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Smart Manufacturing with CAD/CAM Integrating Automation and Optimizing Product Lifecycle Management

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Abstract- Modern manufacturers use CAD, CAM, CNC automation, quality systems and PLM platforms that often operate as isolated data silos, causing duplicated effort, delayed change propagation and weak traceability. This paper presents an integrated smart-manufacturing framework that links CAD, CAM, automation and data acquisition, inspection and Product Lifecycle Management (PLM) through a continuous digital thread. The framework is demonstrated in two case studies: (i) CNC machining of a bearing housing, covering CAD release, CAM tool-path simulation, sensor-based data logging and inspection linked to drawing revisions; and (ii) a Cortona3D workstation-planning study, in which a Siemens Teamcenter bill of materials drives interactive 3D work instructions for a motorcycle assembly and maintenance process. Compared with manual work planning, the integrated approach reduced work-instruction authoring time by about 75–80% (40–60 h to 8–12 h), first-time-through assembly defects from 8.5% to 1.8%, and operator training from 5 to 1.5 days, while enabling real-time propagation of engineering changes. The results indicate that connecting design, manufacturing and lifecycle data improves productivity, quality and traceability, and offers a scalable route to Industry 4.0 adoption for small and medium-sized enterprises (SMEs).

Index Terms— smart manufacturing, CAD/CAM integration, industrial automation, product lifecycle management, digital thread, Cortona3D, Industry 4.0.Keywords- Shared decision-making, patient-reported outcomes, Oswestry Disability Index, minimal important change, lumbar decompression, radiculopathy, patient-centred care

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I. INTRODUCTION

Manufacturing has moved from manual, stand-alone operations toward digitally connected production. Computer-Aided Design (CAD) provides accurate 3D product definitions, Computer-Aided Manufacturing (CAM) converts that geometry into machining strategies and CNC programs, and automation using PLCs, sensors, robots and CNC machines improves repeatability and productivity. However, automation alone does not create a smart factory; the benefit is realized only when design, production, quality and maintenance systems exchange information [1], [11]. Smart manufacturing builds on IoT/IIoT, cloud computing, analytics, digital twins and cyber-physical systems (CPS) so that machines, products and information systems can communicate [9], [10], [12]. Product Lifecycle Management (PLM) complements these technologies by controlling product data—CAD models, drawings, bills of materials (BOMs), revisions, process plans, quality records and service history—from concept to end-of-life. The continuous flow of such information across lifecycle stages is referred to as the digital thread [1]–[3]. In practice, many organizations, particularly SMEs, still run CAD files, CAM programs, CNC logs, inspection reports and PLM records as separate datasets. Design changes may not reach the shop floor promptly, and production or quality feedback rarely returns to engineering. This paper addresses that gap. The main contributions are: (1) an integrated CAD → CAM → automation → data acquisition → inspection → PLM framework with feedback to design; (2) a CNC machining case study that demonstrates the workflow on a bearing housing; and (3) a workstation-planning case study using Siemens Teamcenter and Cortona3D that quantifies gains over manual working planning.

II. RELATED WORK

Systematic reviews identify the digital thread as a key enabler of lifecycle-wide data continuity. Abdel-Aty and Negri show that data silos between design, manufacturing, quality and maintenance systems are a central obstacle and stress data linkage, authoritative sources of truth and interoperability [1]. Zhang et al. review 94 publications (2015–2023) and conclude that collecting data is insufficient unless it is associated with the correct product, process, machine and lifecycle stage [2]. Hedberg et al. use graph models to link data across the lifecycle [3], and Bonham et al. report a multi-partner digital-thread system for additive manufacturing [4]. Digital twin research provides the second pillar. Soori et al. [5], Böttjer et al. [6] and Leng et al. [7] review digital twins for monitoring, simulation, predictive maintenance and system design, while Dafflon et al. [8] and Napoleone et al. [9] examine CPS challenges and

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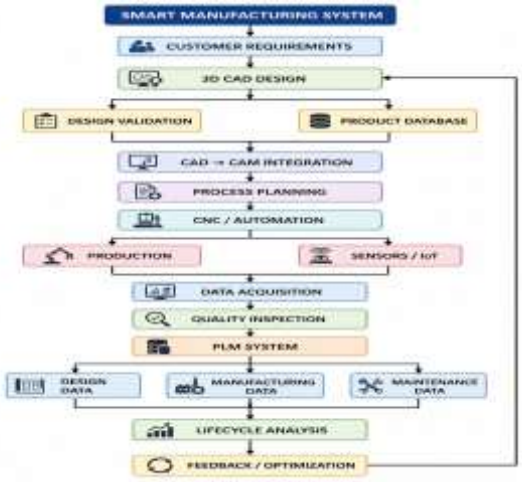
characteristics. Zheng et al. [10] and Lu et al. [11] present smart-manufacturing system frameworks and a review of automation standards, and Sahoo and Lo [12] survey enabling technologies. For SMEs, Mittal et al. [13] and Moghaddam et al. [14] highlight maturity and reference-architecture gaps, and scheduling and production-planning reviews [15], [16] emphasize connected, data-driven decision making. Zheng et al. [17] and Rojas and Rauch [18] further confirm interoperability and connectivity as persistent challenges.

Research gap. Most studies address a single technology (digital twin, CPS, IoT or scheduling) or remain conceptual. Few provide a practical, scalable workflow that connects CAD/CAM, automation, data acquisition, inspection and PLM with closed-loop feedback, validated on a mechanical-product case study.

III. PROPOSED METHODOLOGY

1. Integrated Framework

The framework in Fig. 1 starts from customer requirements and a parametric 3D CAD model. The model is validated, stored in a product database and passed to CAM for process planning, tool selection and CNC programming. Automation hardware (CNC, sensors, PLC/ESP32 controllers) executes production, while a data-acquisition layer records cycle time, temperature, vibration, machine status and quality results. Inspection records and machine data are stored against the released drawing revision and batch in the PLM system, which feeds lifecycle analysis and optimization back to CAD/CAM.



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2. Workflow and Digital Thread

The case-study sequence is: requirement specification → CAD model → drawing release → CAM setup → tool selection → cutting parameters → tool-path simulation → CNC program → sensor integration → machining → inspection → PLM record → KPI analysis → optimization → feedback to CAD/CAM. Only the released revision (Rev-A, Rev-B, Rev-C) is linked to production CAM and CNC programs, which prevents the use of obsolete data.

C. Performance Measures

Manufacturing performance is evaluated using production time, productivity, machine utilization, rejection rate, first-pass yield and Overall Equipment Effectiveness (OEE):

$$OEE = A \times P \times Q \quad (1)$$

where A is availability, P is performance efficiency and Q is quality rate. For machining, spindle speed and feed rate are

$$N = 1000\, Vc / (\pi D), \quad F = N \cdot z \cdot fz \quad (2)$$

where Vc is cutting speed (m/min), D tool diameter (mm), z number of flutes and fz feed per tooth (mm).

D. PLM Record and Information Flow

PLM is the backbone that keeps every dataset attached to the correct product revision. Each product record stores the product identifier, CAD revision, drawing, BOM, CAM program, tool list, machine and batch, sensor log, inspection report and any engineering change order (ECO). Information flows CAD → CAM → CNC → sensors → inspection → PLM → analysis → optimization (Fig. 2), and analysis results are returned to CAD/CAM as design or process improvements, so that optimization is a continuous activity rather than a one-time machining-parameter exercise.

Figure 4.7 Digital information flow



Fig. 2. Digital information flow through the lifecycle with feedback.

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IV. CASE STUDY 1: CNC MACHINING OF A BEARING HOUSING

1. Component and CAD Model

A bearing housing was chosen because it combines precision features (bore, mounting holes) with conventional machining operations. The specification is given in Table I. The parametric CAD model (Fig. 3) comprises the main body, bearing boss, Ø40 mm bore, four mounting holes, fillets and chamfers, and acts as the master product definition for CAM and PLM. Modelling follows a fully constrained sketch, extrusion, boss and bore creation, patterned holes, fillets/chamfers, material and tolerance assignment, drawing generation and interference/manufacturability checks before release as Rev-A.

TABLE I

BEARING HOUSING SPECIFICATION

Parameter	Specification
Overall size (L × W × H)	120 × 90 × 65 mm
Bearing bore / Mounting holes	Ø40 mm / 4 × Ø10 mm
Material	Aluminium alloy / mild steel
Process / Inspection	CNC machining / dimensional

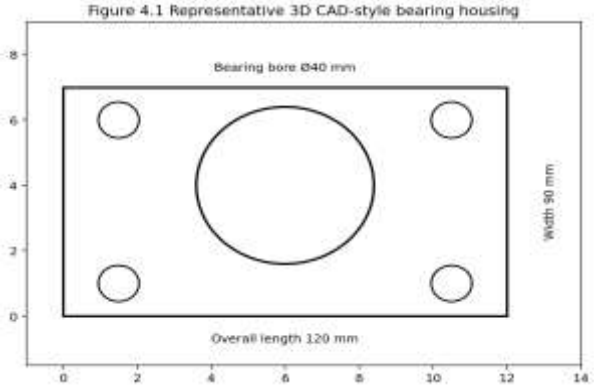


Fig. 3. Representative CAD-style view of the bearing housing.

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2. CAM Planning and Simulation

The CAD geometry is imported into CAM, where the workpiece, fixture and datum are defined. Operations are facing, roughing, feature milling, drilling, boring and chamfering with tools selected per feature (face mill Ø50, end mills Ø12 and Ø8, drill Ø10, boring tool Ø40). The cutting parameters in Table II are representative starting values; final values must follow the tool-maker data and machine capability. Spindle speeds follow (2); for example, facing with Vc = 160 m/min and D = 50 mm gives N ≈ 1019 rpm. Tools are listed in Table III, and the setup and tool-path strategy are shown in Fig. 4. Tool paths are simulated before the CNC program is generated to detect collisions and setup errors.

Table Ii
Representative Cutting Parameters

Operation	Tool Ø (mm)	*Vc* (m/min)	*N* (rpm)	Feed (mm/min)	DOC (mm)
Facing	50	160	1019	250	1.0
Rough milling	12	180	4775	700	2.0
Feature milling	8	180	7162	500	1.5
Drilling	10	80	2546	180	5.0
Boring	40	100	796	120	0.5
Finishing	8	200	7958	350	0.3

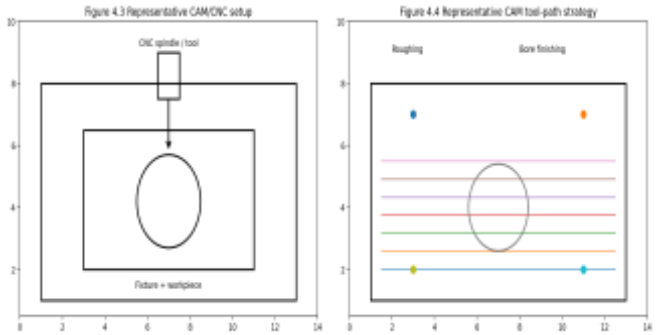


Fig. 4. (a) CAM/CNC setup with fixture and workpiece; (b) roughing and bore-finishing tool-path strategy.

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Table III Tool Selection

Operation	Tool	Ø (mm)	Purpose	Type
Facing	Face mill	50	Reference surface	Carbide insert
Roughing	End mill	12	Material removal	4-flute carbide
Feature milling	End mill	8	Feature machining	4-flute carbide
Drilling	Twist drill	10	Mounting holes	Carbide/HSS
Boring	Boring tool	40	Bearing seat	Adjustable
Chamfering	Chamfer mill	10–12	Edge finishing	90° tool

3. Automation and Data Acquisition

Fig. 5 shows the automation architecture. Sensors on the CNC machine are read by a PLC/ESP32 controller; the data-acquisition layer stores cycle time, temperature, vibration and machine status in a database that feeds both analytics and the PLM record. Over ten representative machining cycles the logged cycle time varied between 78 s and 83 s, temperature rose from 32 °C to 38 °C and vibration from 1.0 to 1.6 mm/s, with all parts classed OK. These values are representative placeholders that illustrate the recording format and must be replaced by measured data in a physical trial.

Figure 4.5 Proposed automation architecture

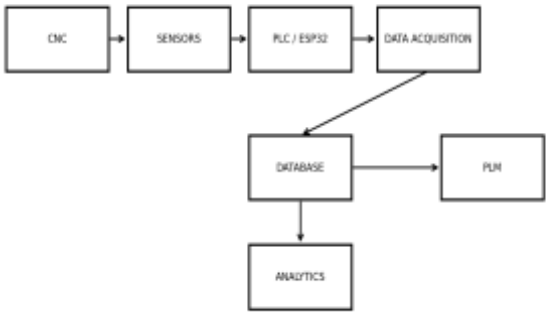


Fig. 5. Proposed automation and data-acquisition architecture.

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4. Inspection and Traceability

After machining, critical dimensions are measured and each result is linked to the drawing revision and production batch (Table IV). All representative measurements lie within tolerance, and the stored link between product ID, CAD revision, CAM program, sensor log and inspection report provides the traceability needed for root-cause analysis.

Table Iv
Representative Inspection Results (Mm)

Parameter	Nominal	Tol.	Measured	Dev.	Status
Overall length	120.00	±0.10	120.04	+0.04	PASS
Overall width	90.00	±0.10	89.96	−0.04	PASS
Overall height	65.00	±0.10	65.05	+0.05	PASS
Bearing bore	40.00	±0.03	40.02	+0.02	PASS
Mounting hole Ø	10.00	±0.05	10.03	+0.03	PASS
Hole pitch	84.00	±0.10	83.95	−0.05	PASS

V. CASE STUDY 2: CORTONA3D WORKSTATION PLANNING

The second case study evaluates a multi-stage mechanical assembly and maintenance operation (motorcycle assembly and sub-component servicing) and compares traditional manual working planning with 3D workstation planning using Cortona3D RapidAuthor/RapidManual connected to Siemens Teamcenter. The evaluation covers four pillars: digital design integration (parametric CAD with hierarchical BOM), process planning and simulation, automation and shop-floor execution, and PLM-based change management. Table V summarizes the five operational phases in which the two approaches differ.

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Table V
Workflow Comparison By Phase

Phase	Manual planning	Cortona3D planning
1. Data intake and BOM review	Engineers examine 2D drawings, paper blueprints and static spreadsheets; high risk of misinterpretation.	Direct PLM/database integration (e.g., Teamcenter); structured BOM with interactive 3D preview.
2. Engineering data usage	Manual extraction of part numbers and dimensions; cross-checking of disconnected parts lists.	Import and update of CAD geometry and product structures with single-click synchronization.
3. Authoring work instructions	Text drafted in Word/PDF; separate snapshots annotated in graphics software.	Visual authoring in RapidManual: assigned actions, grouped steps, animated camera views.
4. Visuals and illustrations	Manual screenshots, cropping and balloon labelling; days per manual.	Automated 2D illustrations from 3D views; 20+ exploded views and callouts generated instantly.
5. Publishing and shop-floor access	Printed binders or static PDFs; engineering changes need manual reprinting and replacement.	Interactive HTML5/3D documentation on shop-floor tablets with live BOM links.

1. Phase 1: Engineering Database and BOM

The authoring environment connects to the engineering database and loads the master assembly structure (Fig. 6). Selecting a BOM item highlights its exact 3D geometry, replacing the manual review of disparate 2D drawings and spreadsheets, which is prone to misinterpretation.

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Fig. 6. Teamcenter BOM structure loaded in Cortona3D Technical Publications.

2. Phase 2: Process Authoring and Animation

Process planners define the steps—vehicle jacking, front-wheel removal, brake-caliper detachment and fork disassembly—on a timeline (Fig. 7), assigning motion paths, tool requirements and safety warnings to each step.

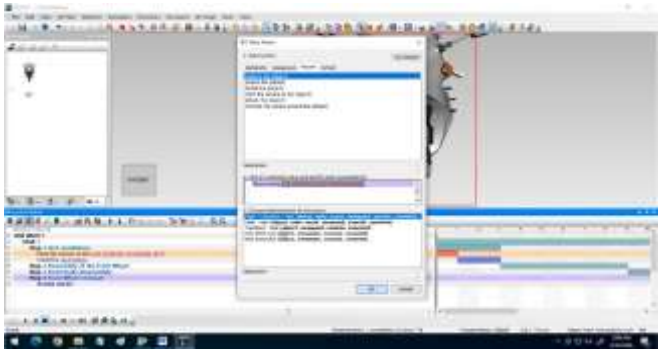


Fig. 7. Process authoring and animation sequencing on the step timeline.

3. Phase 3: Automated Technical Illustrations

Vector 2D illustrations are extracted directly from the 3D model orientation. More than 20 exploded views with automatic balloon callouts are generated in seconds and remain consistent with the current engineering revision, removing a major manual bottleneck (Fig. 8).

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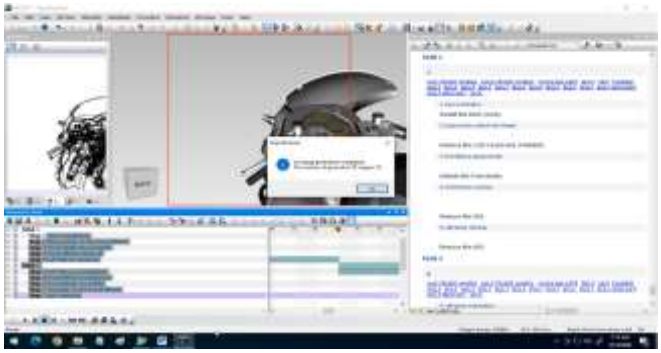


Fig. 8. Automated generation of 2D technical illustrations and part callouts.

4. Phase 4: Shop-Floor Deployment

The finished work package is published as an interactive HTML5 viewer for shop-floor tablets or touch monitors (Fig. 9). Operators rotate 3D animations, click BOM items to identify parts and tick off completed steps in real time, which supplies execution data back to the digital thread.

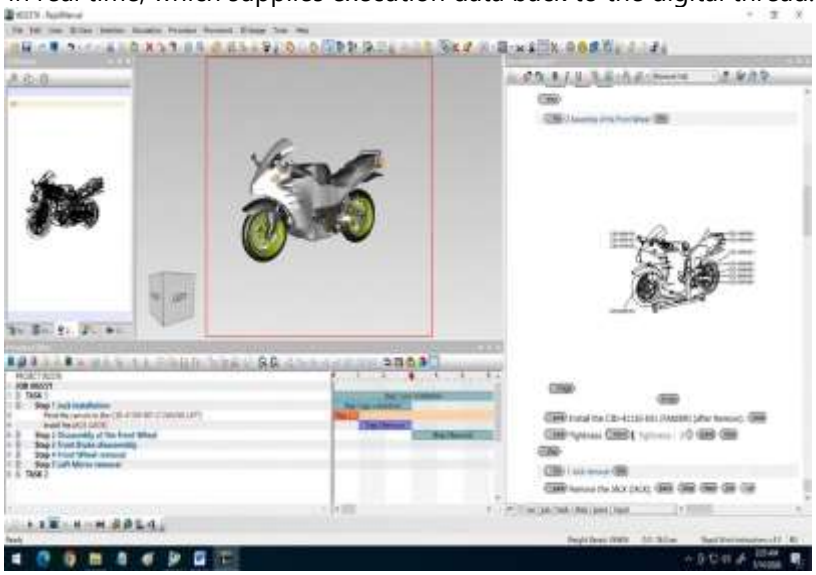


Fig. 9. Interactive 3D work instructions on a shop-floor terminal.

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VI. RESULTS AND DISCUSSION

Table VI compares manual planning with the proposed integrated workstation planning, and Fig. 10 shows the same metrics normalized to the manual baseline (= 100).

Table Vi
Manual Vs. Integrated Planning

Metric	Manual planning	Cortona3D + PLM	Gain
Authoring time	40–60 h per manual	8–12 h per manual	≈75–80% less
Assembly defect rate	8.5%	1.8%	78% lower
Engineering change propagation	2–3 weeks	Real time	Instant update
Operator training	5 days	1.5 days	70% faster

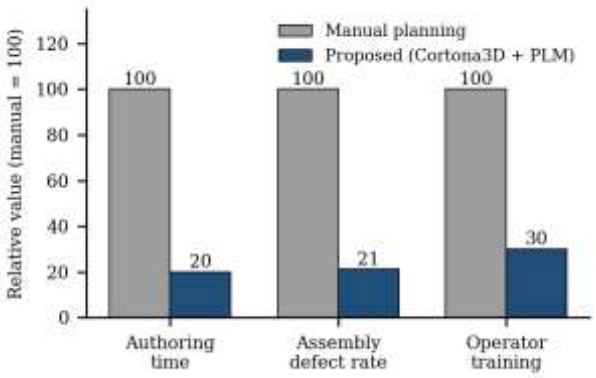


Fig. 10. Normalized performance comparison (manual planning = 100).

The results show that the integrated framework meets the four objectives. (1) A continuous digital workflow is established from CAD databases to shop-floor instructions. (2) Execution time, tool usage

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and verification data from the shop floor are available for quality control. (3) Engineering change orders propagate instantly through PLM, eliminating obsolete paper documents and version conflicts. (4) Authoring time, assembly errors and training duration fall by roughly 75–80%, 78% and 70%, respectively.

The machining case study complements these findings by showing how design revisions, CAM programs, sensor logs and inspection results can be stored under one product record. Its sensor and inspection values are representative, so the quantitative evidence for the integrated framework in this paper rests mainly on the workstation-planning study; a physical machining trial with logged OEE, cycle-time and rejection data is the natural next validation step.

Relative to the research gaps in Section II, the framework contributes in four ways: it provides an end-to-end CAD → CAM → automation → data acquisition → inspection → PLM workflow; it returns production and inspection information to the lifecycle record rather than ending at CNC output; it removes data silos by tying every record to a released revision; and it is modular, so existing CAD/CAM and automation infrastructure can be retained, which is important for SMEs with legacy equipment [13], [14].

VII. ADVANTAGES, LIMITATIONS AND APPLICATIONS

Advantages: shorter authoring and training time, fewer assembly errors, zero-latency change propagation, automated illustration generation and unbroken traceability linking product ID, CAD revision, CAM program, batch, sensor log and inspection report.

Limitations: high licence, server and hardware cost; a steep learning curve for authors, planners and operators; interoperability effort between legacy CAD/CAM, sensors, PLM and execution systems; strict configuration control to keep the digital model in sync; and dependence on stable network and terminal infrastructure.

Applications: automotive assembly and maintenance manuals; aerospace and defense production requiring configuration control; heavy-machinery overhaul (gearboxes, hydraulics, pump assemblies); SMEs adopting Industry 4.0 incrementally; and technical training in digital manufacturing.

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VIII. CONCLUSION

This paper presented an integrated smart-manufacturing framework that connects CAD/CAM, automation, data acquisition, inspection and PLM through a digital thread. A CNC bearing-housing case study demonstrated the workflow from CAD release to inspection records, and a Cortona3D–Teamcenter workstation-planning case study showed measurable gains over manual planning: roughly 75–80% less authoring time, a 78% drop in assembly defects, 70% faster operator onboarding and instant engineering-change propagation. The modular design allows organizations to adopt it without replacing existing equipment.

Future work includes logging real machining data to compute OEE, cycle time and rejection rate; closing the loop with predictive maintenance and digital-twin models; adding AI-based process optimization; and extending the study to a cost–benefit analysis for SMEs.

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