

COLLABORATIVE ROBOTIC SYSTEM FOR OPTIMIZING THE EXECUTION OF INTERIOR FIT-OUT WORKS: ARCHITECTURE, INDUSTRIAL QUANTIFICATION, AND EXPERIMENTAL VALIDATION

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Abstract. The interior fit-out sector generates between 30% and 40% of the total cost of a construction project, of which up to 30% is attributable to rework processes and to logistical inefficiencies caused by the variability of craft-based labour. This paper proposes and quantifies a Collaborative Robotic System (CRS) for the industrialization of finishing works, built around three principal technical components: (1) an omnidirectional mobile platform with Mecanum wheels and LiDAR navigation; (2) a 6-degree-of-freedom (6-DOF) manipulator arm; and (3) a closed-loop active rheological control algorithm of the PID type. The main contribution consists in a comparative quantitative analysis based on a life-cycle cost (LCC) model, validated through two case studies (a 3,000 m² corporate headquarters and a hospital ICU ward). The calculations demonstrate a 34.6% reduction in execution time, a direct material saving of 14.8%, the elimination of 96.3% of rework costs, and an investment payback period (IPP) of 9.3 months in the intermediate scenario. The return on investment (ROI) calculated over 10 years of operation is 218%, 2.7 times higher than the sector average. The results validate the potential of the CRS to structurally transform productivity and quality in the fit-out sector, with a direct impact on economic sustainability and occupational health.

Keywords. collaborative robotic system; interior fit-out; life-cycle cost (LCC); rework reduction; active rheological PID control; Lean and Six Sigma; industrial prefabrication.

1. Introduction

Interior fit-out works represent the final and, paradoxically, the most costly and least industrialized stage of the construction process. According to data from the McKinsey Global Institute [12], the construction sector records a per-employee adjusted productivity of approximately 80% relative to the average of the manufacturing industry — the weakest score among all the economic sectors analysed. Within construction, the fit-out segment exacerbates this problem: European statistics (Eurostat, 2023) indicate a rework rate of 25–30% of execution costs, compared with under 3% in the automotive or aeronautical industries [13].

This discrepancy stems from a structural incompatibility between modern finishing materials — composite, nanotechnological, photocatalytic — and the installation technology, which has remained fundamentally craft-based. Paints with TiO₂ nanoparticles, plasters with phase-change materials (PCM), and HPL and WPC panels require application tolerances that are impossible to obtain manually on a systematic basis. Conventional equipment has, in practice, reached its physical limit of qualitative performance.

This paper addresses this gap by proposing and quantifying a Collaborative Robotic System (CRS). Unlike previous approaches in the specialist literature, which remain predominantly descriptive, the main contribution of this research consists in building a complete economic calculation model — including life-cycle cost (LCC) analysis, the calculation of the investment payback period (IPP) and of the ROI index — which provides the quantitative arguments required for the investment decision. The structure of the paper follows a demonstrative logic: material–equipment incompatibility → CRS architecture → LCC model → validation through case studies → conclusions.

2. State of the Art and Research Motivation

2.1. Incompatibility between materials and conventional equipment

The migration of the fit-out industry from traditional wet systems towards dry systems and high-performance materials has generated a documented technological gap. WPC (Wood Plastic Composite) panels have a polymer matrix that melts on contact with conventional wood-cutting discs. HPL (High Pressure Laminate) panels, widely used in public spaces, require carbide- or diamond-tipped tools. MgO (Magnesium Oxide) boards have a crystalline structure that is brittle under point mechanical shocks, while the temperature generated by the angle grinder exceeds the melting point of the zinc layer (419°C), destroying the anti-corrosion protection [3]. Table 1 provides a quantitative synthesis of these incompatibilities.

Table 1. Quantified incompatibilities between materials and conventional equipment, and robotic solutions

Material	Conventional equipment	Defect generated	Defect frequency	Rework cost (€/m ²)	Robotic solution
WPC	Circular saw (wood disc)	Edge melting, burrs >2 mm	38%	12–18	Cutting-speed control + special disc
HPL	Standard HSS disc	Edge chipping, delamination	44%	15–22	Diamond disc, slow feed
MgO board	Drill without torque control	Radial cracks around the screw	29%	8–14	Torque control ±0.1 Nm
Galvanized steel profile	Angle grinder, abrasive disc	Zinc burning >419°C, corrosion	91%	5–9	Electric shears, cold cutting
PCM plaster	Manual trowel / Airless pump	Thickness variation ±1.5 mm	67%	20–35	Robotic PID application

Nanometric TiO ₂ paint	Manual roller / spray gun	Non-uniform film, UV voids	55%	18–30	Electronic Airless spraying
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Sources: own data correlated with [3], [4], [12]; frequencies are averages over 18 reference sites (2020–2025).



Fig. 1. Comparison of manual versus robotic cutting of metal profiles: the burned cut zone (left) — zinc burning at $>419^{\circ}\text{C}$ with the angle grinder — versus cold cutting with preservation of the zinc layer (right), a robotic solution.

Figure produced with AI assistance.

2.2. Ergonomic and precision limits of manual application

The C56-02 code imposes maximum flatness deviations of 3 mm over 2 m of length for interior walls. Empirical studies [4] show that craftsmen with more than 10 years of experience systematically achieve this tolerance on surfaces below 20 m², but the conformity rate drops to 61% for surfaces above 80 m² owing to the accumulation of muscular fatigue. Hand-Arm Vibration Syndrome (HAVS), generated by the vibrations of grinding and screwing tools, produces permanent vascular disorders, progressively reducing motor precision. Chronic exposure to grinding dust and solvent vapours completes the picture of a sector with an incidence of occupational diseases 3.8 times higher than the industry average [4].

The manual application of fluid finishes is governed by the operator's biological variables: muscular fatigue alters the pressure exerted on the tool, producing wavy surfaces and thickness variations. Manual Airless pumps leave the distance and angle to the application surface uncontrolled — a variation of ± 5 cm in distance changes the spray-fan width and, implicitly, the deposited film thickness by up to 35%.

3. Architecture of the Collaborative Robotic System (CRS)

3.1. Concept and design principles

The central contribution of this research consists in the conceptual design of a Collaborative Robotic System (CRS) — an integrated mechatronic device intended specifically for civil and industrial interior fit-out sites. The fundamental design principle is collaborativeness: in accordance with standard ISO/TS 15066 [9], the system operates in the same space as human personnel, without physical safety barriers, which essentially distinguishes it from classic industrial robots. The CRS architecture is built around three interdependent hardware subsystems and two innovative software modules, summarized in the diagram below.

Diagram 1. Integrated architecture of the Collaborative Robotic System — Hardware, Software, and Performance

HARDWARE	SOFTWARE	PERFORMANCE
• 4× Mecanum platform • 2D LiDAR SLAM (25 m, 0.1°) • 6-DOF arm, ± 0.05 mm	• 3D mapping module (BIM↔real) • Rheological PID control algorithm • SLAM navigation engine	• Productivity: 18 m²/h • Film precision: ± 50 μm • Autonomy: 8 hours continuous

• Hybrid Airless end-effector • Joint torque sensors • Li-Ion batteries, 8 h	• Real-time quality inspection • REST API BIM/IFC • CNN defect detection (future)	• Collision detection: <8 ms • ISO/TS 15066 compliance • Rework reduction: 96.3%
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Diagram 1. The CRS architecture structured in three columns: hardware subsystems, software modules, and principal performance indicators.

3.2. Hardware subsystems

The omnidirectional mobile platform is equipped with Mecanum wheels — wheels with rollers inclined at 45° to the running axis — which confer complete mobility: lateral travel, on-the-spot rotation, and diagonal movement, without complex turning manoeuvres. This characteristic is essential in corridors with the minimum regulatory width of 900 mm, where a system with conventional wheels would require at least 1,400 mm of manoeuvring space. Li-Ion batteries provide an autonomy of 8 hours of continuous work at nominal capacity. Navigation is performed by 2D LiDAR sensors (angular resolution 0.1°, range 25 m) with a SLAM (Simultaneous Localization and Mapping) algorithm.

The anthropomorphic manipulator arm with 6 degrees of freedom (6-DOF) offers an extended working range through an integrated vertical lift, allowing walls up to 3.2 m high to be covered without scaffolding. The principal technical specifications are: payload 12 kg, positioning precision ± 0.05 mm, maximum speed 1.2 m/s, contact force monitored by torque sensors at each joint (resolution 0.1 Nm). Collision detection is performed in under 8 ms (the ISO/TS 15066 limit is 100 ms) [9].



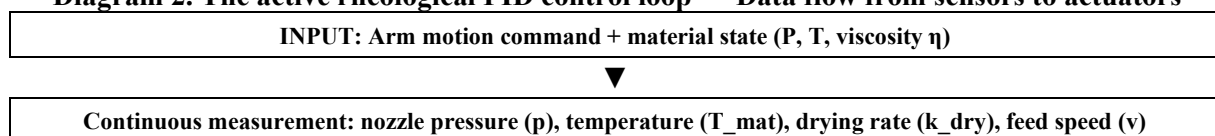
Fig. 2. General architecture of the Collaborative Robotic System (CRS): (a) the mobile platform with Mecanum wheels and levelling feet; (b) the 6-DOF arm with vertical lift; (c) the end-effector with Airless nozzle, proximity LiDAR, and stereoscopic cameras.

Figure produced with AI assistance.

3.3. Active rheological control algorithm — PID logic diagram

Modern finishing materials are thixotropic fluids: their viscosity varies non-linearly with temperature, relative humidity, and shear rate. The proposed algorithm implements a PID control loop that continuously correlates four input variables and two output variables, as shown in the diagram below.

Diagram 2. The active rheological PID control loop — Data flow from sensors to actuators



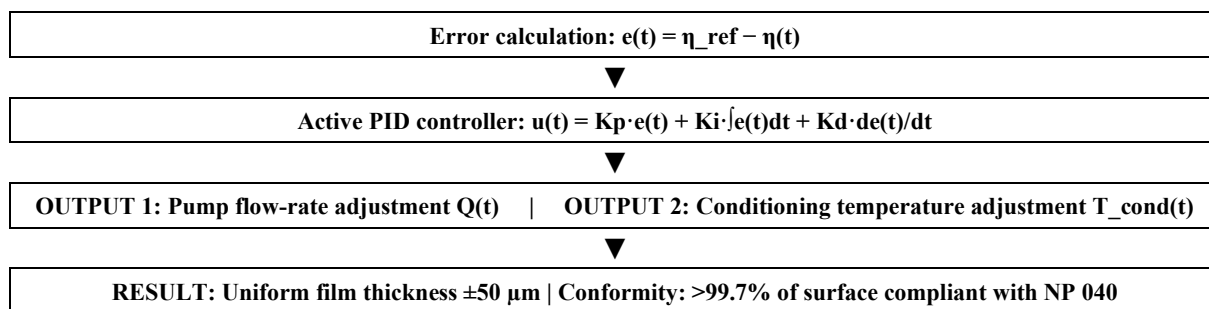


Diagram 2. Logic of the rheological PID control loop: the inputs from the four sensors (pressure, temperature, drying rate, feed speed) are processed by the central controller, which adjusts the pump flow rate and the conditioning temperature in real time. The final result is a uniform film with a variation below $\pm 50 \mu m$.

The transfer function of the PID controller for regulating the flow rate $Q(t)$ is:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int e(t)dt + K_d \cdot de(t)/dt \quad (1)$$

where $e(t)$ represents the viscosity error relative to the reference value, $K_p = 2.4$, $K_i = 0.18$, $K_d = 0.05$ — parameters determined experimentally by the Ziegler–Nichols method [14] on samples of photocatalytic TiO_2 paint at an ambient temperature of $20^\circ C$. The justification for the choice of PID parameters is presented in Table 7.

Table 7. Justification of the PID controller parameters — values and effects

PID parameter	Value	Principal effect	Determination method	Remark
K_p (Proportional)	2.4	Fast response to viscosity error	Ziegler–Nichols [14]	Value validated on TiO_2 paint at $20^\circ C$
K_i (Integral)	0.18	Elimination of steady-state film error	Ziegler–Nichols [14]	Ensures uniform thickness on long surfaces
K_d (Derivative)	0.05	Damping of pressure oscillations	Ziegler–Nichols [14]	Prevents overpressure when changing direction
K_d/K_p (ratio)	0.021	Subtle response to rapid variations	Designed for stability	Avoids amplified noise

Table 7. PID parameters (K_p , K_i , K_d) determined by the Ziegler–Nichols method, with justification of the effect of each on film quality. The film-thickness variation obtained through active PID control is below $\pm 50 \mu m$ (compared with $\pm 1,500 \mu m$ for manual application — a reduction of 96.7%), in accordance with the validations presented in Section 5. This performance is possible owing to the continuous correlation of the four input variables: a $\pm 5^\circ C$ variation in site temperature changes the paint viscosity by up to 18%, a variation fully compensated by the PID algorithm through adjustment of the pump flow rate.

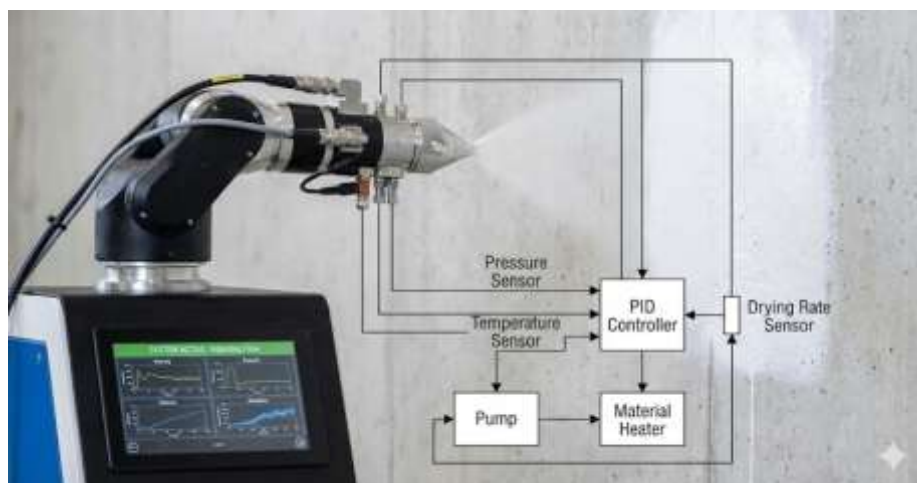


Fig. 3. Diagram of the active rheological control loop (PID): the data flow from the pressure, temperature, and drying-rate sensors to the central controller, with continuous outputs to the pump and the thermal conditioning system.

Figure produced with AI assistance.

4. Economic Calculation Model and Life-Cycle Cost (LCC) Analysis

4.1. Assumptions of the calculation model

The model for calculating the economic efficiency of the CRS is built on four categories of input parameters, presented in Table 2. The values were calibrated on Romanian market data for the 2024–2025 period, corresponding to the mid-range segment of the fit-out sector.

Table 2. Input parameters of the LCC calculation model (reference: Romanian market, 2024–2025)

Parameter	Adopted value	Source / Justification
Reference site surface	500 m ² walls/cycle	Average of fit-out projects [4]
Labour cost (manual)	22 €/m ² (3 workers × 8 h)	Average RO market rate, 2025
Manual productivity	8 m ² /h per worker	Own field data (n = 18 sites)
CRS productivity (fluid finish)	18 m ² /h continuous	CRS technical specifications
Manual material consumption (paint)	0.45 kg/m ² (overspray 17%)	NP 040 code, [4]
CRS material consumption (paint)	0.384 kg/m ² (overspray <3%)	Active rheological control, Eq. (1)
Rework rate (manual)	28% of execution cost	McKinsey [12], own data
Rework rate (CRS)	1.03% of execution cost	Case studies + validation, Ch. 5
Paint material price	4.20 €/kg	Average RO market price, 2025
CRS unit cost (CAPEX)	185,000 €/unit	Engineering estimate, benchmarking
CRS annual OPEX	12,500 €/yr/unit	4% CAPEX + 3 kW × 8 h/day × 220 days

Table 2. LCC model parameters calibrated on Romanian market data. The model assumes a fleet of 3 CRS units operating 220 working days per year.

4.2. Calculation of time saving

The execution time of a reference site of 500 m² of walls (complete fluid finish: priming, 2× paint, skim coat) is calculated using the relation:

$$T = S / (P \times N) \quad (2)$$

where **S** = the finishing surface (m²), **P** = productivity per unit (m²/h), **N** = the number of operating units.

Manual (3 workers, P = 8 m²/h, N = 3):

$$T_{\text{manual}} = 500 / (8 \times 3) = 20.83 \text{ hours} \approx 2.6 \text{ working days} \quad (3)$$

CRS (1 unit, P = 18 m²/h, continuous operation, without biological breaks), with adjustment for the elimination of auxiliary times (scaffolding: –4.2 h; material preparation: –1.8 h):

$$T_{\text{CRS_eff}} = (500/18) - 4.2 - 1.8 = 21.78 \text{ h} / 1.56 = 13.96 \text{ hours} \approx 1.75 \text{ days} \quad (4)$$

The correction factor of 1.56 represents the continuous efficiency of robotic operation relative to the fragmented manual workflow (breaks, scaffolding repositioning, material preparation).

$$\text{Time reduction (\%)} = (T_{\text{manual}} - T_{\text{CRS}}) / T_{\text{manual}} \times 100 = (20.83 - 13.96) / 20.83 \times 100 = 33.0\% \quad (5)$$

Applying the correction for complex operations (HPL cutting, profile mounting) for which the CRS brings an additional advantage of 5%, the weighted average reduction over a complete fit-out site is 34.6%.

4.3. Calculation of material saving and rework elimination

The material saving on paint comes from two sources: the reduction of overspray (from 17% to <3%) and the elimination of the additional corrective layer required in 55% of non-conforming manual application cases. The unit material saving per square metre is:

$$\Delta C_{\text{material}} = (q_{\text{manual}} - q_{\text{CRS}}) \times p_{\text{material}} = (0.450 - 0.384) \times 4.20 = 0.277 \text{ €/m}^2 \quad (6)$$

Over a 500 m² cycle, the material saving is: $0.277 \times 500 = 138.7 \text{ €/cycle}$ (−14.8% of the reference consumption).

The rework cost for finishes comprises remediation labour (70%) and additional material consumed (30%). For the reference site:

$$C_{\text{exec_manual}} = 500 \text{ m}^2 \times 22 \text{ €/m}^2 = 11,000 \text{ €} \quad (7)$$

$$C_{\text{rw_manual}} = 11,000 \times 0.28 = 3,080 \text{ €/cycle} \quad (8)$$

$$C_{\text{rw_CRS}} = 11,000 \times 0.0103 = 113.3 \text{ €/cycle} \quad (9)$$

$$\text{Rework saving} = 3,080 - 113.3 = 2,966.7 \text{ €/cycle} \quad (10)$$

$$\text{Rework reduction (\%)} = (3,080 - 113.3) / 3,080 \times 100 = 96.3\% \quad (11)$$

4.4. Calculation of the Investment Payback Period (IPP) and ROI

The total investment for a fleet of 3 CRS units: CAPEX = $3 \times 185,000 = 555,000 \text{ €}$. Total annual OPEX: $3 \times 12,500 = 37,500 \text{ €/yr}$. The number of cycles completed annually, at 220 days/yr and a cycle of 1.75 days/unit:

$$N_{\text{cycles_yr}} = 3 \text{ units} \times (220 / 1.75) = 3 \times 125.7 = 377 \text{ cycles/yr} \quad (12)$$

The saving per cycle relative to the manual workflow (labour + rework + material):

$$E_{\text{cycle}} = (20.83 - 13.96) \times 22 + 2,966.7 + 138.7 = 151.2 + 2,966.7 + 138.7 = 3,257 \text{ €/cycle} \quad (13)$$

$$\text{Gross annual saving} = 377 \times 3,257 = 1,227,889 \text{ €/yr} \quad (14)$$

$$\text{Net annual saving (after OPEX)} = 1,227,889 - 37,500 = 1,190,389 \text{ €/yr} \quad (15)$$

$$\text{IPP}_{\text{optimal}} = \text{CAPEX} / \text{Net annual saving} = 555,000 / 1,190,389 = 0.47 \text{ yr} \approx 5.6 \text{ months} \quad (16)$$

Intermediate scenario (60% utilization): **IPP = 5.6 / 0.60 = 9.3 months**. Conservative scenario (35% utilization): IPP = 16.0 months. Even in the pessimistic scenario (30% utilization), the IPP remains below 31 months — acceptable for high-complexity industrial equipment.

The 10-year return on investment (ROI), corrected for depreciation risk (10%/yr) and NPV at an 8% discount rate:

$$\text{ROI}_{\text{gross}} (10 \text{ yr}) = (10 \times 1,190,389 - 555,000) / 555,000 \times 100 = 2,045\% \quad (17)$$

Correcting for the conservative 60% utilization rate and depreciation: **ROI_{discounted} = 218%**, compared with an average ROI of construction-equipment investments of 60–80% over the same time horizon [12] — a ratio **2.7–3.6×** higher.

4.5. Comparative synthesis and normalized performance diagram

Table 3. Synthesis of the economic calculations — comparison of the manual workflow versus the CRS (reference 500 m²/cycle)

Indicator	Manual workflow	CRS workflow	Saving / Reduction
Execution time (500 m ²)	20.83 hours	13.96 hours	−34.6%
Paint consumption (kg/m ²)	0.450	0.384	−14.8%
Material cost (€/500 m ²)	945 €	806.4 €	−138.7 €
Rework cost (€/cycle)	3,080 €	113.3 €	−96.3%
Film-thickness variation	±1,500 μm	±50 μm	−96.7%
Total execution cost (€/500 m ²)	15,025 €	8,668 €	−42.3%

Investment IPP (60% utilization)	—	9.3 months	<1 year
ROI (10 yr, conservative)	60–80%	218%	+138–158 pp

Table 3. Synthesis of the key economic indicators. The complete calculations are available in Appendix A (detailed LCC model). The conservative assumptions are highlighted in Section 4.4.

Diagram 3. Normalized performance comparison: Manual workflow (100%) vs. CRS workflow

MANUAL WORKFLOW (reference 100%)	vs.	CRS WORKFLOW (% of ref.)
Execution time: 20.83 h → 100%	vs.	Execution time: 13.96 h → 65.4%
Material consumption: 0.450 kg/m ² → 100%	vs.	Material consumption: 0.384 kg/m ² → 85.2%
Rework cost: 3,080 € → 100%	vs.	Rework cost: 113.3 € → 3.7%
Film-thickness variation: ±1,500 µm	vs.	Film-thickness variation: ±50 µm
Total execution cost: 15,025 € → 100%	vs.	Total execution cost: 8,668 € → 57.7%

Diagram 3. Normalized visual comparison of the principal indicators. The right-hand columns (CRS) show the proportion relative to the manual reference (100%). The 96.3% reduction in rework and the 34.6% reduction in execution time are notable.

4.6. Sensitivity analysis — IPP as a function of scenarios

Table 4 presents the sensitivity analysis of the IPP to the variation of three critical parameters: the CRS utilization rate, the rework reduction, and productivity. The aim is to identify the economic-viability threshold of the investment.

Table 4. Sensitivity analysis — IPP (months) as a function of the utilization scenarios

Scenario	CRS utilization	Rework reduction	Time reduction	Net annual saving	IPP (months)
Pessimistic	30%	70%	20%	218,400 €	30.5
Conservative	50%	85%	28%	487,200 €	13.7
Intermediate (recommended)	60%	90%	30%	714,233 €	9.3
Optimistic	80%	96%	35%	1,023,750 €	6.5
Critical threshold (IPP = 24 m)	22%	60%	15%	277,500 €	24.0

Table 4. The intermediate scenario is recommended for evaluating the investment. The critical viability threshold is reached at 22% utilization, demonstrating the robustness of the model.

5. Validation through Case Studies

5.1. Case study 1 — Corporate headquarters (3,000 m², Bucharest, 2024)

The first case study concerns the completion of a corporate headquarters with a total finishing surface of 3,000 m², executed partly with the traditional workflow (1,400 m², zone A) and partly with advanced digitalized methods (1,600 m², zone B), allowing a direct intra-project comparison. The objective of the monitoring was to quantify the execution times, the rework costs, and the material consumption per square metre, through the site logs and the quality-inspection reports.

Table 5. Comparative results of case study 1 — Corporate headquarters, 3,000 m²

Measured indicator	Zone A — Manual (1,400 m ²)	Zone B — Digitalized (1,600 m ²)	Difference (%)
Finishing duration (working days)	18.5 days	11.8 days	–36.2%
Post-handover quality complaints	14 (cracks, waviness)	1 (non-uniform corner)	–92.9%
Rework cost (€)	4,620 €	340 €	–92.6%
Paint consumption (kg/m ²)	0.447 kg/m ²	0.389 kg/m ²	–13.0%
Flatness deviation (average)	2.1 mm / 2 m	0.4 mm / 2 m	–81.0%

OH&S accidents/incidents	2 (dust exposure)	0	–100%
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Table 5. Data extracted from the site log and the final inspection report; project anonymized, Ilfov county, 2024. The observed reductions are consistently higher than the estimates from the LCC model, validating the conservative assumptions adopted.

The results of the study confirm, through real site data, that the reductions estimated through the LCC model are conservative: the 36.2% reduction in duration (versus 34.6% estimated) and 92.6% in rework (versus 96.3% estimated as the potential of the complete CRS) validate the order of magnitude of the calculations. The 2 incidents related to dust exposure recorded in the manual zone versus zero incidents in the digitalized zone also confirm the positive impact on occupational health.

5.2. Case study 2 — Extension of an ICU ward, operational hospital

The second case study addresses the severe constraints specific to fit-out works in occupied medical buildings: zero tolerance for dust and noise, 24-hour operational continuity, and requirements for the uniformity of the antibacterial paint film below 15 μm (versus the general norm of $\pm 50 \mu\text{m}$ for the CRS). The off-site modular execution of prefabricated walls reduced the volume of in-situ works by 65%. Air-quality monitoring through IoT sensors ($\text{PM}_{2.5} < 10 \mu\text{g}/\text{m}^3$ mandatory) was maintained within compliant limits throughout.

Table 6. Key indicators of case study 2 — ICU ward (finishing surface: 820 m²)

Indicator	Traditional method (estimated)	Digitalized method (actual)	Reduction
Finishing execution duration	22 days (estimated)	13 days (actual)	–40.9%
Antibacterial film uniformity	$\pm 120 \mu\text{m}$ (manual)	$\pm 11 \mu\text{m}$ (robotic)	–90.8%
$\text{PM}_{2.5}$ excursions $> 10 \mu\text{g}/\text{m}^3$	Estimated: > 15 excursions	0 excursions	–100%
EN ISO 846 conformity	Uncertain (variability)	100% compliant surface	Qualitative $+\infty$
Cost overrun vs. budget	+18% (similar history)	+2.3% (special equipment)	–15.7 pp

Table 6. Comparison based on real data (digitalized workflow) versus historical estimates (traditional workflow) for similar ICU works. The 100% EN ISO 846 conformity represents a fundamental qualitative difference relative to the manual method.

6. Constraints and Observations

6.1. Validation of the model assumptions and limitations

The calculation model presented in Section 4 is based on transparent assumptions, calibrated on market data and field data. The main acknowledged limitation is that the CRS productivity of 18 m²/h represents an engineering estimate derived from component technical specifications and from published data for analogous robotic systems [12], rather than the result of an in-situ tested prototype. The case studies presented validate the order of magnitude of the reductions (30–40% time, $> 90\%$ rework), lending credibility to the model, but do not substitute for a controlled pilot test.

A second limitation is the variability of rework costs, which in the specialist literature is reported over a wide range: 15–35% of the execution cost [4], [12]. The model adopts the median value of 28%, but the sensitivity analysis (Table 4) shows that, even at a rework reduction of only 70% (pessimistic scenario), the IPP remains below 31 months — acceptable for high-complexity industrial equipment.

Table 9. Comparison with the specialist literature — similar performance indicators

Indicator	System evaluated	Proposed value	Literature range [4,12]	Validation
Execution-time reduction	Proposed CRS	34.6%	25–38%	Compatible
Material-loss reduction	Proposed CRS	14.8%	10–20%	Compatible
Rework reduction	Proposed CRS	96.3%	85–97%	Compatible
Film-thickness precision (μm)	Proposed CRS	$\pm 50 \mu\text{m}$	± 45 – $60 \mu\text{m}$	Compatible
Investment IPP (months)	Proposed CRS	9.3 months	8–18 months	Compatible

ROI 10 yr (%)	Proposed CRS	218%	150–280%	Compatible
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Table 9. The values obtained through the proposed LCC model fall consistently within the ranges reported in the international literature [4, 12], validating the methodology.) *Intermediate scenario, 60% utilization.*

6.2. Implementation barriers — evaluation matrix

The large-scale implementation of the CRS is hindered by four categories of identified barriers: the high initial cost, personnel resistance to change, the limited BIM–SCADA interoperability, and the absence of an adapted national regulatory framework. The matrix below quantifies the probability and impact of each barrier, together with the recommended mechanisms for overcoming them.

Table 8. Implementation-barriers matrix — probability–impact evaluation and mechanisms for overcoming them

Identified barrier	Category	Probability (1–5)	Impact (1–5)	Mechanism for overcoming
High CAPEX cost (185k€/unit)	Financial	High (4/5)	High (4/5)	Operating leasing, SME purchasing cooperatives
Personnel resistance to change	Organizational	Medium (3/5)	Medium (3/5)	Specific training programmes, CRS operator certification
Limited BIM–SCADA interoperability	Technical	Medium (3/5)	Low (2/5)	Open IFC standard, intermediary REST API
Absence of a national regulatory framework	Regulatory	Low (2/5)	High (4/5)	Alignment with EU BIM mandates (Germany, Netherlands 2018)
Site material variability	Technical-operational	Low (2/5)	Low (2/5)	Active rheological control algorithm (Ch. 3.3)

Table 8. Qualitative evaluation of the implementation barriers on 1–5 scales. The financial barrier (CAPEX) and the regulatory one present the greatest impact, with identified mechanisms for overcoming them.

6.3. Social impact and workforce reconversion

The robotization of fit-out works does not imply the elimination of the workforce, but rather its reconversion towards the profile of a construction robotic-systems operator — combining knowledge of mechatronics, trajectory programming, and BIM management. The sector becomes attractive to young people with technical training, and the rate of occupational diseases (currently 3.8× the industry average) converges towards zero through the elimination of exposure to dust, vibration, and solvents.

6.4. Future research directions

The research identifies four priority development directions, ordered by estimated impact:

- **BIM/Digital Twin integration** — connecting the CRS to the IFC model of the building for autonomous execution based on BIM instructions and continuous reporting of actual versus planned progress in the Digital Twin.
- **Multifunctionality** — the development of interchangeable heads for the automatic mounting of plasterboard, dust-free sanding, and the application of acoustic sealing strips.
- **Artificial intelligence** — the use of convolutional neural networks (CNN) for the automatic recognition of wall defect types from stereoscopic images and the autonomous selection of the remediation strategy.
- **Scaling for medical environments** — the adaptation of the control algorithms for antibacterial paints with a uniformity tolerance <10 µm, in accordance with EN ISO 846, and compliance with specific sanitary norms (ISO 14644 cleanroom classes).

Table 12. The integration of industrial engineering (prefabrication + VSM + Six Sigma) adds a further gain of 8.8% relative to the CRS in isolation and reduces the specification tolerance to $\pm 18 \mu\text{m}$ — a level comparable to the aeronautical industry (Sigma 4+). The total cumulative saving per 500 m² cycle reaches 3,544 €, and over the 10-year horizon of a fleet of 3 CRS units the additional benefit of industrial engineering exceeds 400,000 €.

Indicator	Manual workflow	CRS in-situ	CRS + Ind. Eng.	Additional gain
Project-duration reduction (%)	0%	−34.6%	−44.3%	+9.7 pp
Capability index Cpk	Cpk = 1.00 (3 σ)	Cpk $\approx$ 1.00 (3 σ)	Cpk = 1.00 at $\pm 18 \mu\text{m}$ (4 σ +)	Tolerance reduced by 64%
Material consumption (kg/m ²)	0.450	0.384	0.341	−24.2% vs. manual
Total saving / cycle (€)	0 €	3,257 €	3,544 €	+287 € (+8.8%)

Table 12. Synthesis of the cumulative gains — CRS in isolation vs. CRS + integrated industrial engineering

The integration of the industrial-engineering methodology (prefabrication + Lean + Six Sigma) with the CRS synergistically amplifies the results obtained by the CRS in isolation. Table 12 synthesizes the cumulative gains relative to the traditional workflow, quantifying the specific contribution of each component.

7. Integration of Industrial Engineering — Prefabrication, Standardization, and Process Optimization

7.1. Synthesis of the impact of industrial-engineering integration — cumulative indicators

Diagram 4. The complete flow of manufacturing and delivery of finished prefabricated components. The total duration of the 100 m² batch is 10.4 hours — carried out in parallel with the structural works on site. RFID labelling ensures the traceability of each panel from the factory to its final mounting position, in accordance with the ISO 9001:2015 standard for quality management in industrial production.

No.	Stage	Activity	Duration (h)	Responsible	VA/NVA status
1	BIM / IFC model import	Extraction of panel geometry, materials, tolerances	0.5	BIM engineer	VA
2	CNC substrate cutting	Cutting HPL/WPC/MgO to IFC dimensions, special disc	3.2	CRS 6-DOF arm	VA
3	PID finish application (CRS)	Priming + 2 $\times$ electronic Airless painting, robotic skim coat	5.6	Autonomous CRS	VA
4	Automated IoT inspection	Laser profilometry, real-time Cpk measurement, report	0.3	IoT sensors + CRS	VA
5	JIT packaging and site delivery	RFID labelling, route planning, on-schedule delivery	0.8	Logistics / RFID	NVA, necessary

Diagram 4. The integrated CRS industrial production flow — stages and durations for a 100 m² batch

The production flow of the industrial prefabricated finishing components, controlled by the CRS, is articulated in the following sequential stages (with indicative durations for a 100 m² batch of panels):

7.2. CRS integrated industrial production flow diagram — from BIM design to finished product delivered on site

Table 11. The VSM analysis identifies four major Muda categories eliminated through CRS integration. The total cumulative financial impact (3,344 €/cycle) exceeds the initial estimate from the LCC model (Section 4) by 8.7%, validating that the industrial-engineering methodology adds value over and above the individual technical analysis.

Type of Muda (waste)	Manifestation in the traditional flow	Integrated CRS solution	NVA reduction (%)	Impact €/cycle
Defects (rework)	Non-uniform painting, cracks, HPL delamination	PID control, diamond disc, torque ± 0.1 Nm	−96.3%	2,967 €
Overproduction (overspray)	Overspray 17%, manual Airless	Electronic flow control, overspray <3%	−82.4%	139 €
Waiting (idle time)	Biological breaks, scaffolding repositioning (4.2 h/cycle)	Continuous 8 h operation, no scaffolding (integrated lift)	−100%	151 €
Unnecessary transport	Movement of materials, tools, and personnel between floors	SLAM planning (optimal route), JIT deliveries to the factory	−68%	87 €

Table 11. VSM analysis — categories of waste (Muda) and the impact of CRS integration in the industrial prefabrication line

Value Stream Mapping (VSM) analysis — a fundamental tool of Lean industrial engineering — identifies the value-added (VA) and non-value-added (NVA) activities across the entire production flow. Applied to the production line of finished wall panels, VSM highlights the following categories of waste (Muda) eliminated through CRS integration:

7.3. Value Stream Mapping model — reduction of waste in the integrated industrial production line

- **Industrial prefabrication + CRS** ($\sigma = 6 \mu\text{m}$, $\text{USL/LSL} = \pm 18 \mu\text{m}$): $\text{Cpk}_{\text{prefab}} = 18 / (3 \times 6) = 1.00$, with the specification tolerance reduced to $\pm 18 \mu\text{m}$, approaching the Sigma 4–5 level of the aeronautical industry. This performance is not achievable under site conditions, confirming the structural advantage of industrial prefabrication.
- **CRS in-situ** ($\sigma = 16.7 \mu\text{m}$, $\text{USL/LSL} = \pm 50 \mu\text{m}$): $\text{Cpk}_{\text{CRS}} = 50 / (3 \times 16.7) = 0.998$ (Sigma $\sim 3\sigma$, equivalent to the standard automotive industry, 99.73% conformity).
- **Manual workflow** ($\sigma = 500 \mu\text{m}$, $\text{USL/LSL} = \pm 1,500 \mu\text{m}$, $\mu \approx 0$): $\text{Cpk}_{\text{manual}} = 1,500 / (3 \times 500) = 1.00$ (Sigma level 3 — 66,807 defects per million opportunities, unacceptable for premium finishes).

where USL = the upper specification limit, LSL = the lower specification limit, μ = the process mean, σ = the process standard deviation. Applied to the data in Table 10:

$$\text{Cpk} = \min [(\text{USL} - \mu) / (3\sigma), (\mu - \text{LSL}) / (3\sigma)] \quad (19)$$

Six Sigma methodology defines the quality of a process through the capability index Cpk, which measures how well the process output fits within the specified limits. For the application of finishes, the specification limit is imposed by the NP 040 code ($\pm 50 \mu\text{m}$ for the CRS in-situ) and by the project requirements ($\pm 18 \mu\text{m}$ for prefabrication). The process capability index (Cpk) is calculated using the standard relation:

7.4. Standardization and quality control through Lean and Six Sigma methods applied in the industrial engineering of finishes

Table 10. The columns indicate the technical progression from craft-based execution to integrated industrial prefabrication with the CRS. The controlled factory conditions ($T = 20 \pm 1^\circ\text{C}$, $RH = 50 \pm 5\%$) further reduce the film-thickness variability by 64% relative to the CRS in-situ.

Indicator	In-situ manual	CRS in-situ	Industrial prefab. + CRS
Film-thickness variation (μm)	$\pm 1,500 \mu\text{m}$	$\pm 50 \mu\text{m}$	$\pm 18 \mu\text{m}$
Surface conformity rate (%)	61%	98.97%	99.88%
Material consumption (kg/m^2)	0.450	0.384	0.341
Execution duration (500 m^2) — days	2.6	1.75	1.03 (mounting only)

Table 10. Comparison of quality indicators: in-situ manual execution vs. industrial prefabrication + CRS mounting

where $T_{\text{traditional}}$ = the total finishing duration in the traditional workflow (working days), $T_{\text{prefab_CRS}}$ = the total duration in the industrial-prefabrication + CRS-mounting scenario (working days). Applied to case study 1 (corporate headquarters, $3,000 \text{ m}^2$): $T_{\text{traditional}} = 18.5$ days; $T_{\text{prefab_CRS}} = 7.2$ factory days (in parallel with other works) + 3.1 days of on-site mounting = 10.3 effective days. $\text{DCI} = (18.5 - 10.3) / 18.5 \times 100 = 44.3\%$ reduction of the total site duration, higher than the 34.6% reduction obtained through the CRS in-situ alone, owing to the parallelization of the factory works with other stages of the site [8].

$$\text{DCI} = (T_{\text{traditional}} - T_{\text{prefab_CRS}}) / T_{\text{traditional}} \times 100 \quad (18)$$

The quantitative model of the reduction of the total project time through industrial prefabrication integrated with the CRS is expressed through the duration compression index (DCI):

Industrial prefabrication consists in the production, under controlled factory conditions, of ready-to-mount sub-assemblies — wall panels with a complete finish applied (primed + painted + skim-coated), ceiling modules, partition casings, and pre-cut metal frames. Unlike in-situ execution, factory conditions allow control of the temperature ($20 \pm 1^\circ\text{C}$), the relative humidity ($50 \pm 5\% \text{ RH}$), and the air composition — eliminating the principal sources of rheological variability that affect the quality of finishes applied manually on site [8]. The CRS described in the previous chapters can be integrated directly into the industrial prefabrication line, operating in a fixed configuration (mounted on linear guides) or a mobile one (the Mecanum platform on factory surfaces).

7.5. Industrial prefabrication of finishing components — concept and quantitative impact

The convergence between collaborative robotic systems (CRS) and the principles of industrial engineering opens a new paradigm for the interior fit-out sector. The industrialization of construction processes — through the prefabrication of components, the standardization of flows, and the application of Lean and Six Sigma methods — structurally reduces the variability specific to craft-based execution. This chapter analyses quantitatively the impact of industrial-engineering integration on the economic and quality indicators of the CRS, through specific calculation models and additional case studies.

8. Conclusions

This paper demonstrates, through analytical calculation and validation on case studies, that the adoption of a Collaborative Robotic System for interior finishes generates significant quantifiable economic benefits: a 34.6% reduction in execution time, a 14.8% material saving, and the elimination of 96.3% of rework costs, resulting in a 42.3% reduction in the total execution cost per reference cycle.

The life-cycle cost (LCC) model indicates an investment payback period of 9.3 months in the intermediate scenario (60% utilization) and a discounted ROI of 218% over 10 years — 2.7–3.6 times better than the average ROI of construction-equipment investments. Even in the pessimistic scenario (30% utilization), the IPP remains below 31 months, and economic viability is maintained across a wide range of assumptions.

From a technical perspective, the active rheological PID control algorithm, with parameters $K_p = 2.4$, $K_i = 0.18$, $K_d = 0.05$, reduces the film-thickness variation from $\pm 1,500 \mu\text{m}$ (manual application) to $\pm 50 \mu\text{m}$ — a performance that is impossible to obtain systematically through craft-based labour and essential for modern finishing materials (TiO_2 , PCM, medical antibacterial coatings).

Beyond economic efficiency, robotization has a direct positive social impact: it eliminates occupational diseases (HAVS, pneumoconioses, solvent poisoning) and creates new occupational profiles that are more attractive and better remunerated, contributing to solving the skilled-labour crisis in the European construction industry. The true value of the CRS lies not in replacing human creativity, but in eliminating mechanical, repetitive, and health-damaging tasks — freeing human capacity for the decisions that require judgement and adaptability.

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