Machine-Learning and Rules-Based Algorithmic Workflows Enable Energy Affordability in Panelized Construction

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ABSTRACT

Eighty percent of the buildings that will exist in the United States in 2050 already exist (Grainger 2022), but these aging buildings present challenges for building owners, occupants, and the grid: they are often under-insulated, drafty, uncomfortable, expensive to operate, and complicated and costly to retrofit. By supplementing industrialized construction methods with machine learning techniques and automated layout tools, energy retrofits that would otherwise be impractical can be achieved by drastically reducing the design and engineering effort. The Simple Panel System developed and demonstrated in this project automates the creation of detailed fabrication and installation drawings based on point-cloud scans of the building, addressing labor shortages and reducing the lead time for comprehensive retrofits. The scalable workflow integrates with existing industry tools and can be tailored to the needs of any panel manufacturer. While previous publications have introduced the conceptual workflow and pilot sites, this paper focuses on the successes and remaining challenges identified after completing the second pilot project, a multifamily building in Denver, CO. Key findings include a 76% reduction in design labor, substantial reductions in site-measurement effort through reality capture, and identification of workflow limitations related to panel-layout logic and shop-drawing generation. Additionally, as expected for such intervention, the pilot project's envelope upgrade alone is projected to achieve $10,700 ($0.10/sf) in annual energy bill savings and contribute a 2.54 kBtu/sf/year reduction in site energy use intensity toward the overall target reduction of 11.5 kBtu/sf/year required to comply with Energize Denver's energy conservation targets. Critically, the envelope retrofit also reduces interior condensation potential, risk of structural deterioration, and mold risk—particularly on ceilings, exterior walls, and structural columns.

Introduction

More than 20 million multifamily and attached housing units, along with 50 million single-family detached housing units, in the United States built before 1980 could benefit from deep energy retrofits, according to our building stock analysis (Kaufman et al. 2025). In total, 91.6% of the U.S. housing stock meets the target unit profile for a panelized wall retrofit. Our previously published analysis found a nationwide annual average energy savings potential of 20 MMBtu and $350 in energy bills per housing unit (Kaufman et al. 2025). Single-family homes offer the greatest potential for cost savings, averaging $439 annually. Dwelling units in IECC climate zones 4 and above average modeled annual savings of 26 MMBtu in energy and $414 in energy bills. Other documented benefits of enclosure retrofits include improved indoor air quality, comfort, sound reduction, and increased resilience against severe weather events and grid outages. However, building envelope retrofits are less common than their potential benefits suggest.

Recent retrofit initiatives have explored industrialized construction methods to reduce the cost and complexity of deep energy retrofits. Programs such as Energiesprong (see reference) in Europe and RetrofitNY (see reference) in the United States have examined the use of prefabricated envelope systems to increase construction efficiency and minimize disruption to building occupants. These efforts highlight growing interest in approaches that combine standardized products with streamlined design and manufacturing workflows to improve scalability.

Barriers to building envelope retrofits include a limited supply of skilled labor, a wide range of building typologies, planning complexity, remediation needs that take precedence over energy priorities, split incentives, and a long or nonexistent payback period. Recent research shows that automated processing of point-cloud data can significantly reduce manual feature identification and geometric extraction tasks, which have traditionally limited the scalability of panelized retrofits. Machine learning approaches have demonstrated the ability to automatically classify façades, windows, and openings while maintaining dimensional accuracy suitable for retrofit workflows (Maldonado Puente et al. 2022, Maldonado Puente et al 2023). Recent studies in façade-level point cloud classification show that combining geometric features with deep learning methods improves segmentation performance and reduces manual intervention in building model generation workflows (Tan et al 2024; Wysocki et al. 2023). The most expensive elements in envelope retrofit projects are typically soft costs, such as architectural and structural design (Chan, Less, and Walker 2021).

The Simple Panel System

The “Simple Panel System” (SPS) workflow (Figure 1), developed under the Advanced Building Construction Initiative funded by the U.S. Department of Energy’s Building Technologies Office, streamlines deep energy retrofits by applying advanced site capture, machine learning (ML), and panel layout-optimization algorithms to panelized construction.

Once the point-cloud scan is registered, the ML algorithm identifies and classifies (or “segments and classifies”) building elements, including walls, doors, windows, roofs, columns, wires, vegetation, and other attached components. The panel configurator tool then automatically optimizes the envelope panel product layout based on the user’s selected parameters for panel dimensions, spacing, fastener requirements, and interface preferences.

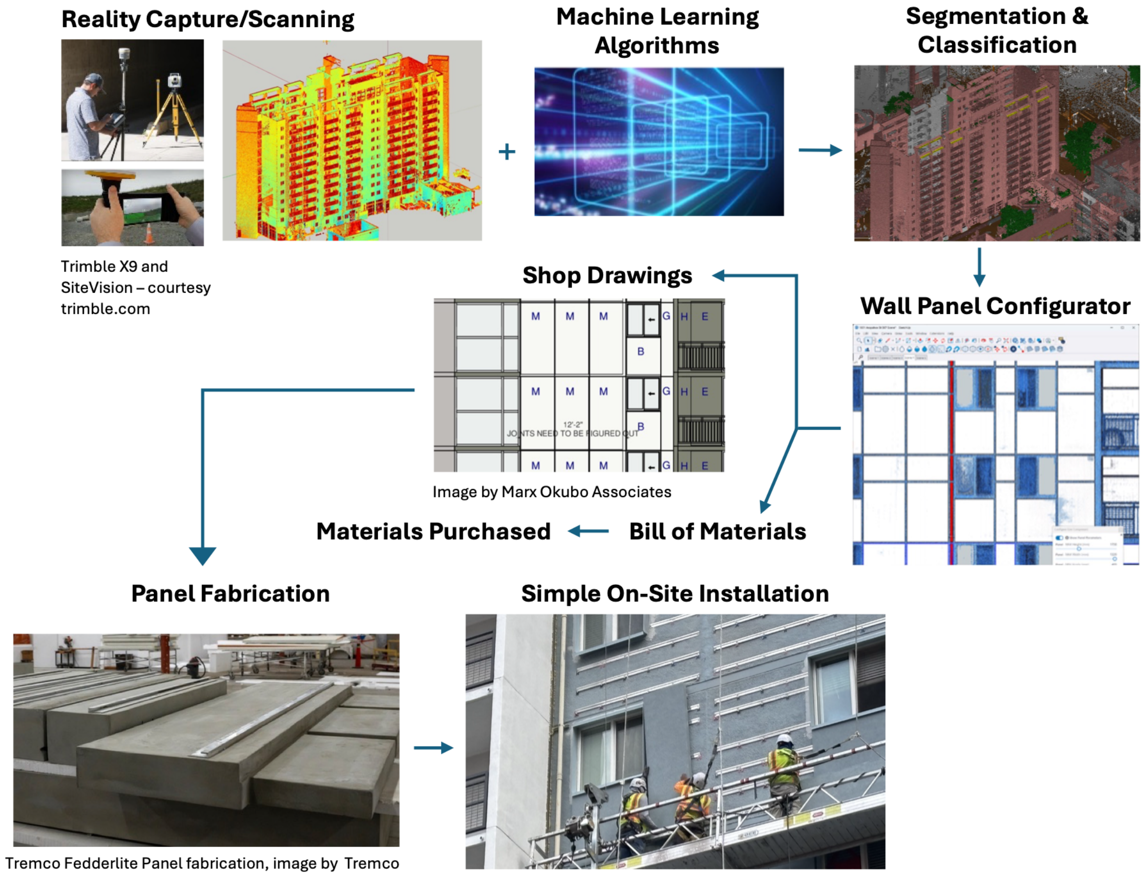

Figure 1. The SPS incorporates reality capture, machine learning, and panel configurator algorithms to take retrofit projects from scanning to shop drawings and factory fabrication to on-site installation in an integrated, streamlined workflow.

Others, such as CanmetENERGY's Prefabricated Exterior Energy Retrofit (PEER) project funded by Natural Resources Canada, have used similar concepts, developing systems that translate building scans into the manufacture of prefabricated exterior panels (Natural Resources Canada 2024). The SPS builds on this concept and further automates the process by adding ML with a panel configurator, or "panelizer." Emerging workflows now connect automated façade segmentation directly to optimized panel layouts, demonstrating the feasibility of reducing human intervention across multiple retrofit design stages (Philips et al 2025). While the SPS aims to drastically reduce the engineering and labor required for envelope retrofits, it maintains a "human in the loop" to verify that the automatically configured shop drawings and layouts are accurate and appropriate, and to make adjustments when needed or desired. This verification ensures that common mistakes made by artificial intelligence are avoided. As demonstrated by the PEER project, and as reported by Less et al. in a detailed cost study, soft costs often account for about 50% of U.S. energy retrofit project costs (Less et al. 2021). Most of these soft costs are architectural services. Reducing soft costs through the SPS workflow promises accessibility for energy retrofit projects as never seen before, and the demonstration projects undertaken for this endeavor begin to prove the potential.

Demonstration Project and Research Questions

The first demonstration project was a single-story proof-of-concept in Murray, Utah, which used point-cloud scanning technology to reduce measurement time and labor. Although post-retrofit data collection for that project is ongoing, it has already provided valuable insights into the benefits and challenges of panelized retrofits using reality capture, as discussed in Kaufman et al. (2025). The next project, a midrise multifamily building in Denver, Colorado, serves as an initial case study for process and labor data using an established panelized product, Dryvit's Fedderlite M panel. Panelization algorithms were developed during the retrofit, and the extended workflow was applied to the point-cloud scan retrospectively to compare the time and labor required for the retrofit using the existing panelized methodology with that required using the SPS workflow. Specifically, this demonstration sought to answer the following questions:

- How do elements of the SPS workflow enhance or change the process, timeline, and cost for a panelized façade retrofit to a midrise multifamily building?
- What lessons can be learned from this project to improve the SPS workflow?
- What additional features could augment the workflow to better support building enclosure retrofits?

The Denver demonstration project is subject to the Energize Denver ordinance, which requires energy efficiency measures to be implemented on qualifying buildings to reduce benchmarked energy consumption to the building-specific target energy use intensity (EUI) by 2032, with incremental thresholds applied before 2032. Built in the 1970s, the apartment building is nearly 120,000 square feet and fully occupied. Its structure is primarily concrete with insulated (R-13) metal framing and exposed concrete floor slabs (diagrammed in Figure 2). Structurally separated stacked balconies accompany each apartment unit, with vertical fins that provide privacy and are slightly offset from the building (see Figure 3). Figure 2 presents a thermal analysis of the wall assembly pre- and post-retrofit, with red isotherm lines representing the dew point temperature at 35% and 50% interior relative humidity at the extreme exterior heating design temperature.

The fins posed a challenge to the panelized wall retrofit strategy; the prefabricated panels were ultimately designed to stop before reaching the fins, where thinner prefabricated panels were fitted behind the fin walls.

The building's benchmarked, weather-normalized pre-retrofit EUI in 2019 was 55.7 kBtu/sf/year, and the Energize Denver 2032 target is 44.2 kBtu/sf/year, representing a 20% reduction goal. To achieve this, the project team proposed the measures listed in Table 1. These measures were modeled individually, rather than sequentially, to assess their separate impact, so their effects are not additive. The Marx Okubo team used Carrier HAP v5.11 to model the building, calibrating the as-built pre-retrofit model to the benchmarked energy consumption reported by Xcel Energy through ENERGY STAR® Portfolio Manager. Energy cost savings are projected using current utility rates and account for both owner and occupant energy costs.

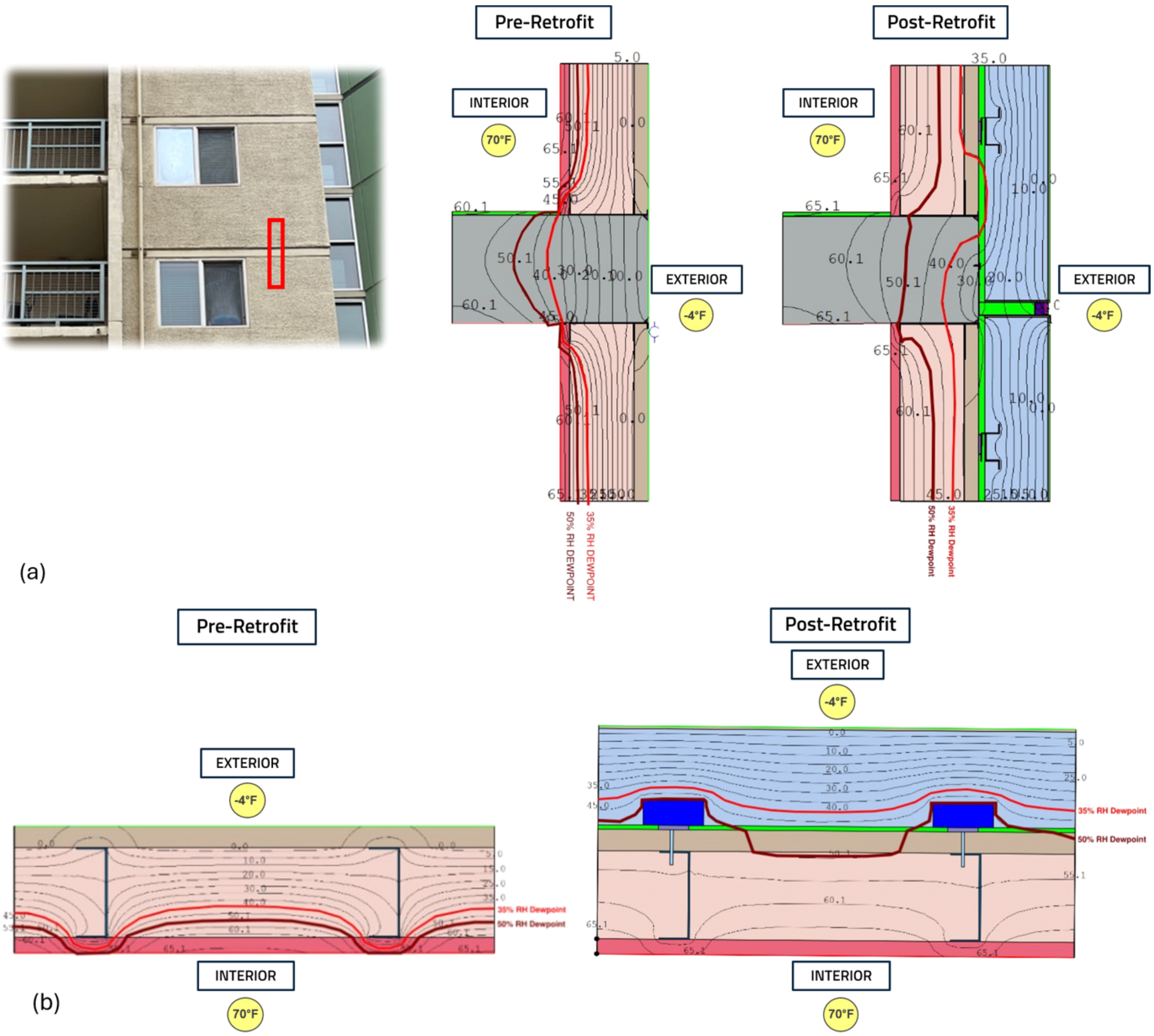

Figure 2. Pre- and post-retrofit wall assemblies and 2-dimensional heat transfer modeling. (a) Section through wall and floor assembly. (b) Plan view of wall assembly. *Source:* Marx Okubo Associates.

Figure 3. Representative details where exterior fins and balcony slab meet over a mechanical vent. *Source:* Marx Okubo Associates.

Table 1. Denver demonstration project proposed retrofit measures and modeled impacts

Measure	Modeled EUI reduction (kBtu/sf/year)	Modeled Annual energy cost savings
Panelized envelope retrofit (3.85 inches expanded polystyrene foam panels – R-15.4)	2.54	$10,678
Variable frequency drives (VFDs) implemented on chilled water pumps	5.63	$28,064
Retro-commissioning of the building automation system (BAS)	3.52	$4,366
Total	11.69	$43,108

The VFDs are expected to have a significantly greater financially impact per unit reduction in EUI than BAS retro-commissioning because of the high relative cost of electricity compared to other fuels. The VFDs, proposed for installation on chiller pumps, affect only electricity consumption, whereas the BAS control systems affect electricity, gas, and steam. Although the envelope measure alone achieves only a modeled 2.54 kBtu/sf/year reduction, it was still considered important for improving thermal comfort, energy affordability, and durability by reducing the risk of interior condensation, rusting of metal framing, and biological growth on interior surfaces. Windows had already been recently replaced, so wall insulation was the primary envelope focus. The model assumed no changes in airtightness from implementing the wall panels.

Because modifications to building envelope thermal properties affect the building's thermal loads and, therefore, the mechanical system requirements, the envelope retrofit was selected as the first measure. The team needed to complete the panelized retrofit within a limited amount of time—prior to the winter of 2025-2026 to achieve the required results within the given schedule and to avoid conditions too cold for the necessary construction activities. Additionally, the project required tenants to remain in place during the retrofit to minimize disturbances and avoid added project costs. Therefore, the panelized approach was considered essential. The project also faced structural limitations imposed by building code, which allowed a maximum increase of 5% in the existing building weight before additional foundational structural analysis and support would be required. Using a lightweight insulated façade panel, such as the Fedderlite panel, provided the project team with a straightforward solution that avoided excessive analysis and augmentation, although a wind load analysis of the lightweight system was still necessary.

Measurements

A schematic wall panel design was initially created using rough building dimensions from existing floor plans, as more precise measurements were not available until many months later. At that point, the design was revised to match the accurate data. The façade measurements were compiled using a combination of LiDAR scanning and manual measurements in areas where the ground-based LiDAR scanner lacked a direct line of sight, such as behind vertical fins and balconies.

Only part of the SPS workflow was used in this pilot project, but the effects of each step are estimated based on the collected data. Scanning technology was implemented, whereas the ML algorithms and the panelizer tool were still under development; their impact is projected retroactively by going through the exercises of taking point-cloud scans of the building through to full panel layouts using the automated tools, then comparing this labor effort with that documented for the actual project.

This paper reports measured labor hours associated with site measurements and projected labor reductions from the SPS workflow, including the labor reduction achieved with scanning technology, the labor savings from using ML algorithms for façade segmentation and classification, the labor impact of the panelizer tool, and the additional projected impact of the SPS automated scan-to-shop-drawing workflow.

Results

Creating a wall panel layout involves two main steps: 1) Measuring the existing building geometry, and 2) Creating the panel layout. Step 1 can be influenced by reality capture, or, in this case, LiDAR scanning. Step 2 is influenced by the availability of the panelizer tool and the ML model.

Impact of Reality Capture

Different building typologies and contexts require varying levels of effort for manual measurement or digital scanning. For this analysis, we report on data gathered from the pilot demonstration discussed. Takeaways from this analysis can be extrapolated to other projects but should not be considered exact, as each project will have different variables and challenges. In particular, this project is 12 stories tall and located in an urban area, but stationary LiDAR scans were able to capture most building measurements from the ground. The most difficult features to capture included areas obstructed by balcony railings and vertical fins.

Before LiDAR scan measurements were available, manual measurements were taken to develop an initial panel layout. This provides a baseline data point for the labor required for manual measurement, which totaled 760 hours for approximately 70,000 square feet of façade area. The scanning process took 32 hours, and manual measurements required to supplement scan dimensions due to obstructions were estimated at about 217 hours. Comparing scan-process versus manual-process measurement hours, the time reduction associated with using scanning technology for this project was 543 hours, or 71%. This reduction is important because measurement and documentation labor can be a major barrier to scaling façade retrofit projects.

In the future, drone-based and/or hand-held site capture could be implemented to further reduce labor hours required for measuring building dimensions; however, it is not as simple as mounting a LiDAR scanner on a drone. The drone must be extremely stable, and the payload must be light enough to facilitate this activity. The National Laboratory of the Rockies' initial investigations into using drones for site capture revealed that drone photogrammetry (generally lighter than LiDAR equipment) had the potential to provide sub-centimeter accuracy and could capture areas obscured by building components and other obstructions when using only ground-based scanning (Randby and Goldwasser 2025). However, photogrammetry is limited in specific lighting conditions or when there is no visible texture or detail on the building. Further investigation would be helpful to determine if drone-based scanning could assist in reducing site-capture labor expenditure in situations where balconies and other 3D building elements are present, where a roof must be dimensioned, or where a building is too tall or inaccessible to be captured with a line of sight from the ground.

Impact of Panel Configurator Tool

Traditionally, creating panel geometry involves two steps: 1) Feature identification—i.e., identifying which building areas should be covered by panels, which areas are windows, doors, balconies, penetrations, etc., and 2) Panel layout.

The SPS workflow streamlines this process into four distinct but less time-consuming steps. First, the ML workflow identifies and classifies façade elements from the point cloud. Second, the software generates building geometry from the classified surfaces. Third, the panelizer applies configurable layout rules to generate panel dimensions and spacing. Finally, designers manually review and adjust layouts as needed to accommodate atypical conditions or aesthetic preferences: 1) ML segmentation and classification (feature identification), 2) Building geometry generation, 3) Panel layout (Figure 4), and 4) Manual layout adjustments.

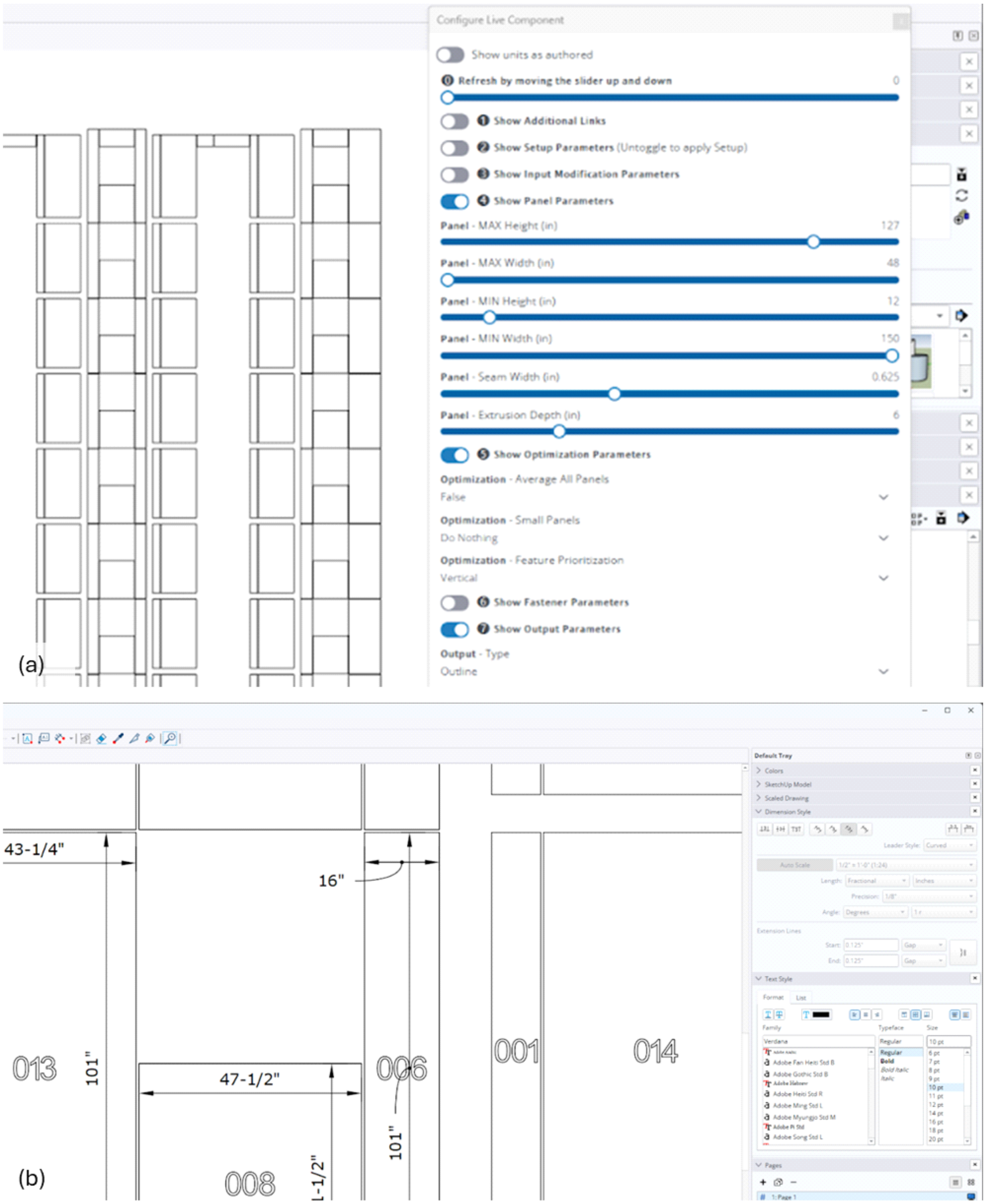

Figure 4. (a) Panelizer tool being applied to the pilot project's building façade. (b) Dimensioned and labeled drawings ready for export. *Source*: Trimble.

We use the pilot project as a case study to compare the time required to complete the manual workflow and the SPS workflow. We use labor hours reported by the designers for the traditional workflow and by the authors who developed an equivalent layout using the SPS workflow for this comparison. The panelizer tool involves geometry created in SketchUp, where the panelization tool functions as a Live Component. The 3D panel model is then imported into Trimble Connect for quality assurance with the 3D building geometry. Parameters were set in the panelizer for the Tremco panel product used. The panelizer was able to replicate most, but not all, panel dimensions compared to the designers' final layout. We noted several differences between the panelizer-generated layout and the actual design, particularly in areas where the layout does not follow a strict logic:

- The panelizer can currently optimize for either maximum panel size or equal panel size within a discrete geometric area. Some areas of the actual design did not follow either of these objectives (Figure 5).
- The panelizer lays out panels from right to left, whereas the designers optimized for symmetry within certain building segments (Figure 6). This can be manually adjusted after the panelizer is run.
- On the top floor, a very short but wide panel runs above windows in the as-built design (Figure 7). This breaks the rules for maximum panel width compatible with fabrication and transportation constraints; however, because it is so short, it can be considered a rotated vertical panel that observes the rules if rotated 90 degrees. This can be easily rectified manually after using the panelizer.

Figure 5. (a) Manual panels K1-M2-K1 follow a medium-large-medium pattern. (b) The Panelizer panels 001-025-025 follow a right-to-left full-full-reduced pattern. *Source*: Trimble.

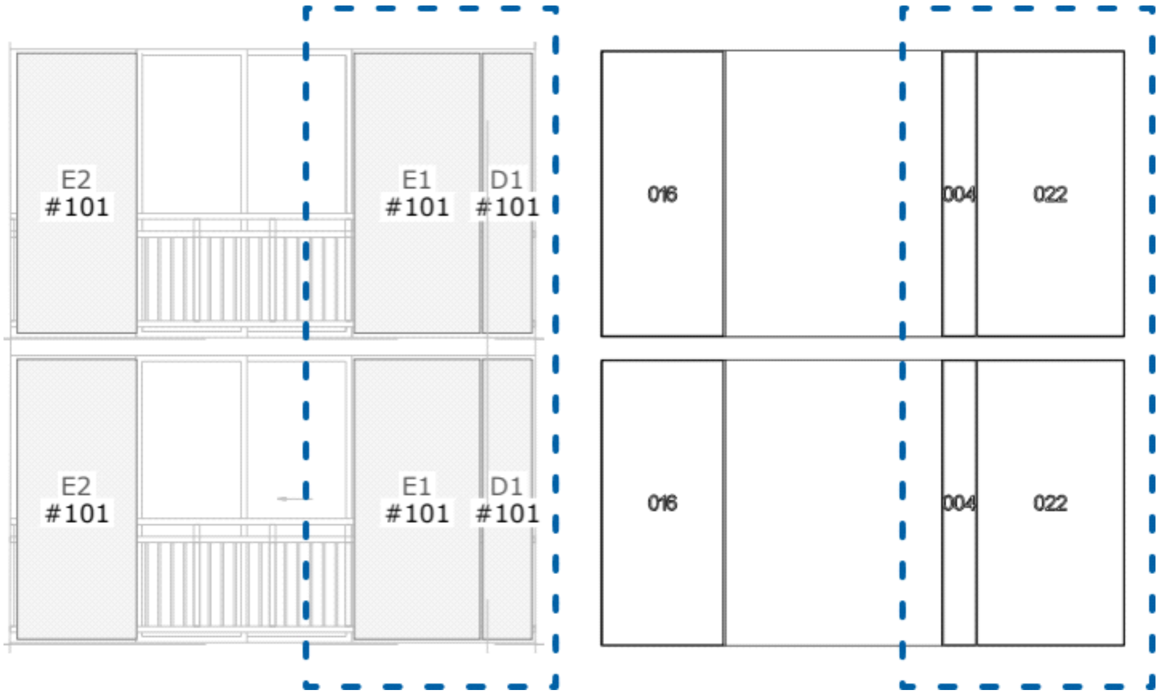

Figure 6. (a) Manual panels E1 - D1 follow a left-to-right largest-to-smallest layout for certain areas of the facade. (b) The Panelizer panels 004-022 follow a right-to-left largest-to-smallest layout throughout the whole building. *Source*: Trimble.

Figure 7. (a) Manual panel XX is a horizontally rotated panel. (b) The Panelizer panels 000-003 strictly adhere to the maximum width parameters and take the form of multiple panels. *Source*: Trimble.

The output of the panelizer is parametric, allowing users to make further adjustments while automatically propagating changes across repeated panel instances. This improves consistency and reduces opportunities for drafting errors. All identical instances are updated automatically, significantly reducing the time required for any design change or update.

The panel configurator, as currently built, cannot accommodate different labeling systems. As a result, translating the panel layout into shop drawings is not yet automatic and may require some additional work. However, we anticipate that it will be possible to easily produce the file types required for most shop drawings using the tools in this workflow, further reducing the cycle time for the full scan-to-panel-assembly workflow. The output from the panelizer will be ready for manufacturing, without any need for translation or re-drawing in another system.

Table 2 compares the labor hours required for the traditional and SPS workflows. The SPS workflow is divided into two options: one using the ML algorithms “SPS with ML” and one without “SPS without ML”. SPS with ML is the estimated automated model setup time to use the panelizer; it includes an estimated 30 minutes to review and make adjustments. SPS without ML is the actual measured time of 2 hours to manually setup the model to use the panelizer. It is worth noting that the 2 hours for manual setup was an expert SketchUp user (specifically, the SketchUp developer who created this capability) who had already completed the process multiple times. The manual work would likely have taken a typical experienced user 4-8 hours. To compare the total time required for all design stages, we also include the labor hours for the measurement step, as reported in the previous section.

Table 2. Labor hour comparison between traditional panel-layout workflow and SPS workflow on the Denver pilot project

Design stage	Individual step	Manual	SPS without ML	SPS with ML
Building measurements	Manual measurements	760	217	217
	Scanning	-	32	32
Panel layout creation	Building geometry creation	-	2	0.5
	Panel layout	365	0.3	0.3
	Manual adjustments	-	16	16
Total design hours		1,125	267.5	266
Percent faster than manual baseline		-	76%	76%

The panel configurator tool has the greatest impact on the time required for the design stage. We observe a 95% reduction in the time needed for panel creation when using the panelizer tool compared to drawing each panel by hand. We drew a portion of the building by hand to estimate how long the entire building would take without the panelizer. While the ML model provides a more modest reduction in design labor hours for this project (4x), its key benefit is that the time savings is scalable. For a project with multiple buildings and significantly greater exterior wall surface area, the automated geometry creation step would still take only a few minutes, saving designers many hours, days, or even months that would otherwise be spent identifying building features and creating geometry manually. Other panel products and projects may require different rules for panel spacing, depending on whether a panel abuts another panel, a window, a door, a balcony, or another object. This would make automated feature identification, classification, and geometry creation even more valuable in terms of both time and accuracy.

The manual geometry creation step also involves determining which areas are close enough in measurement to be identified as having the same dimensions, and therefore repeatable panel layouts. The ML geometry creation workflow treats each measurement as completely unique, even if two measurements differ by as little as 0.001 inches. To avoid falsely identifying areas as uniquely dimensioned, instead of requiring the human-in-the-loop to adjust the areas to be identical, the panelizer tool can accommodate small measurement differences within a configurable tolerance. For example, if the joints between panels can range from 0.25 inches to 0.75 inches, a geometric area with three vertical joints (e.g., two panels plus their outside edges abutting fenestration) could have a total tolerance of 1.5 inches. This would reduce manual steps and the time spent spot-checking the ML model.

Additional SPS Workflow Impacts

This paper primarily quantified the benefits of using site capture, ML models, and the panelizer tool for building envelope renovations; however, the SPS workflow provides additional advantages. Employing scanning technology and the tools developed in this project can reduce the time needed to develop an accurate panel layout and lower the barriers to creating schematic design drawings for bidding or permitting.

The SPS workflow also enables easier conversion of detailed designs into shop drawings for designers, manufacturers, and installers. The suite of software used in this project is flexible and can output dimensions and information in various formats. The project team plans to investigate streamlining shop drawing creation directly from the panelization step in future efforts to meet panel manufacturers' requirements, further reducing the engineering labor needed to translate designs into manufacturing specifications. The design team expects the need for a human-in-the-loop to verify accurate translation of designs, but this allows employees to focus on more projects and handle greater volume.

Completing detailed design tasks quickly and cost-effectively can determine whether a project can be executed within the required timeframe. For example, the pilot project faced a tight schedule to complete design and engineering tasks, order and manufacture panels, and finish the retrofit before the winter of 2025-2026. Implementing scanning technology was helpful, but the availability of panelization tools would have streamlined the project even further. The design team also noted that having scan measurements available earlier would have significantly reduced time spent on manual measurements and minimized the need to update schematic designs to match existing dimensions.

Previous projections estimated a 66% reduction in soft costs for projects using the SPS workflow (Kaufman et al. 2025; Kaufman 2024). Observing a projected 76% savings potential for façade design labor in this pilot demonstration using the SPS methodology, a 66% overall soft-cost savings remains consistent with current findings. Applying the labor cost breakdown from CanmetENERGY's pilot project with architectural design and shop drawings accounting for 29% of project costs (Natural Resources Canada 2024), and applying a 95% savings for panel layout creation, we project a 27% total project cost savings (56% soft cost savings) by applying the panelizer workflow. Point-cloud scanning further improves project savings by reducing on-site measurement labor; however, additional data is needed to compare manual measurement wages and point-cloud-scanning wages to determine associated cost savings.

Pilot Project Lessons Learned

The team encountered several challenges related to retrofit costs, transportation logistics, and construction sequencing that indicated opportunities for improvement. Cost overruns occurred primarily in the materials category, resulting in a higher than typical proportion of material costs in the total project cost. The project team initially expected the panel factory for this Denver project to be located in Texas; however, the only available factory at the time was on the East Coast, resulting in significantly higher shipping costs. Late-stage panel sequencing decisions also changed the order in which panels were fabricated and required shipping of less-than-full truckloads due to the immediate need for certain panels. Additionally, the number of panels that could fit on a single truck was overestimated, further increasing the need for transportation and reducing its efficiency. Other unanticipated costs included remediation of sections of concrete throughout the building.

To date, only the envelope retrofit has been implemented on the Denver pilot. The project team hopes that the updated envelope, combined with the VFD and BAS measures noted in Table 1, will achieve the target energy reduction mandated by Energize Denver, and the team will track EUI impacts in the coming months and years. We are able to track some impacts more immediately. Notably, the envelope retrofit reduces interior condensation potential, rust, and mold risk—particularly on ceilings, exterior walls, and structural columns because the envelope retrofit mitigated thermal bridging. It also improves sound attenuation, as reported anecdotally by the project team and residents.

Conclusions

The interdisciplinary project team has made significant progress in developing the tools needed to realize the vision of the SPS workflow, using advanced site capture, ML, and a rules-based automated panel geometry creator to reduce soft costs of building envelope upgrades by an estimated 56-66%. Since soft costs account for about 50% of typical project costs, this translates to an overall 27-33% average project cost reduction when the discussed tools are fully implemented. The multifamily pilot project discussed here provided a unique opportunity to compare a more typical panelized retrofit workflow with the augmented proposed workflow, and its findings will inform the continued development of the tools and workflow.

Although the proposed SPS workflow automates much of the design and engineering process and enables designers and engineers to complete projects more quickly and take on more work, it still requires specialized professionals to serve as "humans-in-the-loop" to address safety, aesthetics, detailing, structural requirements, thermal bridging, atypical conditions, and to check and adjust the work of the automated tools. The goal is to make it as easy as possible for these design professionals to use these tools and make the required adjustments. Some of these outstanding challenges may be addressed by incorporating structural parameter inputs into the panelizer tool and using the ML model to identify special cases (e.g., complicated details or thermal bridges). Ultimately, the SPS process could be applied not only to multifamily retrofits but also to commercial and institutional buildings. The project team plans to use the latest development of the SPS tools and workflow on a panelized retrofit of a school and will track and report lessons learned from that project as well.

Further reductions in labor time and costs may be realized in the future by implementing drone-based scanning techniques instead of relying on time-intensive manual measurements where ground-based scanning cannot reach. Reductions in transportation and material costs may be achieved by co-locating panel fabrication facilities with project sites. Additionally, productizing the panels by using common repeatable sizes that are factory- and transportation-friendly can lower costs and decrease project delivery time.

Future work includes further developing SPS tools, collaborating with additional panel manufacturers to incorporate helpful parameters, tracking pilot projects, and workforce development activities, such as in-person and recorded trainings for trades organizations, designers, engineers, manufacturers, and colleges and universities. The research team also plans to further develop and integrate the ML model to accurately identify large amounts of scanned geometry in less time, with more granular classification. As these tools move from beta stages to implementation, this powerful workflow is likely to have an increasing impact on the ability to offer panelized façade retrofits.

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