73%
651290	890,537	265,325	70%
687795	1,220,844	117,958	90%
694827	1,551,280	401,865	74%
705384	1,006,313	265,588	74%
729485	545,698	157,459	71%
729580	780,544	227,915	71%
837295	2,294,111	305,265	87%
853147	664,157	210,919	68%
941756	8,653,249	693,537	92%
Mean	1,425,794.7	256,830.3	76%

Afterward, researchers developed simplified volumetric models of each house and orthographic plan drawings for each level of each house from the point clouds. Volumetric modelling development workflow and criteria are discussed below. Plan development involved use of the "Clipping Plane" command in Rhinoceros 3D to approximate orthographic projection geometry from the point clouds. The BLK2Go orients point clouds to align "up and down" in the scan with the Z-axis of the 3D modelling coordinate system. As such, clipping planes following Rhino's XY plane orientation can approximate plan cutting planes. However, stilt houses are highly variable in the squareness and straightness of their construction relative to a cartesian coordinate system. Therefore, as illustrated in Figure 3, construction of orthographic plan drawings entailed use of multiple clipping planes for each level and space in a stilt house. Researchers drafted plans by approximating spatial separations and furnishings as shown in clipping planes at the highest, lowest, and middle height locations in each level and space. Selected results of drafting plan drawings through this method are illustrated in section six, along with spatial programming area data from each house case. First, however, the following session provides a detailed discussion of Volumetric Development Analysis (VDA), a new technique developed for this project elaborated below.

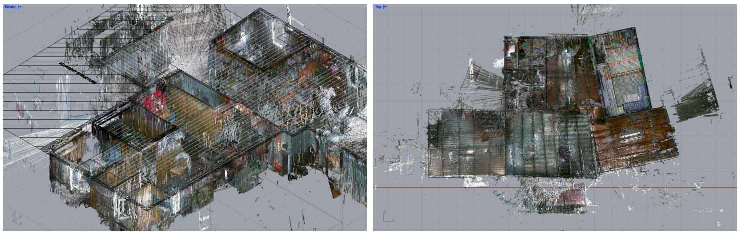

Fig. 3. Skewed (left) and aligned (right) views showing use of clipping planes to derive plans from point clouds.

5. Volumetric Development Analysis – VDA

VDA is an algorithmic analysis technique designed to describe buildings' relative volumetric complexity as an extension of typological analysis techniques. The research question driving our development of this technique is as follows: what range and variation do we see in relative, volumetric geometric complexity in housing architecture? Are there any relationships between ranges and variation of geometric complexity and other housing architecture attributes, particularly housing development model and adaptation over time? Turner's scholarship on housing mentioned above is the impetus for asking these questions. Given Turner's thesis that housing decision-making is highly complex in self-designed housing environments like Tai O Village, we wanted to know whether we could expect associated levels of relative volumetric geometric complexity, especially when compared to housing developed through different models. This presentation of VDA is our first development of a method to explore this question, with results of our case work in Tai O Village presented below.

The extent of geometric complexity description within abstract mathematics is outside the scope of this discussion [16-17], and the VDA method is highly circumscribed by architectural tools for computation and description. To further define the scope for this technique, we add that our interest was in a method for describing *physical volumetric* complexity. This distinguishes first from non-physical measures of complexity, whether described by behavior, history, socio-cultural relationships, or otherwise. Second, this distinguishes from alternative scales and attributes for describing architecture's physical intricacy. Technological or tectonic complexity, for example in terms of building techniques, details, and methods within a given building is not our concern in this technique. Volumetric complexity concerns, therefore, the relative level of geometric intricacy and information required to describe the architecture's overall, three-dimensional form, whether in terms of exterior form, interior space, or any combination of the two.

The reason for this choice is twofold. First, volumetric complexity is easier to describe quantitatively for existing buildings with limited recorded history. Without data on, for example, labor hours in either design or fabrication embodied in each detail it is difficult to quantify differences in physical complexity at the detail level apart from nominal or Boolean distinctions between houses. Second, volumetric complexity is hypothesized to emerge from greater levels of difference between housing development models and design decision-making precipitated therefrom. Arguably, differing levels of design autonomy and flexibility between, for instance, centralized public housing provision models and incremental self-design models, as in Tai O, could create volumetric, i.e., different numbers of levels and overall house geometry.

We developed the VDA algorithm in the Grasshopper dialogue for Rhino 7. This allowed us to script the VDA method into a so-called "black box" technique that automates the technique and, if used properly, creates higher parity between housing cases for comparison. The steps for implementing the technique are listed as follows, with more detailed explanations below:

- Draft a simplified, watertight volumetric model of the house case. The properties menu in Rhino should designate this geometry as one or more, "Closed, Solid Polysurfaces."
- Import the volumetric model as into the "BRep" container of the Grasshopper algorithm.
- Optimize the relationship between the volumetric model and the universal coordinate system to limit artificial indications of complexity.
- Choose directions for incremental contouring one at a time, whether in the XY, XZ, or YZ plane.
- Set the algorithm to record data and animate the contouring slider to complete incremental contouring.
- Export data and repeat with contours in the remaining directions.

The first step should indicate the importance of the word *relative* volumetric complexity in using this technique. Point cloud geometry cannot be described or manipulated volumetrically in Rhino, short of returning an overall volume of a bounding box around the cloud. As such, researchers must use solid editing tools to model a simplified volumetric model of the architecture in Rhino: Box, MoveEdge, MoveSrf, and so on. This necessarily requires interpretation from the point cloud into abstract geometry, and as such the rules and criteria for conversion will affect whether two cases can be meaningfully compared with the algorithm. To that end, our rules for drafting simplified volumetric models were as follows (see Figure 4):

- The model's exterior surfaces should touch the outermost limits of the point cloud describing the house.
- Spaces included as part of a house but with no roof are not part of the volumetric model.
- Spaces included as part of a house with a roof, but only partial enclosure are modeled as solid volumes.
- Small elements at the volume periphery are omitted from the model if a human cannot fit inside them.

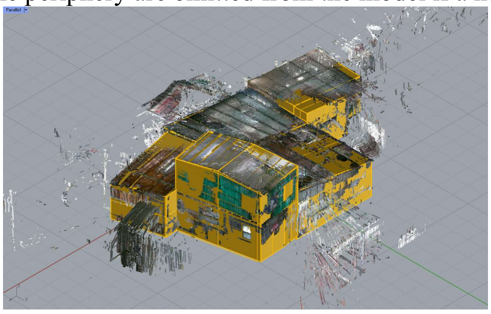

Fig. 4. Screenshot showing relationships between the simplified model (Yellow) and the point cloud.

This means our first use of VDA measures the exterior-most volumetric geometry of each house, with interiors modelled as solid. We anticipate applying VDA to more complex volumetric models in the future with interiors hollowed out from the overall volume. After the volumetric model is complete and imported into Grasshopper, the algorithm optimizes the relationship between the house geometry and the global coordinate system by minimizing the difference between the house geometry's volume in meters cubed (m^3) and the volume of a bounding box aligned with the universal coordinate system in m^3. This ensures that the algorithm minimizes levels of complexity reported because of the orientation of the house model geometry. Lastly, the algorithm slices the house model with contours parallel to the selected XY, XZ, or YZ coordinate plane, spacing contours evenly throughout the body of the model and gradually increasing the number of contours from two to 102. The algorithm must start with two contours due to constraints of the program, and 102 is chosen as an arbitrary maximum to generate one hundred values for each coordinate plane. The algorithm then extrudes these contours to create a segmented "hypothetical volume" or "sketch" of the original geometry and make volume sum comparisons between the sketch and the original model. Using the "Animate" command on the contour count slider and using data recorders in Grasshopper allows researchers to return four measures of relative volumetric complexity contours cutting parallel to each of the three universal coordinate planes, as shown in Table 4. These can then be exported to .csv files for manipulation and visualization in Excel and using line graphs:

Table 4. Summary of VDA Comparison Variables.

Variable Name	Variable Description	Hypothesized Relationship to Relative Complexity per Number of Cutting Contours
Raw Contour Control Points (RCP)	A summary count of Control Points generated by contouring the house geometry for a given number of contours. Control Points can include mid-points or curvature control geometry as well as contour "corners" or end points.	Positive, i.e., the higher the RCP count at the algorithm returns for a given number of contours, the more relatively complex the model is when compared to other models cut with the same number of contours.
Contour Discontinuity Points (CDP)	A summary count of Control Points generated by contouring, but with points that do not indicate a corner removed from the sum. RCP should always be lower than CDP for a given model and number of contour cuts.	Positive, as above.

Raw Contour Percentage Error of Hypothetical to Real Volume (RCPE)	The difference between the summed volumes of all contours in m^3 and the original model volume in m^3, divided by the original model volume and converted to a percentage. In effect, this gives an estimate of how well the hypothetical sketch model approximates the original.	Negative, i.e., if the percentage error between the original and hypothetical models drops as the number of contour cuts increases, this indicates the model is better described using more contours, possibly indicating higher relative geometric complexity.
Culled Polyline Percentage Error of Hypothetical to Real Volume (CPPE)	As above, but with invalid or null contour geometry removed. Null geometry sometimes occurs during contouring where contours loop back on themselves or do not close.	Negative, as above.

Grasshopper affords the advantage of automating this algorithm such that reproducing this data with volumetric models used in the project, or applying the technique to other architecture geometry is relatively simple. The algorithm is available for download [18]. For clarity, Figure 5 below demonstrates the steps entailed in executing the technique using a volumetric model of Villa Almerico Capra Valmarana, more commonly known as Villa Rotunda, and designed by Andrea Palladio. The basis of this model, which we converted from a mesh to detailed and simplified NURBs models, is from [19]. Data results from applying the VDA algorithm to the twenty stilt house cases is discussed in section six below.

6. Data Results

This section presents data generated from the typological analysis and VDA methods described above and applied to the twenty stilt houses we sampled. Attributes of the twenty stilt house cases, as given in Table 1 are shown in Table 5, along with mean values for the different variables across the twenty cases. VDA results for each of the twenty cases are presented as line graphs showing the levels of each VDA variable with increasing number of cutting contours across a range of one hundred. Line graphs detail VDA progression within each case with XY, XZ, and YZ plane contour values separated, and across cases as well in Figures XXX-XXXX. Conclusions and discussion extractable from these data are in section seven below.

Table 5. Typological Variable Attributes for sampled stilt houses.

	Variables										
House Case Number	GFA	NFA	NFA/GFA	BeR GFA	BeR Count	BaR GFA	BaR Count	Li GFA	DiR GFA	W Area	W/GFA
023157	100	78	0.78	27.03	2	5.38	2	27.23	19.27	7.79	0.077
069817	174	150	0.86	25.01	4	7.90	2	66.12	12.25	14.33	0.094
128590	107	93	0.87	16.91	1	4.56	1	22.75	9.62	4.36	0.051
169032	128	118	0.92	27.51	4	2.70	1	14.50	16.95	7.54	0.068
241590	142	90	0.63	24.70	1	4.95	1	24.73	0	8.23	0.083
261094	218	207	0.94	46.75	5	5.48	2	38.78	36.03	38.81	0.194
326789	109	103	0.93	8.04	1	4.03	1	14.92	13.92	6.24	0.092
328954	104	99	0.95	5.11	1	4.22	2	21.51	0	6.47	0.081
478523	105	96	0.91	38.26	7	1.24	1	11.25	24.03	6.67	0.063
539775	105	99	0.94	35.29	3	4.37	1	12.65	7.01	7.88	0.096
583904	67	59	0.88	27.66	4	2.81	1	5.29	8.02	7.63	0.112
651290	154	149	0.96	39.17	2	2.16	1	4.32	22.94	15.14	0.166
687795	120	113	0.94	10.71	2	3.32	2	12.95	21.01	14.92	0.148
694827	197	183	0.92	11.45	2	5.01	2	46.54	21.92	16.78	0.105
705384	144	143	0.99	22.86	4	2.99	1	41.85	19.14	14.59	0.155
729485	60	56	0.92	18.49	3	1.45	1	6.54	6.70	6.85	0.139
729580	95	91	0.95	15.03	1	3.49	1	32.44	7.01	8.13	0.120
837295	92	86	0.93	5.70	1	2.68	1	17.22	18.94	11.62	0.139
853147	108	100	0.92	22.68	2	2.39	1	0	14.03	9.88	0.090
941756	137	132	0.96	19.22	4	2.99	1	52.86	15.55	18.95	0.193
Mean	123	112	0.90	21.62	2	3.70	1	23.72	14.71	11.64	0.113

7. Conclusions and Discussion

Acknowledgements

This research is supported by the University Grants Council General Research Fund (GRF) of the Hong Kong Government, project 15600621.

References

[1] Anonymous. History of Tai O. *Tai O Heritage Hotel*. 2021. Accessed 24 April 2023. https://www.taioheritagehotel.com/en/about-tai-o/history-of-tai-o/.
[2] Wong, Wai King. *Tai O: Love Sories of the Fishing Village*. Hong Kong: Concern Group for Tai O's Culture and Antiquities; 2000.
[3] Schofield, Walter. "PILE HOUSES AT TAI O, LANTAU ISLAND, HONG KONG, 10TH JANUARY 1937." *Journal of the Hong Kong Branch of the Royal Asiatic Society*; 1970, p. 197-200.
[4] Khun, Eng Kuah and Liu, Z (eds.). "Heritagizing lifestyle in Hong Kong: social capital and cultural memories of the Tai O fishing community." In *Intangible Cultural Heritage in Contemporary China*; 2016, p. 11-29.
[5] Squatter Control Office. *Lands Department – Small House Matters*. 2021. Accessed 12 March 2021. https://www.landsd.gov.hk/en/squatter_control/sqctrl.htm
[6] The Government of the Hong Kong Special Administrative Region. "LCQ1: Conservation of the Stilt Houses at Tai O." *Press Releases*. 2019. Accessed 17 March 2021. https://www.info.gov.hk/gia/general/201905/22/P2019052200546.htm
[7] Li, Yuan, et al. "3D LiDAR and multi-technology collaboration for prervation of built heritage in China: a review." *International Journal of Applied Earth Observations and Geoinformation*; 2022, p. 1-11. DOI: https://doi.org/10.1016/j.jag.2022.103156.
[8] Gomes, M. Glória and A. Tomé. "A digital and non-destructive integrated methodology for heritage modelling and deterioration mapping. The case study of the Moorish Castle in Sintra." *Developments in the Built Environment*; 2023, p. 1-11. DOI: https://doi.org/10.1016/j.dibe.2023.100145.
[9] Pervolarakis, et al. "Three-Dimensional Digitization of Archaelogical Sites – the Use Case of the Palace of Knossos." *Heritage*; 2023, 6, p. 904-927. DOI: https://doi.org/10.3390/heritage6020050.
[10] Pervolarakis, et al. "Visiting Heritage Sites in AR and VR." *Heritage*; 2023, 6, p. 2489-2502. DOI: https//doi.org/10.3390/heritage6030131.
[11] Jong, T.M. de. and D. J. M. Van der Voordt (eds). *Ways to Study and Research Urban, Architectural and Technical Deisgn*. Delft: DUP Science; 2002.
[12] He, Ming and Jingyi Qi. "Study on the Theory of Rafael Moneo Architctural Typology. *IOP Conference Series: Materials Science and Engineering*; 2019, Vol. 592 (1), p. 12105.
[13] Turner, John F.C. *Housing by People: Towards Autonomy in Building Environments*. 1976. Marion Boyars, London.
[14] Furey, Edward. "Random Number Generator." *Calculator Soup – Online Calculators*. 2006-2023. Accessed 24 April 2023. https://www.calculatorsoup.com/calculators/statistics/random-number-generator.php
[15] Elkin, Daniel. "Scans of Stilt Houses in Tai O Village." *Daniel Elkin – Spatial Agency Research*. 2021-2023. Accessed 26 April 2023. https://www.elkinspatialagencyresearch.com/content/p/scans-of-stilt-houses-in-tai-o-village
[16] Landsberg, J.M. "Geometric complexity theory: an introduction for geometers." *Ann Univ Ferrara*; 2015, 61, p. 65-117.
[17] Mulmuley, Ketan D. "GEOMETRIC COMPLEXITY THEORY V: EFFICIENT ALGORITHMS FOR NOETHER NORMALIZATION." *Journal of the American Mathematical Society*; 2017, Vol. 30: 1, p. 225-309.