ENVIHEI

Title of the PBL challenge: **Design and Development of Smart and Sustainable Automated Systems**

Name of the responsible lecturer

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University / Department / Degree program

Silesian University of Technology / Department of Computational Mechanics and Engineering / Bachelor's Degree in Industrial Automation and Robotics

Course / Subject in which implemented

4th Course / Projects in Technical Informatics

Implementation period (dates)

March 1, 2026 – June 30, 2026

Total duration (weeks/hours)

16 weeks / 45 hours

Number of students involved

18 students

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1. Project Design

1.1 Brief description of the project and the challenge proposed

The students worked on three practical projects focused on applying programming, automation, computational methods, and sensor-based technologies to address real-world problems. The challenges proposed were:

- **Strength Calculator Project**: Develop a C++ software tool to automate structural and mechanical calculations. The Strength Calculator addresses four fundamental load cases in strength of materials: axial tension, simple bending, torsion of circular shafts, and the calculation of bending moments using the Clebsch method. The overarching challenge was to minimize human computational errors and drastically reduce the time required for static analysis of structural elements.
- **Smart Dual-Action Plant Pot Project**: An intelligent plant care system designed to autonomously control irrigation and UV lighting based on real-time environmental data. The project aims to solve the common household problem of plant neglect due to a lack of time or memory. Originally planned for an ESP32 microcontroller, the system was successfully implemented on an ATmega328p (Arduino platform). It utilizes a capacitive soil moisture sensor and a light intensity sensor to ensure optimal plant growth conditions without manual intervention
- **Automated Greenhouse Project**: Develop a comprehensive concept for an automated greenhouse. The system is designed to independently control the essential environmental conditions required for optimal plant growth, specifically targeting temperature, air humidity, and soil moisture. By implementing this system, the necessity for manual labor is significantly reduced, the stability of the microclimate is enhanced, and users are provided with real-time monitoring capabilities. The system automatically manages heating, irrigation, and ventilation (window

operations) based on real-time sensor data, operating in either a fully automatic or manual override mode.

Together, these projects challenged students to apply their technical and programming knowledge to the design of functional solutions, combining theoretical concepts with practical problem-solving and technological implementation.

1.2 Expected learning outcomes (academic and transversal competences)

The three projects provided students with practical, hands-on experience in applying theoretical knowledge to the design, programming, implementation, and control of technological solutions. The main competencies developed included:

- **Software Engineering**: Developing C++ logic in the Arduino IDE, implementing sensor calibration, creating algorithms with non-blocking delays (interval logic), developing modular code architectures that allow for easy expansion, implementing mathematical logic and validation to prevent programmatic errors (e.g., division by zero), translating complex theoretical physics and mechanics into functioning C++ code, and gaining a deeper understanding of the relationships between physical quantities in strength analysis.
- **Electronic Design**: Safely separating 5V logic circuits from higher-power actuator circuits using MOSFET transistor modules and managing dual power supplies with a common ground.
- **Mechanical & Rapid Prototyping**: Designing and manufacturing physical housing and mounts using FDM 3D printing (PLA filament) and assembling hydraulic components.

- **Industrial Automation and Control Systems**: Designing and implementing SCADA visualization systems (using SCADA Promotic) linked with relational databases; specifying and integrating industrial-grade hardware (pneumatics, contactors, 4-20mA sensors) to solve real-world problems; and developing dual-architecture control logic, comparing industrial PLCs (Siemens LOGO!) with educational microcontrollers (Arduino Mega).
- **Safety Engineering**: Applying safety engineering principles, such as utilizing hard-wired thermal cutoffs and bistable pneumatic valves to prevent catastrophic failures during power loss.

1.3 Targeted sustainability competences

The projects directly target environmental sustainability by addressing resource conservation and sustainable computing and engineering practices. They minimize water waste by ensuring the plant is watered only when strictly necessary, through the deployment of precise soil moisture sensors and automated retention pumps. Furthermore, by optimizing the photosynthesis process with automated UV lighting, they reduce the risk of crop failure, thereby preventing the waste of soil, fertilizers, and water associated with dying plants. The intelligent heating and ventilation control logic ensures that energy is only consumed when environmental parameters fall out of the optimal growth range. The projects also focus on optimization of material usage by providing precise calculations to prevent material over-engineering, green computing by optimizing code and limiting required computational resources, and environmental safety by extending product lifecycles through accurate mechanical limits testing.

1.4 Sustainability approach and how it is integrated into the project

Sustainability was addressed through different approaches across the three projects:

- The **Automated Greenhouse Project** embedded sustainability in the hardware selection and operational logic. The system utilizes rain/retention water via the Omnigena WQ 180F pump, reducing reliance on municipal water lines. The FDR (Frequency Domain Reflectometry) soil sensors are immune to corrosion from fertilizers, ensuring long-term operational sustainability without frequent hardware replacement. Energy efficiency is also tackled by utilizing bistable pneumatic valves (SMC SY5220-5LZD) that maintain window positions without continuous power draw.
- The **Smart Dual-Action Plant Pot Project** addressed sustainability using an intelligent threshold-based watering system that ensures the pump is activated only when soil moisture drops below 30%. In addition, the use of a capacitive moisture sensor instead of a resistive one prevents rapid galvanic corrosion, greatly extending the operational life of the device and reducing electronic waste.
- The **Strength Calculator Project** integrated sustainability via a "Green Computing" philosophy. By creating a tool that facilitates precise remote work (online capability), it indirectly reduces the carbon footprint associated with commuting to physical testing labs or workplaces. Furthermore, the high precision of the tool contributes to safer and more sustainable mechanical designs that avoid premature failure.

1.5 Methodologies and tools used (PBL structure, facilitation techniques, etc.)

The projects used different methodologies and tools according to their specific objectives, combining collaborative engineering, software engineering, modular systems engineering, simulation, prototyping, and testing approaches:

- The **Smart Dual-Action Plant Pot Project** utilized a collaborative engineering approach with distinct roles assigned to each member. Key tools and components included:
    - **Hardware**: ATmega328p microcontroller, capacitive soil moisture sensor, MH-Sensor-Series light module, mini water pump, UV LED, and XY-MOS modules.
    - **Software**: Arduino IDE (C++) was used for programming the control logic.
    - **Testing methodology**: Iterative breadboard prototyping, dry/wet calibration phases, and long-term 24-hour stress testing.
- The **Strength Calculator Project** heavily relied on software engineering methodologies, specifically modular programming in C++. Key technical tools and standards included:
    - **Strict SI Unit Standardization**: Enforcing the use of Newtons (N), millimeters (mm), Megapascals (MPa), and Newton-millimeters (Nmm) to ensure consistency with Eurocode design norms.
    - **The Clebsch Method Algorithmic Implementation**: Utilizing the Clebsch bracket (a conditional step function) to describe the loading state of an entire beam with a single mathematical equation, avoiding traditional interval-based segmentation.
- The **Automated Greenhouse Project** used a development methodology focused on modular systems engineering and simulation. The key tools included:

- **SCADA Promotic**: Used for creating the user interface, visualizing the greenhouse microclimate, and providing a control panel for manual/auto mode switching.
- **Hardware specification**: A rigorous selection process for industrial components (Festo, Danfoss, Mean Well) based on environmental durability (IP65 ratings, moisture resistance).
- **Control systems**: Evaluated in two tracks: an industrial standard track (Siemens LOGO! 8 24CE) and an educational track (Arduino Mega 2560 with Ethernet).

1.6 Organization of the project (group formation, timeline, milestones)

The projects were executed collaboratively by student teams of different sizes, with the workload distributed according to the specific requirements and technical areas of each project:

- The **Smart Dual-Action Plant Pot Project** was carried out by a five-member team, with responsibilities distributed across programming, 3D construction, electronics, mechanical and hydraulic assembly, testing, and documentation.
- The **Strength Calculator Project** was executed collaboratively by a seven-member engineering team, with the workload distributed among conceptual design, algorithm creation (such as the specific Clebsch function module), user interface design, and testing/validation.
- The **Automated Greenhouse Project** was executed by a six-member team, with the workload distributed across hardware specification, SCADA interface design, control logic programming, and system integration documentation.

1.7 Deliverables requested from students (type, format, deadlines)

The projects resulted in a range of technical and documentation deliverables, including functional prototypes and software applications, technical documentation, project reports, presentations, and system designs:

- The **Smart Dual-Action Plant Pot Project** delivered a functional hardware prototype, documented C++ source code for the microcontroller, an electrical schematic, and a comprehensive project report detailing the testing and calibration phases.
- The **Strength Calculator Project** successfully delivered a functional C++ executable application with an intuitive Graphical User Interface (GUI), a comprehensive Technical Report outlining the computational standards, modules, and performance metrics, and a Presentation summarizing the core functionalities and ecological aspects.
- The **Automated Greenhouse Project** produced a comprehensive technical specification document detailing component selection and wiring philosophy, a fully functional SCADA visualization dashboard design, and a final project report outlining the system's operational logic and future expansion possibilities.

1.8 External collaborators involved (mentors, companies, experts...) and their role

No external collaborators were involved in this implementation.

2. Project Evaluation

2.1 Assessment criteria and methods used

The three projects were assessed according to their specific technical requirements, with evaluation focusing on practical validation, accuracy, technical rigor, safety, and functionality:

- The **Smart Dual-Action Plant Pot Project** was evaluated through rigorous practical validation in its intended environment. A key assessment method was the "Stress Test 24h," designed to verify the stability of the hybrid power architecture under continuous load without causing microcontroller freezes or MOSFET overheating.
- The **Strength Calculator Project** was assessed against manual analytical methods. Evaluation criteria focused on algorithmic accuracy, execution speed, error handling (validation of inputs like negative moments of inertia), and adherence to standard engineering frameworks (SI units).
- The **Automated Greenhouse Project** was evaluated on its technical rigor, safety considerations, and the completeness of its automation logic. Key criteria included the appropriate usage of 4-20mA signals to mitigate voltage drop over long cable runs, the inclusion of hardware-level safety cutoffs (e.g., Danfoss KP79 thermostat), and the clarity and functionality of the SCADA interface.

2.2 Evidence of student learning (examples, outputs, results)

Evidence of successful problem-solving and learning is demonstrated through the teams' ability to adapt technologies, refine logic, improve performance, and make technically justified design decisions:

- The **Smart Dual-Action Plant Pot Project**: demonstrated successful problem-solving through the ability to pivot technologies and refine logic:

- Successfully migrating from an ESP32 to an ATmega328p to match the 5V logic requirements of the sensors and modules.
- Overcoming Linux serial port permission issues to successfully flash the bootloader and code
- Developing an "anti-inertia" watering algorithm.

- The **Strength Calculator Project** demonstrated successful execution through the application's performance metrics. Comparative testing showed that the Strength Calculator reduced calculation times by over 99% compared to traditional manual methods, while maintaining perfect repeatability of results across variable input parameters.
- The **Automated Greenhouse Project** demonstrated successful problem-solving through the detailed component specification and the students' ability to successfully architect a system comprising:

Subsystem	Selected component	Technical justification
Heating	Lighthouse 2kW & Danfoss KP79	Forced circulation eliminates condensation. Hard-wired thermostat prevents crop overheating at 40°C.
Ventilation	Festo DSBC-32-200 & SMC SY5220-5LZD	Pneumatic cylinders with bistable valves ensure windows remain in place safely during a power loss.
Irrigation	Danfoss EV220B 15B & Omnigena WQ 180F	Solenoid valves and float-switch protected pumps for safe water management.
Sensors	APAR AR252 & JXBS-3001-TR	4-20mA loop prevents signal degradation. Sintered filters and resin casting protect against harsh greenhouse elements.

3. Reflections and Recommendations

3.1 Main achievements and strengths of the project

The projects achieved significant results through the development of practical, efficient, and innovative technological solutions:

- The **Smart Dual-Action Plant Pot Project** demonstrated that simple, low-cost electronics (~30 PLN budget) can yield highly effective and reliable automated systems. The successful implementation of an interval-based watering cycle, which prevents plant flooding, showcases a deep understanding of physical system dynamics.
- The **Strength Calculator Project** achieved the innovative implementation of the Clebsch bracket in C++. This allows the program to calculate the bending moment M(x) continuously along the entire length of a beam. This drastically speeds up static analysis and provides a strong foundation for generating internal force diagrams.
- The **Automated Greenhouse Project** achieved the formulation of a highly robust, fault-tolerant greenhouse control architecture. The dual-path control option (Siemens LOGO! vs. Arduino) makes the concept adaptable for both commercial implementation and educational deployment. The SCADA visualization provides an intuitive, user-friendly interface that aggregates complex sensor data into actionable insights.

3.2 Challenges faced and how they were addressed

The projects involved different technical challenges that were addressed through practical problem-solving and appropriate design decisions:

- The **Smart Dual-Action Plant Pot Project** faced two major challenges:
    - **Power Load Management**: Actuators (pump, UV LED) draw too much current for a microcontroller. The team solved this by

creating an isolated power circuit using XY-MOS transistor modules.

- **System Inertia**: Water takes time to seep into the soil and reach the sensor, which originally caused the pump to run too long and flood the plant. The team implemented interval watering (3 seconds of pumping followed by 5 seconds of resting) to allow the water to absorb and the sensor to stabilize before deciding if more water is needed.

- The **Strength Calculator Project** faced the major challenge of digitizing the complex, piecewise nature of beam analysis. The team successfully addressed this by programming a custom logic function that automatically nullifies bracket terms when the argument (x-a) is negative. This conditional logic perfectly mimics the analytical Clebsch method and ensures accurate readings at intermediate beam points.
- The **Automated Greenhouse Project** faced significant hardware challenges when designing for a high-humidity, potentially corrosive agricultural environment. The team addressed this by deliberately selecting industrial-grade components: choosing capacitive FDR soil sensors over easily corroded resistive ones, selecting IP65-rated enclosures, and using 4-20mA current loops for reliable long-distance analog signal transmission.

3.3 Lessons learned for future implementations

The **Smart Dual-Action Plant Pot Project** demonstrated the importance of component selection in harsh environments (e.g., using capacitive sensors to prevent soil electrolysis). For future iterations, the project could expand its IoT capabilities, re-integrating Wi-Fi functionality (perhaps using the ESP32 as

originally planned but with proper logic level shifters) for remote monitoring via a web dashboard.

The **Strength Calculator Project** demonstrated that the modular structure proved to be a highly effective design choice. For future iterations, the team recommends utilizing the current application as a calculation engine that can be expanded to include fatigue analysis and structural stability (buckling) modules. There is also potential to connect this engine to more advanced GUI frameworks.

The **Automated Greenhouse Project** demonstrated that the foundational design is highly modular, opening multiple pathways for future enhancement. For future iterations, planned implementations include the development of a dedicated mobile application for remote control and real-time monitoring, implementation of historical data logging to analyse long-term microclimate trends, integration of alarm systems for critical events (e.g., pump failure, extreme temperatures), and addition of water level sensors, light intensity sensors, and automated supplemental plant lighting systems.

4. Supporting Material

4.1 Lecturers' materials and project documentation

Lecturers' materials and project documentation are available in the following link:
https://drive.google.com/drive/folders/1bH_gyWJLXF3JNfLPTuDmviE-6Q9klzx6?usp=drive_link

4.2 Deliverables produced by students, final presentations or pitch materials

An example of deliverables produced by students is available in the following link:

https://drive.google.com/drive/folders/1yqQtFAqNGo6Xg6JoVg47F4F8QdFFDw7z?usp=drive_link

Students' final presentations are available in the following link: https://drive.google.com/drive/folders/1hg6rp6XcuOSeGTOhn68S9s-vvt5u3Uly?usp=drive_link

4.3 Images/videos (with consent)

Photographic and video records were captured with the explicit consent of the participating students, and are available in the following link: https://drive.google.com/drive/folders/1lHPRfaj88KLxRsvGqRjCOeM0fnBQxLCc?usp=drive_link

4.4 Any other relevant material

All the materials, including this report, are available in the following link: https://drive.google.com/drive/folders/1qGPSzd5J-A0DyTS82zYHQJWIjfXvB21u?usp=drive_link