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Analyzing Deformations in As-Found Buildings for Accommodation In Panelized Retrofit

Prochnau, Kristine[1]*, Fallica, Simone[2], Mendoza, Jessica[3], Jemtrud, Michael[4], and Fai, Stephen[5]
[1] Carleton Immersive Media Studio, Carleton University, Canada
[2] Carleton Immersive Media Studio, Carleton University, Canada
[3] Carleton Immersive Media Studio, Carleton University, Canada
[4] DeCarbonized ARchitecture and Building (DECARB) Research Group, McGill University, Canada
[5] Carleton Immersive Media Studio, Carleton University, Canada
* kprochnau@cims.carleton.ca

Abstract: A significant aspect of deep-energy retrofits involves the recording and modelling of existing conditions. This paper discusses proposed best practices and ongoing challenges. Our discussion draws on the work of the Carleton Immersive Media Studio (CIMS) over the past decade in the context of heritage documentation and Heritage Building Information Modelling (HBIM). In contrast to recording and modelling for heritage—which demands a high level of correspondence between the physical asset, the data from the documentation process, and the HBIM—the retrofitting of non-heritage buildings for energy performance has little or no imperative to preserve the character of the original building. Rather, deep energy retrofits typically look to reconcile generalized construction solutions with unique as-built conditions. In comparing techniques for recording architectural heritage with techniques for capturing as-built conditions for deep energy retrofits, questions of levels of detail, information, and accuracy become paramount. Recognizing the differences but drawing on our experience in HBIM, we argue that accurate modelling from point clouds in a BIM environment can allow for a better understanding of the deformations of a building prior to fabrication—allowing designers to better understand how the building has deformed in non-uniform ways. The paper will examine the processes of building capture and modelling in a BIM environment for a deep energy retrofit of a commercial building constructed in the 1970's. Similarities and differences in scan-to-BIM best practices for heritage and rehabilitation will be discussed.

Keywords: Building Capture; BIM; Deep Energy Retrofit; Panel Fabrication

1 INTRODUCTION

In its response to the climate emergency, National Resources Canada's (NRCan) *Canada Green Buildings Strategy (*2022) advocates for the retrofitting of the "majority of the standing buildings in this country". The DeCarbonized ARchitecture and Building (DECARB) research group—led by the McGill Chair in Architecture, Energy, and Environment and partnered with Hydro Quebec and the Quebec Ministry of Energy and Natural Resources—is working to develop a systematic approach to achieve Deep Energy Retrofits (DERs) at scale; researching possible solutions to reconfigure conventional procurement, finance, and legislative structures as well as design, manufacture, and construction workflows for mass retrofitting of Canada's existing building stock. This paper will focus on research conducted as part of the ReCONstruct pilot project for the Centre Socioculturel de l'Île-Bizard, an ARMCO Steelox commercial building constructed in the 1970's located in the Île-Bizard-Sainte-Geneviève borough of Montreal. The Centre Socioculturel was targeted for a pilot project using exterior panel envelope insulation because of its current condition, which requires major renovation, as well as its importance to the community as a public space and disaster relief center. Further, there are many buildings of this typology in Quebec and Canada, including arenas and community centers, representing a large number of potential projects. The building is a two-story metal structure with a (relatively) rectangular footprint hosting a gymnasium, offices, as well as a daycare room and storage. It is clad in corrugated metal siding and features a simple gable roof. There are few overhangs and facade undulations, making it an ideal candidate for a panelized DER approach. While Deep Energy Retrofits encompass a wide array of building interventions to decrease the resource consumption (ie. electricity, water) and Greenhouse Gas (GHG) emissions of a building, a DER specifically refers to a retrofit that addresses the building holistically. For the Île-Bizard Pilot Project this entails a panelized building envelope solution and total overhaul of the MEP systems. The project also involves monitoring and occupancy interviews before and after interventions.

The complexity and breadth of a retrofit project like this is best managed through the use of Building Information Modelling (BIM). As Lim et. al. (2021) demonstrates, there has been a significant increase in both green retrofit case studies and the use of BIM to facilitate their execution between 2018 and 2020. Already a standard tool for executing new construction projects and facility management, the use of BIM for DERs provides numerous benefits for project management, communication, simulation, and decision-making frameworks. To be able to support each of these functions, the BIM should be constructed out of accurate and persistent data. This is particularly complicated for projects where existing documentation is non-standard, and an as-built model does not exist—which is the case for the Île-Bizard Pilot Project. When beginning a DER project with no as-built model, a crucial first step is the digitization of the existing structure—or building capture.

The knowledge and experience of building capture from heritage and conservation professionals can be beneficial in approaching the creation of a BIM for DER. As Yang et. al. (2020) surveys, there is a vast field of researchers and professionals familiar with documenting and modelling the idiosyncrasies and deformations of existing buildings. However, in contrast to heritage conservation, the retrofitting of buildings for energy performance has little or no imperative to preserve the character of the original building. Rather, retrofits look to reconcile generalized construction solutions (ie. panels) with unique as-built conditions. In comparing techniques for recording architectural heritage with techniques for capturing as-built conditions for rehabilitation, questions of levels of detail, information, and accuracy become paramount. The Carleton Immersive Media Studio (CIMS) has more than fifteen years of experience with recording existing buildings in the context of heritage conservation and heritage building information modelling (HBIM). For the first phase of the Île-Bizard pilot project, CIMS was responsible for building capture and BIM creation. This paper focuses on the use of an as-built BIM to support the design and fabrication of a panelized envelope system for the existing structure.

Section 2 of this paper reviews relevant literature on the field. Section 3 outlines the building capture and BIM creation process for the Île-Bizard pilot project. Section 4 describes the analysis of the model to measure non-uniform deformations to aid panel design and as a method of interpreting modelling decisions. Section 5 discusses further steps forward and new potential areas of research. Section 6 concludes with an overview of the outcomes achieved so far by the present research.

2 LITERATURE REVIEW

A significant segment of scholarly discourse on the use of BIM for green retrofits is primarily centered on utilizing the model to quantitatively assess and predict energy performance from the existing building and potential results from the DER. Surveying the relevant literature (Lim et. al. 2021), the use of BIM in green retrofitting most often falls into the following categories: energy analysis—including operational energy analysis (Sanhudo et. al., 2018); thermodynamic performance and Life Cycle Analysis (LCA); cost of retrofit interventions (D'Angelo et. al., 2022); and simulation of retrofit performance (ie. solar studies). The ability to simulate and analyze the various impacts of a retrofit also allows a BIM to be used as a decision-making tool through the integration of scripting and plugins within the BIM authoring environment. In this way the

BIM can be used to manage the complexity of ongoing projects, as well as determine future green retrofit candidates. Comparatively less emphasis is accorded to the creation of a BIM for green retrofit or DER. The existence of the BIM asset is often assumed as a pre-existing condition.

HBIM has also begun to appear within the context of green retrofits. However, the unique natures and contexts of existing buildings make it difficult to provide a universal process for modelling from building capture for DER. Ide et. al. (2020) show that maintaining the character defining elements of the building can limit the extent of the green retrofit, and thus negates the need for a BIM to complete the project. The time and labor investment required to construct a BIM from building capture far outweighs the benefits that a detailed geometric model tied to accurate data would bring to the project. However, De Oliveira et. al (2021) shows that introducing green retrofitting to building conservation necessitates the creation of a BIM to facilitate energy modelling.

In Canada two significant retrofit demonstration projects have been completed as part of the National Resources Canada (NRCan) Prefabricated Exterior Energy Retrofit (PEER) program: the Presland PEER pilot by Ottawa Community Housing and the Sundance Cooperative in Edmonton by Butterwick Construction. The PEER program ran from 2017 to 2023 and concluded with the publication of the *Prefabricated Exterior Energy Retrofit (PEER) Project Guide* (Carver et.al., 2023) through CanmetENERGY. The *Project Guide* outlines the current state of Canadian housing stock and energy usage; describes the program's inspiration from innovative European projects like Energiesprong; and provides in-depth detail on each aspect of the demonstration projects from conception to completion. Significant emphasis is placed on the procedures for building capture including surveying, photogrammetry, and laser scanning. However, little information is provided on the process of translating the resulting point clouds into geometry in 3D modelling software. The lack of extensive description of the modelling process in the document reveals the complexity of the task, and the continued reliance on skilled modellers to translate point cloud data into useful geometry.

Level of Detail, Information and Accuracy in Building Information Modelling of Existing and Heritage Buildings (Graham, Chow, and Fai, 2018) begins to formulate a structure for the complex and asymmetrical nature of creating an as-built or as-found model based on CIMS' on-going work at the Parliament Hill National Historic Site in Ottawa, Canada (Chow et. al., 2018). The paper discusses the merits and shortcomings of several BIM guidelines for HBIM applications before proposing a new benchmark tailored to the nuance and complexity of existing heritage buildings. The BIM guidelines covered include: Level of Development Specification 2016 (BIMFORUM); architecture, engineering and construction (Can) BIM Protocol (CanBIM); PAS 1102-2: Specification for Information Management for the Capital Delivery Phase of Construction Projects Using BIM (British Standards Institution); and Level of Accuracy Specification Guide (US Institute of Building Documentation). Going beyond more standard definitions of Level of Detail (LOD) —which typically combine the development of geometry, information, and accuracy into one definition—CIMS proposes using Level of Detail, Information, and Accuracy (LODIA) as a measurement of an HBIM, allowing each characteristic of an element to develop individually and relationally. In this guideline, each of the three categories has five levels of definition. LOD describes the graphical representation of the model from a symbolic placeholder to a detailed model. Level of Information (LOI) is determined by the data available and can be based on existing drawings, specification documents, and onsite observations and measurements. Level of Accuracy (LOA) reflects the level to which the deflection and deviation of the building element is modelled in the BIM. The separation of these three categories is especially pertinent to BIMs for retrofits as each element of the as-found building will be analyzed in a variety of ways throughout the project timeline, including but not limited to: structural capabilities, to be demolished or removed during retrofit, material composition and embodied carbon, thermodynamic performance, and energy use. Each of these different lenses requires different types and levels of information from the model and the clear communication of the level of that information to every model user.

3 BUILDING CAPTURE AND BIM CREATION

The building capture to BIM workflow for the Île-Bizard pilot project consisted of three phases: on-site documentation, data processing, and modelling. The work was completed by a team from CIMS in collaboration with the larger ReCONstruct group.

3.1 On-site documentation

On-site building capture was completed over two site visits in 2023. Three devices were used: a Leica TS11 total station, a Leica RTC360 laser scanner, and a DJI MINI 3 PRO drone. The Centre Socioculturel is surrounded on four sides by parking lots. To the north of the site is a single-storey library building. While the site did not have many of obstructions for terrestrial laser scanning and survey (only the two trees directly in front of the building were in the way), the isolated nature of the building meant that the laser scanner had little access to the roof of the building. Therefore, drone-based aerial photogrammetry was used to capture the roof of the building, and connect the photogrammetric capture to the building elevations.

The terrestrial survey was carried out through the combined use of the total station and laser scanner. Overall, forty-six laser scans were recorded; arranged along one closed loop surrounding the entire building, and a network of scans through the interior of the gymnasium. The two sets of scans (exterior and interior) have been linked to each other by using intermediate scans taken across multiple doorways dispersed around the perimeter of the building. The building capture focused on the building envelope and the gymnasium interior to capture the elements most pertinent to an exterior panelized retrofit: structure, general wall thicknesses, and the geometric features of window and door openings. This approach resulted in the documentation of the entire building envelope and its immediate surroundings, as well as a good portion of the interior. Smaller interior spaces, not crucial for the DER design—including the second floor—were omitted from the digitization effort (unless partially captured simultaneously).

Three flights were carried out with drone to fully capture the roof, and tie it to the building facade and site:

1. A spiral pattern: starting at an initial height of 13 m above grade, climbing to a final height of 35m
2. Loops at 5m & 8m above grade respectively, facing the building elevations
3. A top down grid pattern at a height of 40m above grade

The resulting photo sets had an average 60% photo overlap to ensure the redundancy necessary to obtain a geometrically accurate registration. This workflow allowed the onsite team to navigate the challenges posed by vegetation, traffic, building occupants, and the shadows and reflections caused by direct sunlight, while balancing the quality of the data capture with the duration of time onsite.

3.2 Data Processing

Registration of terrestrial laser scans was carried out in Cyclone REGISTER 360 PLUS. The photogrammetry was processed in Bentley's ContextCapture. The resulting point cloud was scaled and oriented in the same software using survey points from the total station.

In order to verify the congruency of the overlap between the laser scanner and the photogrammetric point clouds, both were imported into CloudCompare, an open-source point-cloud-processing software that allows for a semi-automatic calculation of the cloud-to-cloud distance. Overall, the photogrammetric point cloud had an average error below 2mm from the laser-scanned point cloud, which is acceptable for the level of tolerance required by the project. The point clouds were then registered together in Autodesk Recap before being brought into the BIM authoring software, Autodesk Revit.

3.3 BIM Creation

For the purposes of this paper, the description of modelling will focus on the roof of the Centre Socioculturel. The roof is the largest element in the as-found model (AFM) of the building, with the most visible deformation. The size, planar nature, and corrugated cladding of the roof also made it more challenging to model accurately to the collected point cloud data.

According to the standard established by the CIMS team, each element of the AFM should generally be within +/- 5mm of the point cloud. This tolerance was chosen to provide the maximum number of future applications of the BIM. However, the adherence of geometry to this value is non-uniform throughout the model. High precision in modelling is required around elements like windows and doors that will play a prominent role in the design of the panelized system and require a smaller overall tolerance than elsewhere on the building (Carver et. al, 2023). For elements with large surface areas like walls, floors, and roofs a balance must be achieved between the precision of the geometry, the intricacy of the element, and the time necessary to model the element. Further, a verification system has been implemented in the model to communicate the LOA of each element in the *Properties* panel. Each modeled element has been associated with one of three levels of verification: *verified to point cloud* (elements captured in their totality by the point cloud), *not verified to point cloud* (elements not visible in the point clouds), and *partially verified to point cloud* (elements partially visible in the point clouds, ie. only one side of a wall). Elements that do not require a high degree of detail in their geometry can also be listed as *placeholder* geometry.

The AFM roof is modeled in two parts: a primary generic surface that captures the slope and general form of the roof, and a face-based parametric family that captures the corrugated cladding of the roof. The primary generic surface of the roof was created using 544 sub-element control points arrayed in a 32 x 17 grid with 1400 mm spacing. Fascia and soffits were applied to the generic roof surface using average profiles derived from the point cloud. The eaves troughs were omitted as it is clear that they will be removed during the retrofit. The corrugated panel family was modeled parametrically as a single unit and then placed on the generic roof geometry and adjusted to align with the point cloud. The thicknesses of both the existing corrugated panel family and the generic roof surface are an approximation as the underside of the roof is covered by ceiling treatments inside the gym of the Centre Socioculturel, categorizing both elements as *partially verified to point cloud*. Following CIMS' LODIA guideline, the AFM roof model can be defined as:

- LOD 3: the model element is represented graphically with high precision. The material palette is shown and connection pieces are modeled—but fasteners are not.
- LOI 2: more non-graphical data are specified and are in-part project specific. Overall materiality is labeled but may not include complete wall assembly details. Type is specified but not specific manufacturer information.
- LOA 2: element deflection/deviation is modeled at a predetermined grid spacing (typically between 1,000 mm and 3,000 mm) and at corners or changes of material. Deflection/deviation is shown in positioning, not in material thickness.

After creating the AFM of the Centre Socioculturel, the pilot project moved into the design phase for the panelized DER. This transition highlights the importance of nuanced classifications for LODIA as the BIM becomes a hybrid of as-found elements and proposed interventions. This stage of the project also necessitates the implementation of phasing parameters in object properties to designate elements that will be demolished, as well as new construction elements. The phase parameters can be used to filter the model by construction phase.

Each proposed roof panel measures approximately 3.2x6m. However, the exact dimensions vary slightly to ensure that the panel joints follow the exact position of the existing structural members bearing the roof. As panels were modeled and applied to the building, it became apparent that while the AFM geometry captured the deformity of the existing building visible in the point cloud, these irregularities were not readily apparent by simply viewing the model. The effects of this were most visible when placing panels over the roof. Due to inconsistent slope throughout the roof, the generically rectilinear panels intersect the geometry of the existing roof when placed on a consistent slope.

To accurately quantify the extent of deviations, an experiment was conducted to compare the AFM roof with its ideal geometry—a roof model lacking the deformations to the as-built building over time. To this end, working from the original 1978 construction drawings by Chartel Construction Inc. a second roof was modeled. This drawing-based model (DBM) was constructed simply using the given profile and length of the roof in the drawings. Using CIMS' LODIA guidelines, this roof can be defined as:

- LOD 2: the model element is graphically represented with primary materiality shown. Connections and secondary materials are minimally represented.
- LOI 2: more non-graphical data are specified and are in-part project specific. Overall materiality is labeled but may not include complete wall assembly details. The type is specified but there is no specific manufacturer information.
- LOA 0: no deflection/deviation is modeled. An average dimension is used for position and material thickness.

The DBM roof uses material assemblies to denote the composition of the roof, including the corrugated paneling used as cladding. This method does not incorporate three-dimensional representation of the corrugated panels, nor the soffits and fascia.

4 MODEL ANALYSIS

In order to compare the AFM roof to the DBM roof the generic roof surface of the AFM roof had to be isolated from the corrugated panel family. Removing the corrugated geometry removes the chance of reading the high and low points of the corrugation as deformation in the roof itself. Next, both roof geometries were brought into Rhinocerous3D to make use of the visual programming software plug-in Grasshopper. To begin, the AFM roof and the DBM roof must be positioned in relation to a third planar surface, located one meter above their highest point. The distance of each roof from the planar surface is then measured using a grid array of sample points (fig. 1).

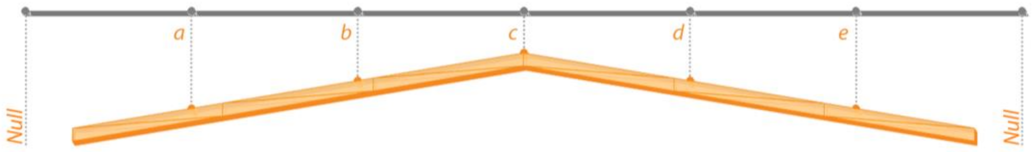

Figure 1: Diagram of distance measurement between the AFM Roof (orange) and the planar surface (grey)

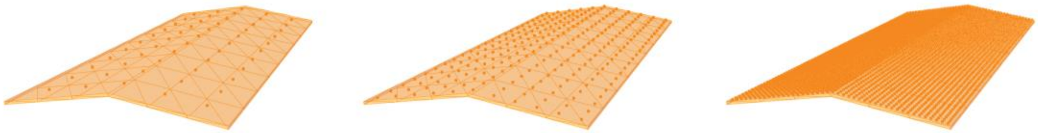

Figure 2: Different sample point densities (from left to right): large (4m spacing), medium (2m spacing), and small (0.5m spacing).

Three densities of sample points were used: small (0.5m spacing), medium (2m spacing), and large (4m spacing) (fig. 2). To be able to compare the measurements of each roof to the planar surface against one another, it is crucial that both roofs are located in the same position relative to the planar surface. Even with simply a visual alignment, it is apparent that the AFM roof has different dimensions than the DBM roof. Therefore, the apexes of the roofs were used as anchors when registering the roofs one to another. This positioning minimizes vagueness in the comparison of results by ensuring that the highest and lowest points on the roofs are in comparable locations.

Through scripting, the distances between the sample points on the planar surface and each roof are easily measured and exported to Excel. However, this generated a large amount of data: the smallest spacing of sample points generated 3913 individual measurements for each roof. Therefore, two different strategies were developed to visualize and compare the results.

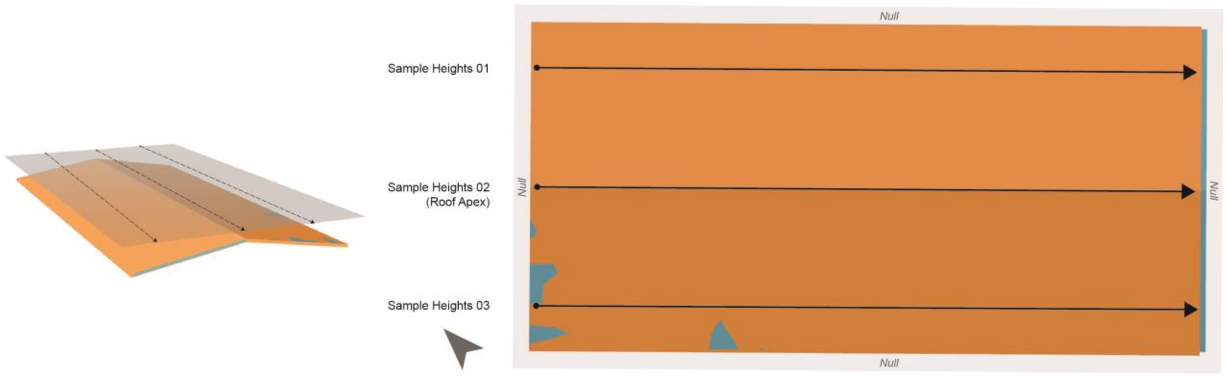

Figure 3: Positioning of three selected rows of sample points for visualisation on the roofs (from top to bottom): Sample Heights 01, Sample Heights 02, and Sample Heights 03. The DBM roof is shown in blue, the AFM roof in orange, and the planar surface in light grey.

First, three rows of sample points were chosen to graph for each roof and each sample distance (fig. 3); one row on each side of the gable (Sample Heights 01 and 03), and one row along the apex of the roof (Sample Heights 02). Figures 4, 5 and 6 show the difference between the DBM measurements and the AFM measurements at the small and large sample point spacing for each sample selection. While the distance of the DBM roof to the planar surface remains constant in all graphs, the distance of the AFM roof to the planar surface fluctuates across all three data samples. Not only are there minute undulations between adjacent measurements, but the graphs reveal an overarching trend of the roof sinking along the length of the building from back to front.

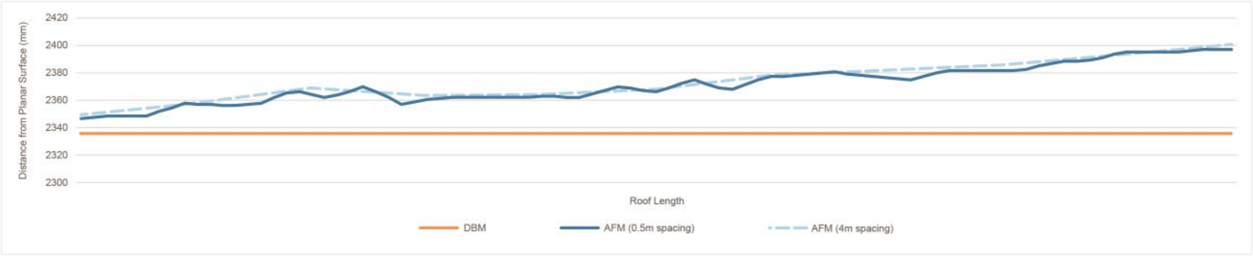

Figure 4: Graph of measurements from planar surface for Sample Heights 01, comparing DBM roof (orange) to AFM roof at large sample distance (light blue, dashed), and small sample distance (dark blue).

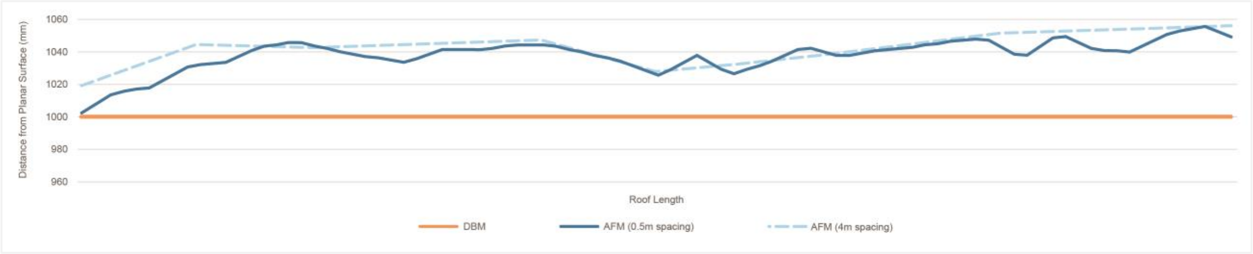

Figure 5: Graph of measurements from planar surface for Sample Heights 02, comparing DBM roof (orange) to AFM roof at large sample distance (light blue, dashed), and small sample distance (dark blue).

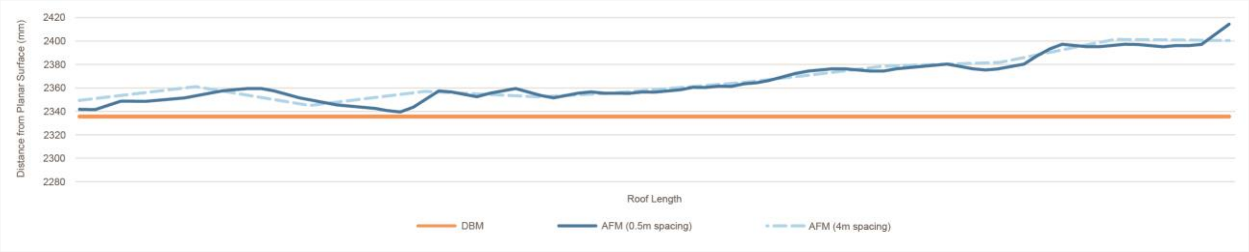

Figure 6: Graph of measurements from planar surface for Sample Heights 03, comparing DBM roof (orange) to AFM roof at large sample distance (light blue, dashed), and small sample distance (dark blue).

Second, scripting within Grasshopper was used to visualize the measurements spatially using a heat mapping effect (fig. 7). While the DBM roof has even and consistent coloring, variegation in the coloring of the AFM roof highlights areas of non-uniform deformation.

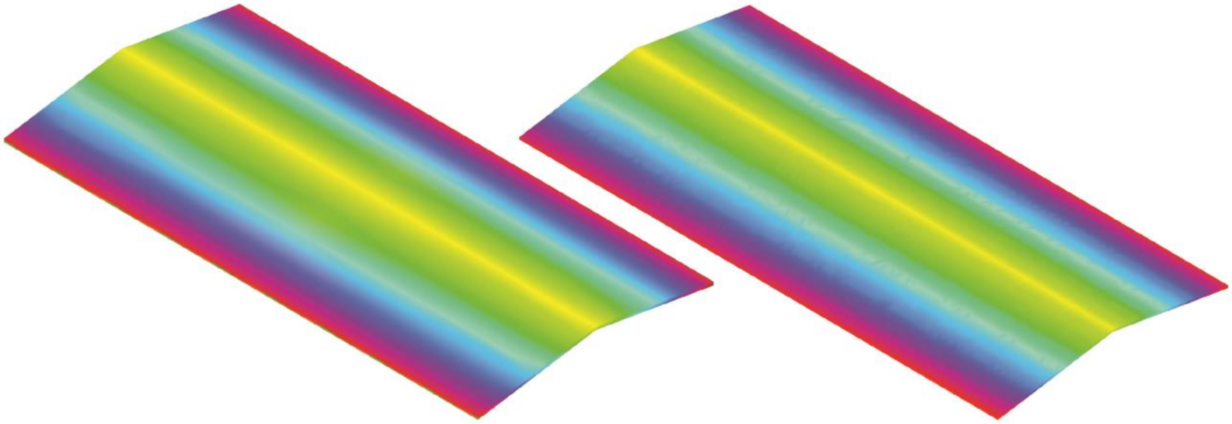

Figure 7: Heat map visualisation of non-uniform deformations. DBM roof (left) compared to AFM roof (right).

The deformations that are visible in the two methods of interpretation have very real implications on the design of the DER panel system. At the bare minimum, the change in height in the roof across the building's length will require more customization in wall panel heights depending on which facade they are placed. Further, the consistency of this vector across all three data sample columns raises questions about how the building has settled over time and the integrity of the structural elements. The non-uniform deformation across the surface of the AFM roof confirms what the initial panel placement indicated: the as-found roof slope is not consistent. To work around this in the implementation of the panelized DER could result in a variety of outcomes including, but not limited to: a customizable installation system that is able to accommodate changing angles of installment; wider margins between the panels and the existing building; and possibly significant intervention to the existing roof. Each of these outcomes has implications on the cost, timeline, and embodied carbon of the project.

5 DISCUSSION

The analysis described above raises several questions that impact the broader scope of the research project outside of the design of the DER panels for the Île-Bizard Centre Socioculturel. While the benefits of an accurate BIM for simulation and decision-making are clear, the benefits of the method of BIM creation are not so obvious. To model the as-found geometry by hand from the point cloud requires an investment of time and skilled personnel. This also means that the accuracy of each element is determined by the decisions of the human modelling team. In the case of the roof comparisons, it was impossible to filter out the individual decisions of the modellers who made the roof in the BIM environment from the deformations that exist in the as-found building. Measuring the distance of the roof to the planar surface at multiple sample point densities safe-guarded against modelling irregularities skewing the results: when comparing figures 4,5, and 6 the overarching trend in the distance of the AFM roof remains consistent, even if the nuance of the small sample spacing does not. Additionally, the growing palette of automated scan-to-BIM tools questions the time and labor investment of modelling from another angle. Esfahani et al., (2021) investigates accuracy levels achieved in manual and semi-automated scan-to-BIM workflows, providing an overview of how automation and modeller training affect the accuracy and the “dimensional certainty” of BIMs generated by Scan-to-BIM workflows. The use of automation tools for scan-to-BIM will be explored in future research, but it is important to understand from the start what LODIA is necessary for the desired BIM applications, and what these tools can provide.

Moving forward, the applications for the Île-Bizard Centre Socioculturel BIM will pursue the facilitation of LCA and experimenting with BIM-to-fabrication workflows. These new use cases will require different LODIA from different building elements than for the panel design process. Contributions such as Darko et. al., (2024) take a further step forward by highlighting the effectiveness of digital-twin models for existing architecture, which can complement the static building information—easily obtainable from scan-to-BIM processes—with the real-time dynamic data provided by Internet-of-Things sensors.

6 CONCLUSION

The intersectional approach outlined in this paper has shown the considerable potential underlying the combination of the typical HBIM workflow and Deep Energy Retrofit design strategies, which in turn aim to harmonize standardized construction solutions (ie. design and prefabrication of thermal insulation panels) within unique as-built conditions. These peculiarities often elude the original design of the building—which, for this reason, never coincides with the as-found conditions —as they are the result of its natural evolution, the building adapts to environmental conditions through alterations of its structural, geometric and performance-related characteristics in various ways. This aspect has to inevitably be taken into account by any retrofit strategies through their on-site installation. Accurate modelling from point clouds in a BIM environment paves the way for analysis which provides a better understanding of the geometric deformations of the building, thus allowing designers to provide more effective guidelines for standardized fabrication processes. Through a refined understanding of levels of detail, information, and accuracy, the Île-Bizard Centre Sociocultural BIM has successfully become a strategic planning tool able to tailor generalized DER strategies to suit the distinctive characteristics of the as-found building.

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