Date of first submission	2026-06-01
Date of acceptance of article for publication after review	2026-06-30
Date of publication/publication	2026-07-25

MODERN TECHNOLOGIES IN STEEL STRUCTURE FABRICATION: AN INTEGRATED PRODUCTION MANAGEMENT MODEL FOR SMALL AND MEDIUM ENTERPRISES

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Abstract. *Published research on steel fabrication covers individual technology domains (CNC cutting, BIM integration, ERP systems, quality standards) but does not offer a practical model for combining these elements into a unified production workflow within the resource constraints of small and medium enterprises. This article contributes in two parts. A comparative evaluation of plasma, oxy-fuel, and abrasive disc cutting methods is conducted using manufacturer data and independent technical sources, establishing the technological baseline for structural steel fabrication. An integrated production management model developed by the author at Kharkiv Stal LLC (Ukraine) over the period 2013–2025 is then presented. The model connects three components: ERP-based material reservation with three-status differentiation (available, reserved, committed), project-style order execution with stage-gated accountability, and a four-level quality inspection sequence embedded in the production cycle. Operational records from 2021–2025 document the following outcomes: order fulfillment cycle compressed from 10–14 days to 2–5 days, production delays reduced by approximately 70%, fabrication throughput increased by 30–40% without proportional workforce expansion, material preparation time shortened by 15–20%, and financial exposure to raw material price volatility decreased by 10–15%. Findings indicate that process integration methodology produces greater operational gains for resource-constrained fabricators than investment in advanced equipment without corresponding workflow coordination.*

Keywords: steel structure fabrication, integrated production management, CNC plasma cutting, ERP material reservation, quality control, small and medium enterprises, order fulfillment optimization.

Introduction

Global structural steel market volume reached USD 113 billion in 2024, with projections indicating expansion to USD 188 billion by 2034 at a compound annual growth rate of 5.24% [1, 14]. Fabricated and prefabricated steel sections represent the fastest-growing segment at approximately 20% CAGR, driven by demand for modular construction and off-site production [1]. Infrastructure renewal in developed economies, rapid urbanization in emerging markets, and post-conflict reconstruction needs in countries such as Ukraine reinforce sustained demand across the sector [2, 16].

Production of steel structures requires coordinated execution of multiple sequential operations, from initial order processing through cutting, welding, and surface treatment to final inspection and delivery. Large enterprises manage this coordination through dedicated engineering departments, procurement teams, and automated production lines backed by substantial capital. Small and medium fabricators face structurally different conditions: limited budgets restrict access to CNC equipment and robotic welding, lean staffing compresses several management functions into single roles, and informal verbal communication between departments replaces systematic process control [3, 4]. Since these enterprises account for a

ISSN: 2787-9364

significant share of structural steel output in regional markets, their operational efficiency has direct implications for construction timelines and costs.

Research in operations management suggests that in resource-constrained manufacturing environments, process integration delivers greater performance gains than incremental upgrades to individual equipment [5]. Applied to steel fabrication, this principle implies that a workshop using standard plasma cutting and semi-automatic welding can achieve shorter delivery cycles and lower defect rates than a better-equipped competitor, provided its material flow, production scheduling, and quality verification operate as a unified system rather than as disconnected departmental functions. When these elements remain fragmented, costly symptoms emerge: material double-allocated across orders causes production stalls, unverified drawings generate rework at the welding stage, and quoted delivery dates bear no traceable connection to actual workshop capacity.

Existing academic and industry literature covers individual components of this problem. BIM integration reduces design conflicts in steel construction projects [6, 7]. CNC cutting technology achieves documented tolerances and speeds [8]. IoT and automation reshape production monitoring and maintenance [9, 10]. Quality management standards define inspection protocols and acceptance criteria [11, 12]. What remains absent is a documented methodology for combining these elements into a single production workflow within the resource constraints typical of small and medium fabricators, supported by operational performance data from an enterprise outside Western European or North American contexts.

This article addresses the identified gap through two complementary contributions. First, a comparative analysis of contemporary fabrication technologies establishes the technical foundation upon which production management operates. Second, an integrated production management model developed by the author at Kharkiv Stal LLC (Kharkiv, Ukraine) over the period 2013–2025 is presented. The model unifies digital inventory control, staged production management with defined accountability, and embedded quality assurance into a single coordinated workflow. Operational data from the enterprise quantify the model's impact on cycle time, throughput, delay frequency, and financial risk exposure.

Scientific novelty of the study consists in the development and empirical validation of an integrated production management model that connects ERP-based material reservation with three-status differentiation, stage-gated order execution, and sequential quality inspection within a single steel fabrication workflow. While individual components (ERP, stage-gate, inspection protocols) exist in established management practice, their documented combination and quantified performance impact within structural steel fabrication at the SME scale have not been previously reported in the reviewed literature.

Literature review

BIM application in steel construction has generated evidence primarily at the project coordination level. Avendaño et al. [6] developed a BIM-DFE methodology through practitioner consensus, confirming that BIM adoption reduces erection-stage conflicts and improves phase-to-phase coordination, though the study mapped the project lifecycle without measuring fabrication-stage outcomes such as cutting accuracy, order cycle duration, or defect rates.

Soliman et al. [7] correlated BIM maturity with project delivery indicators in Egyptian steel construction, while Wang et al. [4] demonstrated BIM-based structural safety assessment for prefabricated steel frames. Both studies operate at the project or organizational level; neither disaggregates fabrication performance from overall project metrics.

CNC plasma cutting technology has reached documented maturity levels stratified by system class. Hypertherm technical documentation [8] reports that entry-level CNC systems maintain tolerances of approximately ±0.77 mm; light industrial systems with torch height control reach ±0.38 to ±0.64 mm; high-definition systems achieve ±0.25 to ±0.51 mm on steel plate up to 50 mm thickness. True Hole technology on high-definition platforms produces bolt-

ISSN: 2787-9364

ready openings, eliminating secondary drilling and removing one operation from the fabrication sequence per connection point. Actual shop-floor precision depends on consumable condition, material surface quality, and calibration frequency, meaning that manufacturer specifications represent achievable ceilings rather than guaranteed baselines. Oxy-fuel cutting retains a defined niche for heavy plate exceeding 50 mm, where plasma systems reach operational limits, but its wider heat-affected zone and lower speed confine it to applications where material thickness dictates the method rather than production rate.

Quality management in steel fabrication operates within a regulatory framework established by two principal standards. EN 1090-2 [11] defines four execution classes (EXC1 through EXC4) that determine permissible dimensional tolerances, inspection scope, and documentation requirements for steel structures based on consequence class and service category. ISO 3834-2 [12] establishes comprehensive quality requirements for fusion welding: personnel qualification, equipment calibration records, welding procedure specifications, and inspection documentation. Both standards prescribe what must be controlled and verified, but neither addresses how inspection activities should be sequenced within a production workflow to minimize total cost of quality. Catching a dimensional error after cutting costs one re-cut part; discovering the same error after welding costs disassembly, re-cutting, re-welding, and schedule disruption.

Industry analyses from 2024 identify technology trends including collaborative robots accessible to small fabricators [9], hybrid additive-subtractive manufacturing and AI-driven quality prediction [10], and IoT-enabled predictive maintenance with reported 20–30% downtime reduction [13]. Each report identifies a promising direction; none quantifies the cumulative effect of deploying multiple technologies within a single coordinated production workflow.

A whole-life-cycle intelligent construction framework proposed by the Journal of Building Technology [5] combines BIM, IoT, and cloud computing for construction monitoring from design through demolition. Its relevance here is limited: the framework addresses construction-site management rather than fabrication-shop workflow and remains at the conceptual stage without empirical validation.

Production organization in small and medium manufacturing enterprises presents a distinct challenge. Stage-gated workflow models, which require completion verification before work proceeds to the next phase, have demonstrated effectiveness in product development and batch manufacturing [15]. ERP systems configured with material requirements planning (MRP) and shop floor control modules provide the digital infrastructure for such coordination; empirical studies confirm that ERP adoption in manufacturing SMEs improves operational efficiency, reduces production cycle times, and strengthens cost control [17, 18]. Tasevska et al. [19] documented ERP-based project planning practices in Macedonian SMEs, finding that smaller firms tend to use ERP for basic scheduling rather than for integrated workflow management. Published implementations of full process integration, however, concentrate in automotive, electronics, and food processing sectors where production volumes and product standardization differ substantially from the project-oriented, low-batch, high-variability environment of structural metalwork. Documented case evidence of integrated process management in steel fabrication at the SME scale has not been identified in the reviewed literature.

Across the reviewed sources, each domain contributes validated knowledge within its scope: BIM at the project level, cutting technology per machine class, emerging tools per technology category, and quality standards per inspection requirement. What remains undocumented is how these contributions interact when combined within a single SME production management system, and what measurable operational outcomes such integration

ISSN: 2787-9364

produces. The gap is not in any individual domain but in the absence of a documented model connecting them into an integrated fabrication workflow. This article addresses that gap.

Table 1. *Reviewed literature: thematic coverage, methods, findings, and unaddressed gaps*

Source	Domain	Method	Principal finding	Gap relative to this study
Avendaño et al. [6]	BIM / steel construction	Delphi survey, 31 practitioners, 3 rounds	BIM-DFE methodology improves design-fabrication-erection coordination	Fabrication-stage operational metrics not measured
Soliman et al. [7]	BIM adoption factors	Structural equation modeling, Egypt	Digital literacy and software compatibility are primary barriers	Fabrication performance not separated from project-level outcomes
Wang et al. [4]	Structural safety / BIM	Finite element analysis, case studies	BIM-based assessment identifies design flaws before production	Safety compliance measured, not production efficiency
Hypertherm [8]	CNC plasma cutting	Manufacturer technical data	HD plasma: ±0.25–0.51 mm; True Hole eliminates secondary drilling	Manufacturer data; shop-floor results vary by conditions
EN 1090-2 [11]	Execution standards	Regulatory standard	Execution classes define tolerances and inspection scope	Prescribes requirements without workflow sequencing guidance
ISO 3834-2 [12]	Welding quality	Regulatory standard	Comprehensive welding QA: personnel, equipment, documentation	Process-agnostic; no production integration methodology
AM Industries [9]	Industry 4.0 trends	Industry survey	Cobots, IoT, additive manufacturing accessible to SME fabricators	No cumulative impact assessment across technologies
WeldFlow Metal [10]	Fabrication trends	Industry review	Hybrid manufacturing and AI quality prediction gaining traction	Descriptive trends without enterprise-level case evidence
Benchmark Steel [13]	IoT / maintenance	Industry report	Predictive maintenance reduces unplanned downtime 20–30%	Estimate without disclosed measurement methodology
J. Build. Technol. [5]	Intelligent construction	Conceptual framework	Whole-life-cycle BIM-IoT-cloud system for steel buildings	Theoretical; no empirical validation; construction-site focus
Precedence Research [1]	Market analysis	Market modeling	Structural steel: USD 113B (2024), CAGR 5.24% to 2034	Market-level data without enterprise operational analysis
El-Baz et al. [17]	ERP in manufacturing	Survey, SEM, Middle East firms	ERP improves production process performance and cost control	General manufacturing; not specific to steel fabrication or SME workflow integration
Tuli [18]	ERP / operational efficiency	Literature review	ERP adoption enhances productivity and reduces cycle times	Review-level findings; no enterprise-specific case data
Tasevska et al. [19]	ERP in SMEs	Case study, Macedonia	SMEs use ERP for scheduling but underutilize integration features	Non-steel sector; basic ERP use without full workflow integration

Source: compiled by the author.

ISSN: 2787-9364

Materials and methods

Two methodological approaches structure this study. Comparative technology analysis synthesizes published data from 2019 to 2025 identified through Scopus and Google Scholar (search terms: “steel fabrication technology,” “CNC plasma accuracy,” “BIM steel construction,” “welding quality control SME”). Manufacturer technical documentation (Hypertherm, ESAB) and market reports (Precedence Research, World Steel Association) supplement academic sources. Inclusion criteria required quantitative performance data: tolerances in millimeters, speeds in mm/min, defect percentages, or cycle time measurements. Cutting technologies were compared across five parameters: dimensional tolerance, applicable thickness range, cutting speed on 10 mm structural steel, heat-affected zone characteristics, and automation potential. EN 1090-2 [11] and ISO 3834-2 [12] were used as regulatory benchmarks for assessing quality control practices against established industry requirements.

Practice-based documentation covers the production management approach developed by the author at Kharkiv Stal LLC (Kharkiv, Ukraine), established in 2013. Operational data span the period 2021–2025, during which the model operated in its mature configuration after eight years of iterative refinement. Six performance indicators were tracked from internal management records, grouped into three categories. Time-based indicators include average order fulfillment duration (calendar days from confirmed order to shipment) and material preparation time (hours from order confirmation to production-ready material staging). Volume and reliability indicators comprise concurrent order capacity (number of active orders in fabrication without schedule degradation), production delay frequency (share of orders shipped past committed date), and unplanned production stoppages (events per month caused by material unavailability or scheduling conflicts). Financial exposure is measured as variance between quoted and actual material costs (percentage deviation serving as a proxy for price volatility risk).

Baseline values for the period prior to full model implementation were reconstructed from archived order logs, delivery records, and financial reports covering 2013–2018, when individual components of the model were being developed and tested sequentially. Comparison between the baseline period and the 2021–2025 observation window therefore reflects the cumulative effect of the integrated model against conditions where its components were either absent or operating independently of each other.

A full description of the enterprise’s production infrastructure, equipment inventory, and supply chain is provided in Section 4.1, where it serves as the operational context for the model presentation.

Methodological limitations require explicit acknowledgment. Data originate from a single enterprise and reflect management records rather than controlled experimental conditions with randomized variables. Observed performance changes may be influenced by concurrent factors beyond the model itself, including market conditions, workforce experience accumulation, and incremental equipment maintenance. Comparative technology parameters compile manufacturer specifications alongside practitioner observations; actual performance varies with equipment age, consumable condition, material properties, and operator skill. Results are presented as documented practice outcomes, and generalization beyond the specific enterprise context requires further validation through multi-site studies.

Results and discussion

1. Production context and enterprise infrastructure

Kharkiv Stal LLC was established in 2013 in Kharkiv, Ukraine, building on a decade of the founder’s prior experience in metal trading as a sole proprietor. Current operations combine three business lines. Wholesale supply covers rolled steel products: profile and round tubes, rebar, sheet and coil stock, angles, channels, I-beams, galvanized and stainless sheet. In-house fabrication produces steel structures including trusses of 12 m and 24 m standard span, frames,

ISSN: 2787-9364

gates, platforms, fencing, and custom metalwork. A roofing and cladding line manufactures profiled sheeting in C8, C10, C20, and H44 corrugation patterns, metal roofing tiles, and welded masonry and reinforcing mesh.

Production occupies three working areas totaling approximately 4,100 m^2. The primary area (2,500 m^2) is served by a 20-ton bridge crane with remote control; two secondary areas (800 m^2 each) operate with 5-ton hoists. Fabrication equipment includes plasma and oxy-fuel cutting stations, semi-automatic MIG/MAG welding units, manual arc MMA welding sets, a spot welding station, a coil-fed profiling line with programmatic length setting and automatic waveform deviation monitoring, and sheet metal bending equipment. A forklift and crane-beam complement the overhead cranes for material handling across the site.

Metal is sourced from certified suppliers: Metinvest-SMC, ArcelorMittal Kryvyi Rih, Cascade, Slavsant, AV Metal Group, and selected European and Asian mills. Every incoming shipment carries mill certificates, and the enterprise works exclusively with material of confirmed origin and documented mechanical properties. Inventory, order processing, material reservation, invoicing, and production planning operate through a 1C-based ERP platform. Supplementary calculations (order costing, material take-off estimates) are handled in spreadsheet models.

Client categories span construction firms executing structural and finishing works, industrial enterprises requiring metalwork for equipment supports and facility modifications, and private builders purchasing small quantities of rolled stock or roofing materials. Delivery is performed by the company's own vehicle fleet across Kharkiv and the surrounding region, with same-day dispatch available for stock items and established clients operating on post-delivery payment terms.

2. Production cycle stages

Steel structure fabrication at Kharkiv Stal follows an eight-stage sequential process, schematically represented in Figure 1. Each stage generates outputs consumed by the next, forming a dependency chain where delays or errors at any point cascade downstream.

At stage one, order receipt and classification, the client submits specifications ranging from a simple material list to detailed engineering drawings. Orders are classified as standard (catalog items, stock trusses of 12 m or 24 m span) or custom (bespoke dimensions, non-typical connections, unusual load requirements). Standard orders bypass engineering review and proceed directly to material allocation. Stage two, cost estimation and scheduling, calculates material quantities from specifications, checks current stock against the ERP database, and establishes a production timeline based on workshop loading. For standard orders, this stage completes within hours; complex custom projects may require one to two working days of engineering assessment.

Stage three, drawing verification and technical coordination, represents the highest-leverage error prevention point in the entire cycle. Dimensional feasibility, connection details, and standards compliance are confirmed before any material is committed. An error caught here costs minutes of engineering time; the same error discovered during welding requires re-cutting and re-fabrication at a cost multiplied by material, labor, and schedule impact. Stage four, material reservation and procurement, links confirmed orders to specific stock within the ERP system. If required material is not available, procurement is initiated with lead times incorporated into the production schedule.

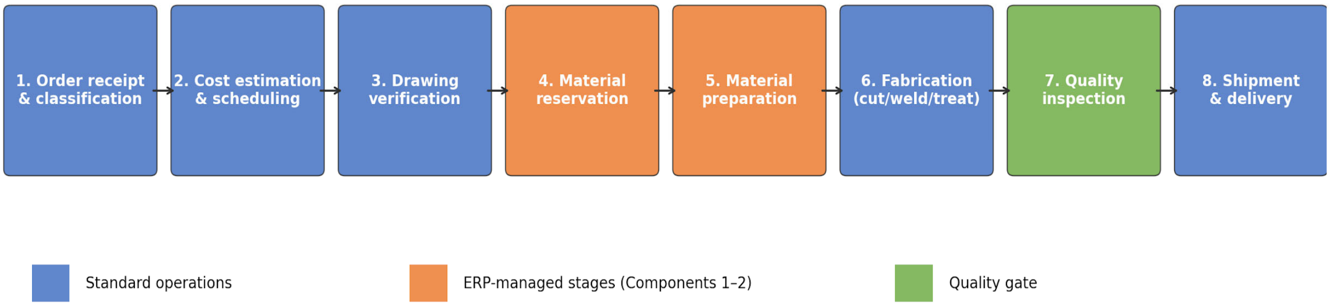
Stage five is material preparation: incoming metal is sorted, measured for thickness and dimensional conformity against delivery documents and quality certificates, then marked and positioned for cutting. Stage six encompasses primary fabrication operations: cutting (plasma, oxy-fuel, or abrasive disc), drilling, welding (semi-automatic MIG/MAG, manual arc MMA, or spot welding depending on joint type), seam grinding, and surface treatment (priming,

ISSN: 2787-9364

painting). Each operation follows the sequence specified in the production drawing, with hold points for dimensional checks after cutting and weld quality verification after joining.

Stage seven is final quality inspection: completed structures are checked against original drawings for dimensional accuracy, component completeness, weld quality, and surface finish. Stage eight is packaging, loading, and shipment via the company's own transport, hired vehicles, or client self-collection. Standard orders are typically fulfilled within one to two working days; custom structures require two to five days, with complex projects extending to two weeks.

Fig. 1. *Eight-stage steel structure fabrication cycle at Kharkiv Stal LLC*



Source: developed by the author.

3. Comparative technology baseline

Table 2 consolidates the cutting method comparison introduced in the literature review into a single reference, adding the distinction between standard and high-definition CNC plasma, manual plasma data, and bolt-hole capability as parameters relevant to structural fabrication practice. Figure 2 visualizes the tolerance ranges across methods to illustrate the accuracy hierarchy.

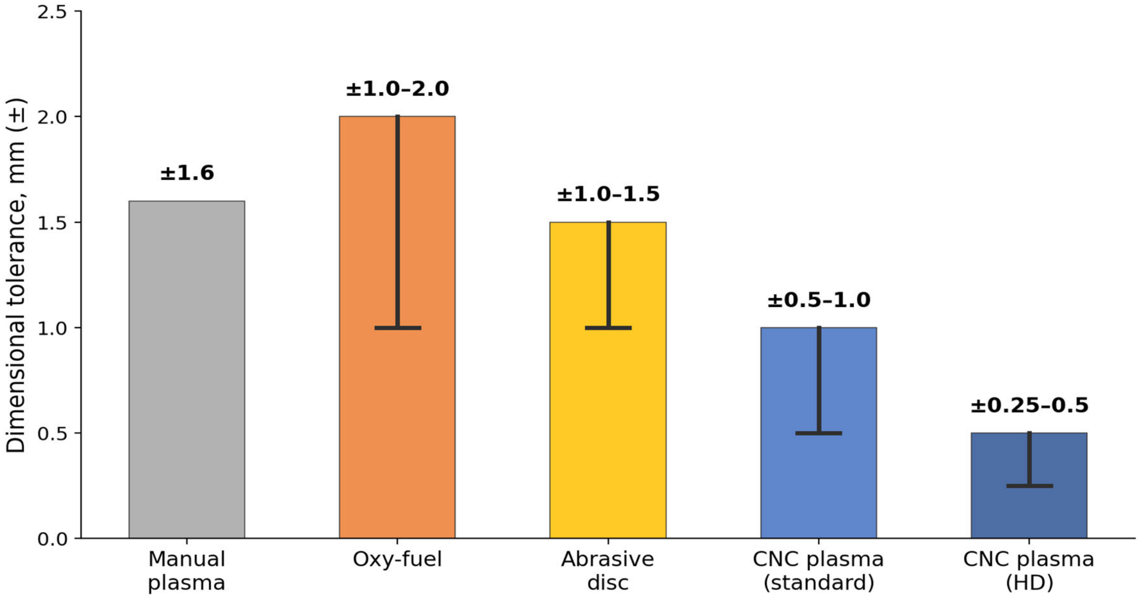
Table 2. *Comparative parameters of metal cutting methods in steel structure fabrication*

Parameter	CNC plasma (std)	CNC plasma (HD)	Oxy-fuel	Abrasive disc	Manual plasma
Tolerance, mm	±0.5–1.0	±0.25–0.5	±1.0–2.0	±1.0–1.5	±1.6 or wider
Thickness range, mm	0.5–50	0.5–50	3–300	up to 100	0.5–38
Speed, 10 mm steel, mm/min	2,000–4,000	2,000–3,500	300–600	200–400	600–1,200
Heat-affected zone	Moderate, narrow	Narrow	Wide	Minimal	Moderate, variable
Automation potential	High	High	Moderate	Low	None
Bolt-ready holes	Limited	Yes (True Hole)	No	N/A	No

Source: compiled by the author based on [8, 9, 11, 12].

ISSN: 2787-9364

Fig. 2. *Cutting method tolerance comparison for structural steel (based on Table 2 data)*



Source: compiled by the author based on [8, 9, 11, 12].

At Kharkiv Stal, plasma cutting handles most plate and section processing for structural fabrication, while oxy-fuel is reserved for occasional thick-plate work. Abrasive disc cutting serves bar, angle, and tube sections where thermal distortion must be minimized. Manual plasma, once the primary cutting method during the enterprise's early years, has been progressively displaced by CNC-guided operation for all work where dimensional accuracy affects assembly fit.

Welding divides along functional lines. Semi-automatic MIG/MAG welding is the primary production method for truss chords, frame joints, and custom structural connections, operating at deposition rates of 3–8 kg/h depending on wire diameter and joint configuration across the typical 4–12 mm plate thickness range used in structural work. Manual arc MMA welding (1–3 kg/h deposition rate) addresses field repairs, tack welding during assembly, and positional work in confined areas where torch access precludes semi-automatic equipment. Spot welding is dedicated to mesh production, where thousands of wire-crossing joints per shift demand speed and repeatability over penetration depth.

Profiled sheeting production operates on a separate workflow from structural fabrication. Coil steel (0.35–0.85 mm thickness, galvanized or polymer-coated) feeds continuously through the profiling line. Sheet length is set by program; the line halts automatically if corrugation geometry deviates from stored parameters. Output includes C-profile sheeting for wall cladding and fencing, H-profile sheeting for load-bearing roof applications, and metal roofing tiles cut to individual order lengths. Bending equipment produces complementary roofing elements such as ridges, valleys, and gutters.

4. Integrated production management model: structure and operating mechanisms

Recurring operational problems during the first years of the enterprise's growth motivated development of the integrated model. Material allocated to one order would be consumed by another due to informal stock tracking, causing unplanned production stalls. Delivery dates quoted by sales staff reflected optimistic estimates rather than verified workshop capacity, eroding client confidence when deadlines were missed. Price quotations calculated from outdated supplier lists created margin losses when actual procurement costs proved higher. Individual employees performed their functions competently, but the absence of a connecting logic between sales, warehouse, production, and dispatch meant that each department optimized locally while the overall order flow suffered.

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The model that emerged through iterative refinement between 2013 and 2020 comprises three interlocking components. Each is described below in terms of its operating mechanism and the specific problem it addresses.

Component 1: ERP-based material reservation with three-status inventory.

Every stock-keeping unit in the 1C system carries one of three statuses. Available denotes uncommitted inventory open for allocation to new orders. Reserved denotes material assigned to a confirmed order but not yet physically moved to the production area. Committed denotes material staged at the cutting or welding station for a specific job in progress. Status transitions follow a strict sequence tied to order lifecycle events. Upon order confirmation, reservation is initiated and the system verifies that required material exists in available status or can be procured within the quoted lead time. Insufficient stock is flagged before the commitment is finalized, not after production has been scheduled.

In daily operation, reservation status is reviewed against the production schedule each morning to confirm that reserved material is physically accessible. When material moves from reserved to committed (physically transferred to the production area), the status update is entered immediately, preventing other orders from claiming that stock. Cancelled or postponed orders trigger a documented reversal that frees reserved material for same-day reallocation. The mechanism distributes responsibility across commercial and warehouse functions, with each status transition requiring confirmation from the responsible party.

Before this mechanism was in place, the most frequent cause of production delays was double allocation: two confirmed orders drawing on the same physical stock, with the conflict surfacing only when the second order reached the cutting station and the material was already consumed. Reservation with status differentiation eliminates this failure mode by making every unit of inventory visible as either free, claimed, or in use. Procurement decisions are similarly informed: replenishment is triggered by the gap between total reserved quantities and available stock, replacing the previous approach of reordering based on periodic visual inspection of warehouse shelves.

Component 2: Project-style order execution with stage-gated accountability.

Each confirmed order is registered as a discrete operational project in the ERP system with a defined stage sequence: technical review, material staging, cutting, welding, surface treatment, quality inspection, and shipment preparation. Progression from one stage to the next requires a completion entry by the responsible person. Cutting cannot begin until material staging is confirmed. Welding cannot proceed without post-cutting dimensional verification. Surface treatment awaits weld inspection sign-off. Shipment requires final quality clearance.

Each transition is logged with timestamp, responsible party, and exception notes. When delays occur, the blocking stage is immediately identifiable, replacing retrospective investigation with real-time bottleneck visibility. Management can see at any moment how many orders occupy each stage, where capacity constraints are forming, and which deliveries are at risk.

Scheduling operates on verified capacity rather than sales-driven promises. Before a delivery date is quoted, the system checks material availability (Component 1), current workshop loading across all active orders, and estimated processing time for the new order based on its complexity classification. Dates that the workshop cannot support are flagged before the commitment reaches the client. This connection between scheduling and actual capacity was absent in the enterprise's early operations, when sales and production functions operated on different information sets.

Component 3: Adaptive commercial logic linked to real-time production data.

Pricing under this approach uses actual material costs drawn from current ERP stock valuations at the moment of quotation rather than from a static price list. In markets where monthly material price swings of 5–10% are routine, this mechanism ensures that every

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quotation reflects the current cost base, eliminating the margin erosion that occurs when prices are calculated from outdated procurement data.

Order-specific profitability is tracked from quotation through production to invoicing, comparing actual material consumption and labor hours against initial estimates. Deviations visible at order closure enable identification of product lines where estimates consistently diverge from actual costs. Over time, this feedback loop improves estimation accuracy and highlights where process improvement yields the greatest margin recovery.

The three components interact as a closed loop. Material reservation data feed into production scheduling, which determines achievable delivery dates, which anchor commercial commitments. When conditions change (a delayed supplier shipment, an urgent order insertion, a material price shift), the connected system propagates the impact across all affected orders and surfaces scheduling conflicts before they cause missed deadlines. The model operates within standard 1C functionality configured for manufacturing and requires consistent process discipline across all staff roles rather than proprietary software or custom development.

5. Operational outcomes of model implementation

Table 3 presents performance indicator values for the baseline period (2013–2018, when model components were under development or operating independently) and the observation period (2021–2025, with the full integrated model in operation). Baseline values for order fulfillment cycle were reconstructed from archived delivery records. Remaining indicators were not systematically measured during the baseline period; reported percentage changes reflect management's retrospective assessment of conditions before and after full integration, cross-referenced with available order logs and financial records.

Table 3. *Performance indicators: baseline versus integrated model operation*

Performance indicator	Baseline (2013–2018)	Integrated model (2021–2025)	Change
Average order fulfillment cycle	10–14 days	2–5 days	−60–75%
Production delay frequency	Not systematically recorded; delays were a regular occurrence	Substantially reduced	−~70%
Fabrication throughput (concurrent orders)	Not systematically recorded	Increased without proportional staff expansion	+30–40%
Material preparation time	Not systematically recorded	Reduced	−15–20%
Unplanned production stoppages	Multiple events per month	Occasional	−~30%
Financial risk from price volatility	Not systematically recorded; margin losses from outdated pricing were common	Reduced through live cost linkage	−10–15%
Emergency procurement costs	Not systematically recorded	Reduced	−10–15%

Source: compiled by the author based on operational records and management assessments, Kharkiv Stal LLC.

ISSN: 2787-9364

Order cycle compression results from three simultaneous mechanisms rather than a single cause. Pre-staged material through reservation (Component 1) eliminates wait time that previously separated order confirmation from production start. Stage-gated workflow (Component 2) prevents accumulation of partially processed orders blocking workshop capacity for new work. Verified scheduling ensures that production sequences are optimized for equipment utilization rather than defaulting to first-in-first-out arrival order.

Throughput increase without proportional staff expansion traces to elimination of non-productive time previously absorbed by material searches on the warehouse floor, status tracking through in-person inquiries, and rework cycles caused by specification errors caught late in production. With every order carrying a defined stage status in the ERP system, supervisory attention shifts from locating information to resolving actual production constraints.

Reduction of unplanned stoppages connects directly to the reservation mechanism. Before three-status inventory control, production stalls from material unavailability recurred multiple times monthly, each incident idling equipment and labor for hours while alternative stock was located or emergency procurement arranged. With reservation, competing claims on the same stock surface at the moment of order confirmation, days before production is scheduled, rather than at the cutting station.

Financial risk mitigation is a direct consequence of the live cost-to-quote linkage described in Component 3. Quotations based on outdated price data, even by one to two weeks, can convert target-margin orders into losses in a volatile raw material market. Connecting each quotation to current ERP-recorded procurement costs keeps commercial commitments aligned with actual material expenditure and eliminates the margin erosion that characterized the baseline period.

External validation comes from long-term business partners across construction and industrial sectors. Enterprises collaborating with Kharkiv Stal for periods exceeding ten years have reported improved delivery predictability, reduced need for status follow-up communication, and consistent material quality. In documented cases, supply reliability enabled partner firms to compress their own project timelines by 10–15%, as dependable material delivery allowed them to schedule downstream trades with greater confidence. Clients operating under framework supply agreements note that the real-time pricing model provides competitive terms without exposing either party to speculative risk, since prices adjust with the market rather than being locked to a historical snapshot.

6. Quality assurance as an embedded production function

Quality inspection within the integrated model is distributed across four levels aligned with the production stage sequence rather than concentrated at the endpoint. Figure 3 presents the inspection framework schematically, showing the four levels, their position in the production chain, the parameters verified at each level, and the cost implications of defect detection at progressively later stages.

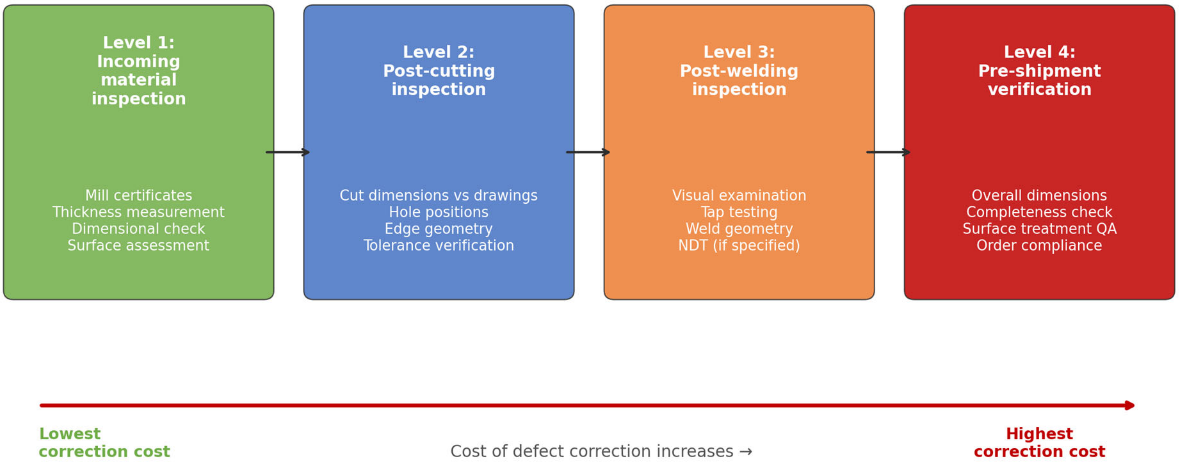
Level one operates at material entry. Incoming steel is checked against delivery documentation (mill certificates, quality passports), measured for actual thickness and dimensions, and visually inspected for surface defects (corrosion, mechanical damage, delamination). Rejections at this level are infrequent due to established supplier relationships but remain a necessary safeguard; occasional thickness deviations or surface damage are intercepted and returned before they consume production resources.

Level two follows cutting. Dimensions of cut parts are measured against production drawings: lengths, widths, hole positions, edge angles. For plasma-cut components, typical deviations fall within the CNC system's stated tolerance band. Parts produced by manual methods receive denser measurement sampling due to higher operator-dependent variability. Dimensional errors caught at this stage require re-cutting of one part; the same error

ISSN: 2787-9364

discovered after welding requires disassembly, re-cutting, and re-welding, a cost multiplication that justifies the inspection investment.

Fig. 3. *Four-level quality inspection framework embedded in the production cycle*



Source: developed by the author.

Level three addresses weld quality. Visual examination assesses surface regularity, absence of visible porosity, undercut depth, and spatter distribution. Tap testing identifies hollow or poorly fused areas through acoustic response differences. Dimensional measurement confirms throat thickness and leg length for fillet welds, and bead profile for butt joints. For standard structural connections, these three methods provide sufficient quality verification. When engineering specifications or applicable codes require higher assurance, non-destructive testing (ultrasonic or radiographic) is arranged through external testing laboratories.

Level four is pre-shipment verification. Completed structures are measured for overall dimensions against the original order, checked for component completeness (all elements, fasteners, and accessories present), assessed for surface treatment coverage and quality (primer adhesion, paint uniformity, absence of bare spots), and matched against the order specification for quantity and marking accuracy. Only structures clearing this gate proceed to loading and dispatch.

Embedding inspection at each production stage converts quality control from a post-production rejection function into a progressive prevention mechanism. A defect intercepted after cutting costs material and machine time for one re-cut part. A defect intercepted after welding adds welding labor, consumables, grinding time, and schedule displacement to that cost. A defect that reaches the client adds transport, on-site disruption, return logistics, and reputation damage. The four-level framework positions detection at the earliest viable point in the value chain, minimizing total quality cost across the production cycle.

7. Development prospects for steel fabrication technology

Three technology directions hold near-term relevance for fabricators at the scale described in this study, each building on the integrated management foundation rather than replacing it.

Collaborative robotic welding offers the most immediate productivity impact for enterprises with repetitive structural joint types. Standard truss chord-to-web connections, frame corner joints, and plate stiffener welds follow consistent geometries amenable to robotic programming. A single cobot station integrated into the existing stage-gated workflow would occupy one position in the welding stage, processing standardized joints while skilled welders concentrate on complex positional work and custom connections. For enterprises where

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standardized trusses and frames constitute 40% or more of output, capital recovery within 18–24 months appears achievable based on published pricing and productivity data [9, 10].

IoT-based equipment monitoring addresses a different constraint: unplanned maintenance downtime. Connecting machine health data to the ERP system enables maintenance scheduling during planned production gaps rather than emergency response during active orders. Integration with the stage-gated workflow means that maintenance-triggered delays become visible to scheduling and can be communicated to affected clients proactively, preserving delivery commitment credibility even when equipment issues arise.

Additive manufacturing of connection nodes and complex brackets remains a future consideration rather than a near-term implementation target. Current build speeds and material costs position metal 3D printing as viable for prototype development, one-off replacement parts, and geometrically complex nodes where conventional fabrication would require extensive jigging and multi-pass welding. Volume production of structural components is not yet practical at this technology's current maturity, but monitoring its cost trajectory is warranted as the technology continues to mature [9].

Discussion

Results obtained at Kharkiv Stal can be situated within the broader findings reported in the reviewed literature, though direct numerical comparison is limited by differences in scale, methodology, and measured outcomes.

BIM-focused studies by Avendaño et al. [6] and Soliman et al. [7] demonstrated that coordination improvements at the project level reduce conflicts and rework during construction, with reported rework reduction of 10 to 15% [6]. The approach described in this article operates at a different level: within the fabrication shop rather than across the project lifecycle. Yet both findings converge on the same underlying principle, that systematic coordination between sequential process stages can produce returns that exceed the apparent effort invested. Where BIM coordinates information flow between organizations, the author's model coordinates material flow, production scheduling, and quality verification between departments within a single enterprise. The scale of cycle time improvement at the shop-floor level suggests that intra-enterprise coordination may offer substantial efficiency potential comparable to or exceeding inter-organizational coordination, particularly for small fabricators where departmental fragmentation is the dominant bottleneck.

The relationship between the four-level quality inspection framework and the requirements of EN 1090-2 [11] and ISO 3834-2 [12] merits specific comment. Both standards define what must be inspected and to what acceptance criteria, but they do not prescribe the sequence in which inspection activities should be positioned within a production workflow. The four-level framework fills a practical gap between regulatory prescription and operational implementation: it answers the question of when in the production sequence each inspection type should occur to minimize total quality cost. Positioning incoming material checks before stock enters the production stream, dimensional verification after cutting but before welding, weld inspection before surface treatment, and comprehensive final checks before shipment ensures that defects are intercepted at the point where correction cost is lowest.

Industry trend reports [9, 10, 13] identify cobots, IoT monitoring, and additive manufacturing as transformative technologies for metal fabrication but do not address the management infrastructure required to absorb them effectively. Operational evidence suggests that advanced technologies produce their intended returns only when deployed onto a coordinated production base. A cobot welding station delivers productivity gains only if several preconditions are met: material must arrive on schedule (Component 1), the preceding cutting stage must be completed and dimensionally verified (Component 2), and welding parameters must be set for correctly specified material (accurate ERP order data). Without this infrastructure, robotic equipment risks standing idle for the same reasons that previously idled

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human welders. Workflow coordination therefore functions as a prerequisite for effective technology adoption rather than an optional enhancement.

Generalizability of these findings is constrained by the single-enterprise origin of the operational data. Observed improvements may partly reflect enterprise-specific factors such as management continuity, regional market characteristics, and workforce stability that would manifest differently elsewhere. Retrospective baseline reconstruction introduces recall bias for indicators that were not concurrently measured. No parallel control group of comparable enterprises was available. These constraints do not invalidate the documented outcomes but require that they be interpreted as evidence from one implementation rather than as universally replicable benchmarks.

Despite these limitations, the core finding aligns with established operations management theory regarding system-level optimization [5, 15] and with empirical ERP research confirming that integrated digital systems improve operational efficiency in manufacturing environments [17, 18, 19]. Coordination across material management, production staging, and quality inspection appears to yield gains that exceed what isolated improvements in any single area would produce. The mechanisms documented here represent one possible implementation of this principle. Transferability to other SME fabricators is likely highest for the structural elements (stage sequencing, status-based reservation logic, inspection positioning) and lowest for specific ERP configurations and process parameters, which depend on local software availability, workforce digital literacy, and production mix.

Conclusions

Comparative analysis of contemporary fabrication technologies confirmed CNC plasma cutting as the optimal method for structural steel plate in the 0.5–50 mm thickness range, delivering tolerances of ±0.25 to ±1.0 mm at cutting speeds several times higher than oxy-fuel or abrasive alternatives. High-definition systems with True Hole capability further compress the fabrication sequence by eliminating secondary drilling operations. For small and medium fabricators, however, cutting technology alone does not determine competitive position; the method by which available technologies are connected into a managed production sequence proves to be the decisive factor.

The management approach presented in this article suggests that unifying ERP-based material reservation, stage-gated order execution, and adaptive commercial logic within a single workflow can produce improvements across multiple performance dimensions simultaneously. Across all six tracked indicators, observed improvements ranged from 10% to 75%, with the largest gains observed in order cycle duration and delay frequency. These outcomes were achieved within standard ERP functionality without proprietary software or disproportionate capital investment, confirming that the model's core value lies in process discipline and coordination logic rather than in technological sophistication of individual tools.

The four-level quality inspection framework embedded in the production cycle addresses a gap between regulatory standards (EN 1090-2, ISO 3834-2), which prescribe what must be verified, and operational practice, which must determine when and in what sequence verification occurs. Positioning inspection at material entry, post-cutting, post-welding, and pre-shipment stages minimizes total quality cost by intercepting defects at the earliest point where correction remains economical.

Prospective technology adoption (collaborative robotic welding, IoT-based equipment monitoring, additive manufacturing of complex nodes) should follow rather than precede establishment of the integrated management foundation. Evidence from this study suggests that advanced equipment deployed without underlying workflow coordination may deliver diminished returns, which positions workflow coordination as an important enabler of operational improvement and a foundation for absorbing subsequent technological upgrades. For fabricators operating in markets with urgent demand, such as post-conflict reconstruction,

ISSN: 2787-9364

the emphasis on delivery speed, consistent quality, and cost predictability may be particularly relevant.

Further research should extend validation of the proposed model to multiple enterprises across different markets and production profiles, employ controlled comparative methodologies where feasible, and quantify interaction effects between the management model and advanced technologies as these become accessible to fabricators at the small and medium enterprise scale.

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