Development of AI-Enabled Cyber-Physical Digital Twin Architecture for Sustainable Glass Manufacturing in Industry 5.0

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Abstract

One of the high-temperature industries that have an enormous contribution to carbon emissions in the world is the glass manufacturing industry, which operates high-energy furnaces and produces continuously. Sustainable manufacturing solutions are needed desperately with an emitted CO_2 per ton of glass of almost one ton. The paper provides a review and conceptual framework of an AI-based Cyber-Physical Digital Twin architecture of sustainable glass production within the Industry5.0 framework. The research combines the breakthroughs in AI, cyber-physical systems (CPS), digital twins, and automation to solve the problem of high fuel consumption, inefficient combustion, and heat losses. It focuses on predictive AI models (ANN and hybrid SVR Firefly optimization) applied along with real-time CPS monitoring and digital twin simulations to optimize the process.

The proposed framework allows the smart control of important parameters including air-fuel ratio, cullet, and thermal efficiency, as well as robotic inspection and human-oriented work. It also identifies research gaps in the application of AI, CPS, and sustainability-based digital twins in the glass industry. The 10-15% fuel savings, 15-20% CO_2 reduction, better product quality, and more predictive maintenance are expected. The work offers a guide to building sustainable and intelligent glass manufacturing systems that are harmonized with Industry 5.0.

Key words: Artificial Intelligence (AI), Digital Twin, Cyber-Physical Systems (CPS), Industry 5.0, Sustainable Glass Manufacturing.

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1. Introduction

Glass, steel and cement industries are important to the manufacturing of the world, but are very energy-consuming as they run at temperatures above 1000 °C and use fossil fuels. In the glass industry, specifically, the emissions of CO_2 per ton of glass are about one ton, with combustion in the furnace (≈80%) and decomposition of raw materials (≈20%).The traditional glass production entails continuous furnace production in which thermal loss is high and the adaptability is low. The conventional control systems do not provide real time intelligence, hence leading to poor utilization of energy, irregular quality and high environmental impact. This brings about the necessity of green and smart production.

Industry 5.0 is a human-centered and sustainable solution that incorporates the use of technologies, including Artificial Intelligence (AI), Cyber-Physical Systems (CPS), and Digital Twins. AI can be used to assist in predictive modeling and optimization, CPS can be used to allow integration of systems in real-time, and digital twins can be used to give virtual models that can be monitored and simulated.

Nonetheless, the available literature considers these technologies individually and there is little involvement of integration to achieve sustainability and little emphasis on emission model and cullet maximization. Thus, this paper suggests an AI-powered Cyber-Physical Digital Twin architecture to enhance the efficiency of energy consumption, emissions, and overall performance in the production of glasses.

2. Problem Statement

Industry 5.0 offers intelligent, human-centered, and sustainable manufacturing by incorporating AI, Digital Twins (DT), and Cyber-Physical Systems (CPS). Their joint use in the production of glasses is however limited especially when it comes to high temperature and energy consuming processes. The current DT models are mainly generic or discrete and do not provide real-time adaptive control, interoperability, and domain-oriented AI.

In addition, the difficulties of data acquisition in severe conditions, scalability, and cybersecurity limit real-life implementation. Therefore, an AI-powered cyber-physical digital twin framework that would be suitable in efficient and green glass production should be developed.

3. Research Objectives

To create an AI-based Cyber-Physical Digital Twin architecture to enable sustainable and efficient glass production in an Industry 5.0 environment with the following specific goals of

- To model the glass manufacturing processes with the help of CPS.
- To create an all-encompassing digital twin structure to make use of IoT-based data acquisition.
- To create AI/ML models to optimize the process and predictive control.
- To enable real-time synchronization and adaptive control between physical and digital systems.
- To include the sustainability measures like energy efficiency and emission reduction.
- To either verify the proposed system by simulation or case study.

4. Literature Survey

Industry 5.0 is a paradigm shift to the human-centric, sustainable, and resilient manufacturing systems rather than automation-based production. In contrast to Industry 4.0, which focused more on digitization and automation, Industry 5.0 unites highly innovative technologies, including Artificial Intelligence (AI), Digital Twins (DT), and Cyber-Physical Systems (CPS) with human interaction and environmental sustainability [1], [2]. The given shift applies especially to energy-consuming sectors like glass production, where sustainability, energy efficiency, and waste minimization are essential issues.

One of the Industry 5.0 building blocks is the Digital Twin technology that enables the creation of virtual replicas of real-life systems that enable real-time monitoring, simulation, and predictive decision-making [3], [4]. It has been found that DTs have the potential to significantly simplify the production process as it is possible to predict the maintenance, optimize the processes and coordinate the real-time between the physical and digital world [4], [5]. Additionally, AI-driven digital twins can build upon such capabilities by adding machine learning algorithms to perform intelligent analytics and adaptive control to improve operational efficiency and reduce environmental impact [6].

In a recent literature, the combination of AI and machine learning in the context of sustainable manufacturing, the use of AI methods to optimize energy use, reduce waste, and enhance the quality of products is emphasized [7]. Within the glass manufacturing industry, where the temperature is high and a lot of energy is required, the use of AI-based optimization can be instrumental in minimizing carbon footprint and increasing resource efficiency. Predictive models using AI can also be used to assist in fault detection and process control to enhance reliability and sustainability of the system [7].

Digital twin architectures revolve around the notion of Cyber-Physical Systems (CPS). CPS combines both physical processes with computational models which allows real-time data acquisition, communication and control [3]. CPS, when used together with the IoT and cloud computing, supports the smooth exchange of data among machines, sensors, and digital platforms. The integration is critical to the introduction of closed-loop control systems in manufacturing settings, which can continuously monitor and optimize production systems [8].

Recent research has suggested multi-layered digital twin systems which introduce data acquisition, communication, modeling, analytics and application layers [9]. These architectures allow implementation of DT systems in complex industrial environments in a scaled and flexible manner. One of the illustrations is an intelligent 6-layer architecture, which is aligned to the principles of Industry 5.0, is equipped with edge AI, a digital twin, and models of the circular economy to enhance its sustainability and functioning possibilities [9]. Such structures are particularly related to the glass production where complexity of processes, and energy demand are too intense and demand high-level monitoring and control systems.

Another characteristic of Industry 5.0 is human-centricity. Digital twins have also been applied more in human-machine collaboration, worker safety, ergonomics and decision-making [3]. As it has been demonstrated, human-in-the-loop systems, paired with AI-powered DTs, can be astonishingly more efficient and, at the same time, more secure and sustainable [3], [10]. This is especially essential in the glass production environments which are typified by hazardous environments such as heat and heavy machines.

Besides operational advantages, the digital twin technology facilitates the shift to the circular economy as it allows optimizing resources and minimizing waste. The Industry 5.0 systems demonstrate how the manufacturing process could be adjusted to the environmental and social objectives [1], [11]. AI-powered DT systems are able to oversee material flows, anticipate waste production and streamline recycling, which in turn contributes to sustainable production systems.

In spite of such developments, there are a number of issues in developing AI-enabled digital twins designs. Availability and quality of real-time data is one of the main difficulties because it is required to make appropriate modeling and decision-making [3]. Also, there is the problem of high computational complexity, interoperability, and cybersecurity that is a major impediment to scale [3], [12]. Complex integration of heterogeneous systems and standards is also another research gap that is critical, especially in complex industrial environment like the glass manufacturing.

The other field of research that is emerging is the combination of extended reality (XR) and immersive technologies and digital twins to improve visualization and decision-making [13]. These technologies allow the operators to communicate with virtual simulations of manufacturing systems to enhance situational awareness and process control. Moreover, the implementation of standards like ISO 23247 on digital twins is receiving attention, which offers the guidelines on integrating the digital and physical manufacturing systems [14].

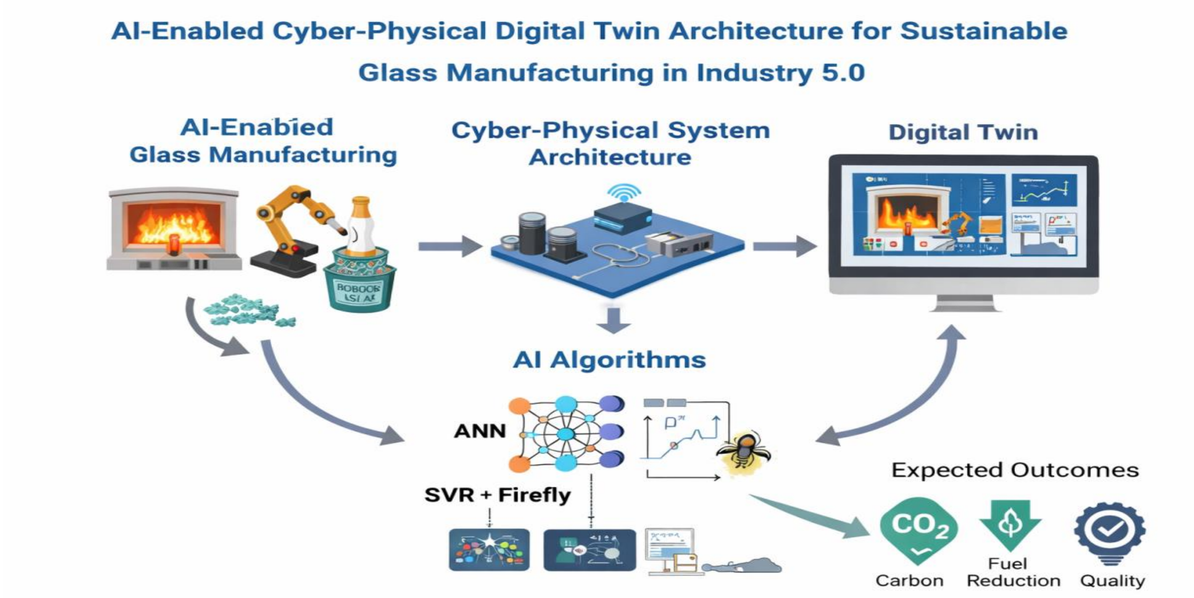
On the whole, the literature shows that AI-based digital twins architectures can greatly change sustainable manufacturing of Industry 5.0. Nevertheless, domain-related research on glass manufacturing is insufficient, especially in the creation of integrated frameworks, which integrate AI, CPS, and DT technologies. The next generation research must be oriented towards developing scalable, secure, and energy efficient architectures that would be responsive to the special needs of the glass manufacturing processes.

5. Research Gap

Although the Artificial Intelligence, Digital Twins, and Cyber-Physical Systems have achieved a great progress in the field, the combination of their use in the creation of glass has not been studied in detail. Available literature is mainly dealing with generic or discrete manufacturing systems and does not contain domain-specific models of glass manufacturing processes of high temperature and energy-demanding processes. Moreover, real-time adaptive control and sustainability-oriented optimization with AI-enabled digital twin frameworks in this domain have little research.

6. Conceptual Methodology

In this work, the authors suggest an AI-enhanced Cyber-Physical Digital Twin (CPDT) system of sustainable glass production in Industry 5.0. The framework incorporates real-time monitoring, AI-based prediction and simulation of digital twins to streamline furnace processes and minimize energy use and CO_2 emissions.



6.1 System Architecture

The architecture consists of four layers:

- Physical Layer: Data collection with the help of glass furnace, sensors (temperature, gas), and robots.
- Cyber Layer (CPS): Enables real-time communication via IoT.
- Digital Twin Layer: Simulation and performance analysis model.
- AI Layer: Uses ANN/SVR models and Firefly optimization for parameter tuning.

6.2 Workflow

1. Data collection from sensors
2. Data pre-processing
3. Prediction of temperature, energy, emissions (AI-based).
4. Digital twin simulation
5. Optimal control action (air–fuel ratio, cullet %)
6. System improvement with continuous feedback.

6.3 Optimization Model

A **hybrid SVR–Firefly approach** is used:

The movement of fireflies is given by:

$$x_i^{t+1} = x_i^t + \beta_0 e^{-\gamma r_{ij}^2}(x_j - x_i) + \alpha\,\epsilon$$

Where:

- β_0 = Initial attractiveness
- γ = Light absorption coefficient
- r_{ij} = Distance between fireflies i and j
- α = Randomization parameter
- ϵ = Random vector

In the hybrid approach, FA optimizes SVR parameters:

$$\theta = \{C, \gamma, \epsilon\}$$

The objective (fitness) function is typically:

$$\min_{\theta} \text{ RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - f(x_i,\theta))^2}$$

- SVR predicts system behavior
- Firefly algorithm optimizes parameters

(a) Firefly Algorithm (FA) Movement Formula Formula

(b) Hybrid SVR–Firefly Optimization

This approach allows real time optimization, efficiency, and sustainability of operation in glass production.

7. Flowchart Proposal

The suggested system is based on a systematic flow of work that incorporates AI prediction and optimization in a cyber-physical digital twin system:

1. Start – Initialize system and acquire operational parameters
2. Data Collection – Sensors collect real-time furnace data (temperature, fuel rate, gas composition)
3. Preprocessing – Data cleaning, normalization, and feature selection
4. SVR Prediction – Predict energy consumption, furnace temperature, and CO_2 emissions
5. Firefly Optimization – Optimize parameters (air–fuel ratio, cullet %)
6. Control Action – Apply optimized parameters to the physical system
7. Feedback Loop – Continuously update system using real-time data

8. Proposed Mathematical Models and Formulations

This section contains mathematical models of energy consumption, CO_2 emissions, and optimization in the proposed AI-enabled Cyber-Physical Digital Twin framework, as well as the series of steps that need to be followed to apply the Firefly Optimization algorithm. The key arguments are [1] Energy Consumption Model, [2] CO_2 Emission Model, [3] Cullet Ratio Impact Model, [4] Air fuel Ratio

Optimization, [5] SVR Prediction Model, [6] Objective Function to be optimized, [7] Firefly Optimization Update Equation.

9. Expected Outcomes

The paper is a review-based analysis of the proposed Cyber-Physical Digital Twin (CPDT) architecture that is also based on AI and shows its enhancement in terms of energy efficiency, emissions, and general performance of the processes in the glass manufacturing industry. AI and digital twin simulation combine to promote better furnace control, which will result in 10-15% of fuel efficiency due to the increased utilization of cullet. Maximized burning and reused material use result in a 15-20% decrease in CO_2 emissions.

Table-1: Expected outcomes based on five important parameter identification

Parameter	**Unit**	**Baseline** (Conventional)	**Optimized Target** (Industry 5.0)	**Research Impact / Result**
Cullet Ratio	%	20% – 30%	75% – 85%	15–18% Energy Reduction
Fuel Type	Oil /Gas	Heavy Fuel Oil	Oxy-Fuel + Natural Gas	20% Reduction in CO2
Air-Fuel Ratio	Ratio	1.15 (Excessive)	1.05 (Precise)	Reduced NO2x by 12%
Heat Recovery	Temp (°C)	400°C Pre-heat	1200°C (Regenerative)	Doubled Furnace Efficiency
Robotic QC	Reject %	8% – 12%	< 2%	Significant Material Savings

The hybrid SVR-Firefly model allows to optimize the processes effectively as the main parameters are supported in real-time, which increases the efficiency of the combustion processes and minimizes thermal fluctuations. Moreover, AI-based inspection and automation can increase the quality of the products by reducing the number of rejections to less than 2%, and predictive maintenance can increase the reliability of the systems by about 30.

10. Conclusion

The paper presented at this conference offered an AI-enabled Cyber-Physical Digital Twin (CPDT) of sustainable glass production under Industry 5.0 paradigm in response to major issues of elevated energy usage, greenhouse gases (CO_2) emissions, and low process flexibility. The framework can be used to monitor operations in real-time, predictively model, and optimize furnace operations based on a hybrid SVR-Firefly approach by incorporating AI, cyber-physical systems, and digital twins' technology. The analysis shows that it may result in the reduction of 10-15% of fuel usage and 15-20% of emissions, as well as in product quality and predictive maintenance. In general, the framework facilitates the transition to efficient, low-carbon, and resilient manufacturing in line with the sustainability and circular economy objectives.

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