Circularity in Construction: Scaling Up Glass Reuse with Silicone

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Abstract

The laminar glass bonding process using silicone, initially presented at GPD2023, has been successfully applied to renovate the façade of the Herostrasse building in Zurich, Switzerland. This innovative approach combines glass and silicone to create intelligent hybrid materials that support the circularity of building materials. By utilizing window or spandrel glass at the end of its lifespan in combination with silicone, the glass can be repurposed as cladding material for façades. This glass-silicone hybrid can be separated after use, allowing both materials to be recycled. This paper reviews the mechanical (impact) and safety (fire) performance of the composite glass-silicone-frame. Observations from the Herostrasse building implementation are discussed, and potential pathways for scaling up the method to larger projects are explored. The re-manufacturing process holds significant potential, as the large amount of flat glass replaced annually in window renovations could be reused effectively. The flexibility in formats and shapes opens a wide range of applications, and cutting to size is straightforward. Machine vision and optimization tools enable the reuse of these glass elements in both conventional façades and new geometric configurations and designs.

Keywords

Silicone, glass, construction materials reuse, digital

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1. Introduction

The construction industry is increasingly recognizing the importance of sustainable design, and silicones are playing a pivotal role in this transformation. Silicones enhance the durability of building envelopes and improve energy efficiency through innovative applications such as multi-pane glazing. Dow's DOWSIL™ Carbon-Neutral Silicones Service exemplifies the industry's commitment to reducing the carbon footprint of silicone production, aiming for continuous annual reductions in embodied carbon. Additionally, silicone bonding techniques offer material efficiency benefits by reducing the need for additional materials and facilitating disassembly at the end of a building's life cycle.

Previous work by the authors (Hayez 2021, Cutri 2023) highlighted how silicones can enable reuse of materials, such as glass used as cladding material for spandrels or opaque wall build ups. Many windows, window façades or curtain walls from the 1940s to the 1970s are currently replaced or the whole buildings are deconstructed. The established dismantling and deconstruction process demands a component separation. Windows are taken away in containers and most of the glazing remains unbroken in the frames. The formats vary from small window sizes to shopfront sizes. Most of this glass is monolithic and in an annealed state, typically 3mm to 8mm thick. In Switzerland, approx. 61’000 tonnes of such flat glass per year is fed into the recycling process. The recovered figure does not include the glass from large industrial enterprises. Once taken away from site or works, a substantial part of the glass is shredded out of the frames and processed to foam-glass as compression resistant insulation or road fill. By avoiding the downcycling and activating the urban glass mines for reuse and remanufacturing, the containers must be replaced by glass cradles. The safe storage and transport in the glass cradle and the cutting to size are the only steps to be carried out prior the industrial reuse und remanufacturing processes. The concept of glass reuse through silicone was first developed with a case study, project Herostrasse in Zurich. This office building is today used as a vocational college. Since taking the building into service in 1972, no significant servicing or refurbishment work had been carried out. Therefore, the condition of the façade varied. The façade consists of floor to ceiling height elements in timber, steel and glass. The spandrel area consists of a timber chipboard, 30mm mineral wool, a fiber cement board, a ventilation gap and enamelled glass sheet as cladding. A timber-aluminium window and venetian-blinds are integrated above the balustrade build up. In 2021, the city of Zürich decided to refurbish the façades without taking the building out of service, and therefore without touching the interior surfaces and other building components. In a competition entry with Ekinci Architekten GmbH, the chosen concept proposed to maintain the balustrade timber buildup on the inside. The proposal was to reuse the inner, structural active balustrade buildup and the glass as cladding material.

After the technical and visual assessment of the glass, it became clear that it could be reused visually without any negative effects. A life span of another 40 to 50 years was deemed to be possible. Nevertheless, the technical investigation showed that the glass was lacking the required impact performance consistent with safe failure mode and a post failure resistance. A reuse by simple cleaning and reapplication was therefore not possible. A remanufacturing process was required to meet state-of-the-art performances. As post lamination was not considered, as it would increase the GWP due to the new glass pane and energy required for the lamination. Silicone laminar bonding was selected as alternative solutions. DOWSIL™ 7094 self-levelling silicone was used to bond a perforated back sheet in aluminium to the glass. The composite buildup ensures the required performance such as invisible fixation, unchanged glass colour and glass haptic. During the early stages of the project, sample applications, first bonding and compatibility tests were carried out (Cutri 2023).

This follow-up technical paper delves deeper into the performance of the glass-silicone-frame assembly especially in terms of impact resistance and fire performance. Most of the tests are intended to highlight the potential of the concept but should be considered as indicative. Observations from the Herostrasse building implementation are discussed, and potential pathways for scaling up the method to larger projects are explored. Finally, the paper explores machine vision and optimization tools enable the reuse of these glass elements in both conventional façades and new geometric configurations and designs.

Fig. 1: Picture of the finished Herostrasse project. phase 1.

2. Scale up

After the successful trials on small A4 samples (Figure 2) in the office of Dr. Luchinger Meyer LMP (Cutri, Willareth 2023), the concept needed to be scaled up to allow efficient remanufacturing of the larger panels (size from 0.8-2.1m²) for the project Herostrasse in Zurich.

Fig. 2: Preliminary A4 trials performed at Dr. Luechinger Meyer (LMP) offices in Zurich.

First the cleaning process of the original glass panels was determined. The reused glass panels were washed in a conventional glass cleaning machine with deionized water. All dirt could be removed, and no significant scratches were observed afterwards.

Next, the aluminum mesh back pane was selected. Like the preparation exercises in the office, an aluminum mesh of 2mm thickness was used, with perforation holes of 8mm diameter. The holes are needed to enable full cure of the mono-component silicone and enhance connection.

To allow even thickness application of the flowable silicone, panels were placed horizontally on trestles.

Fig. 3: Horizontal placement of the panes and surface preparation/cleaning.

A constant thickness of 4mm silicone is required between the aluminium and the glass to accommodate mechanical loads and thermal dilatation of glass and aluminium. A white spacer tape, compatible with the silicone was used on the surface and around the perimeter of the panels to guarantee the thickness on the whole panel surface, act as a dam of 4mm height and contain the silicone (Figure 4).

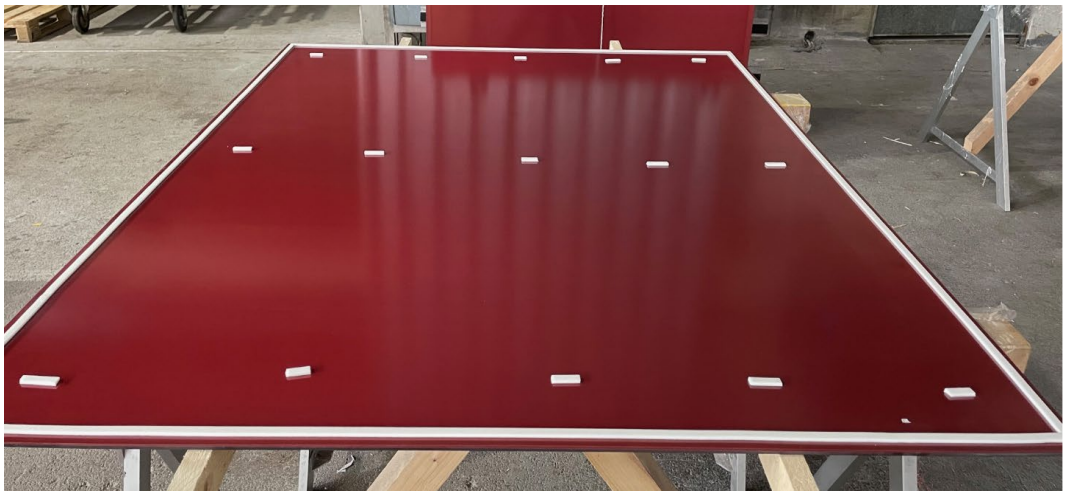


Fig. 4: Spacer tape on the surface and along the perimeter.

The next step was to define how silicone would be dispensed in an industrial process. Initially a simple 1 component gear pump was considered for the application. However, the flowability of the silicone allows eliminating this step. The amount required to cover the panel surface with 4mm of silicone was poured from the 20kg pail in a smaller container, which was consecutively emptied onto the surface delimited with the tape (Figure 5). A simple spatula was used to help the silicone spread out on the surface (Figure 6).

Fig. 5: Silicone poured from the smaller container on the glass surface with exact volume of silicone needed for this panel.

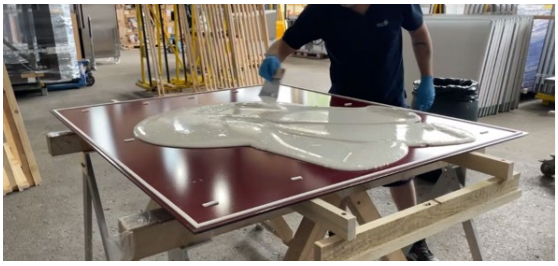


Fig. 6: Spreading the silicone on the glass surface using a spatula.

After dispensing the silicone, the metal sheet was laid down on the silicone layer (Figure 7). The assembled panel was then moved for storage during cure (Figure 8).

Fig. 7: Metal sheet is placed on the silicone.

Fig. 8: Assembled panel is moved to storage during curing.

The panels should remain horizontally during the curing of the silicone. The minimum curing time for the silicone was 7 days due to the low thickness and large area contact with the ambient, unlike a linear joint. Special wooden racks were designed, which had to be simple, cheap, recyclable and enable the handling of the panel during process and storage of the panels. The wooden racks were stackable and optimized in height to limit the required space in the factory. After a minimum curing time of 7 Days, the finished panels were sent on site to be installed to the refurbished and thermally improved facade.

Fig. 9: Panes are stacked with the special wooden rack.

Fig. 10: Panels were left for cure during 7 days.

The elements were transported vertically on glass racks to the site of Herostrasse. No special protection of the elements is required for the transport of the elements (Figure 11).

Fig. 11: Finished cured panels delivered on site from a close production place (10.4Km).

The installation back into the facade was done manually and the panels were installed via a simple clicking in of the panels into the substructure of the facade (Figure12/13).

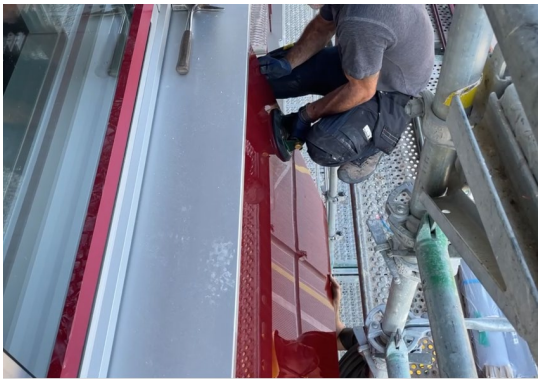


Fig. 12: The panel was placed into the exact position under the window sill to meet the substructure.

Fig. 13: Then the panel was clicked into the substructure.

3. Structural Evaluation

Basic FEA was performed using SJ MEPLA to assess the plausibility of the structural performance of the assembly (ICOMET 2024). The rear-ventilated façade is in the parapet area. The elements consist of a glass with a perforated aluminum sheet glued with DOWSIL™ 7094 Flowable sealant to the glass over the entire back surface. Aluminum square sheets are then riveted to the perforated aluminum sheet. These are then hung in the substructure. The elements have a dimension of 1450x1165mm.

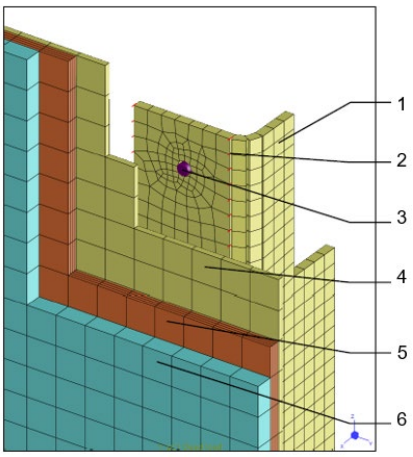


Fig. 13: Static model of the assembly: (1): mounting, aluminium sheet, 3mm thickness, mesh size ≤5mm, (2): contact only through compression, beam elements; (3): rivets, Aluminium 4mm thickness, beam elements every 185mm; (4): perforated aluminium sheet, thickness 2mm, mesh size ≤ 10mm; (5): DOWSIL™ 7094 Flowable Sealant, thickness=4mm, volumetric analysis, mesh size≤ 10mmx1mm; (6): Glass: ESG enamelled, thickness=6mm, shell model, mesh size ≤ 10mm

Three load conditions were evaluated: dead load (LC1), wind load in compression 800Pa (LC2) and wind load in tension 1156Pa (LC3). The serviceability evaluation determined a maximum glass deflection of 37.558mm. Under wind pressure, the glass utilization reached 82%. Under wind tension, it reached 76%, whereas the aluminum utilization was 144%. This is due to stress peaks at the edge of the sheet close to the rivet. The load-bearing safety can be fulfilled without further ado. To model the DOWSIL™ 7094, a 1st order Ogden material model was used with parameters μ_i= 0.122095359MPa, a_i= 2.25739510 and D_i=0.66407996MPa. A dogbone was modeled at failure to determine the corresponding value of Von Mises (VM) stress at failure. The model predicts that the maximum Von Mises Stress is around 2.67 ~ 3.519 MPa for an elongation of 400 ~ 500% strain.

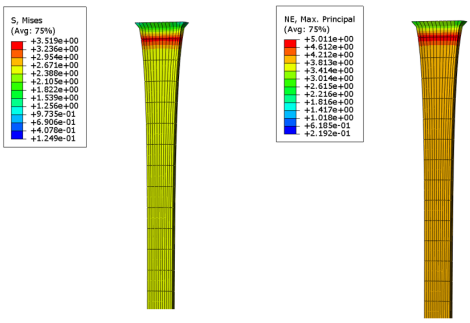


Fig. 14: DOWSIL™ 7094 Flowable sealant dogbone FEA model with predicted VM stress at 5mm/min.

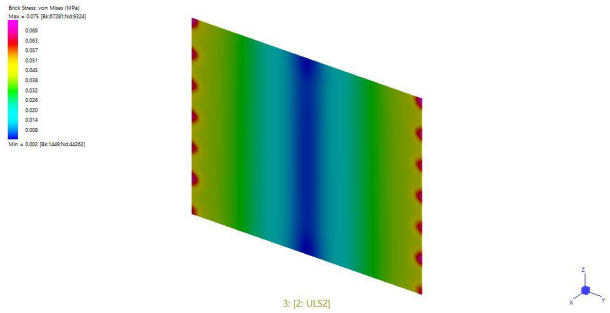


Fig. 15: VM stress in DOWSIL™ 7094 Flowable sealant layer under ULS2 (wind tensile load).

The assembly was consecutively modeled and a maximum VM stress of 0.075MPa was determined which is well below the VM stress value at failure. The assembly was therefore accepted from a structural perspective.

4. Mechanical performance

- Recognising and managing possible risks is crucial for the successful establishment of re-use and on-use as well as remanufacturing applications. In the described re-use of existing glass as high-quality, durable and quasi-inert facade cladding with a minimal CO2-Eq, the glass is transferred from a two- or four-sided panel support to a new static system. This usually has smaller spans, or a partial bedding due to the silicone application on the back. Even if the characteristic glass resistance is conservatively assumed to be lower due to surface abrasion, the structural safety is ensured due to the adapted static system. The long-lasting bond between glass and silicone and the residual stability of the overall construction under accidental actions are crucial for the successful re-use of the application. The latter must be determined specifically for each project. Over-specification should be avoided. For the Herostrasse project, a hard-body impact was defined as a realistic accidental action scenario. This envisages the impact of a 0.5 kg steel ball (Figure 5). Since the façade cladding does not interface to accessible surfaces and the building is not equipped with a BMU, a heavy soft-body impact is not a realistic impact scenario. As the dimensions deviate from the EN12600 requirement, the test could not be followed, and some adaptations were made. A hard-body impact of a 0.5 kg steel ball falling from a height of 1.2 m (Figure4) was specified for the project. This corresponds to an impact energy of around 6 joules.

Fig. 16: Impact test build up in the factory.

Fig. 17: Impactor on refurbished panel.

- The aim of this was to break the thermally toughened glass (Figure 6). In addition, a residual loadbearing capacity of 72 hours was specified for the project. After the impact, or rather after the glass fracture with a small-meshed pattern, the glass pane must remain bonded to the silicone (Figure7) and the back anchoring and stay safe in position. The hard-body impact test was carried out with the impactor from the Lucerne university in the workshops of Suber Metallbau AG. The subsequent residual loadbearing test significantly exceeded the required minimum duration of 72 hours. Failure due to the damaged glass did not occur. This demonstrates the excellent bond between glass, silicone and metal mesh. The re-use application also demonstrates robust and safe load-bearing and residual load-bearing properties under accidental actions or incidents. The test panel, still performing great the post breakage behaviour of the silicone glass connection, was removed from the test center after 1 Year.

Fig. 18: Broken panel after impact test.

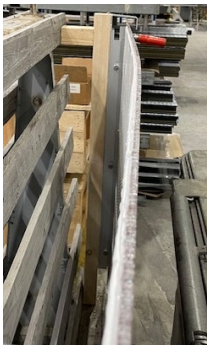


Fig. 19: Deformation of the impacted and broken panel.

5. Fire performance

Current building safety regulations require construction materials used in the façade to have a certain minimal reaction to fire behaviour. Depending on the height of the installation in the façade, requirements may be quite severe for substantial components like building panels (UK regulation), requiring a non-combustible character or a limited combustibility. The goal is to ensure any façade component does not fuel a fire in development or only in a limited way. Although the Herostrasse did not require specific fire performance due to the limited height of the building, it was decided to use this opportunity to validate the reaction to fire performance of the assembly and its potential use on higher buildings.

An indicative single burning item test according to EN ISO 13823 (single burning item test, SBI) (CEN) was performed. This fire test standard evaluates the fire propagation through parameters such as heat release, smoke or flaming droplets development. The self-levelling, one-part silicone sealant was applied on calcium silicate (CaSi) boards, mounted in a corner. To assess reaction to fire, it is possible to replace non-combustible materials like glass with a material of equivalent combustibility like CaSi. The dimensions of the corner short wing are 1,500 mm x 495 mm and 1,500 mm x1,000 mm for the long wing. The perforated aluminium mesh was added on the external face of the product. The assembly is oriented with the aluminium mesh towards the flames to ensure the most onerous configuration, exposing the materials with the highest combustibility. The assembly was exposed for approximately 21 minutes (Figure 2). After the completion of the test, the results indicated that the sample has potential to be classified as class B-s2, d0, in accordance with the European Reaction to Fire classification regulations EN 13501-1:2018. The testing deviated in the number of samples tested (only 1 instead of 3). Furthermore, an ISO 1716 combustibility test and calculation of the assembly is needed to achieve the above classification.

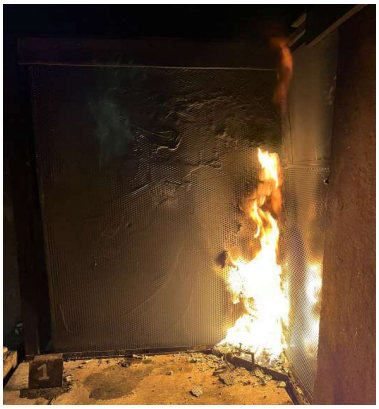


Figure 20: EN ISO 13823 single burning item test of the assembly.

6. Conclusions

Next project where we like to upgrade our idea and take the next step is a project in Switzerland. We explore to take old window glass from the existing old building, cut it into the right size in the park garage of the building and bring it directly back on site without any transport and other special treatments of the glass. The reused glass will be installed as balustrades on the renovated building.

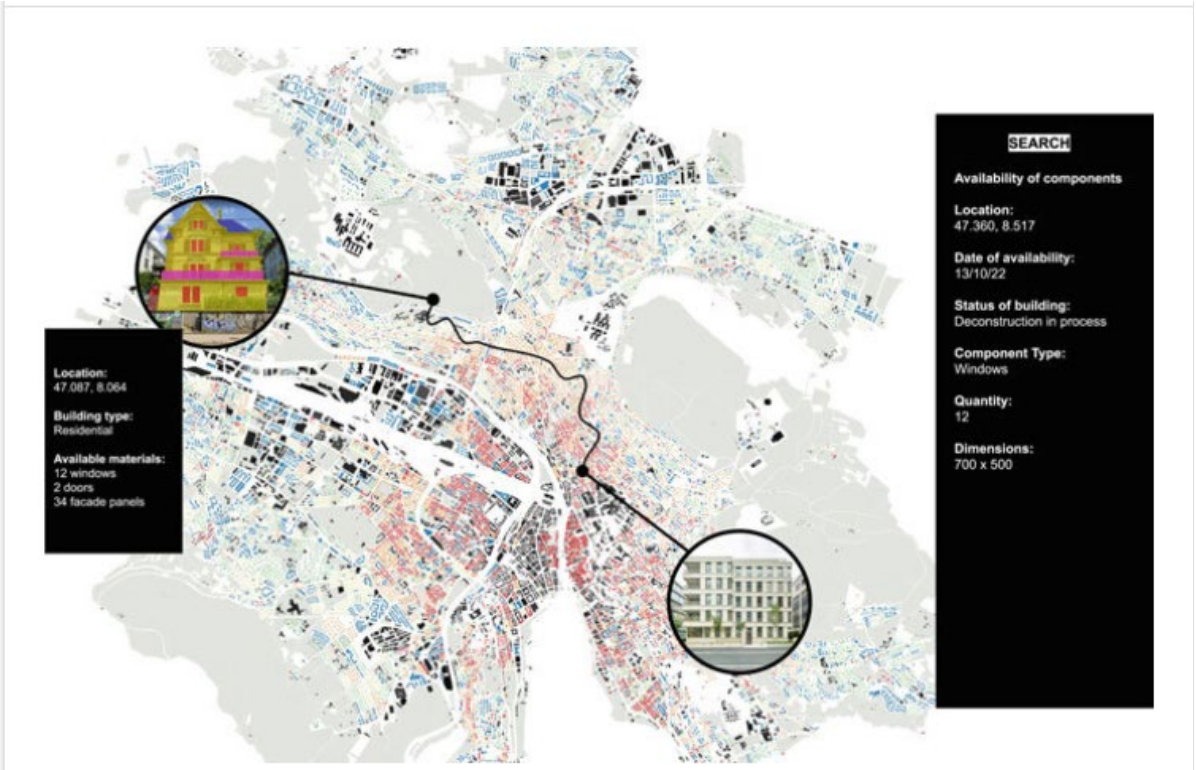
Future step1: Trying to understand where the buildings in need of renovation are located, when the renovation could/should take place and what materials for reuse would be potentially available.

Artificial Intelligence for Predicting Reuse Patterns (Armeni et al., 2024).

Artificial intelligence, particularly computer vision and machine learning, holds significant promise for predicting reuse patterns in the built environment. The increasing availability of sensors that collect visual data opens up new possibilities for digitalizing the built environment. These technologies can be applied to explore design spaces, monitor construction progress, and enhance building performance during operation.

To boost circularity in the built environment, it's crucial to have detailed information about in-use building products, such as their type, material, size, geometry, location and condition. This information serves as a foundation for various circular processes and is essential for creating circular databases. These databases help designers, constructors, and facility managers adhere to circular principles.

Significant progress has been made in academia and industry in extracting this information from visual and other building data. This is useful for predicting material reusability and automating building facade maintenance. However, there are still gaps in adopting and utilizing these technologies for a circular built environment. Challenges include developing comprehensive systems for deployment and robust evaluation. Additionally, business and organizational considerations play a role in the adoption, utilization, and development of these technologies within a circular framework.



2 Visualisation of database with insights on materials and components in supply project (or donor project) derived using CV that can be used for new construction projects (image from Raghu, D., adapted from De Wolf et al., 2023)

Fig. 21: Armeni, I., Raghu, D. and De Wolf, C., 2024. Artificial Intelligence for Predicting Reuse Patterns. A Circular Built Environment in the Digital Age, p.57. https://www.researchgate.net/publication/377145826_Artificial_Intelligence_for_Predicting_Reuse_Patterns#full-text

Future step 2: How can machine learning help us to redesign with reused materials.

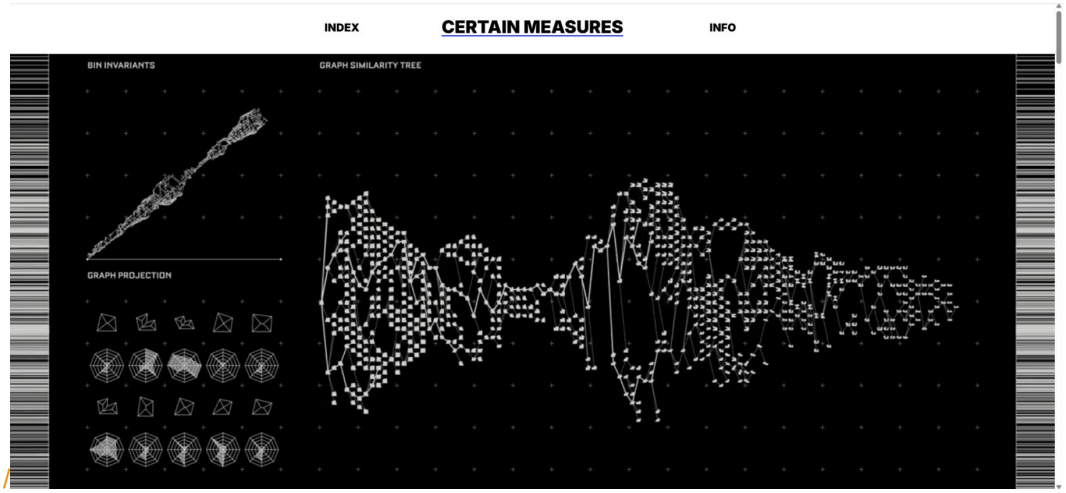


Fig. 22: https://www.certainmeasures.com.

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Certain Measures (CM) is a creative studio that designs spaces, experiences, and products that connect physical and digital realities. We partner with forward-thinking people from across cultural, industrial, and government sectors to realize data-driven projects that fuse imagination and systems thinking. We work between physical structure and bespoke software, bridging across mediums and scales to envision a brighter and more hopeful planetary future.

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- Certain Meassures, Berlin. Tobias Nolte

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