Waste Management Through Digital Twins and Business Process Modeling

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Abstract

Littering is an environmental problem that affects citizens' economy, safety, and health. Natural and rural areas are often targets of abandoned littering, while urban areas often accumulate more waste than can be disposed of in a timely manner. Minimizing littering and waste is a critical sustainability challenge requiring the cooperation of different professionals and agencies. In this paper, we report our vision and preliminary proposal for a model-driven approach to address the automated localization and identification of abandoned waste. Our solution envisages the usage of digital process twins to enable the specification of cost-effective and self-adaptive procedures fed by data crowdsourced from the real world.

CCS Concepts

• **Applied computing** → *Business process modeling*; *Environmental sciences*; • **Information systems** → *Collaborative and social computing systems and tools*; • **Software and its engineering** → *Model-driven software engineering*.

Keywords

MDE, digital process twin, sustainability, littering

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1 Introduction

Littering is an environmental problem that affects citizens' economy, safety, and health. In fact, abandoned waste can cause fire hazards, pollution, flooding, and poisoning of wildlife and animal food sources. Natural areas, which are considered tremendous assets for some regions because they are silent and isolated, are often targets of littering. 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 [10].

Minimizing littering and waste is a critical sustainability challenge that requires the cooperation of different professionals and agencies. In this paper, we report our vision for a model-driven approach to address the automated localization and identification of abandoned waste and the cost-effective management of its disposal.

Previous approaches were not entirely successful because they required too much effort from the community, e.g., due to the high volume of information that must be manually processed [8], or involved technical solutions that were not easily accessible by public authorities, e.g., requiring the access to satellite images [14].

This paper presents an approach developed as part of the COmmunity –Based Organized Littering (COBOL) project [2]. It aims to deliver lightweight littering reporting, engaging all the stakeholders playing a role in the littering disposal process, including citizens. In particular, our work considers the following key challenges:

- Abandoned waste is mainly the consequence of unethical and illegal behavior of citizens. *Involving the citizens* themselves in removing the waste has both short-term and long-term effects. In the short term, if citizens proactively engage in waste disposal, the environment will be cleaner. In the long term, the involvement of the citizens can likely increase awareness and respect for the environment, our cities, and our countryside, prospectively reducing the amount of abandoned waste through education.
- Waste removal may involve *non-trivial processes.* Depending on the nature of the waste, different agencies and organizations may need to be involved and synchronized. For instance, expired

drugs must be managed by specific operators since they can develop toxic substances, asbestos requires procedures that involve specific companies and protective measures, while other waste could be even and simply disposed of by citizens (e.g., as in the initiative launched by the European Environment Agency in 2018 to remove plastic littering from beaches [1]). In a nutshell, to effectively handle the waste disposal process, *solutions that can handle the design and execution of sophisticated processes involving multiple actors are needed.*

- To establish solutions that go beyond the straightforward capability of submitting reports through web and mobile apps, it is necessary to consider that the *waste disposal process is context-dependent*, that is, the same waste might need to be handled differently depending, for instance, on the place where it has been abandoned (e.g., littering managed in big cities, towns, rural areas, or the countryside), and on the administrations and organizations that will be responsible for its disposal, making *impossible the design of a 'one-fit-all' solution.*
- To know how effective a process is, it is important to continuously *monitor results* and further incentivize both citizens and public authorities to participate in the waste removal process. Proper key performance indicators (KPIs) and publicly accessible dashboards must be designed.

To address these challenges, we propose to combine *a model-driven solution*, which can manage various contexts and deal with unexpected events, guiding citizens and authorities in the waste disposal process effectively, with a *digital process twin*, which facilitates the accurate development and continuous refinement of the littering management process. In particular, a digital process twin operating at runtime enables the system to adapt dynamically to real-time changes and unexpected events without re-deploying the entire system. This adaptability ensures that the system can maintain high efficiency and service quality, even under varying conditions, continuously learning from accumulating data, leading to progressively optimized performance.

The concept of *process digital twin* has already been used to analyze and support the waste management process, and specifically to analyze the performance costs and the service quality in some countries [3, 6]. We aim to bring this conceptualization 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.

This paper is organized as follows. Section 2 discusses waste disposal processes in place in different areas, highlighting differences, commonalities, and complexities. Section 3 describes our Digital Twin Process Modeling solution. Section 4 presents related work. Finally, Section 5 provides concluding remarks.

2 On the Need of Process Modeling

The proposed solution shall be easily applicable to different contexts, which may involve multiple organizations working according to different (imperfect) protocols and different types of waste. Managing waste disposal procedures based on different guidelines is challenging due to their differing nature, making standardization difficult. However, among all the differences, the procedures may share commonalities regarding involved stakeholders, operational procedures, required documentation, etc. Additionally, the inherent complexity of these procedures makes it difficult to create a standardized approach. We will illustrate these cases below.

Differences. As an example of a typical difference characterizing two or more waste disposal processes, we report two interesting procedures for the disposal of animal carcasses, based on guidelines defined by two different authorities, namely NetRegs[1] and the Abruzzo region in an official bulletin[2]. The difference here relies on the fact that the guidelines target different subjects, thus foreseeing different procedures. The NetRegs' guidelines specifically target the companies responsible of the disposal processes. Whereas, the Abruzzo region's guidelines target the many stakeholders that might be involved in the disposal of animal carcasses (e.g., public administrations, citizens, disposal operators). A well-defined process model might serve as a common language among all these stakeholders [7]. This can improve communication and collaboration, ensuring that all participants clearly understand their responsibilities and the operations to be followed.

Commonalities. Despite the different nature of the two mentioned guidelines, we can observe commonalities between them. For instance, they both differentiate the operations by geographical area. NetRegs specifies different regulations for Northern Ireland and Scotland. Instead, the Abruzzo region distinguishes between non-protected and protected areas. To deal with cases like this one, process modeling can be used to flexibility supports adaptation of standard processes to the specific case, while maintaining a common operational foundation (e.g., defining a parametric process that works differently depending on the type of local area). This allows customized solutions for each area of interest without compromising overall uniformity and coherence of the procedure.

Complexities. A common aspect of the reported procedures is that we can observe a certain level of fragmentation and intricacy that make the processes complex to model or describe. A sample waste disposal procedure that shows the complex nature of such processes is the one about the disposal of abandoned asbestos. It represents one of the major problems in Italy due to the complexity and costs of disposal, not to mention the possible health risks. For this reason, it is not unusual to find abandoned sites with asbestos mixed with other building materials. Disposing and cleaning a site with asbestos requires communication with the municipality and the local police department. After a visit from the representatives of these entities, a private company specialized in the field will be involved in the disposal process. However, before proceeding with the actual disposal, the health department must be informed to check for any health risks. All these operations will be assisted with documents, forms to be filled in, material to be sampled, and communications, to name a few[3]. These operations' intricate nature and

[1] https://www.netregs.org.uk/environmental-topics/waste/managing-waste-materials/

[2] https://bit.ly/3VxMSnK

[3] The complete procedure can be read at: https://sanita.regione.abruzzo.it/sites/default/files/SPSAL/norme/Linee%20Guida%20amianto.pdf

fragmentation demonstrate the need for rigorous and well-defined processes that can define clear procedures and master complexity. Furthermore, the ability to adapt these models to accommodate the varying regional requirements and constraints is crucial for ensuring efficient and standardized waste disposal processes. Moreover, in specific contexts, there is also the need for self-adaptation of the procedures to dynamic conditions. For instance, the procedure defined in the bulletin provided by the Abruzzo region distinguishes different sub-processes depending on the condition of the carcass at the moment of the discovery. Specifically, if a suspect commits any illegal acts against animals, a specific judicial police procedure must be activated. However, in case of suspected infectious diseases or risks to public health, the handling of the carcass has to follow a different procedure, w.r.t. the basic one.

3 Digital Twin Process Modeling for Waste Management

Figure 1 represents the architecture we designed (not yet implemented) to address the above-mentioned challenges. The architecture is composed of 3 platforms, namely: the *Crowdsourcing*, the *Modeling*, and the *Runtime* platforms. 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 that constitute our architecture in the following sections.

3.1 Crowdsourcing Platform

Citizens shall contribute to littering by reporting geo-localized pictures of waste through a dedicated mobile app, as is already possible with several other systems. Pictures shall include metadata, such as the image's geolocation. The collected data will be anonymized on the fly to avoid disclosing sensitive information. The crowdsourcing platform involves citizens in the waste disposal process, asking and providing them additional information about (a) the nature of the waste, (b) the process that should be followed to remove and/or dispose of the waste, and (c) the contacts to reach the organizations that can dispose of the specifically detected waste when it cannot be simply removed and brought to a landfill. All parties participating in the waste management process (not only citizens) are engaged to be successful.

The proposed approach also establishes gamified processes for both citizens and administrations. Citizens will be rewarded for reporting and removing waste and for confirming or disproving waste removal actions taken by other actors. Administrations will compete on their ability to keep areas clean based on citizens' reports. Further, the indexes derived from the collected data could be used by administrations to demonstrate the impact of actions regarding littering management, as well as in the context of the SDGs[4].

It is important to remark that the gamification and rewarding processes are modeled processes themselves. Different administrations can model these processes according to other rules (using the modeling platform). This guarantees that the waste management and reward processes are decoupled on the one hand, that is, they are modeled separately, but they are also interdependent on the other hand since the events and data generated by the waste management process represent the most relevant source of information for the definition of the reward system. The modeling platform must guarantee the coherence of these two processes.

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.

3.2 Modeling Platform

Waste disposal may include numerous processes, such as collection, transportation, treatment, and recycling. Each contains different stakeholders and a certain degree of variability caused by the specific context in which the disposal happens, as anticipated in Section 2. In this architecture, we propose to exploit process modeling as a fundamental element in identifying and modularizing these processes and actors involved, making them reusable in different contexts and also facilitating the specification of processes that could be complex. This modular approach reduces duplication of efforts, increases operational efficiency, and allows for easier management of process variations.

For this reason, the architecture will combine two technical facets: model-driven development and self-adaptive technologies. Model-driven development (MDD) is exploited to define and customize processes to the specific usage context. We use process modeling with a standard business process language, such as BPMN notation with possible extensions if needed, to rigorously specify our disposal processes. However, workflow automation tools can also be explored, being based on the same formalism. This permits the creation of a clear and detailed visual representation of various waste disposal processes while also incorporating the collaboration between different stakeholders.

The *modeling platform* allows the management and graphical definition of two main types of processes: waste management processes, which involve the collection, transportation, and disposal of waste, and the rewarding processes, which define policies to assign incentives to citizens for proper waste reporting, waste separation, and recycling. These processes are closely interconnected and communicate with each other to ensure efficient and integrated management. Communication between these processes is crucial, as the data collected from the waste management process can directly influence the rewards given in the rewarding process.

Those processes are defined through a web-based modeling tool, persisted in a dedicated model repository, and handled by a *process*

[4]https://sdgs.un.org/goals

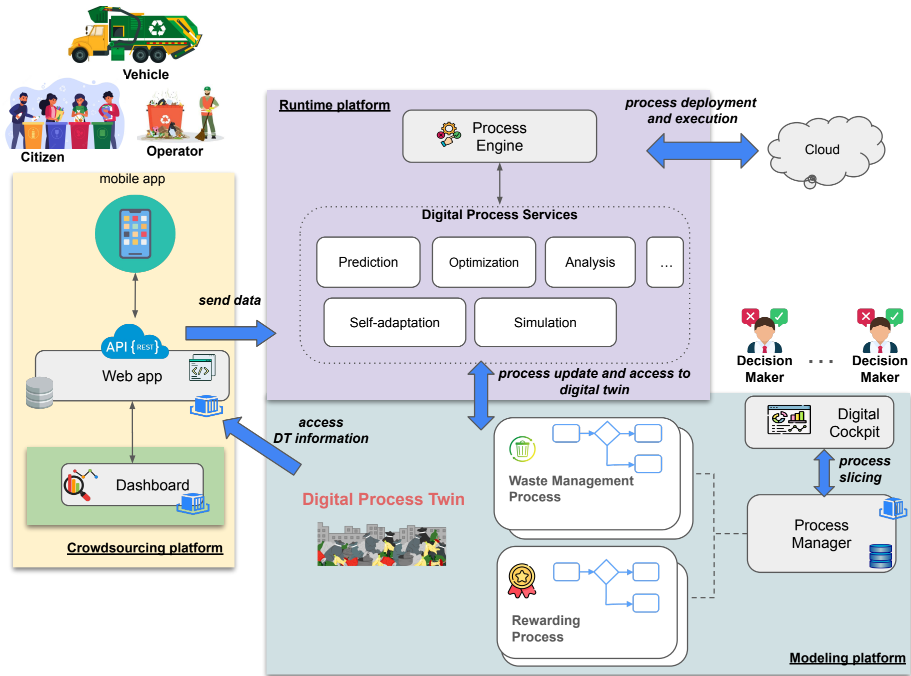

Figure 1: Digital Twin Process Modeling Architecture

manager entity, which coordinates the various processes and a digital cockpit. The *digital cockpit* is the focal point for monitoring and controlling operations in real-time, ensuring a comprehensive and detailed view of ongoing activities. Decision makers interact with the digital cockpit to analyze the ongoing activities and KPIs trends and make informed decisions based on the insights. For instance, a hot area with a high frequency of abandoned sites may be targeted by local police, etc.

Since decision-makers may belong to different organizations (e.g., the municipality or the agency waste disposal agency), they will have their own visibility and change rights on the processes. For instance, the transportation agency may define how transportation should work but cannot change the waste disposal processes in the landfill, although they will also have the visibility of these processes. Collaborative editing of the process will be governed through process model slicing solutions [15] that will ensure collaboration while respecting ownership of the processes.

The modeling platform will also embed analysis routines to check that the final waste disposal process resulting from the composition of all processes provides the correct behavior; for instance, every abandoned waste will eventually be disposed of. Process analysis is crucial to guarantee that every citizen receives the proper level of service and that procedures are followed correctly and uniformly.

Finally, *self-adaptive* technologies will be exploited to enrich processes with the capability to self-organize in case of unexpected events through a digital twin of the processes. For example, if the appropriate person to handle a notification is on vacation, the system will automatically redirect the notification to another suitable individual. These rules may be specified with a notation suitable for defining heuristics or general adaptation rules for each process.

3.3 Runtime Platform

Once the processes are modeled, they can be executed at runtime inside the runtime platform through a *process engine* component. While being executed, these processes can invoke services such as prediction, optimization, simulation, and many others based on real-time input data from the physical world.

For example, simulations might show the impact of adding more litter bins in a specific area or the effectiveness of public awareness campaigns. Meanwhile, optimization services could address situations where the designated cleanup crew is unavailable by generating a new resource allocation and task schedule. All these simulations and analyses may be enabled by replicating the models on which the system reacts. Indeed, the entire runtime platform communicates with the underlying models like an interpreter of the processes defined by decision-makers. The same processes are interpreted at runtime when invoked by the Crowdsourcing platform. For instance, when a new report is submitted through the crowdsourcing system, e.g., via the mobile app, the same report triggers moderation actions by the relevant entities. When the operator validates the reported littering site, the specific process activates the next step, and so on. Such ongoing communications between the process models, the runtime engine, and the actual system are dribbled as a digital process twin.

This dynamic invocation of services enables the processes to be highly responsive and adaptive, ensuring that waste management processes remain effective and resilient despite unexpected events or changing conditions. Since the process engine can be pretty demanding and the workload partially unpredictable, we will deploy and run services on the cloud to guarantee scalability.

4 Related Work

Several studies try to address the waste management process through digital process twins. Cárdenas et al. address the waste management problem in South Africa using a prototype digital twin [5]. They focus on stakeholder prioritization and citizen engagement using an open-source tool for identifying waste containers and disposal sites and waste generation simulations via a control dashboard. Burkhart et al. propose a process digital twin to support the decision-making activities to find a compromise between costs and quality of services using smart waste bins in Switzerland [3]. The digital twin provides benchmarks for implementing similar systems in other municipalities and presents an innovative key performance indicator to measure service quality. However, a significant drawback is that the proposed works do not use modeling to develop or represent the processes or the digital twin. Without such modeling, the system lacks a detailed blueprint for its implementation and refinement. Further, none of the work addresses optimizing or creating a self-adaptive runtime environment for managing the waste disposal process. The lack of self-adaptation limits the system's ability to dynamically adjust to changing conditions and improve efficiency in real-time, reducing its overall effectiveness and responsiveness.

Modeling management processes at runtime has emerged as a promising approach to enhance the efficiency and effectiveness of handling (unexpected) events [9, 16]. These models prevent error-prone and time-consuming manual process adaptations, allowing systems to adapt dynamically to environmental changes. This makes them particularly suitable for the unpredictable nature of littering activities. Business processes, in particular, exhibit positive evidence in capturing processes specification and monitoring activities to identify possible improvements and necessary adaptations at runtime [4, 9, 11]. Traditional notation languages, such as BPMN, graphically support modelers through a narrow space of solutions for activity specification and provide a mechanism to specify how the system will react to expected exceptions.

Santana et al. propose a BPMN-based business process to facilitate requirements engineering in a complex waste management scenario, starting from material acquisition and ending with residue disposal. However, no specifications about the deployment of the actual system or possible changes in the process are discussed [13]. Pelonero et al. present a smart citizen-rewarding process for enhancing user garbage collection through an IoT-based service that promotes waste recycling in door-to-door urban environments [12]. Using QR codes and IoT sensors to collect and monitor essential waste-related data, such as waste composition (paper, plastics, glass, etc.), citizens can earn tax incentives through direct recycling. The authors have not addressed the possibility of having a digital twin and the self-adaptive capabilities that derive from its adoption in the IoT cloud environment modeled through a BPMN-based business process involving citizens and garbage collectors.

5 Conclusions

Littering is a significant problem affecting our society and threatening our environment, including natural, rural, and urban areas. In particular, the timely detection and removal of abandoned waste is an open challenge that requires new cost-effective solutions to be solved. This paper describes our vision of combining process modeling and digital process twins to achieve self-adaptive procedures that can be used to control the waste disposal process. In addition, the integration of a crowdsourcing platform addresses both the need to feed the digital twin processes with actual data about reality and the need to enable participatory processes where citizens are engaged in reporting and removing waste. Future work concerns fostering our collaboration with municipalities to develop and experiment with the proposed solution in controlled scenarios and finally obtain insights about its effectiveness.

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