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Modern Methods for Reducing the Environmental Footprint of Automotive Paint Shops Through Process Parameter Control

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Abstract

The article examines modern methods for reducing the environmental footprint of automotive paint shops through process parameter control and digital optimization tools. The analysis is based on a comparative review of recent empirical and theoretical studies on paint shop energy efficiency, emission abatement systems, digital twins, and algorithmic control of the air environment. It is shown that isolated equipment modernization and the installation of individual purification units do not ensure a sustainable environmental effect and lead to increased capital expenditures without proportional emission reduction. It is substantiated that the key factor is parametric and predictive control of thermal and aerodynamic oven regimes, spraying processes, and ventilation circuits, which enables synchronization between energy consumption and pollutant removal efficiency. It is demonstrated that local optimization of airflow structures and temperature fields reduces the material intensity of repainting operations and the indirect carbon load of ventilation subsystems, while the integration of digital models and autonomous control systems forms a stable balance between energy and environmental indicators. Special attention is paid to the role of machine learning, IoT-based filter monitoring, and digital twins in maintaining VOC removal stability and predictability of thermal regimes. The results indicate that the effectiveness of environmental optimization is determined by the coherence of thermal, ventilation, and digital control loops rather than by the scale of technological modernization. The article may be useful for researchers in industrial ecology, energy-efficiency specialists, and engineers of automotive manufacturing enterprises.

Keywords: *Environmental Footprint, Automotive Paint Shops, Process Parameter Control, Digital Twins, Energy Efficiency.*

INTRODUCTION

Automotive paint shops are among the most energy- and carbon-intensive plant sections and are major sources of VOC emissions. Whereas environmental optimization was previously associated primarily with equipment modernization and purification installations, today the primary tool is becoming process parameter control—oven temperature setpoints, airflow regimes, spraying, and ventilation algorithms [1]. The environmental footprint is increasingly determined by the precision of thermal and aerodynamic regime regulation and energy consumption.

Despite the growth of research on industrial decarbonization, the literature focuses mainly on technologies and alternative energy, while parametric and predictive process control is examined fragmentarily [5]. Most works analyze integral energy consumption indicators or product lifecycles, ignoring the role of operational equipment setpoints and digital models. This creates a methodological gap between industrial ecology and digital control, complicating the explanation of how local regime optimization ensures a measurable reduction in emissions and energy without capital reconstruction of lines.

The aim of the study is to develop and substantiate an integrative conceptual model for reducing the environmental footprint of automotive paint shops based on parametric and predictive control of technological regimes. To achieve this goal, the following tasks are addressed:

– define the main zones of environmental load formation in paint production and their connection to controllable process parameters;

– compare the energy and environmental effects of optimizing curing ovens, spraying systems, and air purification units;

– identify the main algorithmic and digital tools for predictive control of the air environment and heat flows.

The hypothesis posits that reducing the environmental footprint of paint shops is determined not by equipment replacement, but by the integration of parametric and

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predictive control of ovens, ventilation, and purification systems. Fragmentary optimization of individual units does not yield a sustainable effect, whereas comprehensive digital coordination of regimes ensures a simultaneous reduction in energy consumption and emissions.

The scientific novelty lies in the development of an integrative model of environmental management for paint production, where parametric regime control is viewed as an independent decarbonization tool. It is proposed to evaluate the environmental effect through temperature fields, airflow structure, spraying efficiency, and filtration dynamics.

The scope of the study is limited to automotive paint shops and parameters of thermal and air control. Macroeconomic and regulatory factors are not considered. The work is based on a secondary analysis of international research in the field of industrial ecology and digital process control.

MATERIALS AND METHODS

The methodological basis of the study was formed through a stepwise selection and comparative-analytical review of peer-reviewed publications dedicated to the environmental optimization of automotive paint shops, process parameter control, digital twins, and emission purification systems. Source searching was conducted in international scientific databases and publisher repositories for 2023–2025, filtering by thematic relevance, the presence of an empirical or modeling component, and reproducibility of results. Selection focused on studies where the environmental effect was directly linked to parameters of thermal, aerodynamic, ventilation, and filtration regimes of paint production.

The analysis included works with quantitative models, CFD simulations, predictive control algorithms, and industrial case studies. Review publications without original results, duplicates, and studies lacking reconstructible causal links between controllable process parameters and energy consumption or emission indicators were excluded. The primary dataset consisted of 41 publications; after abstract screening and full-text verification, 10 studies formed the final corpus.

The search was performed using following keywords: automotive paint shop, process parameter control, VOC abatement, curing oven energy efficiency, air handling unit predictive control, digital twin manufacturing, paint shop decarbonization, spray atomization, heat recovery automotive, followed by manual relevance screening based on abstracts and reference lists of selected works.

The final corpus was structured according to three analytical levels of environmental effect manifestation: technological-thermal, including curing ovens, spraying, and heat flows; air-ventilation, covering AHU systems, humidity parameters, filtration, and VOC purification; and energy-systemic, associated with heat recovery and integrated energy loops. Such structuring allowed the analysis to focus on repeating mechanisms of transforming process parameters into measurable environmental indicators.

A systemic reduction of the carbon footprint through the integration of heat recovery and CO_2 capture technologies is demonstrated by Martire et al. [7]. Chen et al. [3] quantitatively establish the relationship between spraying and atomization parameters, material overuse, and equipment contamination effects. The role of low-level mapping of energy consumption and oven parameters in paint shop decarbonization is analyzed in the study by Andrei et al. [1].

Succar et al. [9] formalize decarbonization measures as parametric management instruments enabling structured environmental decision-making. Digital monitoring of environmental parameters as a mechanism for operational optimization is examined by Carpitella [2]. Kang et al. [5] confirm the effectiveness of machine-learning-based autonomous control of VOC treatment units.

Granadero et al. [4] demonstrate, using life cycle assessment, the impact of oven exhaust gas cleaning regimes on toxicological load indicators. Energy efficiency improvements in curing ovens achieved through aerodynamic optimization and digital twin implementation are reported by Pendar et al. [8]. Kim et al. [6] show emission reductions enabled by IoT-based monitoring of filtration system status, while Viscito et al. [10] present reductions in AHU energy consumption achieved through physical modeling combined with predictive control approaches.

Based on the comparison of conceptual approaches and empirical results, a theoretical-synthetic analysis of the mechanisms of parametric control influence on paint production environmental indicators was performed. The synthesis consolidated thermal, aerodynamic, and digital factors into a unified conceptual framework without independent empirical verification. The study is of a conceptual-analytical review nature and is oriented toward identifying reproducible mechanisms of energy consumption and emission reduction through process parameters.

RESULTS

Analysis of the thermal and aerodynamic regimes of curing ovens showed that the section's energy efficiency is determined by airflow configuration and heat transfer regimes, rather than by increasing the installed capacity of burners. Simultaneously, the management of thermal and aerodynamic parameters is viewed as a tool for direct impact on the section's carbon intensity, the level of volatile organic compounds, and the material intensity of repainting operations. Numerical CFD/CHT modeling recorded the formation of homogeneous temperature fields during supply air redistribution and the intensification of internal recirculation [8]. Comparison of modeling results with operational data of ventilation circuits confirmed the reduction of load on auxiliary heating systems and a concomitant decrease in the carbon intensity of the paint line.

Aerodynamic evaluation revealed that the direction and speed of air supply determine the structure of near-surface vortex zones along the vehicle body, influencing the intensity of convective heat exchange and the uniformity of coating curing [5]. Aligning oven regimes with spraying parameters demonstrated a decrease in the probability of film defects and a reduction in the volume of repainting operations [3].

Additional analysis of air handling unit behavior showed a direct dependency between the chamber's temperature instability and the growth of the thermal load of air heating blocks, forming a systemic link between oven aerodynamics and the total energy consumption of the section [10]. Table 1 presents key curing process parameters and their impact on the oven's temperature stability and environmental characteristics.

Table 1. Curing Process Parameters and Their Impact on Energy Efficiency (Compiled by the author based on source [8])

Process Parameter	**Variation Range**	**Temperature Effect**	**Environmental Outcome**
Supply air flow rate	±10–25%	Temperature field equalization	Reduction of heat losses
Air supply angle	5–15°	Expansion of recirculation zone	Decrease of coating overheating
Upper/lower channel ratio	Up to 25% redistribution	Stabilization of longitudinal gradient	Reduction of oven energy demand
Air velocity near vehicle body	≤0.28 m/s fluctuation	Film uniformity	Decrease of defects and excess energy use

Analysis of the presented parameters shows that curing oven energy efficiency is formed through coordinated control of airflows and their spatial distribution inside the chamber. Spatial stabilization of flows in the chamber is accompanied by a decrease in the probability of local VOC emissions and a reduction in paint material overuse due to more uniform film formation. Regulation of supply flow rate is associated with temperature field equalization and a reduction of local heat losses, which reflects on the stability of the section's thermal balance. Changing the air supply angle influences the structure of recirculation zones and limits the formation of overheated coating areas, increasing the uniformity of paint layer curing.

Flow redistribution between upper and lower channels demonstrates a direct link to longitudinal temperature stability and a reduction in the need for additional air heating. Air velocity parameters at the vehicle body surface correlate with the homogeneity of the formed film and a decrease in defect probability, which indirectly reduces the material intensity of repainting operations. The aggregate interpretation of parameters confirms that the environmental effect is achieved through precise tuning of aerodynamics and heat transfer without changing the basic equipment configuration.

Analysis of oven operating regimes revealed a persistent dependency of energy load on airflow configuration and the degree of internal recirculation given an unchanged hardware scheme. Comparison of baseline and optimized configurations recorded a sequential reduction in the section's relative energy consumption during supply air redistribution and thermal field stabilization inside the chamber [3]. Verification through air handling unit parameters showed a decrease in thermal load on air heating circuits and a reduction in the duration of active heating element operation [10]. Parallel analysis of spraying regimes confirmed that aligning oven aerodynamics with spray plume characteristics reduces the share of defective coating zones and limits the volume of repainting operations [6]. Comparison of oven energy dynamics with section power supply data demonstrated a reduction in the indirect emission intensity of ventilation subsystems and a decrease in the production zone's fuel load [1]. The relative change in curing oven energy consumption during the transition from the baseline configuration to optimized operating regimes is interpreted as an energy and environmental indicator, since the reduction of thermal load is accompanied by a decrease in indirect carbon emissions and loads on ventilation subsystems. Additionally, the possibility of operational regime adjustment based on digital heat transfer models and air environment sensor data without changing the hardware configuration is recorded. Figure 1 considers the dynamics of oven energy consumption change during regime optimization.

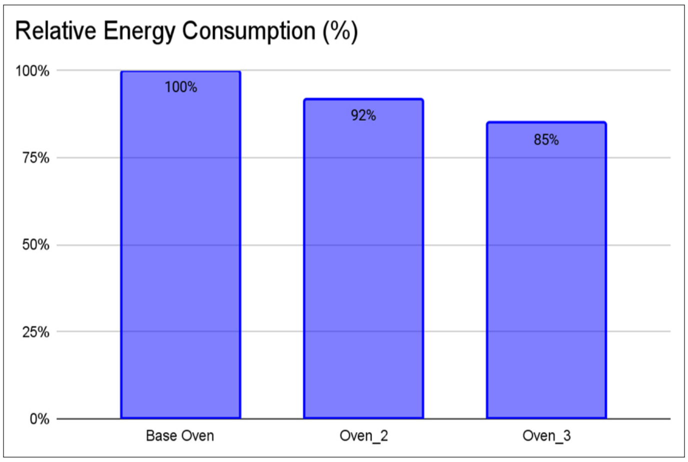

Figure 1. Reduction of Curing Oven Energy Consumption during Coating Process Optimization (Compiled by the author based on source [8])

The diagram demonstrates the relative reduction of oven energy consumption during the sequential optimization of airflow parameters and internal recirculation. The observed non-linearity of the effect indicates the cumulative influence of comprehensive aerodynamic tuning on the system's thermal balance.

The value of 100% for the baseline oven acts as a control point and fixes the initial level of thermal load without flow redistribution and without intensified recirculation. The transition to the 92% regime means a moderate reduction in energy consumption, indicating partial aerodynamic optimization and temperature field equalization without deep changes to internal air circulation; at this stage, the effect is formed primarily by reducing local heat losses and stabilizing supply flow rate. The 85% indicator reflects an already pronounced energy shift and evidences comprehensive flow tuning, where the air supply direction, the balance of upper and lower channels, and the intensity of return heat change simultaneously. The difference between 92% and 85% shows that secondary optimization yields a greater efficiency gain than the primary adjustment, indicating the cumulative effect of internal recirculation and air velocity alignment. Thus, each subsequent configuration demonstrates not just a linear consumption decrease, but a gradual intensification of the impact of parametric control on the oven's thermal balance.

The observed quantitative changes indicate a direct interrelationship between airflow configuration, the chamber's thermal state, and the relative energy load of the paint section while preserving the basic equipment design. Comprehensive interpretation of the obtained data demonstrates the reproducibility of the effect when varying oven regimes and confirms the systemic dependence of the energy consumption level on parametric aerodynamic control without line hardware modernization.

DISCUSSION

Analysis of emission abatement system and ventilation unit operating regimes shows that the environmental sustainability of the paint section is formed not so much through increasing equipment capacity as through the systems' ability to dynamically adjust to changing pollutant concentrations and air environment parameters. Fixed control logic leads to excess energy consumption and an unstable degree of VOC removal, whereas adaptive algorithms ensure the synchronization of purification regimes with the actual load on the installation. The greatest effect is achieved with the simultaneous use of machine learning to select rotary unit operating parameters, digital filter status monitoring, and predictive control of air handling systems. This combination forms a managed air ecosystem in which energy and environmental indicators cease to be competing values and transition into a mode of mutual optimization. Table 2 considers key parameters of the autonomous VOC removal system control and their functional significance in the environmental stabilization loop.

Table 2. Key Parameters of the Autonomous VOC Removal Control System (Compiled by the author based on sources [5, 7])

Parameter Category	Variables	Process Function	Environmental Effect
Control variables	Rotor speed, fan speed	Regulation of adsorption and regeneration cycles	Direct impact on energy demand
Environmental inputs	VOC concentration, temperature, humidity	Determination of system load	Adaptive purification intensity
Output indicators	Energy consumption, removal efficiency	Performance evaluation	Emission and energy reduction
Constraints	Speed and temperature limits	Equipment stability	Prevention of resource overuse

Parameter interpretation demonstrates that autonomous VOC purification control forms a qualitatively different type of environmental stability compared to traditional scheduled regimes. Changing rotor and fan speeds allows adsorption and regeneration cycles to be synchronized with actual pollutant concentration, eliminating the need for the installation to operate constantly at maximum power. An effect is also created by IoT filter monitoring, which shifts maintenance from a calendar to an event-based format and reduces the risk of VOC breakthrough during sorbent saturation. Predictive AHU control enhances this effect by aligning supply air temperature and humidity with purification regimes, reducing thermal fluctuations and stabilizing ventilation circuit energy consumption. Collectively, such an architecture demonstrates the ability to maintain a high degree of pollutant removal while simultaneously reducing energy load, forming a stable balance between air environment quality and production cycle resource efficiency.

Comparison of parametric measures and capital modernization shows the differing nature of the environmental effect and the differing speed of its achievement. Incremental changes to oven, ventilation, and purification system regimes form a rapid response in energy and emission indicators due to the redistribution of existing flows and the elimination of local losses. Capital equipment modernization demonstrates a higher marginal potential for emission reduction; however, its effect manifests with a delay and requires significant investment costs, organizational restructuring, and production cycle stoppages. As a result, the section's environmental dynamics are determined by the scale of technological renewal and the ability to operationally manage current process parameters.

Distinguishing between CAPEX and OPEX in the context of environmental optimization reveals a difference in the mechanisms for achieving sustainability. Investment decisions form a long-term change in energy architecture, whereas operational adjustments ensure constant regime adaptation to changing loads. Parametric control allows thermal and airflows to be redistributed without equipment replacement, reducing specific resource load in the short term. Technological modernization strengthens this effect, but its environmental result becomes dependent on the precision of subsequent regime management and digital monitoring.

Local optimization of oven and ventilation unit parameters manifests a systemic character when integrated with heat recovery loops and energy consumption management of the entire section. Aligning temperature regimes, airflow speeds, and purification cycles forms a unified energy profile in which individual units cease to work in isolation. Under such conditions, digital twins and heat transfer models act as a tool for synchronizing decisions between ovens, ventilation, and purification installations, ensuring load predictability and reducing energy consumption fluctuations.

The integration of heat recovery, digital models, and energy loops forms a top level of optimization, where technological modernization and parametric control cease to be alternatives and transition into a mode of mutual reinforcement. The observed interconnection of local regime adjustments and systemic decarbonization indicates the necessity of viewing environmental stability as a function of the coordinated operation of thermal, air, and digital subsystems of the production cycle.

CONCLUSION

The conducted analysis confirms that the environmental footprint of automotive paint shops is largely determined not by the scale of hardware modernization, but by the precision and coherence of thermal, aerodynamic, and ventilation regime control. The greatest environmental effect is formed during the simultaneous optimization of curing ovens, spraying processes, and air purification systems, when flow redistribution, temperature field stabilization, and adaptive regulation of VOC units lead to a reduction in specific energy consumption, indirect carbon emissions, and the material intensity of repainting operations. The obtained results show that parametric control acts as an independent tool of environmental optimization capable of ensuring measurable improvement in indicators without the mandatory replacement of basic equipment.

Comparison of results with the posited hypothesis demonstrates its confirmation. Sustainable reduction of energy consumption and emissions is achieved primarily through the integration of predictive algorithms, digital heat transfer models, and dynamic air environment control, whereas fragmentary changes to individual units do not form a systemic effect. Comprehensive digital coordination of oven, ventilation, and purification unit regimes manifests a synergistic impact, where energy and environmental indicators transition from a state of compromise to a state of mutual reinforcement.

Prospects for further research are associated with expanding the ecological metrics of parametric control beyond energy consumption and VOC emissions, including water consumption, filtration material waste generation, and the toxicological characteristics of paint coatings. An additional direction represents the development of inter-shop digital twins combining the enterprise's thermal, ventilation, and energy subsystems into a unified load forecasting model. Deepening empirical research on operating production lines and integrating machine learning methods with industrial control systems can ensure the transition from local parameter optimization to a full-format environmental architecture of automotive manufacturing. The practical significance of the results lies in the possibility of implementing parametric control without stopping production lines and without large-scale equipment reconstruction. The theoretical significance consists in the formalization of parametric control as an independent mechanism of industrial decarbonization.

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