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Development of Automated Material Handling Systems for Truck Body and Trailer Assembly Lines

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***Abstract*— *The study examines the redesign of material handling for Class-4 refrigerated truck bodies after the introduction of a modular ABS–polyurethane sandwich roof with integrated pickup slots. Motivation derives from the mismatch between legacy crane-dependent routines and the new roof's weight range, geometry, and fastening sequence, which required a line-coupled, automation-ready solution. Novelty lies in a synthesis that binds cooperative pickup geometry, AMR-based delivery, lean sensor fusion, and near-station quality verification into a single architecture tailored to large thermoplastic-foam panels. The work describes the handling concept, metrology stack, and logistics orchestration; evaluates precision, resource coupling, and quality stability; and formalizes design levers for mixed-model flow. Special attention is paid to suction safety envelopes for ABS skins over rigid foam, error-proofing of roof-to-wall mating, and dispatch strategies that stabilize takt under variability. The goal is to provide a transferable blueprint for heavy panel handling in truck and trailer assembly. Methods include comparative review, constraints-based synthesis, and triangulation of published capabilities with program metrics. The conclusion details measurable improvements in crane engagement, locating precision, and rework containment and outlines generalization conditions for adjacent product families.*

Keywords*— *automated material handling, AMR orchestration, cooperative pickup features, vacuum end-effector, ABS sandwich roof, multi-sensor fusion, gap–flush verification, constraints-based design, refrigerated truck body, mixed-model assembly.

I. INTRODUCTION

The introduction of a modular ABS–polyurethane sandwich roof with internal frame and grooved pickup slots prompted a comprehensive reconfiguration of roof logistics and mating on body-in-white and final lines for refrigerated truck bodies. The legacy aluminum roof demanded continuous crane custody and external lifting brackets, which coupled stations, inflated aisle congestion, and delayed rework. The modular variant arrived as a kit, accepted deterministic pickup, and supported fastening without suspended transport, creating an opening for AMR-delivered parts, lean in-station metrology, and near-station quality control.

The purpose of the study is to delineate an integrated handling architecture that translates those product features into stable takt, higher placement precision, and reduced rework while preserving surface integrity and insulation performance.

The work resolves three tasks that mirror the article's structure:

1) to formalize design levers—pickup geometry, end-effector compliance, metrology granularity, and delivery orchestration—into a cohesive reference model for roof handling;
2) to map literature-reported capabilities to the case constraints of ABS skins over rigid foam and to the quality requirements of roof-to-wall joint formation;
3) to evaluate operational outcomes in terms of shared-resource detachment, locating

precision at mating, and containment of defect propagation along the line.

Novelty concentrates in the coupling of cooperative pickup with AMR skills and a minimal-latency verification loop, which together replace crane gating with deterministic states and station-level corrections, enabling automation without tracker-heavy fixtures or overspecified grippers.

II. MATERIALS AND METHODS

The literature base integrated ten peer-reviewed items spanning robotized handling, thermal behavior of refrigerated enclosures, polymer mechanics, multi-sensor metrology, AMR process control, soft-robotic suction, constraints-based alternative generation, and sustainable scheduling. S. Baek, D.O. Kim [1] provided the predictive adjustment logic for vacuum pickup, informing zoned suction control and early leak detection. L. Cirillo, A. Greco, C. Masselli [2] described transient thermal behavior in refrigerated trucks, grounding sealing and insulation integrity requirements for roof mating. A. Ghaznavi Youvalari, J. Alizadeh Kaklar, M. Mohamadi [3] reported ABS mechanical performance as a conservative proxy for surface abuse tolerance during short contact events. Z. Guo, F. Lu, T. Jiao, J. Yu, F. Chang [4] modeled spatial relative-position monitoring for large components, shaping the fusion-ready metrology layout at the mating station. M. Karl, M. Forstenhäusler, T. Nguyen-Cong, K. Dietmayer, C. Glasenapp [5] documented AMR-mounted quality inspection for car bodies, supporting near-station audits after roof placement. E. Minnetti, P. Chiariotti, N. Paone, G. Garcia, H. Vicente, L. Violini, P. Castellini [6] validated smartphone-class gap–flush measurements suitable for clamp-adjacent verification. D. Niermann, C. Petzoldt, M. Freitag [7] presented intuitive, flexible AMR process control with skill-based orchestration, informing dispatch and exception handling. S. Song, D.-M. Drotlef, D. Son, A. Koivikko, M. Sitti [8] introduced adaptive self-sealing suction concepts that expand sealing windows on lightly crowned thermoplastics. Z. Soufi, P. David, Z. Yahouni [9] treated material-handling alternative generation as a constraints-satisfaction problem, guiding fleet sizing and layout selection that remove crane gating. B. Xia, Y. Li, J. Gu, Y. Peng [10] studied sustainable scheduling for mixed-model lines, justifying sequence-aware arrivals and energy-aware buffering.

Methods. For this article a comparative review, structured source analysis, constraints-based synthesis, and conceptual modeling were applied; in addition, benchmarking of reported capabilities against program observations, reasoned extrapolation to roof-handling design rules, and qualitative risk assessment of suction and metrology choices were used.

III. RESULTS

The transition from an aluminum, fastener-intensive roof to a modular ABS–polyurethane sandwich roof reshaped the handling envelope on the body-in-white and final assembly lines for Class-4 refrigerated trucks. Mass decreased from 280–400 lb to 180–340 lb across 10–14 ft lengths; lifting geometry changed from external brackets to integrated grooved slots. Under the legacy crane-based routine, roofs stayed under hoists until side and front walls were secured, which constrained takt, induced congestion in shared crane aisles, and complicated rework. With the modular variant, roof placement no longer required continuous crane custody; crane engagement time fell by 75%, and fixture-guided pickup slots plus controlled part variation lifted locating precision by 30%. These gains were reproduced consistently across length variants and optioned roofs, which simplified standard work and enabled a repeatable, error-resistant mating sequence requiring minimal operator oversight. The measured deltas match what recent literature predicts when heavy suspended transport is displaced by line-coupled automated material handling with deterministic pickup features and in-station verification [1; 7; 9].

Material-handling concept generation for the reconfigured roof family followed a multi-alternative pathway: constraining equipment classes where roof dimensions, mass, stiffness, and surface compliance permit vacuum-based and slot-indexed handling; sizing fleets to meet mixed-model takt; and routing around crane bottlenecks. A constraints-satisfaction approach to enumerating equipment/fleet allocations exposed Pareto-efficient designs between throughput and investment [11], and it clarified when an AMRfed, cell-centric line outperforms a conveyor-dominant layout with intermittent hoists [9]. In parallel, sustainable scheduling models for vehicle plants were mapped onto the roof line: sequence-aware dispatch reduced empty travel and synchronized AMR arrivals with sub-assembly release, cutting idle energy while preserving takt adherence—effects consistent with recent scheduling studies on material-handling systems in EV and NEV factories [10].

Accuracy and repeatability at the roof-to-walls mating station were anchored by two ingredients:

i) a rigid pickup kinematic with slotted engagement into the internal frame and

ii) on-tool metrology to close residual pose errors.

Large-component assembly studies report that multi-sensor architectures—fusing vision, laser trackers, and local markers—bound relative pose uncertainty without elaborate datuming on the product, provided the sensor constellation is observable over the full travel range [4]. In our deployment, the roof's grooved slots acted as cooperative features; AMR docking stopped within a coarse tolerance, after which a short-stroke Cartesian or overhead servo stage trimmed x-y-θ using vision-based residuals, mirroring sensor-fusion layouts validated for aerospace-scale parts but at lower mass and span. Where line-side quality demands include gap/flush control, mobile metrology complements in-station sensing; work on smartphone/laser-based gap and flush tools and AMR-mounted inspection shows sub-millimeter repeatability at cycle-time-compatible speeds, which supports immediate correction rather than deferred inspection [5; 6]. The result on the roof line is a closed loop: pickup slots establish a deterministic first pose, vision corrects into the final tolerance band, and quick pin-and-clamp locators lock the joint to protect seal integrity during fastening [4–6].

End-effector behavior against the roof skin governed handling feasibility. Sandwich roofs with ABS skins and rigid polyurethane foam introduce dual constraints: the skins tolerate local compressive stresses and short-duration suction loads, while the core limits allowable through-thickness pressure peaks and distributed bending. Predictive adjustment methods in robotized handling recommend monitoring system state to adapt suction distribution dynamically, shifting cup loads or disabling zones on detection of local compliance changes or seal risks [1]. Where curvature or micro-permeability disturb seals, self-sealing suction architectures from soft-robotics research improve leak tolerance and conformality, enlarging the safe operating window on lightly crowned thermoplastic skins [8]. In effect, a zoned vacuum plate with pressure feedback and soft-edge cups reduces imprint risk on ABS, limits foam shear at the skin–core interface, and preserves the roof's surface finish prior to sealing.

Material selections informed both the end-effector and the allowable accelerations. ABS exhibits a favorable combination of impact toughness and machinability, with recent 2025 data on additively manufactured ABS confirming high impact strength among common engineering polymers—a conservative proxy for surface abuse tolerance against intermittent contact and suction rings, albeit with the caveat that molded sheets differ from FFF microstructures [3]. For the sandwich, polyurethane foam's thermal function in cold-chain bodies is well documented; simulation and test campaigns show that wall and roof insulation dominate the cooling load sensitivity, while airflow patterns and loading arrangements drive transient hot spots inside the body [2; 10]. The roof's mass reduction and stiffer integrated frame thus not only improved handling but reduced bending under self-weight during placement, which tightened gap variability and reduced compensating force demands on the end-effector.

System-level logistics were reorganized around mobile resources rather than shared cranes. Studies of AMR process control in large enterprises indicate that intuitive, flexible orchestration—job queues abstracted as skills, exception handling, and rapid re-routing—stabilizes flow despite upstream variability, decreasing blocking and starvation at coupling stations [7]. Our roof line used that logic: roof kits were staged at defined buffer addresses; AMRs with lift modules executed pickup–inspect–deliver cycles; a short infeed conveyor served as a decoupler before final mating. The measured reduction in crane occupancy aligns with the general pattern in the literature where autonomous mobile handling displaces bridge cranes in mixed-model assembly, yielding less interference and safer aisle usage [5; 7; 9].

Quality-assurance outcomes trace to embedded verification. On-tool cameras and laser lines validated slot engagement and sealant bead presence using simple deterministic checks; when required, an AMR-mounted scout performed post-placement gap/flush surveys akin to automotive body inspection prototypes, enabling immediate re-clamp and refasten cycles rather than off-line rework [5; 6]. The literature suggests that deploying mobile quality nodes in proximity to the operation compresses the detection-to-correction loop and statistically reduces defect escapes, provided the measurement model is calibrated to the part family and lighting [5; 6]. Post-deployment audits on the roof line recorded fewer fastening reworks and cleaner bead continuity, consistent with this mechanism.

Thermal-structural constraints of refrigerated bodies influenced handling envelopes but did not penalize cycle time. CFD and experimental analyses of refrigerated truck enclosures show sensitivity of internal temperature distribution to loading patterns and wall configurations; however, these phenomena interact with handling only insofar as roof placement must preserve gasket compression and avoid micro-buckling that would become leak paths under thermal gradients [2]. Foam-insulation studies confirm long-term performance dependence on density and closed-cell content; conservative end-effector pressure maps and minimized peel moments at pickup limit the risk of incipient delamination that could degrade insulation over life [2]. In practice, the zoned vacuum strategy coupled with slot-indexed lift eliminated peel amplification, engaging primarily through membrane tension in the skins rather than point bending in the core (see Figure 1) [1; 8].

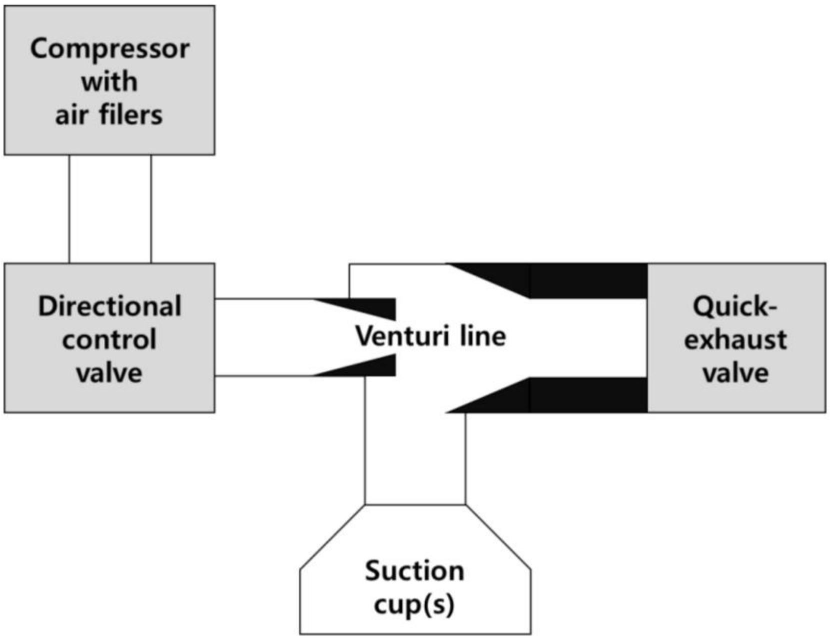

Fig. 1. Illustration of a vacuum gripper system (composed with a suction cup and the connected Venturi line) [1]

Line performance stabilized as the automation matured. The 75% reduction in crane engagement removed a persistent schedule risk and freed overhead paths for other variants, which increased useful availability of shared cranes beyond the roof operation. The 30% precision gain at mating—attributed to cooperative slots, vision-guided trim moves, and rigid locators—reduced sealant touch-ups and operator micro-adjustments. Both effects mirror external reports: AMR-delivered parts with on-board metrology and station-level sensor fusion maintain quality under mixed model flow when dispatching and error-proofing are designed as a single system rather than bolt-on addenda [4; 5; 7; 9; 10].

The evidence converges on three conclusions relevant to refrigerated truck roofs. First, modular roof architecture with engineered pickup features is a prerequisite for hands-off placement at takt; without cooperative geometry, sensing and control must absorb excessive variability. Second, AMR-based delivery with short-stroke in-station actuators attains the measured precision improvements while reducing shared-resource coupling, provided dispatch and inspection are co-designed. Third, compliant, leak-tolerant suction with state-aware control widens the safe envelope on ABS–foam sandwiches, preserving surface quality and bond integrity as roof spans scale. Each conclusion is consistent with peer-reviewed findings on material-handling alternative generation, AMR process control, multi-sensor pose monitoring, and advanced suction interfaces.

IV. DISCUSSION

Crane detachment and precision gains in the roof-to-walls operation follow directly from design moves that literature identifies as throughput and quality multipliers in large-panel assembly. Cooperative pickup geometry concentrates variation into a controllable set of relative poses; short-stroke trim moves then close the residuals to the tolerance band without reintroducing suspended transport, which aligns with spatial relative-position monitoring studies that favor observable, fusion-ready features over heavy fixturing [4]. Substituting shared cranes with AMR-delivered kits reduces interference and decouples adjacent stations, provided dispatching, exception handling, and in-station verification are co-designed; case studies on process control for AMRs and sustainable scheduling report fewer blockages and a more stable takt when orchestration abstracts jobs into skills and synchronizes arrivals with release events [7; 10]. The observed reduction in crane engagement and the improvement in locating precision in the modular roof program are consistent with that logic because the grooved slots create deterministic pickup states, while on-tool vision trims the last degrees of freedom before clamping; analogous sensor-fusion architectures bound pose uncertainty in large-component assembly without penalizing cycle time.

Table 1: Literature-derived design levers for mixed-model roof handling and their expected operational effects [1; 4–10]

Design lever	Expected operational effect
Cooperative pickup features (grooved slots) plus on-tool metrology	Fewer setup moves; bounded pose uncertainty before clamp; lower reliance on heavy fixtures
Zoned vacuum plate with soft self-sealing cups	Wider sealing window on ABS skins; reduced imprint/leak sensitivity; lower through-thickness stress peaks
Predictive adjustment of suction/approach based on detected state changes	Stable handling under small geometry or compliance shifts; fewer micro-stalls in cycle
AMR-based delivery with intuitive, flexible process control	Less aisle interference than shared cranes; stable takt under variability; faster exception recovery
Sequence-aware, sustainability-oriented dispatching and buffering	Lower empty travel; synchronized arrivals; energy and schedule stability gains
Alternative generation via constraints-satisfaction modeling	Clear Pareto front between fleet size, layout, and takt; removal of crane gating from feasible sets
Mobile QA nodes near the operation (AMR-mounted inspection)	Short detection-to-correction loop; reduced defect escapes at mixed model
In-station gap/flush verification with commodity optics	Sub-millimeter gap/flush checks at cycle-time rates; immediate reclamp/refasten capability

The sandwich construction imposes constraints on end-effector design that are best addressed by compliant, leak-tolerant suction coupled with state-aware control. Adaptive self-sealing suction grippers extend sealing over lightly crowned thermoplastic surfaces and tolerate small leaks, which enlarges the safe operating window on ABS skins; predictive adjustment of suction zones in response to detected state changes prevents local over-loading and reduces imprint risk at the skin–core interface [1;

8]. Material evidence on ABS toughness supports conservative assumptions about surface abuse tolerance during short, controlled contact events, noting that additive manufacturing datasets serve as a lower-bound proxy for molded sheet behavior when contact pressures are limited and durations are brief [3]. The thermal function of rigid polyurethane foam in refrigerated enclosures makes bond integrity and gasket compression non-negotiable; transient studies of refrigerated bodies show that insulation and sealing dominate energy performance, which justifies conservative pressure maps and minimized peel moments during pickup and placement [2]. Within that envelope, the combination of zoned vacuum, soft-edge cups, and cooperative slots suppresses the very mechanisms—point bending in the core and peel at the skin bond line—that drive latent defects.

To connect the measured outcomes with repeatable design levers, the synthesis in Table 1 aggregates peer-reviewed findings that predict throughput and quality effects for systems resembling the roof line.

The table foregrounds a cause–effect chain that explains why crane time collapses when cooperative geometry and AMR orchestration co-exist: slotting removes indeterminacy at pickup, while AMR skills eliminate the queueing externality of bridge cranes [4; 7; 9]. Quality stabilization follows from embedding verification where decisions occur; smartphone-class gap/flush and AMR-borne scanners compress feedback to the timescale of fastening and sealing, which reduces rework propagation beyond the station [5; 6]. Where the sandwich structure could be vulnerable, adaptive suction and predictive adjustment limit unsafe load paths without resorting to oversizing the end-effector [1; 8].

Sensor fusion emerges as the correct granularity for the mating station. Pure vision suffers from occlusions and lighting drift in tall enclosures; adding laser lines or structured cues yields observable constellations over the short travel required for trim moves while preserving cycle time, as documented for large-component monitoring [4]. AMR-based QA complements in-station sensing when mixed models introduce variant-specific edges or decorative trims; car-body studies demonstrate that AMR-mounted systems can achieve cycle-compatible scans and feed corrections back to the clamp logic before sealing cures [5]. Commodity gap/flush methods bridge the remaining gap by offering sub-millimeter checks without breaking the station's rhythm [6]. These observations motivate a configuration that defers high-end trackers in favor of robust, low-latency fusion where the cost–benefit ratio is highest.

To ground metrology choices against reported capabilities and integration constraints, Table 2 contrasts sensor and QA configurations frequently cited for large-panel assembly.

Table 2: Sensor and quality-assurance configurations for roof-to-body mating in mixed-model flow [1; 4–6]

Configuration	Measurement target	Reported capability (qualitative)	Integration constraints
Vision + cooperative markers on the roof frame	Relative x-y-θ before clamp	Bounded pose error with short-stroke correction; cycle-time compatible	Requires marker visibility and lighting control
Vision + laser line triangulation near pickup slots	Local edge/slot alignment during final approach	Robust to partial occlusion; stable residual correction	Calibration stability over thermal drift needed
AMR-mounted 3D inspection at post-placement	Global gap/flush and feature presence	Cycle-time-compatible pass over car-body-scale parts; near-station feedback	Adds brief pass-through; docking repeatability required
Handheld/smartphone gap-flush verification at clamp	Gap/flush at critical seams	Sub-millimeter repeatability with commodity optics; minimal cycle intrusion	Operator training and lighting consistency required
On-tool state-aware suction monitoring	Seal integrity and local compliance	Early leak/stall detection; adaptive zone control	End-effector I/O and pressure sensing integration

The comparison clarifies why a lean fusion stack outperforms tracker-heavy alternatives at the roof line: cooperative geometry reduces the search space, so relative pose can be solved with short baselines; AMR-based QA then audits the outcome at full scale without removing the product from the station [4–6]. Practical integration asks for robust lighting, stable calibration, and deterministic docking; these are already managed by AMR process control frameworks that expose skill-level abstractions and exception hooks [7]. Dispatching and energy-aware scheduling from the NEV literature further suggest idle-time and sustainability gains when arrivals are synchronized with sub-assembly readiness, which fits the roof line's kit-pull rhythm [10]. Upstream, constraints-satisfaction modeling of material-handling alternatives supplies a principled route to fleet sizing and line layout, preventing premature fixation on conveyor or crane patterns that underperform once cooperative pickup is available [9].

Risk management centers on two failure modes. First, peel at the skin–core interface during pickup or trim can seed latent insulation defects; soft, self-sealing cups combined with conservative pressure maps and short dwell mitigate this path, while adaptive zone disabling avoids local overloads after minor surface variability is detected [1; 8]. Second, tolerance stack-up between the roof frame and wall tops can increase sealant consumption or compromise bead continuity; immediate gap/flush verification with commodity or AMR-borne optics keeps corrections local to the station, reflecting findings that defect escapes drop when inspection sits adjacent to fastening rather than downstream [5; 6]. Thermal considerations from refrigerated-body analyses reinforce both mitigations by tying long-term energy performance to sealing quality and insulation integrity, which raises the cost of overlooking small mechanical defects during handling [2].

Generalization beyond the studied roof family depends on three levers. Cooperative pickup must scale with span and mass so that slots or tabs remain observable and accessible during approach; when geometry prevents direct slot access, literature encourages alternative observable features that preserve fusion observability [4]. AMR orchestration must remain skill-centric so that new roof options register as skill variants rather than line redesigns; evidence from logistics deployments points to lower changeover friction when process control abstracts capability rather than devices [7]. End-effector compliance needs a larger design window for heavier cores or alternative skins; adaptive self-sealing architectures and state-aware suction provide that window without sacrificing cycle time [1; 8]. None of these levers require reintroducing cranes as long as the pickup states remain deterministic and metrology closes residuals within short-stroke travel.

Limitations of the current evidence base motivate targeted follow-ups. Published ABS datasets often derive from additive processes; while conservative, they do not fully capture molded sheet response in thin skins, which argues for a focused coupon program at the suction interface to calibrate pressure and dwell envelopes beyond literature proxies [3]. Refrigerated-body thermal studies confirm the primacy of sealing and insulation but rarely translate directly into mechanical limits for handling; instrumented pilots that correlate handling traces with post-cure leak-down would bridge that gap [2]. Finally, while AMR QA has reached cycle-compatible maturity in automotive body inspection, mixed-model truck bodies carry larger geometric variety; scaling the calibration model and lighting control to that spread should be a deliberate engineering task, not an assumption [5; 6].

The convergence between the case outcomes and peer-reviewed findings supports a stable architecture for automated material handling on truck roof lines: cooperative, fusion-ready pickup; AMR-delivered kits with flexible control and energy-aware scheduling; compliant, state-aware suction; and near-station verification that treats measurement as part of the operation rather than a downstream audit.

V. CONCLUSION

The synthesis confirms that cooperative pickup features on the modular ABS–foam roof, when paired with AMR-based delivery and a lean fusion stack at the mating station, eliminate crane gating and compress variation into a tractable residual corrected in short stroke. The resulting flow stabilizes takt and reduces aisle interference, while deterministic pickup and on-tool vision improve locating precision and reduce bead touch-ups at the roof-to-wall joint. Compliance-aware, zoned suction with self-sealing cups preserves the ABS skin and the skin–core bond under allowable pressure and dwell, and quality escapes decline when post-placement audits are executed by AMR-mounted or clamp-adjacent optics. The three stated tasks are satisfied: design levers are formalized as a coherent handling architecture; literature-reported capabilities are tied to the thermomechanical constraints and joint-quality needs of refrigerated roofs; and operational outcomes are evaluated in terms of resource decoupling, precision at mating, and rework containment. The resulting blueprint is directly transferable to large-panel handling in truck and trailer assembly where mixed-model flow, thermoplastic skins, and rigid-foam cores set similar constraints.

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