

# Sustainability and Energy Efficiency in Administrative Processes: A Control Theory Approach with P-graph Optimization

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As institutions seek to reduce their environmental impact, administrative processes must be optimized for energy and resource efficiency. This study integrates control theory with P-graph methodology to develop a structured framework for sustainable administrative workflows, focusing on university enrollment systems. P-graph-based optimization identifies minimum-energy pathways and optimal resource configurations, while Model Predictive Control (MPC) and nonlinear control enable real-time process adaptation under dynamic conditions. A Life Cycle Analysis (LCA) compares the carbon footprint of digital and paper-based workflows, evaluating IT infrastructure energy use versus traditional operations. Simulated control strategies support energy-efficient decision-making, highlighting best practices for emission reduction and operational flexibility. The result is a decision-support framework that embeds P-graph into a dynamic control context, guiding control strategy selection to minimize energy use and emissions. This scalable approach supports sustainability-oriented process management across public service domains.

## 1. Introduction

Faced with climate change, public administrations increasingly aim to make their processes more sustainable and energy efficient. Paper use, energy consumption, and travel contribute significantly to CO<sub>2</sub> emissions (Cambaz et al., 2018). Digital alternatives—such as paperless solutions and e-government—can reduce the carbon footprint (Yi, 2025), but real impact depends on thoughtful system design. An Italian LCA study showed that digitisation reduced transport- and paper-related environmental impacts by 55–99 % (Mirabella et al., 2013). Digitisation can be sustainable only if the IT infrastructure is energy-efficient and secure, as Yousufi (2023) emphasizes, the irresponsible or excessive use of digital technologies—such as redundant data storage and inefficient digital workflows—can significantly increase the carbon footprint, thereby undermining the environmental benefits of paperless operations. Reducing waste and simplifying processes is another pillar of sustainable public administration. Green Activity-Based Management (ABM) enables precise measurement and optimisation of energy use and emissions through activity-level data (Wesumperuma et al., 2013), while the Five-Circle Model highlights resource and social efficiency (Bamdad et al., 2023). Inefficient processes—like enrolment systems causing overtime—are common in public administration. Smart space usage and lock technology can cut annual energy by 14 % and significantly reduce CO<sub>2</sub> emissions with quick payback (Mainini et al., 2025). Green Business Process Management (Green BPM) helps redesign workflows using environmental indicators such as energy or emission reduction, yet its maturity remains low in SMEs, especially in modelling and optimisation (Sohns et al., 2023). Combining lean principles with digitalisation and appropriate software (e.g., green metrics, visualisation) effectively reduces waste (Stadtländer et al., 2019). Green HR is also key: employee values, awareness, and competences strongly influence sustainable BPM implementation (Brajer-Marczak and Piwowar-Sulej, 2023). Green BPM is both a methodology and a research agenda (Cockuyt and Van Looy, 2019), but its integration across the BPM lifecycle is still limited—mainly to environmental aspects, with social and economic dimensions often overlooked (Magdaleno et al., 2016). Still, it

is increasingly evident that ecological performance must complement traditional indicators like time, cost, and quality. Several studies (e.g. Liu and Chen (2024)) show that digitising administration and improving user experience enhances both efficiency and sustainability. A 2024 analysis confirms BPM's significant positive impact on corporate environmental performance. LCA is suitable for evaluating environmental impacts over a process's life cycle (Fritsch et al., 2022), though it is often confined to energy aspects, rarely addressing social or economic ones (Gbededo et al., 2018). Research suggests integrating LCA into BPM to identify the stages that cause the greatest burden. For example, in a case study in Slovakia, the energy retrofit of an office building — involving upgrades such as improved insulation, window replacement, and HVAC system modernization — resulted in annual energy savings of 143 GJ and cost reductions of € 6,300, with a payback period of 6–12 y (Teplická et al., 2024). LCA helps identify emission sources and supports environmentally informed decision-making. Regulatory tools are also essential for sustainable operations. Predictive building control, for instance, can save 17–18 % of energy (Bamdad et al., 2023). Model Predictive Control (MPC) uses real-time data for forecasting and optimal resource use, applicable not only to buildings but also to human and Information Technology (IT) capacity management. Nonlinear MPC, especially with unscented Kalman filters, ensures stable control in complex, uncertain systems (Rathore et al., 2021). These principles can also be adapted to public administration systems, for example to reduce emissions in traffic management. The P-graph methodology was originally developed for the optimization of chemical process networks (Friedler et al., 2019), but has more recently been successfully applied to the design of administrative workflows. Recent studies have demonstrated the potential of P-graph in various administrative and public service contexts. For instance, Eisinger and Buics (2024) used P-graph to optimize the university enrolment process, identifying inefficiencies and alternative pathways that were not visible with conventional tools, resulting in improved administrative transparency and reduced resource use. Earlier, Tick (2013) had already demonstrated the applicability of P-graph to administrative workflow modeling and simulation, particularly in dynamic decision environments. The study highlighted its usefulness in identifying bottlenecks and reconfiguring task sequences to improve overall process efficiency. These examples underscore the versatility of P-graph beyond its engineering origins, showing its ability to address the growing demand for transparency, efficiency, and sustainability in administrative systems. It can generate optimal and alternative solutions by mapping the entire search space of possible process structures. It also can be a useful tool in the planning of carbon management and decarbonisation networks (Migo-Sumagang et al., 2022). Optimizing an enrolment process, the P-graph methodology identified structurally distinct workflow configurations that traditional approaches—often limited to local or sequential exploration—could not discover due to their partial search space coverage (Tapia et al., 2022), with significant reductions in work time and resources. The five core elements of the P-graph model (inputs, outputs, operations, and their connections) enable sustainability-informed decisions. While Green BPM and LCA have supported sustainability in administrative processes, the integration of control strategies—such as Model Predictive Control (MPC) or nonlinear feedback—is still rare. Moreover, most P-graph applications focus on structural optimisation and lack support for dynamic decision-making. This study addresses this gap by combining control theory, P-graph modelling, and LCA to enable real-time, energy-aware administrative process optimisation. Focusing on university registration workflows, it explores how predictive, feedback-based, and nonlinear control strategies can improve energy efficiency, reduce CO<sub>2</sub> emissions, and enhance operational performance. LCA is used to assess the sustainability trade-offs between digital and paper-based workflows, offering a data-driven basis for environmentally conscious decisions. The study develops a control-theoretic framework for sustainable process management and extends the scope of P-graph methodology to include energy and emissions management in administrative services. It also introduces a control-integrated LCA approach to quantify CO<sub>2</sub> impacts across process types. Finally, it compares MPC, nonlinear, and hybrid optimisation strategies in terms of their effectiveness in supporting real-time, energy-efficient decisions in administrative systems.

## 2. Materials and Methods

The university admissions process was selected as the case study sample on the basis of its structured but dynamic nature, involving both digital and human-reliant administrative processes. The process involves some energy-hungry processes such as data capture, document processing, communication, approval processes, and handling of records. It further comprises both electronic infrastructure (e.g. databases, email) and non-electronic processes (e.g. printing, filing, paper-based approvals), and thus is a natural candidate for assessing energy use-versus-CO<sub>2</sub>-emissions trade-offs. Its cyclical demand—aligned with calendar cycles within academic calendars—also allows dynamic control-based optimization under varying workload conditions to be investigated. Initial review of the enrollment process revealed a series of inefficiencies in both energy usage and resource utilization. Some of these include the duplicate handling of documents (e.g. unnecessary data entry,

multiple reviews), paper-based approval processes resulting in energy and material wastage, and unanticipated workload spikes, which result in inefficient use of IT infrastructure and human capital.

To analyze and quantify such inefficiencies, the process was modeled using Business Process Modeling (BPMN) and P-graph techniques, then segmented into tasks according to their energy profile (energy intensity, digital or manual, fixed or variable load). The admission process was simulated as a dynamic system with inputs being student applications, human resources, and digital services, states being process stages such as registration, verification, and approval, and outputs being accepted/rejected applications and archived records. By state-space modeling, the dynamics of the process were mathematically characterized to assist in control strategy development. The P-graph framework was then used to determine optimal resource paths, with minimum energy and service quality preserved. P-graph was applied to define all feasible process structures, to examine resource dependencies and constraints, and to select lowest-cost, lowest-energy process options for varying input loads. This structural examination was then embedded in a broader control-based system, thereby enabling process paths to be dynamically realigned based on real-time feedback or predicted pattern of demand.

To evaluate the dynamic sustainability performance of the process, three control strategies were examined:

- Model Predictive Control (MPC): Used to predict future process loads based on past enrollment patterns, adjusting resource allocation and task scheduling accordingly. MPC allows anticipatory load balancing to avoid system overload and power spikes.
- Nonlinear Control: Applied to capture complex interdependencies in the system, particularly when small variations in application volume cause disproportionate rises in resource utilization. The method enhances the process stability under variable, nonlinear conditions.
- Hybrid Control (Discrete-Event + Continuous Control): Comprises discrete workflow leaps combined with real-time continuous power monitoring to make execution modes of tasks reconfigurable (manual/digital) at run time.

All control strategies were compared against baseline (non-controlled) conditions using simulation-based analysis.

### 3. Calculation

To assess the environmental impact of the registration process in different configurations, a Life Cycle Analysis (LCA) was undertaken. This involved the estimation of energy consumption for each process alternative (fully digital, hybrid, paper), the CO<sub>2</sub> emission estimation from energy profiles for computing resources (computers, e-mail, storage) and physical resources (paper, print), and the aggregation of results into sustainability measures like carbon footprint per application processed, energy consumed per activity of the workflow, and process efficiency ratios. Scenario analysis was used to evaluate the effect of a full switch to a digital workflow, implementation of predictive scheduling with MPC, and utilization of adaptive reallocation of digital/human resources during periods of high load. The energy consumption of the university admissions process was approximated by defining process activities and assigning them typical energy consumption values based on literature and empirical estimates. All activities in the workflow were assigned as digital-intensive (email-based communication, database queries), manual-intensive (manual form processing, paper-based checking), or Mixed/conditional, depending on the specific configuration (staff document checking). Energy was measured in kWh per occurrence of an activity, supported by literature regarding ICT energy use and power consumption of common office equipment. CO<sub>2</sub> emissions were estimated from a regional electricity emission factor (kgCO<sub>2</sub>/kWh) that can be used in the institutional context. For modeling the enrollment process's sustainability performance, the following scenarios were defined: every scenario was tested with varying numbers of students (1,000, 5,000, 10,000 applications) to verify scalability and nonlinear behavior under load.

The formulas used for the calculations are for the energy consumption per task:

$$E_i = P_i * t_i * n_i \quad (1)$$

$$E_{total} = \sum_{i=1}^N E_i \quad (2)$$

Where  $E_i$  refers to the energy consumption of task  $i$  (in kWh),  $P_i$  denotes the power consumption of the device or activity used in task  $i$  (in kW),  $t_i$  represents the time required to perform task  $i$  (in hours),  $n_i$  indicates the number of instances of task  $i$  in the process, and  $N$  stands for the total number of tasks in the scenario process. The formula used for the calculations are for CO<sub>2</sub> emission is:

$$CO_{2total} = \gamma * E_{total} \quad (3)$$

where:  $\gamma$ : Grid-specific emission factor (kg CO<sub>2</sub>/kWh);  $E_{total}$ : Total energy consumed by the process (kWh). The P-graph models were solved for each scenario to determine the optimal workflow structure, resource utilization efficiency, and energy-minimizing task sequences. Output metrics included minimum energy process pathways (kWh/application), redundancy elimination in task execution, and resource bottlenecks under control-based reallocation.

#### 4. Results

The total energy consumption for every 1,000 processed enrollment cases was calculated across five given scenarios. Outcomes indicated clear variation depending on workflow organization and the control strategy used. As shown in Table 1, the Hybrid Control strategy, combining discrete and continuous control approaches, demonstrated the lowest overall energy usage. This reflects its dynamic ability to alternate between manual and digital execution streams according to the dominating workload and energy cost, as modeled by the P-graph algorithm. For a regional average emission factor ( $\gamma=0.366$  kg CO<sub>2</sub>/kWh), CO<sub>2</sub> emissions and cost (0.20 EUR/kWh on average) were calculated for all scenarios:

Table 1: Energy consumption, CO<sub>2</sub> Emission Reduction and LCA Results

Scenario	Energy Use (kWh/1,000 cases)	CO <sub>2</sub> Emissions (kg)	Emission Reduction (%)	Cost (EUR)
Baseline	182.00	66.61	–	36.40
Digital Static	128.42	47.00	29.4	25.70
Digital + MPC	97.27	35.60	46.5	19.46
Digital + Nonlinear	103.90	38.02	42.9	20.78
Digital + Hybrid	89.58	32.78	50.8	17.92

Figure 1 illustrates the total energy consumption and corresponding CO<sub>2</sub> emission reduction for five administrative workflow scenarios, demonstrating that control-based optimization, especially the Hybrid and MPC strategies, significantly lowers both energy demand and carbon footprint, with the Hybrid scenario achieving over 50 % reduction in both metrics.

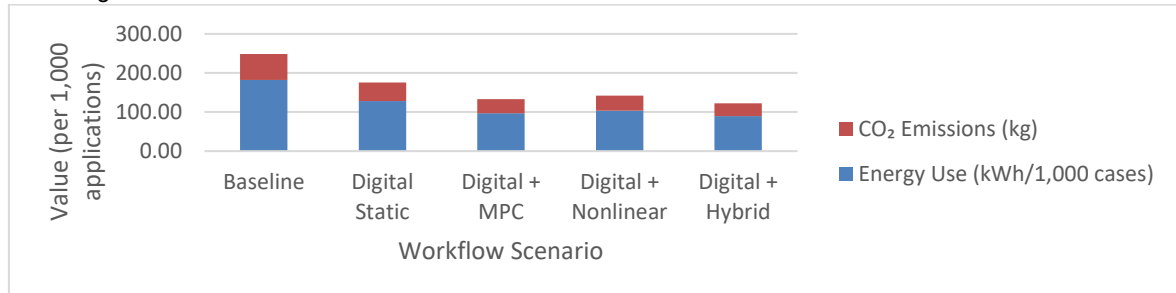


Figure 1: CO<sub>2</sub> Emission and energy use comparison across five simulated control scenarios

The hybrid model attained the highest overall performance with more than 50 % CO<sub>2</sub> emissions reduction and the lowest energy profile (89.58 kWh/1,000 applications). It adapted manual and digital tasks dynamically in real time, regulating the changes in workload in terms of resource usage. The MPC strategy attained notable savings (46.5 %) and was extremely effective for cyclic or anticipated workloads; however, it was rigid under uncertain demand. Nonlinear control was robust to uncertainty at the cost of slightly higher energy consumption and cost. These results confirm that optimization based on control significantly reduces the carbon footprint of administrative processes. Most importantly, MPC and hybrid control approaches show strong performance in high-load situations by their forecasting and adaptive features, respectively. The Hybrid Control scenario, derived through the P-graph-based structural enumeration, achieved the lowest energy consumption (89.58 kWh) and highest CO<sub>2</sub> emission reduction (50.8 %). Compared to the baseline (182.00 kWh), this represents a 50.7 % decrease in energy demand. This optimal configuration was discovered through P-graph's exhaustive search, which identified a workflow variant that bypasses redundant manual tasks under high load, an option not reachable via local or sequential optimization methods. Similarly, the MPC and Nonlinear scenarios, also generated from the P-graph solution space, showed 46.5 % and 42.9 % emission reductions respectively—demonstrating how the model offers a suite of near-optimal alternatives depending on operational constraints and predictability of workloads.

The P-graph framework models the process space using a bipartite graph structure composed of operating units (O-type nodes) and material/task elements (M-type nodes), with constraints embedded directly into the topology. In administrative workflows, tasks, resources, and conditions can be represented as nodes and arcs, allowing the exploration of all structurally feasible workflow variants. The generation of the maximal structure—which contains all potential process configurations—and the solution structure generation algorithm (SSG) enables full enumeration of all admissible workflow architectures. This approach ensures that the global optimum is identified, unlike conventional heuristics that often converge to local optima. P-graph analysis provided the following benefits to the control-guided decision-making process: Uncovered energy-optimal workflow routes in real-world limitations, revealed redundant task execution and inefficient routing in the baseline setting and enabled scenario-dependent guidance for re-arranged process flows (e.g. bypassing manual steps during surge demand). This embedding was made possible by integrating control parameters (e.g., time-varying demand, energy coefficients, and digital/manual task toggle rules) as boundary conditions within the combinatorial model, enabling structural adaptation in near real time. Though MPC is superior under structured environments with familiar patterns (e.g. semester enrollment increases), nonlinear control offers more resilience under chaotic changes in demand. However, the hybrid solution is the most equitable, combining prediction, flexibility, and structural optimization. Control-theoretic approaches offer practical sustainability gains in administrative workflows by enabling real-time resource distribution and flexible routing. The P-graph's ability to explore all structurally feasible process variants supports informed, scenario-sensitive decision-making. Unlike traditional methods limited to a single solution, P-graph generates a maximal structure, ensuring global optimality. This was crucial in identifying the hybrid scenario, which achieved the best energy and emission outcomes—demonstrating the method's unique value for sustainability-focused digital transformation.

## 5. Conclusions

This study demonstrated how control theory principles, specifically Model Predictive Control (MPC), nonlinear control, and hybrid control approaches, could be effectively integrated with the P-graph approach to make administrative processes more sustainable and energy efficient. Using an example of a university registration workflow, we implemented five different process configurations ranging from manual to fully automated and dynamically optimized models. The integration with control-oriented optimization and scenario-dependent P-graph modeling enabled the identification of energy-minimizing process paths, dynamic workload variation adaptation, and improved resource utilization. The results showed that control-theory-based approaches had remarkable saving in energy consumption and CO<sub>2</sub> emissions. Hybrid control model had optimal performance overall, with over 50 % of the reduction in emissions compared to baseline and higher capability to respond to changes in the process. Further, application of Life Cycle Assessment (LCA) provided crucial information on the environmental balance between manual and digital processes and justified the incorporation of sustainability indicators with operating models. While the simulation-based results are promising, the current study is not exempt from limitations. First, the energy consumption estimates are based on standardized task parameters and assumed mean infrastructure data, which may vary between institutions. Second, the control measures were implemented within a simulated environment rather than being introduced in an actual real-time system, limiting observations on operational details and user engagement. Third, current P-graph and control paradigms focus on structural optimality and short-term performance, ignoring multi-period decision-making and uncertainty of long-term demand projections. Increased research must be put towards developing a more detailed and dynamic control model that includes advanced workload prediction, cost-based constraints, and time-variable parameters. The results cumulatively confirm that the incorporation of control logic into administration processes yields significant sustainability benefits. Among all the models tested, hybrid control yielded the best overall results with least carbon footprint and energy usage, highest process flexibility and efficiency, and an extensible framework to various administration domains. Additional integration between the P-graph framework and mathematical control model will enable real-time process re-configuration and optimisation. Additional effort will also be put towards integrating control models into operational administrative systems, where real process data will be utilised to evaluate and verify model performance and refine energy and emissions estimates. Finally, future studies will attempt to broaden the analysis to more fields of public administration and incorporate extended LCA models to assess the long-run sustainability of control-based administrative modernization.

## Nomenclature

$E_i$  - energy consumption of task  $i$ , kWh  
 $E_{total}$  - total energy consumed by the process, kWh  
 $N$  - number of tasks in the scenario process  
 $n_i$  - Number of instances of task  $i$  in the process

$P_i$  - power consumption of device or activity used in task  $i$ , kW  
 $t_i$  - time required for task  $i$ , h  
 $\gamma$  - grid-specific emission factor, kg CO<sub>2</sub>/kWh

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