Financial Feasibility Modeling of Robotic FRP Fabrication for Large-Scale Infrastructure Projects

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Abstract

Robotic fabrication of fiber-reinforced polymer (FRP) systems offers a potential route to more consistent, safer, and faster confinement and strengthening of large infrastructure assets, yet capital-intensive automation is often appraised with simplified unit-cost comparisons that neglect utilization, rework, learning, and project-specific risk. This manuscript develops a financial feasibility model for robotic FRP fabrication in large-scale infrastructure projects. The model treats the robotic option as an incremental alternative to conventional manual layup and links process mechanics, including available machine hours, task time, availability, handling and consolidation, and defect probability, to periodic cash flows. It formulates net present value, unit-cost differentials, break-even output, expected rework cost, learning-curve effects, and a risk-adjusted acceptance rule. The formulation distinguishes fixed deployment costs from variable process savings and shows why the same robotic system can be financially attractive on a long-duration, high-volume project and unattractive on a short, fragmented one. It also clarifies how quality variation, schedule delay, material waste, and financing terms alter the ranking of alternatives, and why contingency should be modeled explicitly rather than buried in a single discount rate. The contribution is an analytically transparent appraisal structure that can be populated with project-specific engineering and financial parameters without embedding untested empirical assumptions. The model provides decision support for owners, contractors, and technology providers evaluating whether robotic FRP fabrication should be mobilized, rented, shared across projects, or rejected in favor of conventional methods.

Keywords

robotic fabrication; fiber-reinforced polymer; infrastructure finance; construction automation; break-even analysis; risk-adjusted appraisal

1. Introduction

Large-scale infrastructure projects increasingly depend on externally bonded and near-surface-mounted fiber-reinforced polymer systems for strengthening, repair, and confinement. The engineering case for FRP composites is well established: high strength-to-weight ratios,

corrosion resistance, and adaptable geometry make them attractive for bridges, buildings, industrial facilities, and marine structures [1]. Their application in rehabilitation has expanded because FRP systems can restore or enhance capacity with relatively low added mass and limited disruption to service [2]. These attributes matter most where access is constrained, service interruptions are costly, and quality consistency is difficult to maintain across many hand-laid plies.

Automation has therefore attracted interest as a way to improve the execution of composite work. Construction robotics research has examined task-specific machines, mobile manipulators, and integrated process control for operations that are repetitive, hazardous, or sensitive to craft variability [3]. Implementation studies have long emphasized that technical capability alone does not determine adoption; utilization, organizational fit, training, maintenance, and project scale also shape economic outcomes [4]. For FRP fabrication, the central financial question is not whether a robot can execute a controlled layup sequence, but whether the incremental capital, deployment, and operating costs are justified by savings in labor, material, schedule, and rework across the relevant project portfolio.

Conventional feasibility exercises often compare a robotic day rate with a manual crew rate. That comparison is incomplete. A robot that is technically productive in the laboratory may be idle on a short project because mobilization, programming, safety approval, and system integration dominate the early work. A system with high nominal speed may be uneconomic if availability is low or if quality monitoring adds cycle time. Conversely, a slower system can be preferable when it reduces defect rates, material waste, and schedule overruns on a large, repetitive asset. Financial appraisal must therefore connect engineering process variables to cash flows and treat uncertainty explicitly. Flexibility in engineering design is valuable when deployment can be staged, rented, or shifted among projects [5], and cost contingency should reflect identifiable risk drivers rather than a generic percentage [6].

This article develops a financial feasibility model for robotic FRP fabrication in large-scale infrastructure projects. The contribution is an incremental appraisal framework that integrates production mechanics, quality-adjusted output, learning, capital recovery, and risk. The model is analytical rather than empirical: it defines the relationships that determine feasibility and provides decision rules that can be populated with project-specific engineering and financial parameters. The next sections specify the process and cash-flow model, derive break-even and quality relationships, examine learning and multi-project utilization, and formulate a risk-adjusted acceptance rule.

2. Process and Financial Modeling Framework

Robotic FRP fabrication for in-situ confinement combines surface preparation, primer or adhesive application, fiber placement, resin delivery or wet-out, consolidation, and cure monitoring. Mobile manipulators can extend composite confinement to locations where manual access is constrained, while sensing and control can reduce variability in overlap, alignment, and compaction [7]. Construction-robot taxonomies distinguish such specialized platforms from general-purpose construction equipment because their economics depend on task repetition, setup effort, and integration with existing work sequences [8]. These features imply that feasibility is project-specific: the same machine may be productive in a long bridge retrofit and inefficient in a small, geometrically irregular repair.

Process variables also determine cost. Resin viscosity, fiber wet-out, compaction pressure, ambient temperature, and cure kinetics influence both cycle time and defect formation [9].

Industrial composites manufacturing literature highlights trade-offs among layup speed, tooling complexity, and quality control; higher deposition rates are not automatically cheaper if they increase voids, incomplete wet-out, or rework [10]. For a robotic FRP system, the economically relevant output is therefore not nominal deposition rate but completed, accepted area per period after setup, handling, consolidation, inspection, and rework are included.

The financial model compares the robotic alternative with a conventional manual or semi-mechanized baseline. Let period t denote a project reporting interval, such as a month or quarter. The incremental net cash flow of the robotic option is defined as the difference between the two alternatives after all project-specific costs and savings are included. Engineering-economy conventions for incremental cash-flow analysis provide the accounting basis [11]. The periodic incremental cash flow is

$$\Delta CF_t = S_L, t + S_T, t + S_M, t - C_R, t - C_O, t - C_F, t$$

where ΔCF_t is the incremental net cash flow of robotic fabrication over the conventional method in period t; S_L,t is labor and supervision savings; S_T,t is schedule-related savings, including reduced access duration, user costs, or delay penalties; S_M,t is material savings from reduced waste and overordering; C_R,t is expected rework and quality-assurance cost; C_O,t is operating and ownership cost, including maintenance, energy, consumables, and support labor; and C_F,t is financing, tax, insurance, and regulatory cost. Capital expenditure is treated separately at the investment date to avoid double counting.

Project feasibility is evaluated through net present value:

$$NPV = - I_0 + \Sigma_{t=1}^{T} \Delta C \frac{F_t}{(1+r)^t} + \frac{V_T}{(1+r)^T}$$

where I_0 is the incremental initial investment for robotics, including mobilization and integration; r is the risk-adjusted discount rate; T is the appraisal horizon; and V_T is terminal salvage, lease residual, or redeployment value. A positive NPV indicates that the robotic alternative creates value relative to the conventional method under the stated assumptions. The formulation also makes clear that feasibility depends on the time profile of savings, not only on their total magnitude. Savings that arrive after a long mobilization period are worth less and are more exposed to project delay.

3. Production, Cost, and Break-Even Mechanics

Effective output is the starting point for linking engineering parameters to financial performance. Let H be scheduled machine hours per period, A be mechanical availability, η be work efficiency accounting for minor interruptions and coordination delays, and u_l, u_h, and u_s be hours per square metre for layup, handling and consolidation, and setup allocated to the completed area. Effective completed area per period is

$$Q = H \cdot A \cdot \frac{\eta}{(u_l + u_h + u_s)}$$

where Q is accepted output before rework adjustment. The denominator is deliberately expressed per square metre so that setup can be allocated according to batch size and geometric complexity. If setup is largely fixed per work zone, u_s falls as the completed area in that zone increases, which captures the economic advantage of repeatable, large-area work. Low availability or high handling time reduces Q directly and may also increase schedule-related costs.

The unit-cost differential between conventional and robotic fabrication can be expressed from the same variables. Let l_c and l_r be labor hours per square metre for conventional and robotic methods, w be the loaded wage rate, m_c and m_r be material mass per square metre including waste, p_m be material price per unit mass, q_c and q_r be defect probabilities, κ_c and κ_r be expected rework cost per defective square metre, and F_r be annualized fixed cost of the robotic option. The annualized fixed cost includes capital recovery at rate i over N years plus maintenance and energy. The per-unit saving from robotics is

$$\Delta c = (l_c - l_r)w + (m_c - m_r)p_m + (q_c\kappa_c - q_r\kappa_r) - \frac{F_r}{Q}$$

where Δc is the incremental saving per accepted square metre. If Δc is positive, the robotic method has lower average cost at output Q. The fixed-cost term F_r/Q shows why utilization is decisive: as Q rises, the ownership burden per square metre declines, while low-volume projects retain a high fixed-cost penalty.

Setting Δc equal to zero gives the break-even output:

$$Q* = \frac{F_r}{[(l_c - l_r)w + (m_c - m_r)p_m + (q_c\kappa_c - q_r\kappa_r)]}$$

where Q is the annual accepted area required for the robotic and conventional methods to have equal average cost. The denominator must be positive for a finite break-even volume to exist. If process savings are negative or too small, no plausible volume justifies the fixed investment without additional benefits such as schedule acceleration, safety improvement, or access in hazardous locations. This expression is more informative than a simple payback period because it separates fixed deployment cost from per-unit process advantage and makes the required utilization explicit.

Learning affects the variable terms in these equations. Repetition reduces programming, path planning, trial layup, and inspection time. A standard learning-curve form is

$$u_n = u_1 n^{-b}, b = -\log_2(\varphi)$$

where u_n is the unit task time for the nth cumulative repetition, u_1 is the first repetition time, n is cumulative production, b is the learning exponent, and φ is the learning rate, with $0 < \varphi < 1$. The formulation is adapted from established production-cost analysis [12], [13]. A lower φ implies faster learning and a larger reduction in task time. In robotic FRP fabrication, learning is not automatic: it depends on reusable digital models, stable material behavior, repeatable geometries, and knowledge transfer between operators. Projects with unique geometry may learn slowly, whereas bridge decks, tunnels, and standard structural members may generate enough repetition to move the system toward its productive asymptote.

4. Quality, Reliability, and Rework Valuation

Quality is a financial variable, not merely a technical acceptance criterion. Defects in FRP systems can require removal, surface re-preparation, additional resin or plies, extended cure time, and reinspection. Their cost includes direct repair and schedule delay, especially when access equipment and traffic control are retained longer than planned. Risk management literature emphasizes that construction uncertainty is multidimensional and that identifiable risk drivers should be assessed explicitly rather than compressed into a single contingency percentage [14]. Infrastructure investment appraisal similarly requires attention to timing, staged commitment, and downside exposure because large projects are vulnerable to delay and cost escalation [15].

Expected rework cost can be represented as

$$C_R = Q \cdot q \cdot (c_r p + d \cdot \tau_r)$$

where C_R is expected rework cost per period, q is the defect probability for the process, c_rp is direct repair cost per defective square metre, d is schedule cost per day, and τ_r is rework delay days per square metre of defective work. The term in parentheses converts a quality defect into both direct and time-related cost. A robot with a higher deposition rate but a higher q can therefore be less economic than a slower system with better process control. Sensing, closed-loop resin delivery, temperature monitoring, and automated inspection reduce q, but they also add capital and cycle time. The model treats these as explicit trade-offs rather than assuming that automation necessarily improves quality.

The quality term also interacts with the material-saving term. Improved wet-out and ply placement can reduce resin consumption and trim waste, but excessive resin use to avoid dry spots may increase cost. In-service durability and long-term performance remain governed by design, material compatibility, and environmental exposure [16], [17], [18]. Financial feasibility should therefore not credit the robotic option with durability benefits unless those benefits are tied to measurable acceptance criteria and project-specific performance requirements.

5. Learning, Utilization, and Multi-Project Deployment

The break-even and unit-cost equations assume that Q is available to the robotic system. In practice, large infrastructure projects are often fragmented by work zones, permits, weather, and coordination with other trades. A system that is technically capable of high output may have low effective utilization because access windows are intermittent. Utilization can be represented as U = Q_actual/Q_capacity, where Q_capacity is the output obtainable at full scheduled availability. Feasibility requires U to exceed the level at which fixed costs are recovered by process savings. If a single project cannot supply that utilization, the decision shifts from project-level adoption to fleet-level deployment across several projects, rental arrangements, or a shared service model.

Learning and utilization are linked. A contractor that deploys the system across repeated work packages accumulates n faster and moves down the learning curve. By contrast, a one-off deployment may never recover programming and commissioning costs, even if the robot performs well during the final work stages. This argument supports staged adoption: begin with repetitive, accessible, high-value work where the process can be standardized, then extend to more complex geometries as the operating envelope and digital work instructions mature. The financial model does not require the robot to be fully utilized on every asset; it requires the portfolio to provide enough cumulative accepted area and enough schedule-critical work to justify mobilization and ownership.

6. Risk-Adjusted Decision Analysis and Sensitivity

The preceding equations are deterministic. Actual project outcomes vary because productivity, material prices, defect rates, discount rates, and schedule costs are uncertain. Let θ denote the vector of uncertain parameters entering the NPV calculation. A risk-adjusted feasibility rule can be written as

$$P_f \;=\; Pr[NPV(\theta) \;\geq\; 0], accept\ if\ P_f \;\geq\; 1 - \alpha\ and\ E[NPV] \;\geq\; 0$$

where P_f is the probability of nonnegative NPV, E[NPV] is expected NPV, and α is the maximum tolerable probability of financial shortfall. The rule prevents a project with a high

expected value but unacceptable downside exposure from being accepted solely on the basis of a point estimate. The joint condition is important because expected NPV and shortfall probability can diverge when the distribution of outcomes is skewed by delay, rework, or low utilization.

Sensitivity analysis should focus on the parameters that alter the break-even volume and the timing of cash flows. The most consequential are effective output Q, availability A, defect probability q, rework delay τ_r, material waste, discount rate r, and the project duration over which fixed costs are recovered. A small increase in q can be more damaging than a proportional increase in labor cost if it triggers access retention and schedule penalties. A decline in A can eliminate the apparent advantage of a high nominal deposition rate. Financing terms also matter: shorter payback requirements or higher capital costs raise F_r and increase Q, while shared ownership or leasing lowers the initial commitment and shifts risk to the technology provider. These effects should be reported as ranges and thresholds, not as single-point forecasts.

7. Conclusion

Robotic FRP fabrication can be technically credible yet financially unattractive if appraisal ignores utilization, quality, learning, and project timing. This article has developed an incremental feasibility model that connects process mechanics to cash flows through effective output, unit-cost differentials, break-even volume, expected rework cost, learning, and risk-adjusted acceptance. The model shows that the decisive quantity is not the robot's nominal speed but the accepted area that can be completed and monetized before fixed costs and financing charges erode the process advantage. It also shows why quality and schedule terms belong inside the same financial framework as labor and material savings: rework and access delay can reverse an otherwise favorable unit-cost comparison.

The framework is intended for pre-project appraisal and portfolio screening. It allows owners, contractors, and technology providers to test whether a robotic system should be mobilized for a single project, shared across a program, leased, or rejected. Its analytical transparency is useful because every term corresponds to an engineering or financial quantity that can be audited, negotiated, and updated as project information improves. The practical implication is that robotic FRP fabrication should be appraised as a capacity-constrained, quality-sensitive investment rather than as a labor-replacement device. Feasibility depends on matching the system's productive envelope, learning potential, and risk profile to the repetition and schedule criticality of the infrastructure portfolio.

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