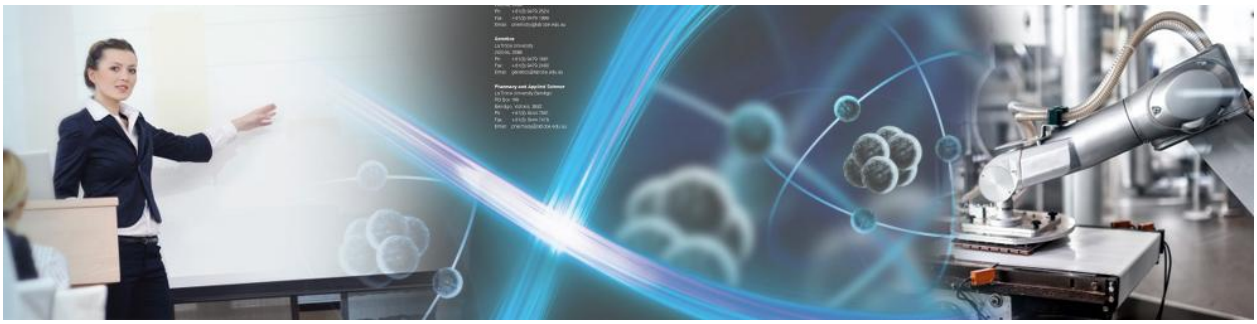
Міністерство освіти і науки України

Харківський національний університет радіоелектроніки

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МАТЕРІАЛИ

X-ої Міжнародної Конференції

ВИРОБНИЦТВО
&
МЕХАТРОННІ СИСТЕМИ 2026

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Харків, Україна

Ярослав Бєлий, Дмитро Гурін

Аналіз принципів нульової довіри для побудови кіберфізичної системи віддаленого моніторингу та керування промисловим обладнанням …… 49

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Comparison of Simulation Environments: Wokwi, Tinkercad, Falstad Circuit Simulator

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Annotation: In this study, a comparative analysis of three popular web-based environments for modeling electronic circuits and microcontroller systems is carried out: Wokwi, Tinkercad Circuits, and Falstad Circuit Simulator. Their specialization, simulation engine architectures, interfaces, analog and digital capabilities, as well as performance are analyzed. The mathematical framework underlying analog circuit calculations is identified, and practical recommendations for using each platform in educational processes and engineering practice are formulated, accounting for simulation constraints and the gap between virtual models and physical hardware (Sim-to-Real Gap).

Ключові слова: modeling, Wokwi, Tinkercad, Falstad, microcontrollers, circuit design, IoT, SPICE.

I. INTRODUCTION

The development of modern information and communication technologies, the Internet of Things (IoT) concept, robotics, and STEM education requires the widespread implementation of virtual prototyping tools [1-10]. The use of software simulators allows solving a number of critical problems in the educational process and engineering development: high costs of physical equipment, limited access to laboratories, distance learning challenges, and the risk of damaging expensive electronic components due to assembly errors.

When developing computer-integrated systems or educational courses, educators and engineers face the choice of optimal software. An important factor when choosing an environment is the ability to automate workflows, including automated firmware testing, batch running of simulation scripts, and integration with version control and continuous integration systems, as discussed in works [11-20]. The modern market of web simulators offers tools with different levels of abstraction and different specializations.

High-level abstraction platforms (e.g., Tinkercad Circuits) are oriented toward visual prototyping and visual programming.

Developer engineering simulators (e.g., Wokwi) provide detailed emulation of code execution for real microcontroller-based systems.

Physical-component simulators (e.g., Falstad Circuit Simulator) focus on numerical analysis and visualization of processes in analog-digital electrical circuits.

An unsystematic choice of environment often leads to inefficient time expenditure or the inability to implement the required algorithm. The objective of this study is to systematize the functional characteristics of Wokwi, Tinkercad, and Falstad, analyze their mathematical and software models, and define the boundaries of their effective application.

The goal of this work is a comparative analysis of the Wokwi, Tinkercad Circuits, and Falstad Circuit Simulator environments in terms of architecture, functionality, depth of analog analysis, and performance, as well as determining the limits of their effective use considering the modeling limitations.

II. ARCHITECTURE AND OPERATIONAL PRINCIPLES OF THE ENVIRONMENTS

The Wokwi platform is a modern environment for modeling microcontroller systems (IoT and robotics). The core of its operation is machine code-level emulation of AVR cores (Arduino Uno/Nano/Mega, ATtiny), Xtensa and RISC-V (ESP32 family), ARM Cortex-M0+ (Raspberry Pi Pico on RP2040, as well as select STM32 boards) directly in a web browser using WebAssembly (WASM).

Wokwi models the operation of in-circuit peripheral units (GPIO, ADC, DAC, PWM, I2C, SPI, UART, Hardware Timers). The platform provides Wi-Fi emulation capabilities (specifically for ESP32 boards); Bluetooth emulation is not implemented at the time of writing. Thanks to the Wokwi IoT Gateway, a virtual microcontroller can send network requests to the internet. The public gateway is available free of charge but does not grant access to the local network; the private gateway, which runs on the developer's computer and opens access to the local network, requires a paid Wokwi Club subscription. The schematic structure is saved in JSON format (diagram.json file), allowing flexible description of pin connections, addition of custom components, and integration of Wokwi with local development environments, including VS Code. The Wokwi extension for VS Code allows working locally, but requires activation using a license key (token) obtained from the platform's website, making the mode not fully offline.

For analog circuits, Wokwi offers experimental simulation support based on ngspice, an implementation of SPICE (Simulation Program with Integrated Circuit Emphasis), a standard engine for analog modeling of electronic circuits.

The visual layout of Wokwi is shown in Figure 1.

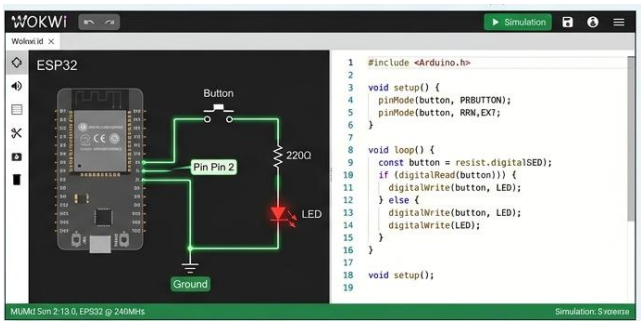


Fig. 1. Wokwi: 2D circuit diagram and code editor

Autodesk's Tinkercad Circuits platform is aimed at beginners, school students, and junior university students. It

utilizes a three-dimensional (3D-like) representation of real components (breadboards, resistors, sensors, motors).

A hybrid code editor mode is implemented: visual block programming (based on Scratch), block-text mode, and pure C/C++.

Tinkercad Circuits runs in the Autodesk web environment and simulates the behavior of a limited set of boards (Arduino Uno, ATtiny85, micro:bit).

Unlike Wokwi, the architecture of the simulation engine is insufficiently described in publicly available documentation; therefore, the comparison was conducted based on observable behavior: performance, timing accuracy, and functionality.

Due to the visualization layer, as the circuit becomes more complex, a significant slowdown in timing calculations (Drop FPS) is observed.

The Tinkercad visual layout is shown in Figure 2.

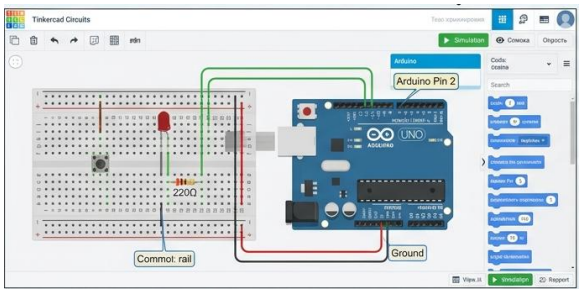


Fig. 2. Tinkercad Circuits, realistic prototyping

Falstad Circuit Simulator is an open-source interactive analog and digital circuit simulator built on numerical methods for analyzing electrical circuits.

Unlike Wokwi and Tinkercad, Falstad does not interpret firmware source code; instead, it calculates the state of each circuit node at every time step Δt. At the same time, Falstad uses its own numerical calculation engine rather than SPICE, so its models are simplified compared to SPICE simulators, but they allow changing parameters in real time.

Falstad uses charge movement animation (running dots on conductors), where the speed and direction are proportional to the current, and the color corresponds to the potential (voltage).

Falstad features built-in virtual two-channel oscilloscopes, voltmeters, ammeters, spectrum analyzers, and function generators.

The visual layout of the Falstad Circuit Simulator is shown in Figure 3.

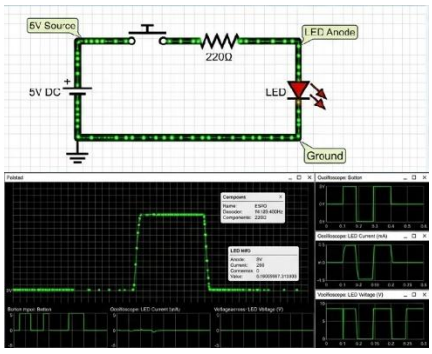


Fig. 3. Falstad Circuit Simulator, current visualization

III. MATHEMATICAL FRAMEWORK AND DESCRIPTION OF CIRCUIT PROCESSES

To describe processes in Falstad, classical electronic circuit equations are used, solved numerically at each time discretization step $t_k = t_{k-1} + \Delta t$.

Although the state of each node is calculated at every step Δt, the computational volume for educational circuits (tens to hundreds of nodes) is small: the system of nodal potential equations is typically solved within a few to tens of milliseconds, so parameter changes are reflected almost instantaneously.

As the number of nodes and nonlinear elements grows, the calculation time increases. Transient process calculation (RC circuits).

The voltage $U_c(t)$ across a capacitor during charging from a constant source U_0 through resistance R is described by the differential equation (1):

$$RC\frac{dU_c(t)}{dt} + U_c(t) = U_0, \quad U_c(0) = 0. \qquad (1)$$

Unlike Wokwi and Tinkercad, where simulation primarily relies on firmware execution, Falstad calculates currents and voltages based on Kirchhoff's laws and the differential equations of components in interactive mode. For example, the voltage across a capacitor $U_c(t)$ in the time domain is described by formula (2):

$$U_c(t) = U_0 \cdot \left(1 - e^{-\frac{t}{R \cdot C}}\right), \qquad (2)$$

where R – circuit resistance (Ohm);

C – capacitance (F);

U_0 – input voltage (V).

Falstad integrates Equation (1) using the implicit trapezoidal method (by default), which provides second-order accuracy; the implicit Euler method serves as an alternative, being simpler but introducing more numerical damping. In Wokwi, microcontroller digital signals are represented by discrete levels (High/Low), while ngspice-based analog simulation is currently experimental.

Tinkercad Circuits provides basic analog tools (multimeter, oscilloscope), but the depth and accuracy of its analog models are limited compared to Falstad. While Falstad operates on analog circuit equations, in the microcontroller environments Wokwi and Tinkercad Circuits, the main calculations relate to matching digital pins with external components.

Calculation of the current-limiting resistor for an LED (Tinkercad/Wokwi). When modeling digital outputs of microcontrollers (Arduino/ESP32), the value of the limiting resistor R is calculated according to Ohm's law for a circuit section using Formula (3):

$$R = \frac{U_{cc} - U_D}{I_D} \qquad (3)$$

where U_{cc} – output voltage of the digital port (for example, 5 V or 3,3 V);

U_D – direct voltage drop across the LED (≈ 1,8…2,2 V);

I_D – operating current of the LED (≈ 10…20 mA).

IV. COMPARATIVE ANALYSIS AND SYSTEMATIZATION OF CHARACTERISTICS

The evaluation of the environments was carried out according to the criteria of purpose, supported hardware base,

interface type, depth of analog analysis, and performance. Summary results of the comparison are presented in Table 1.

Table 1. Comparative characteristics of modeling environments

Characteristic	Wokwi	Tinkercad Circuits	Falstad Circuit Simulator
Main purpose	Microcontroller Programming (IoT, Robotics).	Learning the basics of microcontrollers and 3D design.	Visualization and analysis of electronic circuits.
Supported boards	Arduino, ESP32, Raspberry Pi Pico, STM32.	Arduino Uno, ATtiny85, micro:bit.	Not available (chip/component-level modeling).
Interface	Text code + 2D schematic (fast, text-based).	Visual 3D-like (Drag-and-Drop) + blocks/code.	2D graphic (schematic) with current animation.
Analog modeling	Basic, experimental ngspice support.	Basic.	Extremely deep (oscilloscopes, graphs).
Launch speed	Very high (instant start).	Medium (requires Autodesk account, downloading the editor).	Very high (instant response to parameter changes).
Scalability (complex schemes)	High for digital projects (load depends on code).	Low (frame rate drops as the circuit gets more complex)	Moderate (depends on the number of nodes and Δt step).
Accessibility and price	Free (advanced features, including private gateway, in the paid Wokwi Club subscription).	Free (Autodesk account required).	Free (open-source, no registration).
Network support (Wi-Fi)	Yes (public gateway is free; private with local network access available in Wokwi Club).	None.	Not available.
Offline mode	Limited (VS Code extension, license token required).	Online only.	Offline PC version available.

Wokwi is a modern platform for microcontroller and IoT developers. It supports Wi-Fi emulation for ESP32, uploading arbitrary C++/MicroPython/Rust libraries, and configuring circuits via JSON. A downside is the lack of block-based programming (Scratch). Since code execution takes place in a compiled WebAssembly core, and graphical display is limited to a 2D diagram, Wokwi's performance depends primarily on the code rather than the number of components, ensuring better scalability for digital projects compared to Tinkercad.

Tinkercad Circuits is the best tool for beginners. An intuitive interface with detailed 3D models of breadboards and radio components simplifies adaptation. Drawbacks include the absence of modern platforms (ESP32, STM32) and low speed as the circuit becomes more complex. Falstad Circuit Simulator is an ideal simulator for studying the physics of electrical circuits.

Thanks to visual animation of electron flow (moving dots) and integrated oscilloscopes, it allows visualizing the operation of filters, amplifiers, and generators. A downside is the inability to upload code/firmware for microcontrollers.

V. SIMULATION CONSTRAINTS AND DEVIATION FROM PHYSICAL HARDWARE (SIM-TO-REAL GAP)

To effectively use web simulators, one must account for their technical limitations, which create a gap between the virtual model and the physical device (Sim-to-Real Gap). None of the simulators by default account for the internal resistance of the battery, voltage dips during peak loads (for example, during the start of servo motors or switching on the ESP32 Wi-Fi transmitter), and power supply impulse noise. In Tinkercad, a mechanical push button acts as an ideal switch. In Wokwi, it is possible to enable the bounce attribute in the JSON file; however, it is disabled by default, which accustoms students to writing interrupt handling code without software debouncing. Falstad provides visual analysis of analog circuits, yet fails to account for parasitic capacitance of jumper wires and trace inductance at high frequencies (SPI and other high-speed digital signals).

VI. CONCLUSIONS

In this study, a comprehensive analysis of three simulation environments was conducted: Wokwi, Tinkercad Circuits, and Falstad Circuit Simulator. Based on the conducted research, it was established that none of the examined environments is completely universal, as they feature different levels of abstraction and are tailored to different classes of tasks. It was determined that Tinkercad Circuits serves as the best starting tool for mastering the basics of Arduino microcontroller programming and visual circuit assembly; Wokwi is best suited for the engineering development of complex IoT projects based on ESP32 or Raspberry Pi Pico, while Falstad remains an indispensable tool for deep analysis of analog and digital circuit design. To achieve maximum educational and engineering impact, it is recommended to combine these platforms depending on the development stage or educational course. For instance, a learning sequence could be structured as follows: Falstad for understanding the physics of electrical circuits, Tinkercad Circuits for first-hand experience with Arduino, and Wokwi for ESP32-based projects. At the same time, the gap between virtual models and physical hardware (Sim-to-Real Gap) must be taken into account: none of the simulators account for voltage drops, power supply noise, contact bounce, or parasitic parameters by default; therefore, simulation results must be verified on a physical breadboard.

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