COmmunity-Based Organized Littering

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Runtime modeling environment for the specification of BPMN models with dedicated editors and runtime interpreter

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Abstract

Littering poses a serious environmental issue, impacting the economy, safety, and health of communities. While natural and rural landscapes are frequently subjected to illegal dumping, cities often struggle with excessive waste buildup that exceeds their disposal capacity. Reducing litter and waste is a key sustainability challenge that demands collaboration among various professionals and organizations. We present our vision and an initial proposal for a model-driven strategy to tackle the automated detection and identification of abandoned waste. Our approach leverages digital process twins to define efficient, self-adaptive workflows powered by crowdsourced real-world data.

Keyword list

Digital twins; Sustainability; Model-driven software engineering; Littering; Business process modeling; Low-code

Glossary, acronyms & abbreviations

Item	Description
COBOL	COmmunity-Based Organized Littering
DT	Digital Twin
BPM	Business Process Modeling
SDGs	Sustainable Development Goals
MDD	Model-driven development
BPMN	Business Process Model and Notation
PDT	Process Digital Twin
WATs	Workflow Automation Tools
UI	User Interface
MDE	Model Driven Engineering

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1 Introduction

Littering poses a serious environmental threat with wide-ranging impacts on public health, safety, and the economy. Discarded waste can lead to fire risks, environmental contamination, flooding, and harm to wildlife and their food sources. Addressing this issue is a major sustainability challenge that requires coordinated efforts among diverse professionals and governing bodies.

Cleaning urban and wild areas is extremely expensive. For instance, the Clean Europe Network estimates that the total cost of cleaning up litter on the land throughout the EU is in the range of €10-13 billion (CEN, 2024).

In this work, we outline our vision for a model-driven approach aimed at automating the detection and identification of abandoned waste, as well as enabling its efficient and cost-effective disposal. It aims to deliver lightweight littering reporting, engaging all the stakeholders playing a role in the littering disposal process, including citizens. For doing this, we consider four key challenges:

1. Abandoned waste often results from unethical and illegal actions by citizens. Engaging them in its removal can lead to immediate environmental improvements and, over time, foster greater environmental awareness and responsibility, potentially reducing future littering through education.
2. To effectively handle the waste disposal process, solutions that can handle the design and execution of sophisticated processes involving multiple actors are needed.
3. Effective waste disposal solutions must go beyond simple reporting tools, as the process is highly context-dependent. Factors like the location of the waste and the responsible authorities vary, making a universal, one-size-fits-all approach unfeasible.
4. To evaluate process effectiveness, ongoing result monitoring is essential, along with incentives for citizen and authority participation. This requires well-designed KPIs and transparent, publicly accessible dashboards.

To tackle these challenges, we propose a hybrid approach that combines a model-driven solution capable of handling diverse scenarios and unforeseen events while effectively guiding both citizens and authorities in waste management with a process digital twin (PDT).

PDTs represent business processes by capturing real-world entities and their interactions in digital form. Unlike basic process digitization, which focuses on automating tasks or converting manual processes into digital formats, PDTs provide dynamic, real-time synchronization with the physical processes they model.

This enables businesses to predict outcomes, test scenarios, and make data-driven decisions. Industries like Microsoft and Atos with Siemens emphasize PDTs as valuable tools for exploring "what-if" scenarios, making a forecast, and taking decisions.

We aim to bring the concept of PDTs into the context of littering management, where the digital process twin can collect and analyze real-time data coming from the environment, reflecting the system’s current and future states and providing functionalities such as process optimization and simulation to let the system assist stakeholders and operators in the waste disposal process definition and enable the self-adaptation of the processes, to deal with unexpected events.

The digital twin supports precise design and ongoing enhancement of the litter management process. Operating at runtime, it enables the system to respond dynamically to real-time changes without the need for full redeployment. This flexibility ensures consistent efficiency and service quality under varying conditions, allowing the system to continuously learn from data and improve its performance over time.

2. Characteristics of Process Digital Twins

Given the emergent topic and the consequently low maturity of the PDT concept in the literature, there is still no well-established definition and no common understanding of the key characteristics a PDT should have.

To try to clarify this concept we performed a literature analysis to answer this research question: *What are the key characteristics to represent a PDT?* For this, we used the Scopus database. More details relating to the review we performed can be consulted at https://github.com/gssi/Low-code-Process-Digital-Twins/tree/main/literature-review.

We considered the initial time range for the research from the start of the DT concept (1990) until December 2024. This research returned 145 studies, and after applying inclusion and exclusion criteria (IC and EC) to restrict the search scope of the topic (Kitchenham and Charters, 2007), 13 papers remained on the final list. Figure 1 brings a representation that encapsulates the essential components and interactions within a PDT, obtained from the literature review. This representation, consistent with the DT five-dimensional architecture (Tao et al., 2021), is also inspired by the four-layered metamodeling stack (Kühne, 2006). It follows the typical life cycle of a process definition and instantiation.

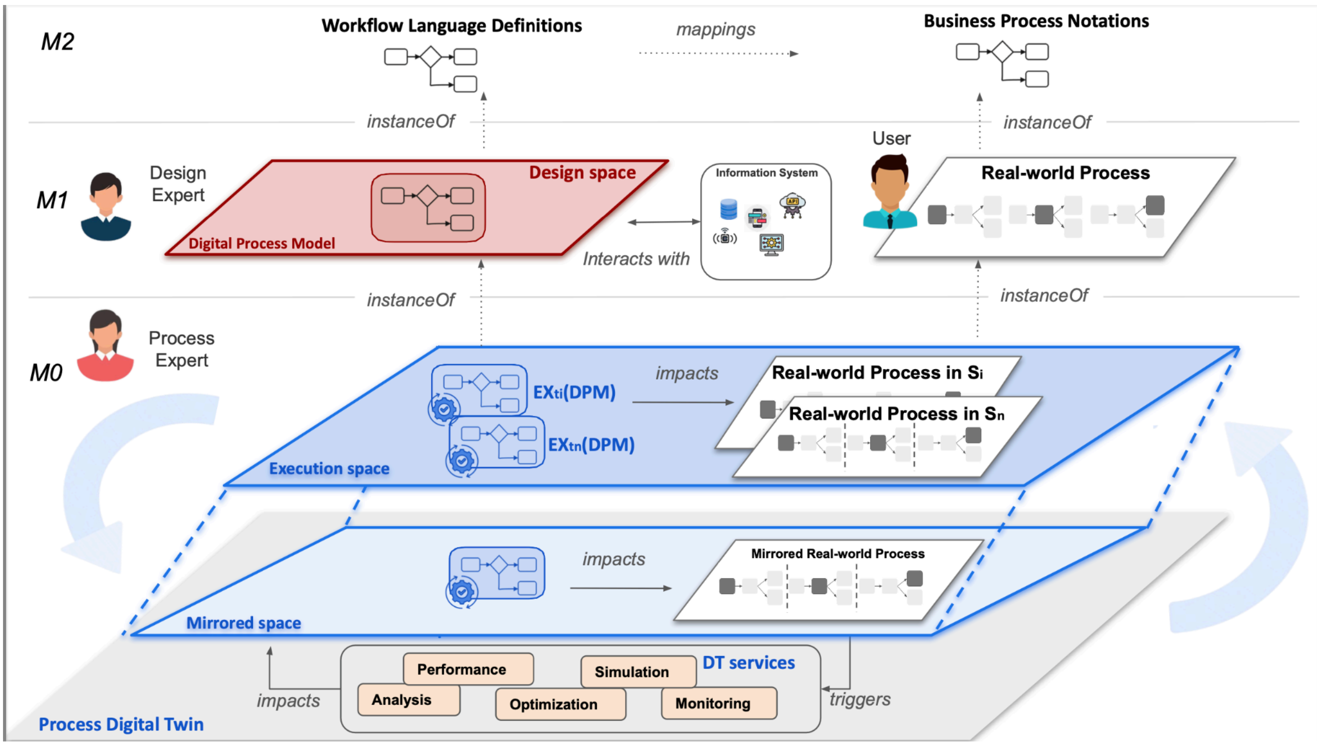

Figure 1: Formal representation of PDTs

A high-level definition for a PDT is *dynamic, data-driven representation of a real-world process that, once instantiated, can enable advanced functionalities*, such as continuous monitoring, simulation, and optimization. It bridges physical process representation and digital execution, integrating real-time data, predictive analysis, and human-in-the-loop decision-making.

A **Real-world process (RP)** is usually represented as status-changing activities, meaning they transition through a series of states over time as tasks are executed, conditions evolve, and external inputs are received. Business process model and notation (BPMN) enable a common understanding and analysis of a business process; for this reason, a specific real-world process can be represented as an instance of them. An RP can be implemented as a **Digital Process Model (DPM)** (or a combination of them), which provides a structured, digital representation of the states where the RP can be through workflows, dependencies, and execution logic.

There is a fundamental relationship between the RP and DPM, which is implicit since a DPM does not represent a 1-1 mapping with the RP, but interacting with external resources, e.g., information systems, can influence its status and transition them. For instance, if the status transition in the RP is simply a mere representation of going from the status "Ready" to "Processing" or "Completed", the DPM can trigger not only the status change and its digital representation but also apply many other actions, such as setting notifications, creating documents and so on.

Once the process is modeled digitally, the *Process Execution (EX)* can be seen as a further instantiation of the DPM, which is a template, against the RP in a specific state s_i, generating a new instance of the RP in another state s_y, i.e. a status transition. The execution EX_t at different times t evolves, dynamically affecting the various states' real-world process state, forward or backward. Different process executions $EX_{t1}..EX_{tn}$ are stored to have mirrored executions that can be used to simulate, analyze, and optimize the processes, reflecting in the loop-back the digital twin's operations.

We report in the following the characteristics we extracted from the literature analysis to answer our research question.

CH1 - Real-Time Process Synchronization: A PDT mirrors a physical process in real-time, allowing businesses to reflect scenarios' current status and operations. This synchronization ensures that the digital representation is always up-to-date, enabling immediate insight into how changes in the physical process affect operations.

CH2 - Process Simulation: Process simulation involves creating dynamic models of business processes that can be tested under various conditions. A PDT permits simulating scenarios and outcomes, helping organizations visualize the effects of changes or improvements before implementing them in the real world, leading to better decision-making and risk assessment.

CH3 - Process Predictive Analytics: Predictive analytics leverages advanced algorithms, ML, and AI to forecast outcomes and detect anomalies within the process from historical data, to make informed decisions.

CH4 - Process Optimization: Process optimization focuses on improving efficiency, reducing costs, and enhancing the process's performance with a continuous feedback loop between the physical and digital worlds.

CH5 - Process Monitoring and Automation: Monitoring and automation capabilities within a PDT enable the automatic execution and monitoring of tasks based on rules and real-time data. This characteristic reduces the need for manual intervention, increases efficiency, and minimizes errors.

CH6 - Process Data Analysis: Data analysis within a PDT involves examining data collected from various sources to understand trends, identify inefficiencies, and make data-driven decisions using dashboards.

CH7 - Source Integration: A PDT requires integrating various data sources, like IoT devices, ERP systems, sensors, etc., to gather real-time or near-real-time data from the physical world.

CH8 - Process Performance: Process performance is the evaluation of the performance of the process over time. This may involve generating detailed reports on how the process behaves under different conditions and identifying opportunities for improvement.

CH9 - Process Interoperability: PDTs must work across different systems and software. Communication between digital models and existing IT systems is necessary for enabling PDT services.

CH10 - Process Scalability: PDTs must scale across various processes, locations, and companies, handling increased data volume, velocity, and variety. This characteristic is required for organizations implementing PDTs across multiple environments or geographies.

CH11 - Traceability: Traceability supports accountability and process transparency for a PDT. It ensures that all actions and actors can be tracked, which is critical for audit trails, compliance, and quality assurance.

3 Waste Management Through Digital Twins and Business Process Modeling

Figure 2 represents the architecture we designed to address the above-mentioned challenges. The architecture is composed of 3 platforms, namely: the Crowdsourcing, the Modeling, and the Runtime.

The crowdsourcing platform collects information from citizens, operators, and vehicles through a web app, which also implements a Mobile front-end, shares the collected data with the running processes, and provides a dashboard for data visualization (e.g., to visualize the ranks generated by the gamification logic, or to visualize the waste reported in the area).

The runtime platform runs various services and processes, such as simulation and optimization, to effectively respond to (unexpected) inputs from the physical world in real time. This supports the process's self-adaptation at runtime, enabling immediate problem resolution.

To make accurate and informed decisions, the modeling platform hosts the digital twins of the monitored areas, mimicking the actual activities required for handling, managing, and disposing of waste.

We describe the three platforms in the following.

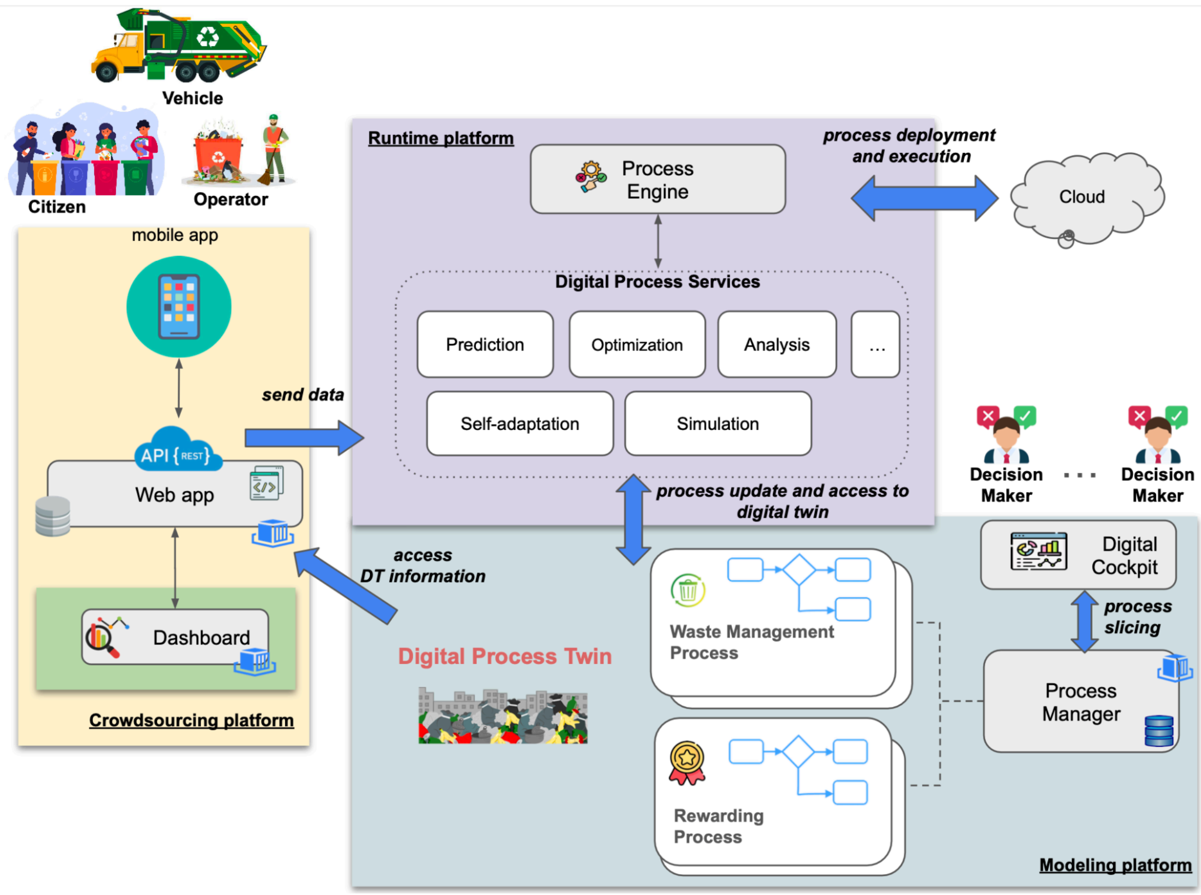

Figure 2: Digital Twin Process Modeling Architecture

Crowdsourcing Platform

Citizens are encouraged to participate in litter management by using a dedicated mobile app to report waste through geo-localized photos, a feature already available in several existing systems. Each submitted image will include metadata, such as location, and will be automatically anonymized to protect users' privacy.

This crowdsourcing platform actively involves the public in the waste disposal process by offering and requesting additional details about: (a) the type of waste reported, (b) the appropriate procedures for its removal or disposal, and (c) relevant contacts for organizations responsible for handling waste that cannot be easily transported to a landfill. Successful waste management depends on the engagement of all stakeholders, not just citizens.

The proposed approach integrates gamification to engage both citizens and public administrations. Citizens can earn rewards for reporting litter, removing waste, and verifying the cleanup efforts of others.

Meanwhile, administrations will be evaluated and ranked based on their effectiveness in maintaining clean areas, as reflected in citizen-submitted reports.

Additionally, data-driven metrics generated through the system can help administrations showcase the outcomes of their litter management initiatives and align their efforts with Sustainable Development Goals (SDGs) (UN, 2025).

The gamification and rewarding processes can be modeled by different administrations, according to other rules (using the modeling platform). This ensures that while the waste management and reward systems are designed independently, they remain closely connected.

The reward system relies heavily on the events and data produced by the waste management process to function effectively. Therefore, the modeling platform must maintain consistency between the two, ensuring they operate in harmony despite being developed as separate components.

Citizens and operators will exploit a dashboard populated with crowdsourced data, jointly with the data computed by the processes (e.g., the reward process and the digital process twins), to obtain information about the waste to be disposed of and the ranks generated by the gamification system.

Modeling Platform

In this architecture, we advocate for the use of process modeling as a core strategy to identify and modularize the involved processes and actors. This modular structure not only supports reuse across diverse contexts but also simplifies the definition of complex workflows. By minimizing redundancy, it enhances operational efficiency and makes it easier to manage variations in process execution.

To address this need, the architecture integrates two key technological components: model-driven development and self-adaptive systems. Model-driven development (MDD) is employed to tailor processes to specific application contexts. Using a standard business process language like BPMN -extended as necessary- we can precisely define waste disposal workflows.

This approach enables the creation of clear, visual representations of complex processes and facilitates coordination among multiple stakeholders. Additionally, workflow automation tools based on the same formalism can be leveraged to streamline execution and enhance consistency.

The modeling platform supports the design and graphical management of two primary process types: waste management processes covering waste collection, transport, and disposal and reward processes, which establish incentive policies for citizens who engage in proper waste reporting, sorting, and recycling. These two process types are tightly interlinked and communicate continuously to ensure cohesive and efficient system operation.

This interaction is essential, as data generated during waste management activities directly informs the reward mechanisms, ensuring that incentives are aligned with actual environmental contributions.

Those processes are defined through a modeling tool and handled by a *process manager* entity, which coordinates the various processes and a digital cockpit. The *digital cockpit* serves as the central hub for real-time monitoring and control, providing a complete and detailed overview of all ongoing operations. Decision makers interact with the digital cockpit to analyze the ongoing activities and KPIs trends and make informed decisions based on the insights.

Because decision-makers may come from different organizations such as municipal authorities or waste disposal agencies each will have distinct permissions for viewing and modifying processes. For example, while a transportation agency can configure transport-related workflows, it cannot alter landfill disposal procedures, though it can still view them.

Collaborative editing will be managed through process model slicing techniques (Taentzer et al., 2018), which facilitate cooperation while preserving clear ownership and control over specific parts of the process.

Finally, *self-adaptive* technologies will be employed to enhance processes with the ability to autonomously adjust in response to unexpected events, using a digital twin representation.

For instance, if the designated person for handling a notification is unavailable, such as being on vacation, the system will automatically reroute the task to an appropriate alternative. These adaptive behaviors can be defined using a notation designed for specifying heuristics or general adaptation rules tailored to each process.

Runtime Platform

After the processes are modeled, they can be executed in real time within the runtime platform using a *process engine* component. During execution, these processes can interact with various services, such as prediction, optimization, and simulation, leveraging real-time data from the physical environment to enhance decision-making and performance.

For instance, simulations can evaluate the potential benefits of installing additional litter bins in a specific area or assess the effectiveness of public awareness campaigns.

At the same time, optimization services can respond to real-world issues, such as an unavailable cleanup crew, by dynamically reallocating resources and adjusting task schedules. These analyses and adaptations are powered by replicating the system's underlying models, enabling it to respond intelligently to changing conditions.

The entire runtime platform functions like an interpreter, continuously interacting with the modeled processes defined by decision-makers. These same models are executed at runtime when triggered by the crowdsourcing platform.

For example, when a new report is submitted through the mobile app, it automatically initiates moderation actions by the appropriate authority. Once the report is validated, the process advances to the next step, whether cleanup, reassignment, or follow-up.

This seamless interaction between the process models, runtime engine, and real-world operations is orchestrated through what we refer to as a digital process twin.

This dynamic service invocation allows the processes to remain highly responsive and adaptable, ensuring that waste management operations stay effective and resilient in the face of unexpected events or evolving conditions.

Given the potentially high demands and variable workload of the process engine, services will be deployed in the cloud to ensure scalability and maintain consistent performance.

4 A Low-code prototypical implementation

Our first attempt was to produce a solution using BPMN. However, we found BPMN models to be difficult to maintain and adapt particularly for non-technical stakeholders, such as municipal staff involved in smart city services and regularly interacting with PDTs. Moreover, the development and upkeep of PDTs are inherently complex (Gao et al., 2022), requiring advanced modeling, ongoing integration of data from diverse sources, real-time synchronization with physical systems, and collaboration among multiple actors.

Traditional modeling languages like BPMN are designed for static workflows and lack the flexibility needed to support real-time feedback, advanced data analytics, and the continuous adaptation essential for effective PDT implementation.

In contrast, the rapid advancement of Low-Code Development Platforms (LCDPs) (Sahay, 2020) has led to the availability of ready-to-use toolkits that enable users with little to no programming experience to easily build, modify, and maintain applications. Features like user authentication, API integration, and database connections are offered as composable blocks. This greatly shortens development time and lowers overall costs.

LCDPs emerged in the early 2000s as a way to simplify software development, allowing individuals with minimal programming experience to create applications through graphical user interfaces and drag-and-drop tools. The idea behind these platforms was to democratize the development process, enabling business users, analysts, and other non-developers to build applications without needing to write extensive code. Being Model Driven Engineering (MDE) and Low-code conceptually close, cross-pollination between the two disciplines is unavoidable (Ruscio et al., 2022).

Over time, as technology advanced, low-code platforms gained traction due to the increasing demand for rapid application development in businesses. They allowed companies to quickly prototype and deploy solutions without waiting for lengthy development cycles or relying on few skilled developers.

LCDPs were especially useful in automating workflows, creating customer-facing applications, and building internal tools to streamline business processes. Its ability to enable collaboration between IT departments and business units allowed for faster iteration and more agile development.

Low-code and No-code platforms exhibit great potential for supporting the implementation of workflow management tools for different use cases, including littering management. Workflow automation refers to using software to complete some tasks and activities (with or without the need for human input). Workflow automation also plays a crucial role in process orchestration.

In the COBOL project (Baresi et al., 2024), a low-code platform results in an efficient and fast solution to develop the crowdsourcing platform.

Among all possible low-code development platforms - workflow automation tools (WATs), the n8n (n8n, 2025) platform was chosen to develop a prototype. The n8n platform allows self-hosting and complete control over the infrastructure. It stands out by enabling users to create workflows through the orchestration of over 200 built-in integrations using a visual node-based interface.

The nodes are grouped into several categories: *Task nodes*, which perform actions within the workflow and include built-in operations as well as core HTTP request nodes for custom REST calls; *Data Transformation nodes*, which manipulate data during execution; and *Flow nodes*, which control the logic of the workflow, such as conditionals and switch statements.

It also offers the possibility of easily integrating external components, such as Notion, email systems, and API REST.

4.1 COBOL case study

A specific removal process should be initiated based on the type of litter identified by humans, with variability depending on how easily the litter can be recognized and the complexity of its handling. For example, removing plastic is relatively straightforward, whereas removing hazardous materials like asbestos requires coordination among multiple public authorities.

In all cases, an information system can gather data from users, which then triggers the appropriate processes, ensuring human involvement remains central to decision-making.

Plastic Removal Process

When a citizen submits a report identifying plastic waste, the process moves from the *report received* state to *waste identified*, triggering the Plastic Removal Process. Based on the report, the system recommends appropriate disposal actions. For non-hazardous plastic waste located in urban areas, the system first asks the user if a plastic recycling bin is nearby. If confirmed, and the user reports placing the waste in the bin, the process is marked as complete.

However, if the waste is too large, difficult to access, or no recycling bin is available, the system escalates the report to the local waste management service. In this case, the process concludes when a designated waste operator collects and removes the reported plastic.

Asbestos Removal Process

The Asbestos Removal Process is significantly more complex than plastic waste disposal due to the serious health and safety hazards associated with asbestos exposure. It begins when a citizen submits a report indicating the possible presence of asbestos, including images or a description of the material. Once submitted, the system classifies the waste as asbestos and initiates the corresponding specialized workflow.

Public health authorities are immediately alerted to the potential risk. A certified asbestos removal expert is then dispatched to inspect the site, confirm the presence of asbestos, assess its friability (i.e., the likelihood of releasing hazardous fibers), and evaluate the associated health risks. Based on this evaluation, a comprehensive removal plan is created, outlining required safety measures, specialized equipment, and qualified personnel. This plan is submitted to the relevant local authorities for approval to ensure compliance with health and environmental regulations.

Once approved, a licensed removal team is deployed to the site to carry out the removal with strict adherence to safety protocols. The asbestos is securely packaged to prevent contamination during transport and delivered to an authorized disposal facility. After removal, the area is thoroughly cleaned and monitored for air quality to ensure it is safe for public use.

A final report documents the entire process, including health assessments and regulatory compliance, ensuring that all procedures followed established safety standards.

These examples clearly illustrate how the system's status is determined by the specific waste removal process, which varies depending on the type of waste. Each process orchestrates the necessary services and coordinates interactions among stakeholders and public authorities accordingly.

For instance, asbestos removal may involve an intermediate status such as "health risk notification" before proceeding to the formal removal request, reflecting the added complexity and safety requirements of handling hazardous materials.

4.2 Implementation

In this case study, the system is designed to trigger distinct removal workflows based on the type of waste identified. To manage this dynamically, we created a Notion database that maps each waste type to a corresponding process ID, which links to a specific workflow in n8n.

This approach provides administrators with maximum flexibility to add, edit, or remove workflows and their associations as needed. We implemented three sub-workflows tailored to handle paper, plastic, and asbestos, selected to reflect varying levels of complexity in resolving waste site issues.

The platform hosts a set of workflows that are triggered either by specific user actions within the information system or automatically, as defined within each workflow, ensuring seamless process execution.

It also includes continuous monitoring capabilities, tracking key performance metrics such as execution times, task completion rates, and efficiency indicators. This enables ongoing analysis and supports continuous optimization of the processes.

The information system is used by both the citizens and the public administration to report waste sites and manage the removal process, step-by-step, with assisted status management. Also, a mobile app has been developed with NotionApps (NotionApps, 2025), which is a UI no-code development platform for Notion, as can be seen in Figure 3a. Indeed, the list of reported waste sites is grouped by status in the typical Notion screen in Figure 3c, where decision-makers and operators can keep the situation constantly under control, in real-time.

A dashboard, reported in 3b, shows the number of reports by waste type on the left, whereas on the right, it shows the number of reports by date. This dashboard, obtained with Notion views, is also used for process data analysis, allowing authorities to identify trends, such as areas with frequent waste accumulation, seasonal variations, and response time efficiency, supporting proactive decision-making and resource allocation.

Each report is also reported on a map-based view (see d in Figure 3), also in this case obtained with no-code solutions.

In the paper removal process, the user is first asked whether they can remove the waste independently. If they respond negatively, the system automatically notifies an operator via email, using Gmail integration to manage the escalation.

This straightforward workflow involves two status stages, one of which is determined by the user's input. In contrast, the plastic removal process directly alerts an operator and tracks the task through a progression of statuses, starting with "in progress" and updating to "done" once the removal is completed.

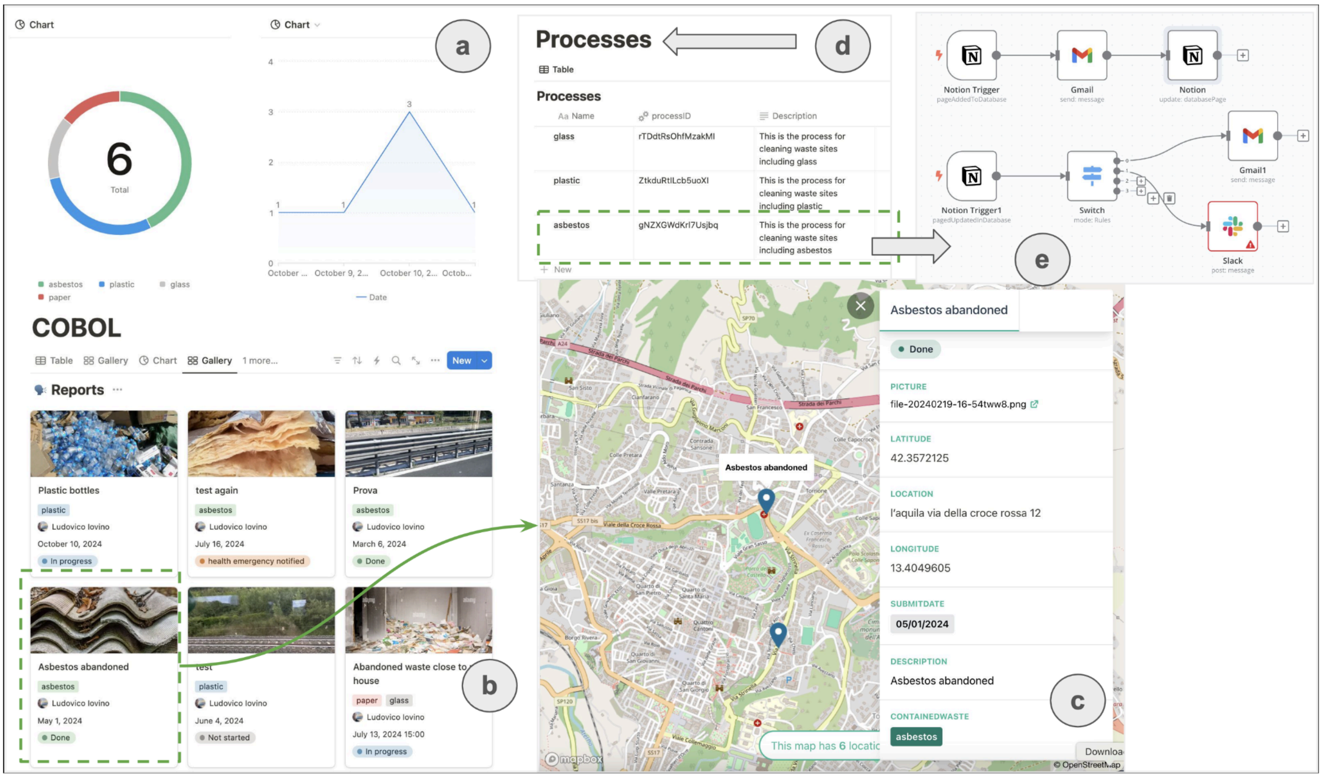

Figure 3: Implementation of the COBOL case study with Low-code platforms

The asbestos management process (see Figure 3 where the workflow is partially reported textually in e and graphically in f) includes multiple status changes since the removal process of this type of waste is more complex.

For instance, when the report arrives, the status is moved into "received", then when it is validated by the public administrator, an health emergency notification status is used to inform the local health department and the user of the possibility of respiratory problems in case of an invalid removal process.

We used *Slack* to simulate a real-time notification, and a video demo can be watched at https://youtu.be/DGcxz1zb-5A. Additionally, before executing the removal workflow, the system can perform process simulation to assess the required resources and potential risks, helping authorities plan the most effective waste disposal strategy.

n8n allows access to a testing environment where the process can be simulated before being exposed to production. Moreover, the process execution is stored and can be re-executed for debugging in case the process is, for some reason, problematic.

In this scenario as well, the system blends human-directed status updates with autonomous actions, mirroring the real-world process. For example, when the operator is prompted to confirm task completion, the system updates the status to "done" based on their input.

To support different removal processes, we created a Notion database to map the type of waste to the ID of a process corresponding to a workflow in n8n that will be triggered (see Figure 3e where the association is reported explicitly by linking the process ID with the type of waste). In particular, there are two cases when a user action must trigger a process status change.

The activation can be implicit; the WAT detects the status changes in the information system and then activates a workflow as a reaction. Otherwise, the activation can be explicit; the WAT asks the user to generate a status change relying on a trigger (e.g., a webhook) that can be “voluntarily” activated by the user, for instance, by clicking a link received by email or a button in the UI of the information system. In both cases, the information system keeps the current status of the real-world process as internal variables.

Vice versa, changes occurring within the PDT are actuated into the physical world through the information system, involving manual status changes. The status change is reflected in real time to all the interfaces the information system offers, e.g., 3a and 3c.

LCDPs and in our experiment, n8n’s flexibility allows it to connect with specialized systems or machine learning models to analyze and optimize workflows and predict future trends and potential inefficiencies. With the integration of these external tools, n8n can enhance its capabilities to monitor process performance dynamically and make data-driven predictions.

5 Conclusions and remarks

We presented our vision of integrating process modeling with PDTs to enable self-adaptive procedures for managing the waste disposal process. The incorporation of a crowdsourcing platform supports this vision by supplying real-world data to the digital twins and promoting citizen engagement in reporting and removing waste.

We implemented a case study using LCDPs looking for reducing development complexity. These advantages make PDTs more accessible to non-technical stakeholders, encouraging broader adoption across various domains.

Looking ahead, our future work will focus on strengthening partnerships with municipalities to implement and test the proposed solution in controlled environments, ultimately gaining valuable insights into its practical effectiveness.

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