AUTOMIZED PLANNING & DATA EXCHANGE FOR PREFABRICATED FAÇADE RENOVATION PROCESSES

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Abstract

Europe's renovation rate remains below what is needed for climate-neutrality targets; scaling façade refurbishment demands standardised, data-driven automation. Current practice relies on bespoke BIM modelling and file-based scan-to-BIM pipelines, which are labour-intensive, sensitive to as-built deviations, and fragmented across design, production, and logistics. We present an end-to-end workflow that ingests 3D point-cloud surveys and performs geometric panelisation to derive storey-scale and small prefabricated façade panels. The system outputs IFC-compliant panel objects with cut-outs and metadata, synchronised via a self-hosted, versioned Speckle hub. A residential case study demonstrates workflow feasibility and reliable handover.

Introduction

Europe's climate-neutrality ambitions, reinforced by energy crises, place immediate pressure on the renovation of the ageing building stock. In the European Union, buildings account for around 40% of total energy consumption and 36% of energy-related greenhouse-gas emissions (European Commission, 2020b). Despite this central role, the annual renovation rate remains persistently low: on average, less than 1% of the building stock is renovated each year (European Commission, 2020a). This is well below the level required to meet European climate targets, which call for at least a doubling of renovation rates by 2030 and the sustained acceleration of renovation activity thereafter to achieve climate neutrality by 2050 (European Commission, 2020b).

At the same time, renovation projects are frequently perceived as slow, costly, and highly disruptive, while the construction sector faces a structural shortage of skilled labour. Together, these factors create a compelling need for a step-change in productivity, predictability, and scalability in renovation processes, particularly for façade retrofits, which offer high energy-saving potential but are still largely executed through bespoke, labour-intensive on-site construction methods.

A widely discussed pathway to address these challenges is the industrialisation of façade refurbishment through prefabricated façade panels or modules. Compared with conventional, largely on-site insulation retrofits, off-site prefabricated façade approaches shift critical activities to factory-controlled environments, enabling shorter on-site phases, improved quality control, and reduced disturbance for occupants during installation (European Commission, 2024; Zimmermann, 2012). In addition, componentised prefabricated assemblies, especially when designed with demountable connections, offer favourable conditions for circular-economy strategies. When combined with digital material passports, such systems can support planned disassembly, higher-value material recovery, and improved material traceability across the building lifecycle (Akinade et al., 2015; ISO, 2020; Çetin et al., 2023).

However, industrialising façade renovation is not merely a matter of developing new construction products. It is fundamentally a process and information-management challenge. Even where technically mature prefabricated solutions exist, their large-scale deployment remains constrained by the high effort required for building surveying, as-is modelling, project-specific design adaptation, multi-stakeholder coordination, and fragmented data handovers across specialised tools and organisational boundaries.

Prefabricated façade renovation

Over the last decade, research and innovation initiatives have advanced prefabricated façade retrofit systems and serial renovation concepts. The TES Energy Façade project established a timber-based modular façade approach for energetic renovation and investigated a survey-to-installation data-flow concept to reduce time and cost (Larsen et al., 2011). EU projects such as SINFONIA implemented prefabricated façade modules in real contexts, albeit sometimes with conventional on-site execution for specific layers (e.g., cladding and sealing) (Andaloro et al., 2019). The iNSPiRe project developed "Industrialised Renovation Kits", including prefabricated timber-frame façade elements with integrated active components to reduce planning and installation effort (Ochs et al., 2015). 4RinEU similarly explored integrated façade modules with active components (e.g., PV, ventilation, shading) as part of deep renovation packages (Noris et al., 2017; Pernetti et al., 2019). On the market-facing side, Energiesprong (n.d.) is often cited as one of the most advanced examples of industrialised renovation combined with an enabling business model, though its roll-out still tends to focus on building typologies that are easier to standardise and replicate. Across these efforts, a recurring observation is that although technical feasibility is demonstrated, planning and process overhead remain a major driver of cost and a barrier to scaling, particularly when each project requires substantial manual adaptation and coordination effort.

From a computing-in-construction perspective, these observations highlight the central role of digital workflows across the entire renovation process, spanning survey capture, scan-to-model transformation, modular design configuration, performance assessment, production planning, logistics, and installation. Multiple studies report that renovation productivity bottlenecks stem not only from tool-level limitations (e.g., the effort and uncertainty involved in converting survey data into reliable as-built BIM), but also from socio-technical factors such as multi-stakeholder coordination complexity, communication bottlenecks, and information losses/redundancies across phases and organisations (Volk et al., 2014; Prieto et al., 2024; Lupica Spagnolo et al., 2022; Chen & Luo, 2026). In this context, continuous end-to-end digital workflows, linking building survey/scan-to-BIM to downstream design, prefabrication/CAM, and on-site assembly, are increasingly highlighted as key enablers to reduce planning effort and rework, mitigate data loss at interfaces, and support scalable deployment of prefabricated façade renovation solutions (Lupica Spagnolo et al., 2022; Fichera et al., 2025; Iturralde et al., 2025).

Scan-to-BIM & as-is modelling

A reliable, planning-grade as-is description of façade planes and openings is a prerequisite for panelised renovation. Scan-to-BIM / as-built BIM creation is commonly decomposed into (i) reality capture and preprocessing (e.g., registration and cleaning), (ii) geometric and semantic interpretation (segmentation / object recognition), and (iii) generation of parametric BIM/IFC entities and their relationships (Tang et al., 2010; Pătrăucean et al., 2015). Recent work increasingly leverages learning-based segmentation to automate recognition and downstream model creation, as exemplified by SCAN2BIM and Cloud2BIM (Campagnolo et al., 2023; Zbirovský and Nežerka, 2025). However, façade openings remain a hard case: measurement quality deteriorates at edges and window glazing often returns few or no points, while occlusions and missing data still necessitate manual validation/correction in practice (Pu and Vosselman, 2007; Tang et al., 2010; Tang et al., 2009). Consequently, renovation-oriented pipelines often adopt hybrid automation with human-in-the-loop controls, targeting a fit-for-purpose envelope representation (e.g., alignment planes and opening extents) that supports panelisation and prefabricated-panel installation rather than a fully detailed as-built BIM (Fichera et al., 2025; Song et al., 2023).

Research gap & Contribution beyond the state of the art

Across the reviewed literature, a persistent gap can be identified: while numerous methods address individual stages of prefabricated façade renovation, such as reality capture, scan-to-BIM transformation, panelisation strategies, IFC-based exchange, or logistics optimisation, far fewer contributions demonstrate an operationally usable, end-to-end workflow that explicitly treats continuous data flow as a primary research concern. In practice, large-scale deployment is constrained by fragmented information exchange across specialised tools and stakeholders, frequent data loss due to file-based handovers, and the absence of workflow-oriented ecosystems capable of linking survey-derived geometry, planning artefacts, and downstream operational outputs through a shared, versioned backbone.

This paper addresses this gap by presenting an integrated, web-based planning workflow for prefabricated façade renovation that prioritises continuous, interoperable data flow from survey ingestion to panel planning and logistics preparation. Rather than optimising isolated algorithms, the work focuses on the ecosystem-level potential of a modular toolchain coordinated through a central workflow layer. Accordingly, the implemented computational components should be understood as research prototypes for validating end-to-end workflow continuity; in future implementations, individual modules may be replaced by mature third-party solutions where interoperable interfaces and data continuity can be maintained. The implemented workflow combines point cloud ingestion and geometric pre-processing, semi-automatic derivation of façade planes and openings, interactive yet automated panelisation with IFC-compliant outputs, and downstream logistics preparation through panel-to-package transformation and interactive container loading.

Methodology

We propose a structured, workflow-oriented system that prioritises continuous data flow from survey to planning and logistics. The system follows the three-block structure shown in Figure 1: site survey as the data source, a 3D renovation planning web interface as the interaction layer, and a backend that provides custom services and a persistent data layer. The interaction layer is a Three.js-based (three.js, n.d.) web application used for both façade panel planning and the logistics planning. The communication with the backend works through GraphQL- and REST-APIs. The backend stores all project artefacts as versioned objects in a self-hosted Speckle server (Speckle, n.d.).

Overall, the workflow proceeds in four stages. First, façade and window point clouds (see Detection of window opening dimensions) are uploaded through the web interface and validated. Second, façade planes are reconstructed from the point clouds and stored together with the cleaned survey data. Third, façade panelisation is generated and reviewed interactively in the Three.js-based web frontend, and the resulting panel objects are persisted via Speckle. Finally, the panel objects are converted into package objects and transferred to the Three.js-based logistics interface for 3D packing and container loading.

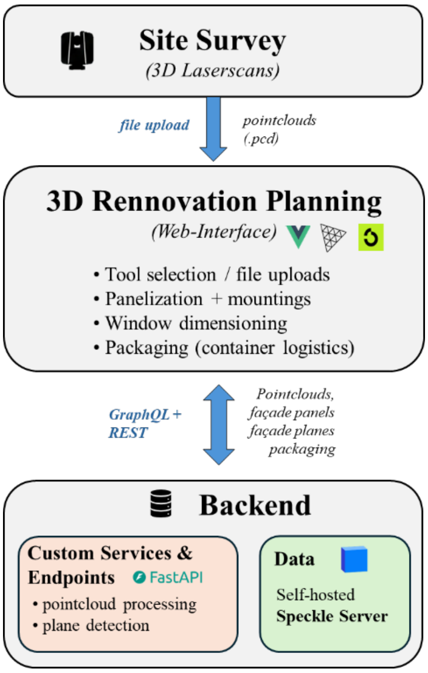

Figure 1 System architecture

Versioned Data Management

When point cloud data are uploaded via the web interface to the backend they get stored as Speckle point cloud. The backend uses the Open3D python library (Zhou et al., 2018) to read the scan data and creates a versioned object graph in the *pointcloud-facade* branch. This gives all downstream tools a consistent and queryable source of truth.

Speckle is used as a versioned common data environment with a deliberate branch/model structure. In Speckle, each project contains named models (branches) that hold a sequence of versions (commits) referencing object graphs. The workflow assigns one model per artefact type so that tools can query the latest version deterministically: *pointcloud-facade* and *pointcloud-windows* store survey data; *facade-planes* stores derived plane objects; and *facade-panels* stores panel layouts in IFC-compliant data format. This convention makes data handovers explicit, reduces ambiguity when multiple tools write to the same project, and enables reproducible retrieval of the latest artefact by model name.

Façade plane reconstruction

A critical process step is the reconstruction of the façade planes from the 3D point cloud data. As discussed already in sub-section Scan-to-BIM & as-is modelling there are existing scan-to-BIM tools. We found however that the results of that tools are not accurate enough to execute a detailed façade planning with prefabricated panels. That is why we implemented a semi-automated approach that lets users define the façade planes directly based on the 3D point cloud data. This ensures a maximum of accuracy and flexibility.

Façade panel generation

The reconstructed façade planes are the basis for the panel generation which follows a parametric grid-based process in the 2D façade plane. The panel system is defined by parameters (standard width & height, minimum width & height, depth, gap width, mounting position, weight) that are iteratively fitted to the façade while respecting openings and façade boundaries. To control where a panel must terminate, the user defines horizontal and vertical break edges (e.g., façade edges and opening boundaries). These break edges induce a rectilinear grid on the façade plane and thus a set of grid fields. Within each grid field, the algorithm first places panels at the standard width/height. If boundary panels would need to be cut, the remaining strip is evaluated against the minimum admissible panel dimension. Whenever the remaining width/height would violate this minimum, the algorithm avoids producing undersized edge pieces by uniformly resizing the panels along the affected direction within that grid field so that all resulting panels satisfy the minimum dimension constraint while maintaining the specified gap. This resizing is applied locally within the affected grid field; standard panel dimensions are preserved in unaffected fields, while only boundary-adjacent panels may deviate where necessary. The resulting panel layout in the 2D façade plane space gets extruded and transformed back to the global 3D coordinate system. The 3D panels are now represented as Three.js geometries with a stable identifier, a façade ID, and dimensional metadata (width, height, depth, gap).

A dedicated IFC writer transforms the generated Three.js panels into IFC-compliant objects (e.g., IfcPlate with swept-area geometry) and attaches property sets containing Width, Height, and Depth. The resulting IFC model is stored on the Speckle server. File-based exports were also implemented (.ifc model with 3D façade panels, .csv lists with panel dimensions and mounting points), but they are meant primarily as documentation features; the operational data for prefabrication and on-site mounting remains available as versioned Speckle objects that can be queried and reused across tools.

Detection of window opening dimensions

Window planning is supported as an optional, separate module. Detailed window design typically requires denser scans than façade-level surveys, so the workflow accepts dedicated window point clouds when they are available. In practice, these local scans are acquired from accessible interior or exterior positions using higher-density close-range measurements, depending on site access and required detail. They are registered to the building-level façade point cloud during survey preprocessing and then uploaded as already aligned window point clouds to the *pointcloud-windows* branch. Then they are processed by a light-weight plane detection routine that produces structured instances with fitted planes which represent the window opening (four reveals and one wall plane). Leveraging Open3D the backend performs a deterministic sequence: The window scan is down-sampled with a voxel size of 0.02, normals are estimated and oriented consistently, and planar patches are detected using normal variance 60°, coplanarity 75°, outlier ratio 0.75, and a k-nearest-neighbour search of k=30. The largest detected plane is interpreted as wall and the remaining planes as window reveal candidates. Each candidate is converted to a rectangular plane using its oriented bounding box and stored alongside the raw point cloud for detailed window planning.

Container packaging

A logistics planning feature was developed and implemented to calculate the number and size of shipping containers required for transporting the planned façade panels. It consists of an interactive 3D environment based on Three.js and ThatOpen bim-components (ThatOpen, n.d.) with a packing solver that is based on 3D-bin-picking algorithm from (Aoulad Lahcene, 2023).

The backend resolves the latest *facade-panels* model through the GraphQL API, loads the referenced object graph, and traverses it to identify panel candidates. Dimensions are taken from attached property sets when available. The backend emits a package list with dimensions, quantity, priority, stacking capacity, and allowed rotations, which is consumed by the logistics tool for packing.

The packing solver uses a greedy heuristic with priorities and open-point placement. Packages are expanded by quantity, grouped by priority, and sorted by volume within each priority. Placement proceeds by testing rotations at available open points, checking container bounds and collision constraints, and honoring stacking limits. New open points are generated on the front, right, and top faces of each placed package, while invalid diagonal points are removed to stabilize the search. A manual drag-and-drop mode remains available for operational corrections that are not captured by the heuristic.

Results & Discussion

The workflow was validated on a representative residential building using terrestrial laser-scan (TLS) data captured with a FARO Focus M70. Figure 2 shows the façade point cloud used as survey input. To anchor the digital planning workflow in a manufacturable solution, a physical prototype of the prefabricated wood-fibre insulation panel was used as planning reference (Figure 3), confirming the feasibility of the intended panel geometry and joint concept for off-site fabrication and on-site installation.

Across the end-to-end validation, three main outcomes were observed. First, the semi-automated façade-plane reconstruction provided planning-grade reference geometry from real scan data, enabling downstream panelisation without relying on fully automatic scan-to-BIM outputs. Second, automated panelisation generated façade module layouts that are directly usable for downstream BIM and fabrication preparation through IFC-compliant objects and associated dimensional metadata. Third, the versioned Speckle-based data backbone enabled a consistent handover from survey-derived façade modules to logistics planning, avoiding repeated file exports/imports and reducing data fragmentation between tools. Given the single-case validation, these results should be interpreted as evidence of workflow feasibility and reduced data-fragmentation effort rather than as a benchmarked productivity gain.

Figure 2 Point cloud of residential building façade

Figure 3 Prototype of prefabricated wood-fiber insulation panels mounted on lab test wall

Based on the survey data, façade planes were reconstructed in a human-in-the-loop step by selecting a small number of corner points directly in the 3D point cloud. In practice, this interaction step acted as a controlled "alignment and interpretation" layer: it resolved ambiguities caused by occlusions and scan noise and ensured that the resulting planes represent the reference geometry required for fabrication-oriented planning. Human input is retained where survey ambiguity or design intent materially affects manufacturability, whereas steps governed by explicit geometric rules and machine-checkable constraints are automated and subsequently interactively reviewed.

Figure 4 exemplifies the resulting panel layout for a reconstructed façade plane. In this validation, user-defined break edges (e.g., storey lines, façade boundaries, opening extents) proved effective to enforce architecturally meaningful alignments while keeping the layout manufacturable. The panelisation outcome demonstrates that minimum-dimension constraints can be respected without producing impractically small boundary pieces; where the grid would otherwise create undersized edge panels, the layout adapts by distributing the residual dimension within the affected grid field. As output, the workflow produces an IFC-compliant façade panel model (IfcPlate entities with dimensional property sets) and a fabrication/installation part list containing panel dimensions and mounting positions.

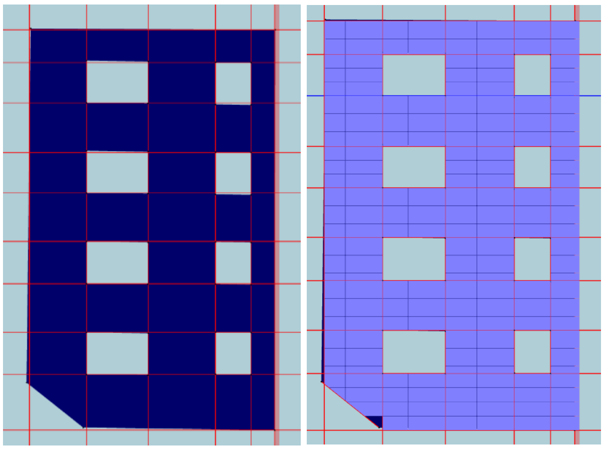

Figure 4 Façade plane (left) and generated panels (right) with grid pattern composed out of break edges (red)

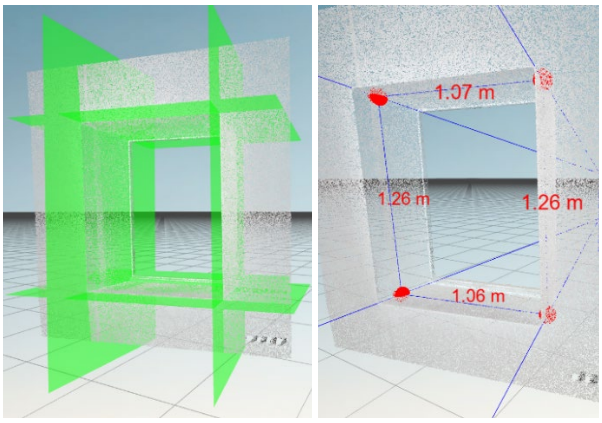

Figure 5 Detected window reveal planes (left) and dimensioning of window opening (right)

For optional window replacement, dedicated window scans were processed to detect planar patches corresponding to the wall plane and window reveals (Figure 5, left). The fitted planes enable robust opening dimensioning. In the shown example, the extracted opening measures approximately 1.26 m in height and 1.06–1.07 m in width (Figure 5, right). These dimensions can be re-used to parametrically define window objects and to validate panel cut-outs and tolerances at the interface between façade modules and window frames.

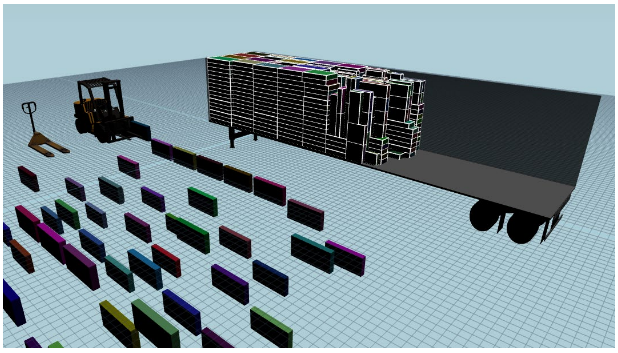

Figure 6 Logistics tool for container shipping with IFC and Speckle APIs

The generated panel objects were subsequently transferred to the logistics planning tool without file-based re-entry. By resolving the latest façade-panels version from Speckle and reading panel dimensions from their attached properties, the backend automatically emitted a package list that was consumed by the Three.js-based packing interface. Figure 6 shows the interactive container-loading environment, where a 3D bin-packing heuristic proposes an initial packing based on priority, rotations and stacking constraints. Planners can apply drag-and-drop corrections when operational considerations require it, i.e., the packing logic functions as decision support rather than a fully automatic optimiser. Overall, this end-to-end handover demonstrates that a versioned, interoperable data backbone can connect survey-derived planning artefacts to downstream logistics decisions in a consistent way.

Encountered limitations

- Operator input remains a dependency for "planning-grade" geometry. While the human-in-the-loop plane reconstruction improved robustness on real scan data, it introduces operator effort and potential variability (e.g., depending on how corner points are selected under occlusion/noise).
- Break-edge definition is a knowledge bottleneck. The quality of panel alignments and module boundaries strongly depends on correctly specified break edges. This provides necessary design control, but it also limits full automation and requires consistent modelling conventions.
- Standardisation vs. manufacturability trade-off. Avoiding undersized boundary panels through layout adaptation improves feasibility, but it can increase the number of non-standard panel dimensions near boundaries/openings and thus may reduce production economies unless size-variant limits are introduced. This effect is expected to become more pronounced for more geometrically complex façades with a higher density of break edges and local exceptions.
- Window dimensioning requires dedicated scan coverage. Reliable opening extraction benefits from denser, targeted scans. Where such data is unavailable or incomplete, window replacement support may be partial and cut-out validation less robust.

- Packing is not fully automatable in operational contexts. Even with a heuristic initial packing, manual adjustments were necessary to reflect practical constraints (handling preferences, sequencing, transport considerations), implying that packing quality should be assessed by "solution usefulness + edit effort" rather than by optimality alone.
- Limited external validity and limited quantitative evaluation. The validation was conducted on a single representative case; additional façade typologies (e.g., highly articulated/non-planar façades, heavier occlusion) and systematic metrics (time-on-task, number of panel variants, amount of manual correction, downstream IFC usability checks) are needed to quantify scalability and robustness.

Conclusions & Outlook

This paper presented an integrated, web-based planning workflow for prefabricated façade renovation that connects survey ingestion, façade and window geometry extraction, automated panel planning, and logistics preparation through a shared, versioned data backbone. In contrast to tool-isolated solutions, the contribution is workflow-oriented: a central object graph provides a consistent "source of truth" across planning stages, while IFC-compliant semantics expose façade modules in a form that is directly consumable by downstream BIM and production environments.

Validation on a residential façade scan demonstrated that a semi-automated, human-in-the-loop reconstruction of façade planes provides the accuracy required for fabrication-oriented module planning, motivated by the observed insufficiency of fully automatic scan-to-BIM outputs for detailed panel planning. On top of this reference geometry, grid-driven panelisation yields IFC-compliant panel objects and installation metadata suitable for fabrication documentation and on-site mounting preparation. Optional window opening dimensioning further supports coordinated window replacement when dedicated, denser window scans are available. Finally, the same panel objects can be transformed into logistics packages and transferred to an interactive container-loading environment without file-based re-entry, demonstrating continuous data flow from survey-derived planning artefacts to downstream logistics decisions.

The validation also highlights practical limitations that shape industrial applicability. First, "planning-grade" envelope geometry currently depends on operator input for plane definition, reflecting a deliberate accuracy–automation trade-off. Second, panel layout quality depends on consistently defined break edges (storey lines, façade boundaries, opening extents), which provide necessary design control but remain a manual knowledge bottleneck. Third, robust window dimensioning depends on scan coverage quality and the availability of dedicated window scans. Fourth, logistics packing relies on a heuristic with an explicit manual correction mode for operational constraints not captured algorithmically. Finally, results are currently based on a single representative case study, motivating broader evaluation across building typologies.

Future work will therefore focus on closing remaining process gaps, strengthening downstream integration, and quantifying robustness and productivity gains under realistic constraints, in particular:

- Socio-technical workflow integration and praxis adoption, including stakeholder roles, validation responsibilities, trust in semi-automated outputs, and acceptance in multi-actor renovation practice.
- Coupling to LCA/LCC assessment to provide early-stage environmental and cost feedback for alternative panel configurations.
- Integration of construction-site simulation and 4D time planning to link panel layouts and logistics decisions to installation sequences, crane operations, and site constraints.
- A production link to prefabrication/CAM systems (e.g., CNC cutting, drilling templates, labelling) to translate panel and mounting-point metadata into shop-floor instructions.
- Refinement of joint/gap modelling and tolerance handling, including explicit as-built deviation compensation strategies, to improve robustness for industrial roll-out.
- Further automation of façade feature extraction (openings, storey lines) and systematic evaluation on additional building typologies, including metrics such as time-on-task, number of panel variants, required manual corrections, and downstream interoperability performance, to quantify time savings and error reduction.

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