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Research on Existing Problems and Intelligent Countermeasures of Harmless Treatment of Solid Waste

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Abstract: With the acceleration of urbanization and the transformation of consumption patterns, the amount of solid waste generated in China has been continuously increasing, and its harmless treatment system is facing multiple severe challenges in terms of environmental, economic and social sustainability. This article delves deeply into the core issues of the current processing system, such as the failure of technical chain coordination, the imbalance of the "triple bottom line", and data silos, revealing that the traditional management paradigm is no longer capable of coping with the inherent complexity and dynamics of the system. Research suggests that shifting towards intelligence is an inevitable path to break through the current predicament. Based on this, this paper constructs a comprehensive countermeasure framework composed of a full-chain intelligent collaborative system based on the Internet of Things and digital twins, a data-driven multi-objective dynamic optimization algorithm model, and a cloud-edge-device collaborative intelligent management platform. This framework aims to drive the evolution of solid waste treatment from the passive and extensive traditional model to a new paradigm that is intelligent, efficient and sustainable by achieving all-domain perception, intelligent decision-making and system collaboration.

1. Introduction

Globally, the sharp increase in solid waste and the environmental and health risks it has triggered have made its governance a major issue in modern urban management. Although China has achieved remarkable infrastructure accomplishments in the field of harmless treatment of solid waste, the traditional treatment model is increasingly approaching its efficiency ceiling. The current system not only faces the inherent complexity and coupling problems brought about by the diversity of processing technologies, but also struggles to seek a balance within the "triple bottom line" framework composed of environmental rigid constraints, economic cost pressure and social nimBY effect. At the same time, it is deeply troubled by data fragmentation and decision-making lag[1]. These interwoven pain points profoundly reveal that the traditional linear and isolated management thinking can no longer adapt to a nonlinear and highly interconnected complex system. Against this backdrop, intelligent technologies represented by the Internet of Things, big data and artificial intelligence offer a brand-new paradigm shift possibility for resolving the aforementioned systemic predicaments. This research aims to systematically analyze the existing problems and construct an intelligent countermeasure system for the future, providing theoretical references and path guidance for promoting the transformation and upgrading of the solid waste treatment industry.

2. Core Characteristics and Evolution Requirements of Solid Waste Harmless Treatment System

2.1. Handle the diversity of technical composition and the complexity of process coupling

The primary core feature of the harmless treatment system for solid waste is reflected in the significant diversity of its treatment technology composition and the profound complexity of the coupling of internal processes. This is far from being summarized by a single technical path, but rather a complex technology cluster with a hierarchical structure composed of multiple heterogeneous unit processes. From physical sorting (such as screening and magnetic separation), biological transformation (such as aerobic composting and anaerobic digestion), to thermochemical treatment (such as incineration, pyrolysis and gasification), and even the final stabilization and safe landfill, each core technology carries specific functional boundaries and optimal treatment ranges. They do not exist in isolation. Instead, it is formed by the interweaving of material flow and energy flow into a highly interconnected network system[2]. This technological diversity directly gives rise to a strong coupling and interdependence within the system. The physical and chemical properties of the output products of the previous processes (such as the residue on the screen, the residue, and the biogas residue) inevitably profoundly restrict and shape the processing efficiency and ultimate fate of the subsequent processes, thus forming a chain reaction characteristic where "one move affects the whole". Therefore, the ultimate efficiency of the entire system is not a simple linear sum of the technical efficiencies of each independent unit, but rather depends on whether precise, dynamic and efficient collaborative matching can be achieved among these heterogeneous units. It is precisely this internal and nonlinear interaction that makes the entire system exhibit remarkable Emergent Behavior, and at the same time constitutes a fundamental challenge for its optimized design and operation management. This, in turn, strongly calls for a systematic methodology and intelligent evolution path that can transcend traditional empiricism and perceive and manage such complexity from a global perspective.

2.2. The multi-dimensional constraints and balance challenges of System operational efficiency

The operational efficiency of the harmless treatment system for solid waste does not pursue the ultimate in a single dimension, but is deeply trapped within a "triple bottom line" constraint framework interwoven with environmental, economic and social factors. This constitutes its most core and challenging operational feature. Under this complex framework, system administrators are forced to undertake an endless, almost sharpest and difficult balance: the environmental dimension demands the maximum reduction of pollutant emissions and secondary environmental risks, which often means the adoption of cutting-edge technologies and high operational investment; The economic dimension coldly pursues the optimization of cost-effectiveness and the financial sustainability of operations, creating a tension that is antagonistic to the former. In the social dimension, it is inevitable to respond to the sensitive "not-in-MY-backyard effect" and the public's perception and acceptance, which injects huge uncertainties into technology selection and facility location[3]. Therefore, any seemingly optimized decision - for instance, introducing expensive sorting equipment to enhance the resource utilization rate or increasing the deodorization budget far beyond the standard to quell community protests - may shift its pressure to another dimension, leading the system as a whole into a "zero-sum game" predicament where one gains while the other declines, and it is difficult to achieve both. The inherent conflicts and intense competitive relationships among these multi-dimensional objectives reveal that system optimization is essentially a highly challenging multi-objective optimization problem, and its optimal solution is by no means an isolated point but a dynamic Pareto frontier. The traditional decision-making model based on linear thinking and local experience has become completely powerless to deal with such nonlinear and complex challenges. Therefore, there is an urgent need for a systematic methodology that can quantify, simulate and intelligently balance these multiple value goals, in order to break the inherent shackles and find the most resilient dynamic balance point under specific spatio-temporal boundaries and socio-economic conditions.

2.3. The data dimensions relied upon for management decisions are lacking and lagging behind

The effectiveness of management decisions for the harmless treatment system of solid waste is based on the quality and timeliness of the information it relies on. However, the current operation of the system is deeply trapped in a structural predicament of systematic lack and profound lag in data dimensions, which constitutes a fundamental bottleneck for the evolution towards refinement and intelligence. The data foundation relied upon by traditional management paradigms mostly stems from periodic, manually recorded isolated samples (such as the daily manual recording of landfill leachate production and the weekly manual sampling and testing of incinerator flue gas). These data not only present significant breakpoints and cracks in time series but also have fatal blind spots in spatial coverage. This results in decision-makers only being able to catch a glimpse of a vague, static and fragmented sketch of the system's operational status, rather than a continuous, high-fidelity and panoramic dynamic picture[4]. The fragmentation and lag of this kind of data directly induce the "nearsightedness" and "sluggishness" of management decisions: Managers cannot perceive the instantaneous fluctuations in the calorific value inside the incinerator in real time to optimize the volume of combustion-supporting air, cannot accurately predict the real-time traffic conditions on the removal route to dynamically dispatch the fleet, and cannot implement source interception and process adjustment at the moment when abnormal signs of pollutant emission indicators appear. All decisions seem like watching a seriously delayed live broadcast. Its intervention actions inevitably become disconnected from the actual state of the system, thus always passively "dealing with problems" rather than actively "anticipating and avoiding problems". Therefore, the failure of such data empowerment not only greatly suppresses the flexibility and response speed that the system should have, but also makes it almost impossible to solve the complex challenges such as the aforementioned technical diversity and multi-dimensional constraint balance. To break through this predicament, a profound data revolution is urgently needed. That is, by building a three-dimensional data collection and transmission network based on the integration of Internet of Things perception, edge computing and cloud computing, the traditional data generation and circulation paradigm should be completely overturned, and a real-time, transparent and all-round "digital twin" should be created for the management system. Thus, it provides indispensable fuel and foundation for moving towards an intelligent advanced decision-making form.

3. Analysis of the Prominent Problems Currently Faced in the Harmless Treatment of Solid Waste

3.1. Failure of technological chain coordination and overall low energy efficiency

The prominent predicament currently faced by the harmless treatment system of solid waste fundamentally stems from the failure of coordination within its internal technical chain and the resulting overall low energy efficiency. This systemic defect makes it difficult for the combination of many advanced technical units to achieve theoretical synergy effects, instead presenting a phenomenon of "1+1<2" diminishing benefits. Although the system has heterogeneous technical units such as incineration, biochemical treatment, and sorting and recovery, these units are often isolated from each other in physical space and management systems, forming "technical islands" that operate independently, lacking a unified and optimized material and energy scheduling strategy. For instance, the waste heat generated by the incineration system failed to be effectively transferred to the anaerobic digestion system to maintain its optimal temperature range, and the low calorific value combustibility produced in the sorting process was not returned to the incinerator as supplementary fuel. This disruption in energy flow and mismatch in material flow led to the waste of a large amount of available energy[5]. At a deeper level, due to the lack of real-time perception and intelligent prediction capabilities for the material properties of the entire chain, the process parameters of each unit cannot be adaptively adjusted according to the dynamic changes of the output products of the previous processes (such as fluctuations in the composition of the incoming garbage and instantaneous changes in calorific value). This leads to the back-end processing system being in an ideal state of "overprocessing" or "underprocessing" for a long time - this not only significantly increases energy and material consumption, but also may cause severe equipment corrosion or excessive pollutant emissions. The consequence of this synergy failure is a sharp deterioration in the overall thermodynamic efficiency of the system and a significant drop in its operational economy: a large amount of chemical energy and material resources that could have been recycled are discharged into the environment in the form of dissipation, residue or low-temperature heat, ultimately leading the entire system into a vicious cycle of rising input costs and decreasing environmental benefits. Therefore, the fragmentation of the technological chain and the absence of nonlinear interactions not only restrict the potential of the system as a whole to achieve energy efficiency optimization, but also become a key bottleneck hindering the evolution of solid waste treatment from "harmless" to the advanced forms of "resource utilization" and "low-carbonization".

3.2. The sustainability crisis triggered by the imbalance of the "triple bottom line"

The field of harmless treatment of solid waste is currently facing a profound sustainability crisis triggered by the structural imbalance of the "triple bottom line". This predicament essentially stems from the irreconcilable internal tension and value conflict among the three dimensions of environmental sustainability, economic feasibility and social acceptance. At the practical level, managers often fall into a perplexing decision-making paradox: adopting cutting-edge technologies and processes to achieve strict environmental goals (such as ultra-low emissions and efficient resource utilization) will inevitably lead to a sharp increase in operating costs, threatening the economic viability of the project. Conversely, if one blindly pursues cost reduction and maximization of economic benefits, they will have to compromise on environmental standards, sowing the seeds of secondary pollution and long-term ecological risks. What is even more complicated is that the "NIMBY effect" in the social dimension is like a sword of Damocles, causing many technically and economically feasible solutions to fail due to a lack of community support, or to be forced to add huge compensation and NIMBY costs under public pressure, ultimately dragging down the financial balance of the entire project. The mutual restraint and vicious cycle of these three-dimensional goals have trapped the system in an unsustainable and fragile equilibrium for a long time - either becoming a "white elephant" that has spent a huge amount of money but is idle, or a source of pollution that has been widely criticized, or it has ceased operations due to financial collapse. The result is that the entire industry is facing severe challenges at the macro level, such as the lack of legitimacy and the loss of its development path. Not only is it difficult to attract continuous investment from social capital, but it may also intensify social conflicts and ultimately shake the fundamental stability of the waste governance system. Therefore, the imbalance of this "triple bottom line" is by no means a local disorder, but rather reveals the failure of a systematic and fundamental governance paradigm. There is an urgent need to re-establish a mutually reinforcing and symbiotic positive relationship among the three through innovative institutional design and technology-management integration solutions, rather than a simple zero-sum game of trade-offs.

3.3. Severe data silos and lack of decision support

The harmless treatment system for solid waste is currently confronted with a structural predicament characterized by a severe lack of decision support capabilities due to the phenomenon of data silos. The essence of this problem lies in the fact that the massive amounts of data generated in each link within the system are confined within isolated heterogeneous data systems, making it impossible to form effective knowledge aggregation and decision-making empowerment. From the GPS trajectories and weighing data of waste collection vehicles, to the real-time process parameters recorded by the DCS control system within the treatment facilities, and then to the emission indicators collected by environmental monitoring stations, these data resources that should be interrelated are fragmented and distributed due to departmental barriers, system heterogeneity and the lack of standards, forming a series of "data chimneys" that do not communicate with each other. This state of data fragmentation directly leads to decision-makers being unable to obtain a comprehensive and panoramic understanding of the system's operational status. All their management decisions - from the optimization of collection and transportation routes to the adjustment of processing parameters - have to be based on incomplete and time-delayed empirical judgments, just like navigating through the fog with an incomplete and vaguely marked map. What is more serious is that this data silo effect has deprived advanced data analysis technologies (such as machine learning prediction and multi-objective optimization algorithms) of the necessary fuel and foundation for their application. As a result, the system is unable to achieve precise prediction and intelligent matching from waste generation volume, component characteristics to the operation status of treatment facilities, nor can it provide early warning and intervention for environmental risks. The result is that the entire system has long remained at a rough and passive response management level, which not only leads to low efficiency in resource allocation and high energy and material consumption, but also misses the historical opportunity to achieve refined and intelligent upgrading through data-driven. Breaking through this predicament has become a key prerequisite for promoting the evolution of solid waste treatment systems towards intelligence. It is urgently necessary to break down the barriers at the organizational and technical levels, build a unified data middle platform and digital twin system, so that the dormant data can truly flow and be transformed into valuable insights that support scientific decision-making.

4. Construction of Intelligent Countermeasures for Harmless Treatment of Solid Waste Oriented to the Future

4.1. Build a full-chain intelligent collaborative system based on the Internet of Things and digital twins

Facing the severe challenge of the failure of technical chain coordination in the harmless treatment system of solid waste, building a full-chain intelligent collaborative system based on the

Internet of Things and digital twins has become the core path to break through the traditional management paradigm and achieve a leap in the overall system efficiency. The essence of this intelligent countermeasure is to deploy multi-level sensor networks throughout the entire process of waste collection, transportation, treatment and disposal, to collect massive multi-source heterogeneous data such as material composition, flow rate, equipment status and environmental parameters in real time, and to build a digital twin with precise mapping, dynamic interaction and in-depth insight capabilities for the physical entity. This virtual model not only can simulate and reproduce the operating status of the physical system with high fidelity, but more importantly, it integrates machine learning and operational research optimization algorithms to achieve full traceability and coordinated regulation of material flow and energy flow: for instance, it dynamically adjusts the combustion air volume and grate speed of the incinerator based on the real-time predicted changes in the calorific value of the incoming garbage. Based on the microbial activity status in the anaerobic digestion tank, the feed load and temperature control strategy are intelligently adjusted. It can even optimize the route planning of collection and transportation vehicles and the dispatching strategies of transfer stations based on the prediction of regional waste generation patterns and traffic conditions. This operation mode of virtual-real interaction and closed-loop optimization has completely broken the traditional fragmented situation where each processing unit operates independently, transforming the system from a passive and lagging mechanical combination into an organic whole with self-perception, self-analysis, self-decision-making and self-optimization capabilities. This system not only maximizes the efficiency of energy and resource recovery, significantly reduces operating costs and environmental pollution risks, but also provides crucial technical support and architectural foundation for the strategic transformation of solid waste treatment systems from "harmless" to "resource utilization" and "low-carbon".

4.2. Deploy a multi-objective dynamic optimization algorithm model driven by data

To break through the core predicament of the imbalance of the "triple bottom line" in the solid waste harmless treatment system, deploying a data-driven multi-objective dynamic optimization algorithm model has become a key technical path for the system to transform from an empirical decision-making paradigm to a scientific decision-making one. This intelligent countermeasure transcends the limitations of traditional single-objective optimization. By constructing a mathematical model that integrates multiple objectives such as environmental benefits, economic costs, and social acceptance, it uses machine learning-based prediction algorithms to predict system state changes in real time and adopts advanced computing methods such as multi-objective evolutionary algorithms and deep reinforcement learning. Continuously search for the Pareto optimal solution set under complex constraints. This model can dynamically balance the competitive relationship among different targets: under the premise of ensuring that pollutant emissions do not exceed the threshold, it intelligently adjusts the operating parameters of each treatment unit to minimize energy and material consumption. Meanwhile, under the condition of meeting the noise and odor constraints of the community, this mode optimizes the routes of collection and transportation vehicles and reduces operating costs. It can even simulate the long-term trajectory of the system's sustainable development under different policy scenarios. This dynamic optimization mechanism endows the management system with unprecedented adaptability and precision. It can independently generate and execute the optimal dispatching plan based on real-time feed characteristics, fluctuations in energy market prices, and changes in environmental capacity, thereby effectively breaking through the decision-making predicament of "neglecting one aspect for another" in traditional management. Ultimately, this algorithm model not only provides scientific and transparent decision support for managers, but more importantly, it builds an intelligent regulation core that can automatically maintain a dynamic balance of environmental, economic and social benefits, laying a solid theoretical and technical foundation for promoting the evolution of solid waste treatment systems towards a sustainable and self-adaptive advanced form.

4.3. Build a cloud-edge-device collaborative intelligent management platform to break down information barriers

To thoroughly address the long-standing data silo predicament and the lack of decision support in the field of harmless treatment of solid waste, building a cloud-edge-device collaborative intelligent management platform constitutes the core infrastructure and key support framework for achieving systematic and intelligent transformation. This platform architecture innovatively integrates the large-scale storage and powerful computing power of cloud computing, the low-latency real-time response capability of edge computing, and the all-domain data collection advantages of terminal perception devices to form a well-structured and functionally complementary organic whole: at the terminal layer, various intelligent sensors and Internet of Things devices continuously collect real-time operational data throughout the entire chain; At the edge layer, edge computing nodes deployed on the side of each processing facility perform on-site cleaning, aggregation and real-time analysis of regional data, achieving local intelligent control with millisecond-level response. In the cloud, it relies on a supercomputing platform to integrate data from the entire domain, runs complex artificial intelligence algorithms and digital twin models, generates the optimal scheduling strategy, and sends it back to the edge nodes for execution. This collaborative architecture not only completely breaks down the data barriers among various departments and links, achieving the integration of all elements of data from the waste generation source to the final disposal point, but more importantly, it builds a "smart brain for urban waste" that integrates real-time monitoring, intelligent analysis, predictive early warning and collaborative decision-making. This platform can provide a data foundation for the aforementioned digital twin system and a computing environment for multi-objective optimization algorithms. Ultimately, it enables the management system to have unprecedented transparency, response speed and decision-making scientificity, thereby truly achieving a revolutionary transformation of the solid waste treatment system from fragmented and passive management to all-domain and proactive intelligent governance. Provide a strong digital infrastructure guarantee for the sustainable development of the industry.

5. Conclusions

This article systematically discusses the necessity and implementation path of the transformation of the solid waste harmless treatment system from the traditional model to the intelligent paradigm. The research first reveals the deep-seated contradictions of the system in three dimensions: technical collaboration, multi-dimensional balance, and data empowerment, clearly pointing out that these structural problems are the main causes of the overall low efficiency and sustainability crisis. Specifically, this paper proposes a three-in-one intelligent countermeasure framework: that is, to use digital twin technology to connect and optimize the entire chain of material and energy flow, to scientifically balance environmental, economic and social goals with multi-objective optimization algorithms, and ultimately to break down information barriers through a cloud-edge-device collaborative intelligent platform, providing a unified foundation for advanced decision-making. This framework emphasizes the deep integration of technology, data and algorithms. Its core value lies in endowing management systems with the capabilities of global insight, dynamic optimization and intelligent decision-making. In conclusion, promoting intelligent transformation is not only a technological upgrade to enhance the operational efficiency of individual facilities, but also a strategic measure to restructure the entire waste management system and achieve its leap from a "cost center" to a "value center". It holds significant importance for building "waste-free cities" and achieving sustainable development goals.

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