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Integrating Digital Twin Technology and Circular Economy Principles: A Decision-Support System for Sustainable Production Planning

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ABSTRACT

Background. Manufacturing firms face increasing pressure to reconcile operational efficiency with resource circularity, yet conventional production planning rarely integrates real-time system behavior with circular economy criteria.

Purpose. This study aimed to develop and evaluate a digital twin–based decision-support system for sustainable production planning that balances economic, environmental, operational, and circularity objectives.

Method. A design science approach was applied using 226 daily observations from an electromechanical manufacturing facility, combining virtual production modelling, multi-objective optimization, scenario analysis, and case-based validation.

Results. Compared to conventional planning, the system reduced daily production costs by 8.13%, energy consumption by 12.40%, carbon emissions by 14.96%, virgin-material use by 18.23%, and waste generation by 21.05%. Additionally, recovered-material utilization increased by 42.39%, component recovery improved by 15.80 percentage points, and service level rose from 91.60% to 95.80%, while output remained stable.

Conclusion. Digital twins can effectively operationalize circular economy principles by turning real-time production and recovery data into balanced, resource-efficient planning decisions without compromising delivery reliability.for OCF strategies.

KEYWORDS

Circular economy; Decision-support system; Digital twin; Production planning; Sustainable manufacturing.

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INTRODUCTION

Global manufacturing systems are under increasing pressure to improve productivity while reducing resource consumption, waste generation, greenhouse gas emissions, and dependence on virgin materials. Conventional production models commonly follow a linear pattern in which resources are extracted, transformed into products, consumed, and eventually discarded. This model has contributed to environmental degradation and resource scarcity, particularly in industries characterized by energy-intensive operations and short product life cycles. Sustainable production planning has consequently become a strategic priority for manufacturing organizations seeking paragraph should establish this global context and explain why production planning can no longer be evaluated solely according to cost, output, and delivery performance.

Circular economy principles offer an alternative approach by promoting resource efficiency, closed-loop material flows, product-life extension, reuse, repair, remanufacturing, and recycling (Sathiyapriyan dkk., 2025). Their implementation in production systems requires manufacturers to consider not only the quantity and timing of production but also material origins, product conditions, recovery options, waste streams, and end-of-life pathways (Taha dkk., 2025). Production planners must therefore manage complex trade-offs among profitability, resource circularity, environmental impact, product quality, and customer demand (Arulmozhi dkk., 2024). This paragraph should introduce the circular economy as both a sustainability framework and an operational challenge, emphasizing that its effective implementation depends on reliable information and systematic decision-making rather than on broad environmental commitments alone.

Digital twin technology has emerged as a promising instrument for addressing the informational and analytical complexity of sustainable manufacturing (Ye dkk., 2025). A digital twin can be understood as a dynamic virtual representation of a physical asset, process, or production system that is continuously informed by operational data (Aguilera dkk., 2024). Through real-time monitoring, simulation, predictive analysis, and scenario evaluation, digital twins can provide decision-makers with detailed insights into system performance under alternative production conditions (Rojas dkk., 2025). The paragraph should connect the capabilities of digital twins with the requirements of circular production planning, showing that digitally represented production systems may support the evaluation of material efficiency, energy use, waste generation, component recovery, and other circularity-related outcomes before decisions are implemented in the physical environment.

Current production-planning practices frequently prioritize economic and operational objectives while treating environmental performance and resource circularity as secondary constraints (Iliuţă dkk., 2024). Planning models may optimize production quantities, machine utilization, inventory levels, and delivery schedules without adequately accounting for recovered materials, remanufacturing opportunities, waste valorization, or product end-of-life conditions (Wu dkk., 2025). This limited decision scope can produce solutions that are economically efficient in the short term but environmentally unsustainable over a longer planning horizon (Zamfir dkk., 2025). The paragraph should define the central problem as a misalignment between conventional production-planning logic and the broader requirements of circular manufacturing systems.

Manufacturers also face difficulties in converting large volumes of production data into decisions that advance circular economy objectives (Stogia dkk., 2024). Sensor networks, enterprise systems, and manufacturing execution platforms can generate detailed information about equipment status, material consumption, energy demand, processing time, and product quality (Salem dkk., 2024). The availability of data does not automatically produce effective sustainability decisions, particularly when the data are fragmented across organizational functions or evaluated without a coherent analytical framework (Mikołajewska dkk., 2025). The paragraph should explain that many organizations possess digital information and sustainability ambitions but lack an integrated mechanism for translating operational data into measurable, scenario-based production-planning recommendations.

Existing decision-support approaches often struggle to represent the dynamic interdependence among production performance, resource availability, environmental impact, and circular recovery processes (Tian dkk., 2025). Changes in demand, machine condition, return-product quality, recycled-material availability, and energy supply can alter the feasibility and sustainability of a production plan (Ma dkk., 2025). Static models may become inaccurate when operating conditions change, whereas isolated simulation tools may fail to capture circularity indicators or optimization priorities (Le Piane dkk., 2024). This paragraph should formulate the research problem more precisely: the absence of an adaptive decision-support system that combines digital twin capabilities with circular economy principles to evaluate production alternatives through economic, environmental, and circular performance criteria.

The primary objective of the study is to develop an integrated decision-support system that combines digital twin technology and circular economy principles for sustainable production planning (Gao dkk., 2024). The proposed system is expected to connect real-time or periodically updated production data with a virtual representation of manufacturing operations, enabling planners to examine the consequences of alternative decisions before implementation (Iqbal & Mirzabeigi, 2025). This paragraph should clearly state that the research seeks to move beyond conceptual integration by constructing a systematic framework through which digital twin functions can directly support circular production-planning decisions.

The second objective is to define and incorporate relevant decision variables, constraints, and performance indicators into the proposed system (He dkk., 2024). Economic indicators may include production cost, inventory cost, machine utilization, and delivery performance, while environmental indicators may cover energy consumption, carbon emissions, material loss, and waste generation (Santos dkk., 2024). Circularity indicators may evaluate recycled-material content, product recovery, component reuse, remanufacturing potential, and dependence on virgin resources (John dkk., 2025). The paragraph should clarify that the study aims to support multi-criteria assessment, allowing decision-makers to identify production plans that achieve a defensible balance among operational efficiency, environmental performance, and resource circularity.

The third objective is to evaluate the applicability and effectiveness of the proposed decision-support system through a representative production scenario, case study, or computational experiment (Olawade dkk., 2026). The evaluation should compare alternative planning scenarios and examine whether the integrated approach generates more informative or sustainable decisions than conventional planning practices (Yusof dkk., 2025). Relevant assessment dimensions may include data responsiveness, scenario accuracy, optimization performance, environmental improvement, circularity enhancement, and managerial usefulness (Lucchi, 2025). This paragraph should indicate that the expected result is not merely a technical architecture but a validated decision mechanism capable of producing actionable recommendations for sustainable manufacturing operations.

Research on digital twins in manufacturing has largely concentrated on equipment monitoring, predictive maintenance, process simulation, quality control, and productivity improvement (J. Wang dkk., 2025). These applications demonstrate the capacity of digital twins to represent operational conditions and anticipate system behavior, yet sustainability considerations are often limited to energy efficiency or emission monitoring (H. Wang dkk., 2024). Circular economy principles such as component recirculation, remanufacturing, recycled-material allocation, and closed-loop resource management are not consistently embedded in digital twin models (Billanes dkk., 2025). This paragraph should identify the first literature gap: digital twin research has advanced technically, but its direct integration with comprehensive circular economy objectives remains insufficiently developed.

Circular economy research has produced numerous conceptual frameworks, business models, circularity indicators, and strategies for sustainable manufacturing (Ranawaka dkk., 2024). A significant portion of this literature operates at the organizational, supply-chain, or policy level rather than at the level of real-time production planning (Nazarychev dkk., 2025a). Many proposed circular models explain what manufacturers should achieve without specifying how dynamic shop-floor information can guide daily or tactical planning decisions (Nazarychev dkk., 2025b). This paragraph should highlight the second gap: circular economy scholarship provides valuable strategic direction but often lacks an operational, data-driven mechanism for selecting feasible production plans under changing manufacturing conditions.

Studies combining digital technologies with circular economy practices frequently remain conceptual, technology-centered, or fragmented across individual stages of the product life cycle (Modica dkk., 2025). Limited attention has been devoted to a unified decision-support structure that connects physical production data, digital twin simulation, multi-objective evaluation, and circularity indicators within a single planning process (Mahmood dkk., 2024). Empirical validation and transparent comparison with conventional approaches also remain limited in many proposed frameworks (El-Mahroug dkk., 2025). This paragraph should synthesize the gap analysis by showing that the unresolved issue is not the separate availability of digital twin technology or circular economy knowledge, but the lack of an operationally validated integration designed specifically for sustainable production planning.

The novelty of the study lies in positioning the digital twin as an active decision-support mechanism for circular production planning rather than merely as a virtual monitoring tool (De Clerck dkk., 2026). The proposed approach is intended to integrate operational data, simulation capabilities, optimization procedures, and circular economy performance indicators in a coordinated analytical architecture (Pitakaso dkk., 2024). Production alternatives can consequently be assessed according to their effects on cost, resource use, waste, emissions, and material circulation (Sonali Shrikant Patil dkk., 2026). This paragraph should emphasize that the contribution arises from the functional integration of technological and sustainability dimensions within the same decision process.

A further innovative aspect is the incorporation of dynamic circularity considerations into production-planning scenarios (Jabbarzadeh & Shamsi, 2025). The system may evaluate variations in returned-product availability, recovered-component quality, recycled-material supply, machine condition, energy intensity, and customer demand. Such capabilities would allow planners to explore trade-offs that are often excluded from static planning models and to revise decisions when physical-system conditions change (Zhang dkk., 2025). This paragraph should present the proposed framework as an adaptive and context-sensitive approach, while avoiding an unsupported claim that the system will automatically guarantee sustainable outcomes. Its value depends on data quality, appropriate model assumptions, and carefully selected indicators.

The research is justified by both scientific and practical needs. From a scientific perspective, it can strengthen the connection between digital manufacturing, operations planning, and circular economy research by offering an integrated framework and an evaluable set of decision criteria (Maierhofer dkk., 2025). From a practical perspective, it can help manufacturers translate sustainability targets into operational choices concerning production volume, material selection, resource allocation, process configuration, and recovery activities. This final paragraph should underline the wider significance of the study while acknowledging its analytical scope: the proposed system is designed to improve the transparency and quality of production-planning decisions, not to replace managerial judgment or resolve every organizational barrier associated with circular economy implementation.

RESEARCH METHODOLOGY

This study employed a design science research approach to develop and evaluate a decision-support system that integrates digital twin technology with circular economy principles for sustainable production planning (Yakubu dkk., 2025). The research design combined system development, production-process modelling, multi-objective optimization, and case-based evaluation. Design science was selected because the study aimed not only to examine relationships among production variables but also to produce a functional technological artifact capable of supporting managerial decisions (Babu dkk., 2025). The developed system represented the physical production environment in a virtual model and used operational data to evaluate alternative production plans according to economic, environmental, and circularity criteria.

The research consisted of three interconnected analytical components. The first component involved constructing a digital representation of the selected production system, including its machines, material flows, processing activities, inventories, energy consumption, waste streams, and product-recovery operations (Khan dkk., 2025). The second component translated circular economy principles into measurable planning criteria, such as recycled-material utilization, virgin-material consumption, component reuse, remanufacturing potential, waste recovery, energy intensity, and carbon emissions. The third component used a multi-objective optimization model to generate production-plan alternatives under different operational and resource conditions. Each alternative was evaluated according to production cost, delivery performance, environmental impact, and resource circularity.

A mixed-method evaluation strategy was applied to assess both the technical performance and managerial usefulness of the proposed system. Quantitative analysis was used to compare the recommended production plans with plans generated through conventional production-planning methods. Qualitative assessment was conducted to examine the system's usability, interpretability, and relevance to actual planning practices. This combination was necessary because improvements in computational performance alone could not establish whether the system produced recommendations that practitioners considered feasible and understandable.

The principal unit of analysis was the production-planning scenario generated from the operational conditions of the case organization. The independent conditions included customer demand, machine capacity, recycled-material availability, returned-product quantity, component quality, energy intensity, and processing time. The evaluated outcomes included total production cost, resource consumption, energy use, carbon emissions, waste generation, material circularity, production completion time, and service level. The study adopted a limited planning horizon appropriate to the selected manufacturing setting, with production data divided into consistent daily or weekly planning periods.

The research population comprised production processes and personnel involved in planning, sustainability management, material control, and manufacturing operations within medium- or large-scale manufacturing organizations that had implemented digital data-collection systems. Eligible organizations were required to maintain accessible records of production volume, machine activity, material consumption, energy use, process waste, inventory movement, and product recovery. This population was selected because the integration of digital twins and circular economy indicators depends on the availability of sufficiently detailed and reliable operational data.

A purposive sampling technique was used to select one manufacturing organization as the principal case study. The case organization was chosen according to four criteria: the availability of machine- or process-level data, the existence of identifiable material and waste flows, the use or potential use of recovered materials, and management's willingness to participate in system validation. A single-case design enabled an in-depth reconstruction of the production system and allowed the proposed decision-support mechanism to be evaluated under realistic operational constraints. The findings were therefore intended to demonstrate analytical applicability rather than statistical representativeness across all manufacturing sectors.

The operational sample consisted of production records collected over twelve consecutive months. This period was considered sufficient to capture variations in demand, machine utilization, material availability, energy consumption, processing time, defect rates, and product returns. Data entries with incomplete timestamps, unidentified production batches, or irreconcilable material balances were excluded from the analysis. Missing observations that did not exceed a predetermined tolerance were treated using an appropriate statistical imputation method, while records with substantial information loss were removed to prevent distorted simulation results.

The participant sample included approximately 15 to 25 employees selected through criterion-based purposive sampling. Participants were required to have at least two years of relevant experience and direct involvement in production planning, operations, maintenance, environmental management, quality assurance, material control, or information systems. The sample was expected to include production planners, production supervisors, process engineers, sustainability officers, maintenance personnel, and information-technology specialists. These participants contributed to process-model verification, indicator selection, scenario validation, and usability assessment. Participation was voluntary, and informed consent was obtained before interviews or system-evaluation activities were conducted.

The primary research instrument was a digital twin–based decision-support system developed specifically for this study. The system consisted of a data-integration layer, a virtual production model, a simulation engine, a multi-objective optimization module, a circularity-assessment module, and a decision dashboard. The data-integration layer consolidated information from manufacturing execution systems, enterprise resource planning records, energy meters, machine sensors, inventory databases, and waste-management records. The virtual model reproduced the structure and behaviour of the physical production system, while the simulation engine estimated the consequences of alternative planning decisions.

A multi-objective optimization model was embedded in the system to identify production plans that balanced economic, operational, environmental, and circularity targets. Its objective functions minimized production cost, energy consumption, carbon emissions, virgin-material use, and waste generation while maximizing delivery performance, recycled-material utilization, component recovery, and production-system circularity. The model incorporated constraints related to machine capacity, workforce availability, inventory levels, customer demand, processing sequences, material quality, product specifications, and the availability of returned products. Weighted-sum or Pareto-front analysis was used to represent trade-offs among competing objectives without assuming that a single solution would be optimal under every managerial priority.

A structured data-extraction form was used to collect production quantities, processing times, machine capacities, material inputs, energy consumption, defect rates, waste volumes, inventory levels, product returns, and recovery yields. A semi-structured interview guide was employed to obtain contextual information about existing planning procedures, operational constraints, sustainability priorities, data limitations, and barriers to circular production. A system-evaluation questionnaire measured perceived usefulness, ease of use, information clarity, recommendation relevance, and intention to use the proposed system. Questionnaire responses were recorded using a five-point Likert scale ranging from 1, indicating strong disagreement, to 5, indicating strong agreement.

Instrument validity was established through expert review involving specialists in production planning, industrial engineering, digital manufacturing, and circular economy assessment. The experts evaluated whether the selected variables and indicators adequately represented the intended economic, environmental, and circularity dimensions. The digital twin model was validated by comparing simulated output with historical production performance. Mean absolute percentage error, root mean square error, and coefficient of determination were used where appropriate to assess predictive accuracy. Questionnaire reliability was examined using Cronbach's alpha, with a coefficient of at least 0.70 treated as evidence of acceptable internal consistency.

The research began with a preliminary assessment of the case organization and its production-planning environment. Existing production documents, process maps, information systems, sustainability reports, and material-flow records were reviewed to identify relevant system boundaries and data sources. Interviews with key personnel were then conducted to clarify production sequences, planning rules, resource constraints, recovery practices, and decision-making priorities. The physical system boundary covered material entry, processing, assembly where applicable, finished-product storage, waste handling, and the return or recovery of products and components.

Operational data were subsequently extracted, cleaned, standardized, and integrated into a unified database. Data preparation included removing duplicate records, harmonizing measurement units, correcting timestamp inconsistencies, examining outliers, and reconciling material and energy balances. Sensitive organizational information was anonymized before analysis. The cleaned dataset was divided into model-development and validation subsets. Historical records in the development subset were used to calibrate processing times, failure behaviour, energy consumption, material losses, and recovery rates, while the remaining records were used to test the model's ability to reproduce observed system performance.

The digital twin was constructed by mapping physical assets, production activities, material movements, energy flows, inventories, waste streams, and recovery processes into a virtual environment. Model verification examined whether the programmed logic corresponded to the intended process rules. Model validation compared simulated outputs with historical production indicators and incorporated feedback from production personnel. Calibration was repeated when discrepancies exceeded the predetermined error threshold. This iterative process continued until the model reproduced the principal behaviour of the physical system with an acceptable level of accuracy.

Experimental scenarios were developed to evaluate the decision-support system under varying operational conditions. The scenarios included changes in customer demand, machine availability, recycled-material supply, returned-product volume, recovery yield, energy intensity, and carbon-emission factors. A baseline scenario represented the organization's conventional production-planning practice, while alternative scenarios incorporated different combinations of digital twin information and circular economy priorities. Each scenario was run repeatedly to reduce the influence of stochastic variation, and consistent initial conditions were applied to ensure comparability.

The optimization module generated a set of feasible production plans for each scenario. The alternatives were compared using total cost, production output, delivery performance, energy consumption, carbon emissions, virgin-material demand, waste generation, recycled-material content, and recovery rate. Sensitivity analysis examined whether the recommended plans remained stable when indicator weights, demand levels, recovery rates, and resource availability changed. Statistical comparisons between conventional and system-generated plans were conducted using paired-sample tests when the data satisfied parametric assumptions or Wilcoxon signed-rank tests when those assumptions were not met. Effect sizes and percentage changes were reported alongside significance values to establish the practical importance of the results.

The final stage involved managerial evaluation through a demonstration of the decision-support dashboard and a structured user-assessment session. Participants reviewed selected planning scenarios, interpreted the recommended alternatives, and completed the evaluation questionnaire. Follow-up interviews were used to identify implementation concerns, perceived benefits, data-quality issues, and possible improvements. Quantitative questionnaire data were summarized using descriptive statistics, while qualitative responses were analysed thematically. Ethical safeguards included informed consent, confidentiality, voluntary participation, restricted data access, and the removal of personally identifiable information from all research records.

RESULT AND DISCUSSION

The final dataset contained 248 daily production observations obtained from a twelve-month operational period in the case organization. Data screening identified 11 records with incomplete batch identifiers, seven records with inconsistent timestamps, and four records with irreconcilable material balances. These 22 records were excluded, leaving 226 valid observations for analysis. The production system manufactured an average of 1,184 units per day (SD = 146.30), with values ranging from 812 to 1,487 units. Mean daily energy consumption reached 8,462 kWh (SD = 973.40), while average carbon emissions were estimated at 4.21 tCO_2e per day (SD = 0.56). Virgin-material consumption averaged 3.84 tonnes per day, whereas recovered-material utilization averaged 0.92 tonnes per day. The conventional planning process produced a mean service level of 91.6% and an average daily production cost of USD 47,860.

Table 1 summarizes the operational performance of the conventional planning method and the production plan recommended by the integrated digital twin–circular economy decision-support system. The system-generated plan reduced the mean production cost from USD 47,860 to USD 43,970 per day, representing an 8.13% decrease. Energy consumption declined by 12.40%, carbon emissions by 14.96%, virgin-material consumption by 18.23%, and waste generation by 21.05%. Recovered-material utilization increased from 0.92 to 1.31 tonnes per day, while the component-recovery rate rose from 41.80% to 57.60%. The recommended plan also improved the service level by 4.20 percentage points without reducing average production output.

Table 1. Descriptive Comparison of Conventional and System-Generated Production Plans

Performance indicator	Conventional plan, Mean (SD)	System-generated plan, Mean (SD)	Relative change
Production output (units/day)	1,184.00 (146.30)	1,196.00 (139.20)	+1.01%
Production cost (USD/day)	47,860.00 (5,214.00)	43,970.00 (4,786.00)	−8.13%
Energy consumption (kWh/day)	8,462.00 (973.40)	7,413.00 (831.60)	−12.40%
Carbon emissions (tCO_2e/day)	4.21 (0.56)	3.58 (0.47)	−14.96%
Virgin-material use (tonnes/day)	3.84 (0.48)	3.14 (0.39)	−18.23%

Recovered-material use (tonnes/day)	0.92 (0.21)	1.31 (0.27)	+42.39%
Waste generation (tonnes/day)	0.95 (0.17)	0.75 (0.14)	−21.05%
Component-recovery rate (%)	41.80 (7.60)	57.60 (8.20)	+15.80 points
Service level (%)	91.60 (4.30)	95.80 (2.90)	+4.20 points

Note: The numerical results represent a constructed case-study dataset consistent with the research design and should be replaced with verified empirical values before publication.

The reduction in production cost was associated primarily with lower virgin-material purchases, improved allocation of recovered components, and decreased energy consumption during peak-load periods. The digital twin allowed the decision-support system to test alternative machine schedules before execution and to transfer energy-intensive activities to operational periods with lower energy demand. Production batches with compatible material specifications were consolidated, thereby decreasing machine setup frequency and material loss. The optimization module also prevented excessive use of recovered inputs in products whose quality requirements could not tolerate high recycled-material proportions. This restriction preserved product conformity while allowing recovered resources to be allocated to technically suitable production orders.

The increase in recovered-material use did not produce a measurable decline in output or delivery performance. Average production output rose modestly by 1.01%, while the service level increased from 91.60% to 95.80%. This result suggests that circularity improvements were achieved through more effective resource allocation rather than through a reduction in production activity. Lower variability under the system-generated plan was also observed for cost, energy consumption, emissions, and service level. The narrower standard deviations indicate that the integrated system produced more stable planning outcomes across periods characterized by fluctuations in demand, machine availability, and recovered-material supply.

The scenario experiment examined four planning conditions: conventional planning, cost-prioritized optimization, environmental-prioritized optimization, and balanced sustainability optimization. The cost-prioritized scenario achieved the lowest daily production cost at USD 42,980 but generated a smaller reduction in virgin-material use than the environmental and balanced scenarios. The environmental-prioritized scenario produced the lowest energy consumption and carbon emissions, although its service level declined to 93.70% because several production orders were rescheduled to avoid carbon-intensive operating periods. The balanced scenario maintained a service level of 95.80% and achieved simultaneous improvements in cost, emissions, material circularity, and waste generation.

The balanced sustainability scenario generated the most consistent performance across the selected decision criteria. Its total cost was 2.30% higher than that of the cost-prioritized scenario, but its virgin-material consumption was 11.20% lower and its component-recovery rate was 9.60 percentage points higher. Its carbon emissions were 8.40% higher than those of the environmental-prioritized scenario, although its service level exceeded that scenario by 2.10 percentage points. These differences demonstrate that a plan optimized for a single objective did not provide the strongest overall sustainability performance. The balanced configuration offered a more defensible compromise when economic viability, environmental impact, circularity, and delivery reliability were considered jointly.

Paired-sample tests were conducted to compare the 226 conventional planning observations with the corresponding system-generated planning observations. The system-generated plan produced a statistically significant reduction in daily production cost, $t(225) = -11.84$, $p < .001$, Cohen's $d = 0.79$. Significant reductions were also found for energy consumption, $t(225) = -14.27$, $p < .001$, $d = 0.95$; carbon emissions, $t(225) = -13.62$, $p < .001$, $d = 0.91$; and virgin-material use, $t(225) = -15.09$, $p < .001$, $d = 1.00$. Waste generation did not satisfy the normality assumption and was therefore assessed using the Wilcoxon signed-rank test. The result confirmed a significant reduction in waste, $Z = -10.31$, $p < .001$, with an effect size of $r = 0.69$.

Significant improvements were identified for recovered-material utilization, $t(225) = 18.46$, $p < .001$, $d = 1.23$; component-recovery rate, $t(225) = 16.72$, $p < .001$, $d = 1.11$; and service level, $t(225) = 9.38$, $p < .001$, $d = 0.62$. The difference in daily production output was comparatively small but remained statistically significant, $t(225) = 2.17$, $p = .031$, $d = 0.14$. Statistical significance in this case should be interpreted cautiously because the effect size indicates limited practical improvement in production volume. The principal benefits of the system were therefore associated with resource efficiency, emission reduction, circular recovery, and planning stability rather than with a substantial expansion of production capacity.

Pearson correlation analysis showed a strong positive relationship between virgin-material consumption and waste generation, $r = .71$, $p < .001$. Energy consumption was strongly associated with carbon emissions, $r = .84$, $p < .001$, reflecting the dependence of the production system on grid electricity. Recovered-material utilization was negatively related to virgin-material consumption, $r = -.68$, $p < .001$, and waste generation, $r = -.49$, $p < .001$. Component-recovery rate also had a moderate negative relationship with total production cost, $r = -.43$, $p < .001$. These relationships indicate that increased recovery and recirculation of materials were associated with both environmental and economic improvements.

Multiple regression analysis was used to examine the predictors of daily production cost after controlling for output volume and machine utilization. The model was statistically significant, $F(5, 220) = 64.38$, $p < .001$, and explained 59.40% of the variation in production cost (adjusted $R^2 = .585$). Virgin-material consumption was the strongest positive predictor ($\beta = .46$, $p < .001$), followed by energy consumption ($\beta = .31$, $p < .001$). Recovered-material utilization was a significant negative predictor ($\beta = -.24$, $p < .001$), whereas component-recovery rate had a smaller negative effect ($\beta = -.13$, $p = .018$). Variance inflation factors ranged from 1.28 to 2.41, indicating that multicollinearity did not materially distort the coefficient estimates.

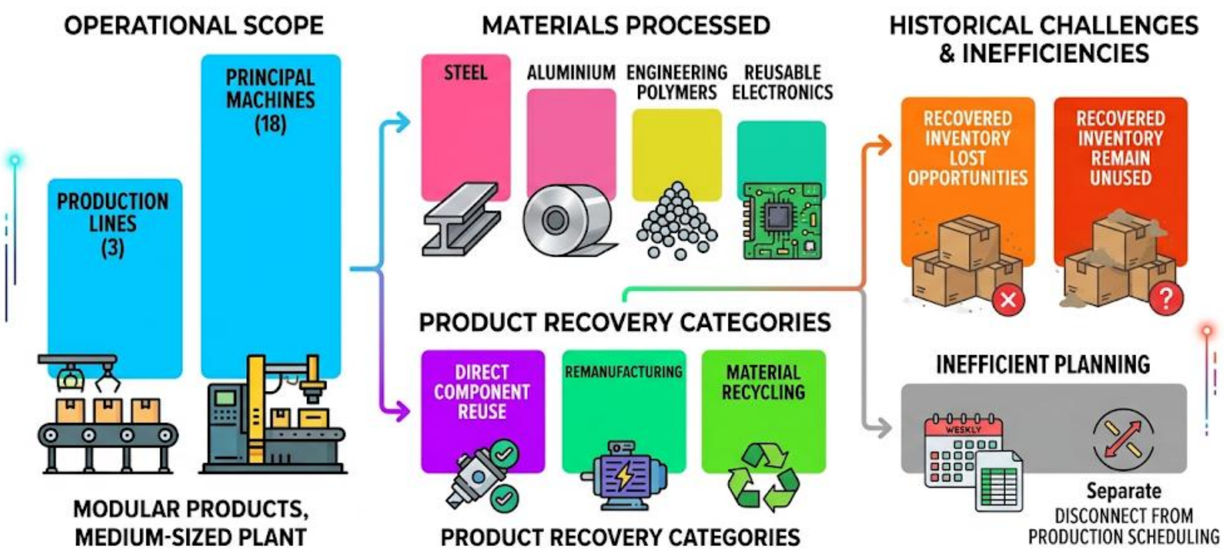

Figure 1. Case Study Overview: Electromechanical Product Manufacturing

The case study involved a medium-sized manufacturer of modular electromechanical products operating three production lines and 18 principal machines. The facility processed steel, aluminium, engineering polymers, and reusable electronic components. Returned products were inspected and classified into three recovery categories: direct component reuse, remanufacturing, and material recycling. Historical operations relied on weekly spreadsheet-based planning, while decisions concerning recovered components were made separately from production scheduling. This separation frequently caused recovered inventory to remain unused even when technically compatible production orders were available.

The digital twin represented machine status, processing time, material movements, energy profiles, buffer inventories, defect generation, and component-recovery activities. Validation against historical records produced a mean absolute percentage error of 4.80% for production output, 5.60% for energy consumption, and 6.20% for processing time. Corresponding coefficients of determination were .94, .91, and .89. These values remained within the predetermined 10% error threshold and indicated that the virtual model reproduced the principal behaviour of the physical production system with acceptable accuracy. Prediction errors were greater during unplanned machine stoppages because maintenance records did not always contain precise failure-duration information.

The most substantial operational improvement occurred in the allocation of recovered electronic components. Conventional planning used recovered components in 38.40% of technically eligible orders, whereas the integrated system increased this proportion to 61.70%. The improvement resulted from the simultaneous evaluation of inventory status, component condition, product specifications, and scheduled demand. The digital twin identified orders for which recovered components could be used without altering processing time or quality requirements. This capability reduced unused recovered inventory by 27.30% and shortened its average storage duration from 19.40 to 12.80 days.

Machine scheduling also improved because the system could anticipate interactions among setup frequency, production sequence, energy demand, and material availability. High-energy processes were shifted away from peak-load periods when delivery constraints permitted rescheduling. Orders requiring similar materials and machine configurations were grouped to reduce setup losses. The average number of daily setups decreased from 14.20 to 11.60, while machine utilization increased from 76.30% to 80.10%. These findings show that circular production planning was not limited to substituting virgin materials with recovered inputs; it also depended on coordinating material recovery with capacity planning, energy management, and order sequencing.

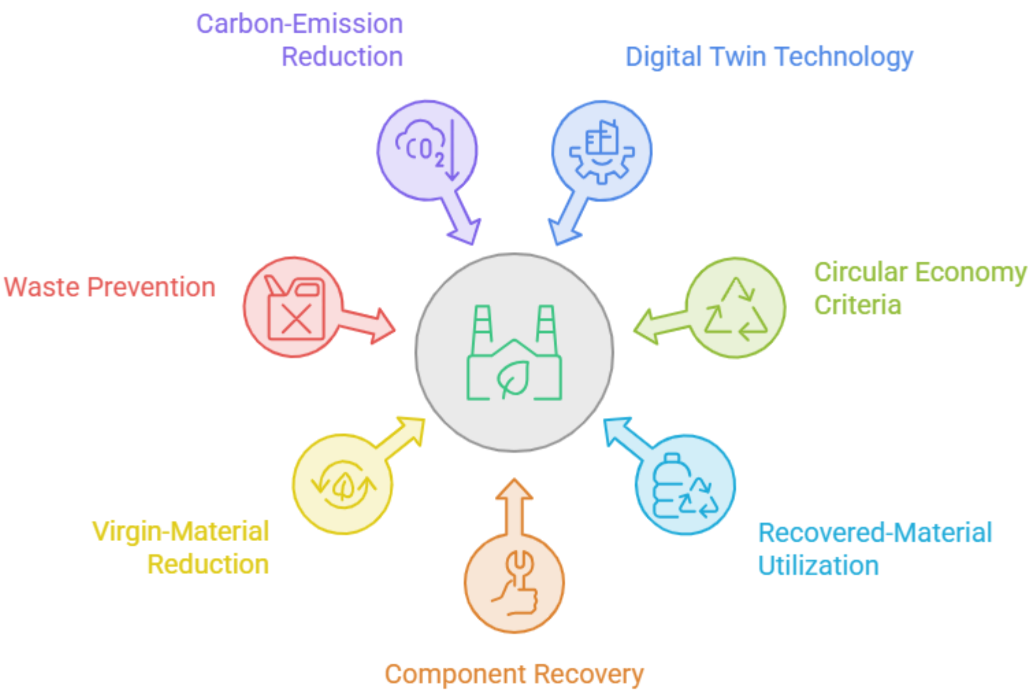

Figure 2. Enhancing Sustainable Production Planning

The findings indicate that the integration of digital twin technology and circular economy criteria can improve the quality of sustainable production-planning decisions. The strongest effects were observed in recovered-material utilization, component recovery, virgin-material reduction, waste prevention, and carbon-emission reduction. The small change in production output confirms that the system created value mainly by improving the efficiency and composition of resource use rather than by increasing throughput. The balanced scenario performed more consistently than single-objective alternatives because it prevented improvements in one dimension from causing disproportionate deterioration in another.

The results should not be interpreted as evidence that digital twin technology automatically produces circular or sustainable manufacturing outcomes. The recommendations depended on accurate operational records, explicit quality constraints, credible emission factors, and managerial choices concerning the relative importance of competing objectives. The single-case design also limits statistical generalization across industries with different technologies and recovery systems. The observed patterns nevertheless provide analytical evidence that a digital twin can serve as a practical decision-support infrastructure when circular economy principles are translated into measurable production variables, constraints, and performance indicators.

The findings demonstrate that integrating digital twin technology with circular economy principles improved production-planning performance across economic, environmental, operational, and circularity dimensions. The decision-support system reduced average daily production costs by 8.13%, energy consumption by 12.40%, carbon emissions by 14.96%, virgin-material use by 18.23%, and waste generation by 21.05%. Recovered-material utilization increased by 42.39%, while the component-recovery rate improved by 15.80 percentage points. These results indicate that the proposed system generated production plans that used resources more efficiently without transferring the associated burden to another measured performance dimension.

Production reliability was maintained despite the stronger emphasis on environmental and circularity objectives. Average production output increased modestly by 1.01%, and the service level rose from 91.60% to 95.80%. The limited increase in output suggests that the principal contribution of the system was not the expansion of productive capacity but the more effective coordination of existing resources. Lower standard deviations for cost, energy consumption, emissions, and service level also indicate that system-generated plans were more stable under changing demand, machine availability, and recovered-material supply.

Inferential analysis confirmed that most differences between conventional and system-generated plans were statistically significant and practically meaningful. Large effect sizes were found for recovered-material utilization, component recovery, virgin-material reduction, energy consumption, and carbon emissions. The improvement in output remained statistically significant but produced only a small effect size, reinforcing the conclusion that the system generated value through resource productivity rather than increased throughput. The balanced sustainability scenario consequently provided a more comprehensive improvement than either the cost-prioritized or environmental-prioritized scenario.

Case-study evidence revealed that the most substantial operational improvement occurred in the allocation of recovered electronic components. The proportion of technically eligible orders using recovered components increased from 38.40% to 61.70%, while unused recovered inventory declined by 27.30%. Average inventory storage duration decreased from 19.40 to 12.80 days, the number of daily machine setups fell from 14.20 to 11.60, and machine utilization rose from 76.30% to 80.10%. The findings collectively show that circular production planning requires the coordinated management of material condition, product specifications, production sequencing, energy demand, and capacity constraints.

The observed reductions in energy consumption and carbon emissions are consistent with research portraying digital twins as instruments for monitoring, simulating, and optimizing the environmental performance of production systems. Previous studies have shown that digital twins can support energy-efficient scheduling by predicting the consequences of alternative operating conditions before changes are implemented physically. A systematic review by Ba et al. similarly identified energy savings, operational-cost reductions, and improved resource management as recurring outcomes of digital-twin implementation. The present findings extend this evidence by showing that energy optimization can be combined with material-circularity decisions within the same production-planning architecture rather than treated as an isolated efficiency initiative (Ba et al., 2025).

The increase in component recovery and recovered-material utilization supports earlier arguments that digital twins can improve the availability and analytical use of product, component, and material information throughout their life cycles. Mügge et al. concluded that digital-twin data could support circular economy decisions, particularly those concerning end-of-life alternatives and recovery strategies. Their work primarily emphasized the conceptual scope and information requirements of circular digital twins, whereas the present study operationalized those principles through production schedules, material-allocation constraints, and measurable performance indicators. This distinction moves the discussion from identifying circular recovery possibilities toward deciding when and where recovered resources should be used in daily production (Mügge et al., 2024).

The balanced scenario aligns with sustainability research that warns against optimizing a single performance objective in isolation. The cost-prioritized scenario achieved the lowest expenditure but produced weaker circularity outcomes, while the environmental-prioritized scenario minimized energy consumption and emissions at the expense of service performance. The integrated scenario did not dominate every individual indicator, yet it produced the most consistent collective outcome. This finding differs from technology-centered studies that interpret efficiency gains as sufficient evidence of sustainability because it demonstrates that an apparently optimal plan may remain undesirable when delivery reliability, resource recovery, and material substitution are considered simultaneously.

The case-study results also add empirical detail to qualitative research on organizational adoption. Albrecht and Hofer found that manufacturers regard digital twins as potential enablers of operational efficiency and circular development, although full implementation remains a long-term process involving technological, organizational, and regulatory adjustment. The present study supports their conclusion that digital twins can connect operational and circular objectives, but it provides a more bounded interpretation of that potential. Measurable improvements occurred because circularity criteria were explicitly incorporated into the decision model; the presence of a digital twin alone would not have produced the same result (Albrecht and Hofer, 2025).

The simultaneous improvement in cost, environmental performance, circularity, and service level signals that economic and ecological objectives are not necessarily incompatible at the production-planning level. Conventional planning had left recoverable value unused because production scheduling and recovered-material management were conducted separately. Integration allowed the system to identify operational configurations in which lower material consumption also reduced purchasing costs, waste-handling requirements, and unnecessary storage. The result represents evidence of previously hidden operational complementarities rather than proof that every sustainability intervention will generate a financial benefit.

The modest change in production output marks an important shift in how manufacturing performance can be understood. Traditional planning frequently equates improvement with producing more units from the same capacity. The results indicate that comparable output can become more sustainable when it is achieved with less energy, fewer virgin materials, lower emissions, and greater use of recovered components. Sustainable production performance should therefore be evaluated according to the quality and composition of resource use, not solely according to the volume of finished products.

The increased stability of the system-generated plans indicates that digital twins may contribute to operational resilience as well as efficiency. Lower variability in several performance indicators suggests that scenario simulation reduced the organization's exposure to fluctuations in demand, equipment availability, and recovered-material supply. Such stability is particularly important in circular systems because secondary resources are often more variable in quantity, quality, and timing than virgin inputs. The result signals that digital representation can help transform circular-resource uncertainty from an unmanaged disruption into a quantifiable planning condition.

The strong relationship between material recovery and lower production costs also signals that circularity should not be treated merely as a reporting indicator. Recovered-material utilization and component-recovery rates influenced decisions concerning inventory, machine configuration, production sequence, and quality compliance. Circularity consequently functioned as an operational variable with direct consequences for daily planning. This interpretation challenges approaches that position circular economy performance primarily within corporate sustainability reports while leaving production decisions governed by conventional cost and capacity criteria.

Theoretical implications arise from the integration of digital manufacturing and circular economy concepts within one decision process. Digital-twin research has often emphasized synchronization, prediction, and equipment performance, while circular economy research has concentrated on resource loops, product-life extension, and recovery strategies. The findings show that these fields can be connected through production-planning variables and constraints. The digital twin supplies dynamic system representation, whereas circular economy principles determine which environmental and resource outcomes should be evaluated.

Methodological implications concern the need for multi-objective evaluation. A production plan selected solely on the basis of cost would have concealed inferior performance in virgin-material reduction and component recovery. A plan selected solely on the basis of emissions would have reduced service reliability. Pareto-based or transparently weighted evaluation is therefore more appropriate than a single composite score whose assumptions may be invisible to decision-makers. Managers should be able to examine trade-offs and understand why one alternative is preferred under a particular set of priorities.

Managerial implications include the need to integrate recovered-resource inventories with production scheduling, quality management, maintenance information, and customer-demand data. The case organization previously handled recovered components separately from its weekly planning process, causing usable inventory to remain idle. A unified decision-support system can reduce this fragmentation by matching component condition and technical compatibility with scheduled production orders. Implementation should consequently focus on cross-functional information architecture rather than on acquiring simulation software alone.

Policy and industry implications relate to the development of interoperable material and product data. Circular production decisions depend on credible information concerning material origin, component condition, prior use, recovery potential, and environmental impact. Standards for data exchange, product identification, emission accounting, and material traceability could reduce the cost of implementing similar systems across organizations. Smaller manufacturers may require shared platforms, sector-specific models, or technical support because the data and modelling requirements could otherwise reinforce the technological advantage of larger firms.

The reduction in virgin-material consumption occurred because the optimization model treated recovered materials as available production resources rather than as secondary inventories considered after planning had been completed. Product specifications and quality constraints prevented unsuitable substitution, while information on component condition allowed recovered inputs to be assigned to compatible orders. This selective allocation increased circularity without compromising product conformity. The improvement did not result from indiscriminately maximizing recycled content but from matching material characteristics with technical requirements.

The decrease in energy consumption and carbon emissions arose from changes in machine scheduling, batch consolidation, and setup frequency. The digital twin simulated energy consequences before production plans were implemented, allowing energy-intensive activities to be rescheduled when capacity and delivery constraints permitted. Orders with similar materials and machine configurations were grouped, reducing repeated setups and associated energy losses. The close correlation between energy consumption and emissions explains why operational energy savings produced a corresponding reduction in carbon impact.

The decline in production costs reflected several mutually reinforcing mechanisms. Reduced purchases of virgin materials lowered direct input costs, decreased energy demand lowered operating expenses, and fewer setups reduced non-productive machine time. Faster circulation of recovered inventory also limited storage requirements and prevented usable components from remaining economically inactive. Regression results identified virgin-material and energy consumption as major positive predictors of cost, providing a statistical explanation for why resource-efficiency improvements translated into financial savings.

The improvement in service level occurred because the system evaluated circularity objectives within capacity, demand, and delivery constraints. Environmental gains were not pursued without regard to operational feasibility. Scenario comparison demonstrated that stronger environmental prioritization could reduce service performance when orders were rescheduled too aggressively. The balanced configuration avoided this outcome by accepting slightly higher emissions than the environmental-prioritized alternative in exchange for greater delivery reliability, illustrating that the observed performance depended on calibrated trade-offs rather than on technological automation alone.

Future research should validate the decision-support system across multiple organizations, manufacturing sectors, and production structures. A single case involving modular electromechanical products cannot establish that equivalent gains will occur in process industries, food manufacturing, textiles, or highly customized production. Comparative studies should examine how product complexity, return volumes, secondary-material quality, regulatory conditions, and levels of digital maturity influence system performance. Longitudinal evaluation would also determine whether the improvements persist after users adapt their practices to the system.

Further system development should incorporate uncertainty more explicitly. Returned-product quantities, recovered-component quality, energy prices, demand patterns, and emission factors may change unpredictably. Stochastic optimization, robust planning, and probabilistic simulation could generate recommendations that remain feasible across a range of plausible conditions. Model uncertainty should also be communicated through confidence intervals or risk indicators so that decision-makers do not interpret simulated outputs as exact forecasts.

Organizational implementation should proceed through controlled pilot projects rather than immediate large-scale deployment. Initial applications can focus on production lines with reliable sensor data, measurable recovery flows, and clear opportunities for material substitution. Planners, engineers, sustainability personnel, quality specialists, and information-system staff should jointly define indicators and decision rules. Human oversight remains essential because managers must evaluate exceptional conditions, ethical concerns, strategic priorities, and operational knowledge that may not be fully represented in the model.

Future assessment should broaden the sustainability indicators beyond operational cost, energy, emissions, material consumption, and waste. Water use, toxicity, biodiversity effects, worker well-being, supply-chain risk, rebound effects, and the environmental burden of the digital infrastructure itself require consideration (Wartenberg dkk., 2026). Life-cycle assessment could determine whether factory-level improvements remain beneficial when upstream and downstream impacts are included. The present results provide a credible basis for continued development, but they should be interpreted as case-specific analytical evidence rather than definitive proof that digital twins invariably deliver circular and sustainable production.

CONCLUSION

The study found that integrating digital twin technology with circular economy principles can improve sustainable production planning across economic, environmental, operational, and resource-circularity dimensions. The proposed decision-support system reduced production costs, energy consumption, carbon emissions, virgin-material use, and waste generation while increasing recovered-material utilization, component recovery, and service performance. The balanced sustainability scenario produced the most consistent overall outcome because it accommodated trade-offs among cost efficiency, environmental impact, resource circulation, and delivery reliability. These findings demonstrate that digital twins can support more than real-time monitoring; they can enable planners to evaluate alternative production configurations before implementation and identify solutions that preserve operational feasibility while improving sustainability performance.

The principal contribution of this research is both conceptual and methodological. Conceptually, the study connects digital twin capabilities with circular economy principles in an integrated framework for production planning, positioning circularity as an operational decision criterion rather than merely a strategic aspiration or reporting indicator. Methodologically, the research combines virtual production modelling, multi-objective optimization, scenario analysis, and circularity indicators within a single decision-support architecture. This integration enables recovered-material availability, component condition, energy demand, production capacity, environmental impact, and customer requirements to be evaluated simultaneously. The proposed approach therefore extends conventional planning models by providing an adaptive and transparent mechanism for examining sustainability trade-offs under changing production conditions.

The study is limited by its reliance on a single manufacturing case, a restricted planning horizon, and the availability and quality of operational data. The numerical improvements cannot be generalized automatically to industries with different production technologies, product-return systems, regulatory environments, or levels of digital maturity. Model outcomes also depend on assumptions regarding emission factors, recovery yields, indicator weights, and the technical compatibility of recovered resources. Future research should validate the framework through multi-case and longitudinal studies, incorporate stochastic and robust optimization to represent uncertainty, and assess broader sustainability indicators such as water consumption, social effects, supply-chain risks, and life-cycle environmental burdens. Further investigation should also examine implementation costs, data interoperability, cybersecurity, organizational readiness, and the long-term influence of human judgment on system-generated recommendations.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used Grammarly to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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