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ИНТЕЛЛЕКТУАЛЬНЫЙ ЦИФРОВОЙ ДВОЙНИК МОДЕЛИ ПРОИЗВОДСТВА СУХИХ СТРОИТЕЛЬНЫХ СМЕСЕЙ НА ОСНОВЕ ТЕХНОГЕННЫХ ОТХОДОВ

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В статье рассматривается разработка интеллектуального цифрового двойника производства сухих строительных смесей с использованием техногенных отходов металлургии и энергетики на основе технологий искусственного интеллекта. Актуальность исследования обусловлена необходимостью повышения ресурсной и экологической эффективности производства сухих смесей, снижением доли клинкерных материалов и внедрением цифровых методов управления технологическими процессами в условиях вариабельности свойств сырья.

Разработанная модель реализована в виде гибридного цифрового двойника, сочетающего дискретно-событийное моделирование технологической линии и интеллектуальную подсистему прогнозирования качества продукции. Управление процессом формализовано с использованием конечного автомата, охватывающего все ключевые стадии производства: дозирование компонентов, смешивание, выгрузку, фасовку и архивирование партий. Искусственный интеллект применяется для оценки физико-механических свойств смеси (прочность, плотность, удобоукладываемость) на основе состава рецептуры и доли техногенных компонентов.

В ходе имитационного моделирования получены количественные результаты, подтверждающие эффективность предложенного подхода. Установлено, что доля техногенных отходов в составе сухих смесей может достигать 40–50 % без критического снижения прогнозируемых качественных показателей. Снижение расхода цемента составляет до 30 %, при этом расчётная производительность линии достигает 15–20 т/ч.

Модель обеспечивает автоматический учёт потребления шлака и золы в разрезе партии, смены и месяца, а также динамическую оценку углеродного следа продукции.

Научная новизна работы заключается в интеграции имитационного моделирования производственного цикла с ИИ-подсистемой оценки качества и экологических показателей в рамках единой цифровой модели. Практическая значимость определяется возможностью использования разработанной модели в качестве цифрового двойника реального производства сухих строительных смесей, инструмента оптимизации рецептур, поддержки управленческих решений и интеграции в SCADA/MES-системы промышленных предприятий.

***Ключевые слова*: искусственный интеллект, цифровой двойник, сухие смеси, технологический процесс, архитектура, моделирование**

ТЕХНОГЕНДИК КАЛДЫКТАРГА НЕГИЗДЕЛГЕН КУРГАК МИНОМЕТ АРАЛАШМАЛАРЫН ӨНДҮРҮҮ МОДЕЛИНИН АКЫЛДУУ САНАРИП ЭГИЗИ

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Статьясында каралат иштеп чыгуу интеллектуалдык санариптик двойника өндүрүшүнүн кургак курулуш аралашмаларын менен пайдалануу, техногендик калдыктарын металлургия жана энергетика негизинде технологияларды жасалма интеллект. Актуалдуулугу жана изилдөөнүн зарылдыгы менен шартталган жогорулатуу, ресурстук жана экологиялык өндүрүштүн натыйжалуулугун кургак аралашмаларын, төмөндөшү үлүшүн клинкерных материалдарды жана киргизүү санариптик башкаруу ыкмаларын технологиялык процесстерге шарттарында вариабельности касиеттерин чийки.

Иштелип чыккан модель технологиялык линиянын дискреттик-окуя симуляциясын жана продукциянын сапатын болжолдоонун акылдуу подсистемасын айкалыштырган гибриддик санариптик эгиз түрүндө ишке ашырылат. Процессти башкаруу өндүрүштүн бардык негизги этаптарын камтыган мамлекеттик машинаны колдонуу менен формалдаштырылган: компоненттерди бөлүштүрүү, аралаштыруу, түшүрүү, таңгактоо жана партияларды архивдөө. Жасалма интеллект формуланын курамына жана техногендик компоненттердин үлүшүнө негизделген аралашманын

физикалык-механикалык касиеттерин (бекемдиги, тыгыздыгы, иштөө жөндөмдүүлүгү) баалоо үчүн колдонулат.

Симуляциялык моделдөө учурунда сунушталган ыкманын натыйжалуулугун тастыктаган сандык натыйжалар алынат. Аныкталса үлүшү техногендик калдыктарын курамында кургак аралашмаларын ыктымал 40-50 % жок критикалык азайтуу болжолдонгон сапаттык көрсөткүчтөрдүн. Азайтуу чыгымдоо цемент түзөт чейин-30 %, мында эсептик өндүрүмдүүлүгү линиясы жетет 15-20 т/ч Модель камсыз кылат автоматический керектөөнү эсепке алуу шлака жана күлдү боюнча партиянын, алмаштыруу жана айдын, ошондой эле динамическую баа углеродного издин продукциянын.

Иштин илимий жаңылык бир санариптик моделдин ичинде сапатын баалоо жана айлана-чөйрөнү коргоо боюнча чакан системасы менен жасалма өндүрүш айлампасынын моделдөө киргизүү болуп саналат. Практикалык мааниси кургак курулуш аралашмаларын реалдуу өндүрүүнүн санариптик эгизи катары иштелип чыккан моделди колдонуу мүмкүнчүлүгү менен аныкталат, формулировканы оптималдаштыруу куралы, башкаруу чечимдерин колдоо жана өнөр жай ишканаларынын ут/сот системасына интеграциялоо.

Баштапкы сөздөр: жасалма интеллект, санариптик эгиз, кургак аралашмалар, процесс процесси, архитектура, моделдөө

AN INTELLIGENT DIGITAL TWIN OF THE MODEL FOR THE PRODUCTION OF DRY BUILDING MIXES BASED ON MAN-MADE WASTE

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The article discusses the development of an intelligent digital twin for the production of dry building mixes using man-made waste from metallurgy and energy based on artificial intelligence technologies. The relevance of the study lies in the need to increase the resource and environmental efficiency of dry mix production, reduce the proportion of clinker materials, and introduce digital methods of process control in conditions of variability in raw material properties.

The developed model is implemented as a hybrid digital twin that combines discrete event modeling of a production line and an intelligent subsystem for predicting product quality. Process control is formalized using a finite state machine that covers all key stages of production: component dosing, mixing, unloading, packaging, and batch archiving. Artificial intelligence is used to evaluate the physico-mechanical properties of a mixture (strength, density, workability) based on the composition of the formulation and the proportion of man-made components.

Quantitative results confirming the effectiveness of the proposed approach were obtained during the simulation. It has been established that the proportion of man-made waste in the composition of dry mixtures can reach 40-50% without a critical decrease in the predicted quality indicators. The reduction in cement consumption is up to 30%, while the estimated capacity of the line reaches 15-20 t/h. The model provides automatic accounting of slag and ash consumption by batch, shift, and month, as well as dynamic assessment of the carbon footprint of products.

The scientific novelty of the work lies in the integration of simulation modeling of the production cycle with the AI subsystem for assessing quality and environmental performance within a single digital model. The practical significance is determined by the possibility of using the developed model as a digital twin of the real production of dry building mixes, a tool for optimizing formulations, supporting management decisions and integrating into SCADA/MES systems of industrial enterprises.

Keywords: artificial intelligence, digital twin, dry mixes, technological process, architecture, modeling

Introduction

The production of dry building mixes is one of the key sub-sectors of the construction industry, directly related to the high consumption of cement, mineral fillers and energy resources. According to the International Energy Agency and a number of researchers, the cement industry generates up to 7-8% of global co_2 emissions, which makes the task of reducing the clinker component and involving secondary mineral resources strategically important for the sustainable development of the construction sector [1].

One of the most promising areas is the use of man—made waste from metallurgy and energy — blast furnace and ferroalloy slag, fly ash from thermal power plants - as active mineral additives. Foreign studies confirm that the substitution of cement with ash and slag in the range of 20-50% can significantly reduce the carbon footprint of products while maintaining the required strength characteristics [2]. However, most of these works are of a materials science or environmental nature and do not address issues of industrial implementation in real production conditions.

At the same time, machine learning and artificial intelligence methods are actively developing to predict the physico-mechanical properties of concretes and building mixes based on the composition and age of samples [2]. Despite the high accuracy of predictions, these models, as a rule, operate outside the production context and do not take into account the dynamics of technological processes, equipment limitations, material flows and operating modes of the line.

The modern concept of digital twins and discrete event modeling is considered as the basis for the integration of data, algorithms and management within Industry 4.0. At the same time, the literature highlights the shortage of applied digital twins for discrete production of building materials, especially with the inclusion of environmental and quality indicators in a single management contour.

Thus, an urgent scientific and practical task is to develop a simulation model for the production of dry building mixes with man-made waste, combining discrete event modeling of a production line, intelligent product quality assessment and calculation of environmental indicators. Solving this problem makes it possible to fill the identified scientific gap between research in the field of materials science, environmental assessment and digitalization of industrial processes, as well as to create a tool focused on implementation in real production.

The paper [1] describes the application of ML algorithms for predicting the compressive strength (CS) of concrete with fly ash based on experimental data and sets of composition/age characteristics, and the use of ML as a substitute for part of laboratory tests. The weak part of the study includes: the model is not tied to the technological cycle, there is no dosage/mixing/packaging, there are no production events and downtime.

In [2], a comparison of several ML models for predicting fly ash and cement is presented. The advantages of the study include the methodology for comparing models, the disadvantages are the lack of production cycle time, mass maintenance, and event logic of the line.

The article [3] presents a hybrid approach (firefly algorithm + random forest) for predicting concrete strength, optimizing ML models. Weaknesses, there is no forecast with an impact on dosing/mixer/packaging.

In [4], the ML predictor of the strength of "green" geopolymer systems based on ash is described as an alternative binder + ML as an accelerator. Weak research sides, there is no reflection of the technological side of production (management, queues, cycle time, packaging, productivity, etc.).

In [5], a comparison of the environmental impacts of ash and slag was performed, taking into account the methods/distances of transportation, showing the impact of logistics on the environmental aspects of production. Weaknesses of the study: no batch dynamics/downtime/equipment limitations, no digital line management.

The work [6] shows the techno-ecological stability of concrete with 100% use of slag as a filler and ash as a substitute. The work focuses on the material and sustainability, but there is no use of ML to analyze the entire process.

[7] presents, at the same time, LCA, production costs, mechanics and durability for mortars/concretes with recycled aggregates and ash, ecology + economics + properties, but does not show the digital twin of the equipment.

The article [8] shows LCA with sensitivity analysis to transport distances (which is important for real regional supply chains) which provides a practical approach. There is no integration of production logic and real-time monitoring of product output.

The paper [9] provides an overview of definitions (AI, IoT, data integration). The overview level does not provide an idea of the use and practical application of artificial intelligence technologies.

The paper [10] shows the strict unification of the term “digital twin” and the distinction between “simulation vs model vs DT". The work is not tied to the actual technological process.

In [11], a review of DT is presented specifically for discrete manufacturing lines: design, scheduling/control, failure prediction, data synchronization problems, delays, accuracy, gives a “checklist of problems” for the Discussion section (real-time interaction, fidelity, optimization). Weaknesses, an overview, not an industry prototype, there is no application model for DCM.

The work [12] describes the steps of implementing and integrating digital twins in discrete production, emphasizes the synergy with MES/ERP and the importance of the “integration framework". The work does not examine dry building mixes.

Thus, an analysis of the work on the research topic showed that there are no scientifically sound solutions for the development of digital counterparts for the production of dry building mixes with man-made waste, combining discrete event modeling of the production line, intelligent product quality assessment and calculation of environmental indicators. Solving this problem makes it possible to fill the identified scientific gap between research in the field of materials science, environmental assessment and digitalization of industrial processes, as well as to create a tool focused on implementation in real production.

Research methods and materials

The research methodology is based on a systematic approach and combines methods of simulation modeling, automatic control theory, artificial intelligence and industrial data analysis. The purpose of the methodology is to form a digital model of a technological line for the production of dry building mixes using man-made waste, which adequately reflects real production processes and allows for quantitative and qualitative assessment of efficiency.

1. The general concept of the study

The research is based on the concept of a hybrid digital twin, which includes:

-a deterministic simulation model of the production process;

-an intelligent subsystem for quality analysis and forecasting;

-a module for calculating environmental and production indicators.

This approach allows combining the advantages of discrete event modeling (accurate description of technological stages and equipment logic) and artificial intelligence (accounting for nonlinear and poorly formalized dependencies between the composition of the mixture and its properties).

2. Simulation of the production line

The method of Discrete Event Simulation (DES) is used to describe the production process. The production line is formalized as a Finite State Machine (FSM), which includes the following states:

-waiting (IDLE);

-dosing of components;

-mixing;

-unloading;

-packing and palletizing (BAGGING).

Transitions between states are triggered by events such as the achievement of a set batch weight, the end of the mixing time, or the completion of packaging. This approach ensures correct modeling of the cyclical operation of the line, accounting for downtime with a shortage of raw materials and calculating productivity in real time.

3. Intelligent subsystem of quality assessment

An artificial intelligence subsystem is used to predict the physico-mechanical properties of a dry building mix. The percentage of formulation components (cement, sand, slag, ash) and their physico-chemical characteristics are used as input data.

The AI module is used to evaluate:

-the predicted strength grade;

-density of the mixture;

-workability;

-sensitivity of properties to changes in the proportion of man-made waste.

The intelligent analysis is integrated into the simulation cycle and is performed when the formulation is changed or the next batch is completed, which provides a link between quality indicators and production parameters.

4. Calculation of quantitative and environmental indicators

Calculations have been implemented within the framework of the methodology:

-line capacity (t/h);

-operating time (uptime);

-the number of batches and bags;

-consumption of man-made waste (kg, t/shift, t/month);

-the proportion of secondary resources in the mixture;

-the relative carbon footprint of the products.

Environmental indicators are calculated based on the emission coefficients of materials and the proportion of their use in the formulation.

5. Programming languages and software tools used

The following technologies were used to implement the model:

TypeScript / JavaScript — implementation of simulation logic, finite automaton, calculations, and module interaction;

React — development of the user interface and visualization of the production line;

HTML5 / CSS / Tailwind CSS — graphical representation of equipment and states;

AI API / intelligent service — implementation of a quality forecasting subsystem;

Real-time web technologies — updating model states in discrete time steps.

The architecture of the software solution is modular, which ensures scalability, reuse of components and the ability to integrate with external systems.

6. Validation and practical applicability

The correctness of the model was verified by analyzing the logical consistency of state transitions, material balances, and ranges of output parameters. The results obtained are comparable with typical indicators of industrial dry building mix lines, which confirms the adequacy of the model.

Results and discussion

Figure 1 shows a functional scheme for the production of building mixes using man-made waste.

The production process is as follows:
-the ground ingredients are filled into bins with a capacity of 25 tons;
- then they enter the conveyor with load cells, weighing takes place.;
-they are moved from the conveyor to the mixer, where mixing takes place for a certain time;
-from the mixer, the finished construction mix passes along the screw conveyor to the filling machine, where it is loaded into bags weighing 50 kg.;
-the finished bag is removed by the robot and placed on a pallet and sent for storage to the finished product warehouse.
Figure 3 shows the architecture of an intelligent digital twin for the production of dry building mixes based on man-made waste.

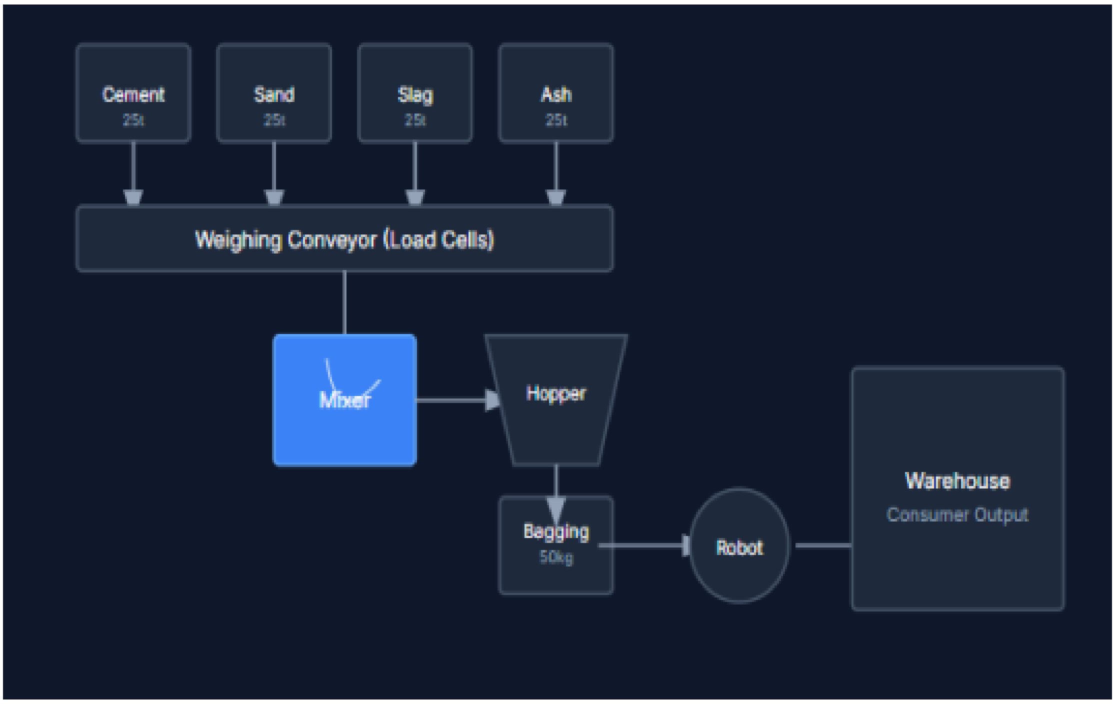

Figure 1-Functional scheme for the production of building mixes using man-made waste

The developed intelligent digital twin for the production of dry building mixes with man-made waste is implemented on the basis of a multilevel (layered) architecture that provides a logical separation of modeling, analysis, management and visualization functions. The architecture is focused on continuous updating of the state of the virtual model and its synchronization with the parameters of the real technological process.
The digital twin functions as a hybrid system combining a deterministic simulation model of a production line and an intelligent subsystem for predicting quality and environmental performance.

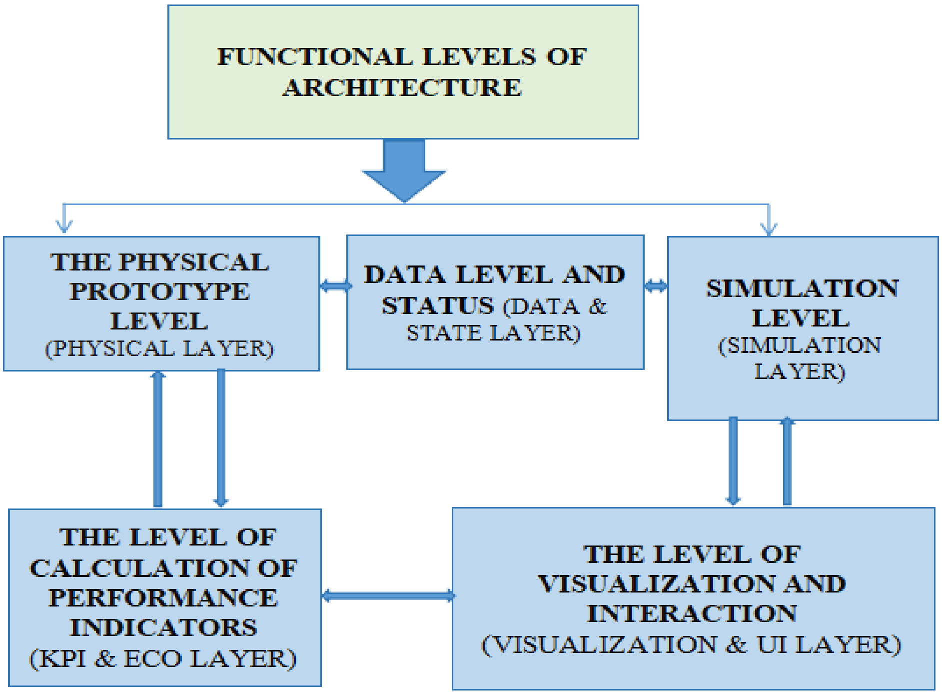

Figure 2- Architecture of an intelligent digital twin for the production of dry building mixes with man-made waste

The Physical prototype Layer

This level corresponds to the actual production line and includes:

-silos of cement, sand, slag and ash (25t);

-metering equipment and conveyors;

-mixing unit-1m3;

-packing unit and palletizer.

In the digital twin, the physical layer is represented as parameterized virtual objects reflecting the capacity, performance, current status, and limitations of the equipment.

Data and State Layer (Data & State Layer)

At this level, a digital representation of the system status is formed.:

-current stocks of materials in silos;

-active formulation of the mixture;

-the stage of the technological cycle;

-equipment loading indicators;

-accumulated statistical data on parties.

The data is updated discretely, with a fixed time step, which ensures the consistency of the simulation process.

Simulation Layer

The key element of the architecture is a discrete event model implemented as a finite state machine (FSM). Each state of the machine corresponds to the technological stage of production:

-IDLE — waiting;

-DOSING — dosing of components;

-MIXING — mixing;

-DISCHARGING — unloading;

-BAGGING — packing and palletizing.

FSM provides a strict sequence of operations, control of transition conditions, and simulation of downtime in case of material imbalance (for example, a shortage of raw materials).

Intelligent Analytical Layer (AI & Analytics Layer)

The intellectual level is designed for analysis and forecasting:

-physical and mechanical properties of the dry mixture;

-the impact of the proportion of man-made waste on quality;

-sensitivity of the parameters to changes in the formulation;

-analysis -delays of 1.5s.

The AI module receives data from the status layer and returns qualitative estimates that are used to support decision-making by the operator or engineering staff.

The level of calculation of performance indicators (KPI & Eco Layer)

At this level, the following are calculated:

-line capacity (t/h);

-operating time (uptime);

-number of batches and bags;

-volumes of slag and ash utilization;

-share of secondary resources;

-the relative carbon footprint of products.

The indicators are updated in real time and are linked to the events of the simulation model.

Visualization and Interaction Layer (Visualization & UI Layer)

The top level of the architecture provides:

-visual display of the processing line;

-indication of equipment status;

-recipe management and operating modes;

-access to the batch archive and reports.

The interface is designed to be used as an engineering tool and a training simulator.

The logic of level interaction

The digital twin works in a closed loop:
-Setting the recipe and production parameters;
-Process Cycle Simulation (FSM);
-Updating the equipment and inventory status;
-Intellectual analysis of quality and ecology;
-KPI calculation and visualization;
-Decision-making and parameter adjustments.
This cycle ensures continuous updating of the digital model and the possibility of scenario analysis without interference in real production.
The proposed architecture of the digital twin allows for:
-integration with SCADA, MES and ERP systems;
-connection of real sensors (weight, humidity, energy);
-expansion of the model due to continuous subsystems (power consumption, equipment wear);
-use in online and offline simulations.
Figure 3-5 shows the main menu of the intelligent digital twin for the production of dry building mixes with man-made waste.

Figure 3- Operation of the digital twin in the dosing mode

Figure 3- Operation of the digital twin in the mixing mode

Figure 3- Operation of the digital twin in the mode of unloading and loading into bags

Figure 3- Operation of the digital twin in the mode of loading bags into pallets

The digital twin of the dry building mixes production line functions as a continuously updated virtual model synchronized with the process parameters. The work is based on a discrete event simulation model, formalized in the form of a finite state machine describing the sequence of production stages: dosing, mixing, unloading and packing. Equipment status, material flows, and time characteristics are updated in real time based on model events.

The intelligent module is integrated into the simulation circuit and provides a forecast of the physico-mechanical properties of the mixture and environmental indicators based on the formulation and proportion of man-made waste. The results of the AI analysis are used to calculate production KPIs and create batch archives, which allows scenario analysis to be performed without interfering with real production.

The scientific novelty of the digital twin is to combine discrete event modeling of a production line with an intelligent assessment of quality and environmental efficiency within a single architecture. The practical significance is determined by the possibility of using the model as a management tool, optimizing formulations and digitalizing the production of dry building mixes.

Conclusion

The paper develops and investigates a simulation model for the production of dry building mixes using man-made waste, implemented in the form of a digital twin of the production line. The model is based on a discrete event approach and is formalized in the form of a finite state machine, which made it possible to adequately describe the sequence of technological stages, material flows and operating modes of equipment. The integration of the intelligent quality forecasting module made it possible to evaluate the physico-mechanical properties of the mixture and environmental indicators depending on the formulation and the proportion of secondary resources.

Based on the simulation results, it was found that the use of man-made waste in dry mixes in a volume of up to 40-50% reduces cement consumption by up to 30% without a critical deterioration in the predicted quality characteristics. The production capacity of the line within the framework of the model reaches 15-20 t/h with automatic control of slag and ash consumption in batches and time intervals.

The scientific novelty of the research consists in combining simulation modeling of the production cycle, intelligent quality assessment and calculation of environmental indicators in a single architecture of a digital twin. The practical significance of the work is determined by the possibility of using the developed model as a tool for optimizing formulations, supporting management decisions, and integrating real dry building mixes into SCADA/MES systems.

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