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Water Treatment Technologies: Development of a Test Bench for Optimizing Flocculation-Thickening Processes in Laboratory Applications

Amine Ennawaoui [1,2,*], Mohammed Badr Rachidi [1], Nasr Guennouni [3], Ilyass Mousaid [2], Mohamed Amine Daoud [4], Hicham Mastouri [2], Chouaib Ennawaoui [2,5], Younes Chhiti [1,3] and Oussama Laayati [3,*]

1 École Nationale Supérieure de Chimie, Ibn Tofail University, Kenitra 14000, Morocco; mohammedbadr.rachidi@uit.ac.ma (M.B.R.); younes.chhiti@um6p.ma (Y.C.)
2 Mohammed VI Polytechnic University, Benguerir 43150, Morocco; ilyass.mousaid@um6p.ma (I.M.); hicham.mastouri@um6p.ma (H.M.); chouaib.enna@gmail.com (C.E.)
3 Green Tech Institute, Mohammed VI Polytechnic University, Benguerir 43150, Morocco; nasr.guennouni@um6p.ma
4 Faculty of Sciences and Techniques, University Abdelmalek Essaâdi, Tangier 93030, Morocco; mddaoudd@gmail.com
5 Laboratory of Engineering Sciences for Energy, National School of Applied Sciences, Chouaib Doukkali University, El Jadida 24000, Morocco
* Correspondence: amine.ennawaoui@um6p.ma (A.E.); oussama.laayati@um6p.ma (O.L.)

Abstract: This study introduces an automated test bench designed to optimize flocculation-thickening processes in the wastewater treatment industry. Addressing current challenges in operational efficiency and cost reduction, the test bench employs Model-Based Systems Engineering (MBSE) principles, leveraging SysML modeling within the CESAM framework. By integrating advanced technologies, including PLC programming and a closed-loop control system, this bench provides precise and efficient testing under varying operational conditions. Economic implications are explored, demonstrating the cost-effectiveness of optimized flocculation processes, which reduce chemical use and operational expenditures while enhancing water clarity and sludge management. The system's 3D modeling enables detailed simulations, aiding in both research and pedagogical applications. This platform highlights the potential of MBSE in creating scalable, robust solutions that contribute to sustainable water management.

Keywords: model-based systems engineering; water treatment; flocculation; thickening; sedimentation

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1. Introduction

Water is one of the most vital natural resources on Earth, essential for sustaining human life, agriculture, and industry. However, with urbanization and rapid population growth, the demand for water has surged, resulting in water scarcity in many regions worldwide. Additionally, water quality has deteriorated due to pollution from domestic, industrial, and agricultural activities, as well as improper waste management. Wastewater treatment mitigates these challenges by systematically eliminating contaminants and pollutants from wastewater, thereby ensuring its suitability for safe reuse or environmentally compliant discharge [1–3].

Wastewater treatment involves three primary stages: chemical, physical, and biological processes. Physical methods are employed to remove solid particles, while chemical

treatments, such as flocculation, utilize specific chemicals like alum or polyacrylamides to eliminate impurities from water, including organic matter, heavy metals, and suspended solids. Biological methods break down organic matter through the action of microorganisms, completing the treatment cycle [4]. In industrial applications, these processes are crucial for various sectors, such as the phosphate industry, where the thickening phase significantly enhances water recovery and sludge concentration [5,6]. This phase relies heavily on the efficiency of flocculation, where flocculants agglomerate particles, accelerating sedimentation and achieving gradual clarification without a distinct interface between solid and liquid phases. The effectiveness of this process is closely linked to the efficiency of the flocculation stage. Flocculants also play a vital role in other industries, including pulp processing, biopharmaceutical downstream operations, and food and fermentation processes. Flocculation and thickening are not only essential for industrial applications but also fundamental to advancing research and education in water treatment technologies. A thorough understanding of these processes enables scientists and engineers to develop innovative, efficient methods for contaminant removal, ultimately contributing to sustainable water management practices and addressing global water challenges [7–12].

Systems engineering adopts an interdisciplinary approach, managing the lifecycle of a system from conception to decommissioning. This methodology is supported by a range of standards [13–15], such as EIA-632, ISO 12588, and IEEE 1220 [16,17], which provide guidelines for best practices in systems engineering. As systems become more complex, especially in digital and industrial domains, Model-Based Systems Engineering (MBSE) is increasingly being used by industries and governmental bodies to manage this complexity [17]. MBSE uses digital models as the primary means of communication and analysis, offering significant advantages in terms of efficiency, accuracy, and traceability [18,19]. MBSE relies on modeling languages such as the Unified Modeling Language (UML) and Systems Modeling Language (SysML), which help structure and represent complex system behaviors and architectures. Various Model-Based Systems Engineering (MBSE) methodologies have been developed and are extensively documented in scientific literature. Notable examples include the CESAMES Systems Architecting Method, the MBSE Grid, IBM Harmony, and the U.S. Department of Defense Architecture Framework (DoDAF) [20–22]. These methodologies offer systematic approaches for organizing and managing system architecture, ensuring that all system elements are effectively aligned and integrated. In the context of this study, the goal is to design and analyze a flocculation-thickening testing apparatus tailored for laboratory applications, leveraging MBSE to effectively manage the complexity associated with the system's design and operational processes. This test bench will be used for studying and optimizing flocculation and thickening processes, critical for applications in water treatment and other industrial processes. The MBSE grid methodology and the CESAM framework were selected to guide the system's design, ensuring a comprehensive and structured approach that fulfills all specified requirements. The SysML was selected as the modeling language to represent the system's functional, behavioral, and structural elements. This language allows for detailed modeling of the system, enabling clear visualization of interactions, flows, and dependencies between different components [20,23].

Delong Cui et al. highlight that as onboard systems in aircraft become more complex, traditional design methods for ground testing equipment are increasingly inadequate. To address these issues, the authors propose using MBSE. They employed SysML, the Rhapsody modeling tool, and the Harmony-SE methodology to improve the design process. By closely integrating requirements, functions, and architecture, MBSE significantly enhances design efficiency, ensures equipment quality, and reduces development costs and risks. This approach offers a robust workflow tailored to meet stakeholder needs in

developing aircraft ground testing systems [24]. Oussama Laayati et al. present a study focused on "designing an educational test bench for smart grids and renewable energy systems. The test bench aims to facilitate research and learning for students, laboratory engineers, and researchers by enabling the study of electrical microgrid systems and the testing of advanced control algorithms to improve energy efficiency". The system's MBSE framework outlines the requirements and case studies, adhering to the principles of frugal innovation by using low-cost hardware and software (Cameo Systems Modeler 19.0 LTR SP3, Vélizy-Villacoublay, France). This approach provides flexibility, enabling users to add new sources, change software platforms, and interface with other simulators. The system facilitates students' comprehension of fundamental smart grid concepts, encompassing defect classification, energy optimization, and energy forecasting, as well as the principles of energy production, transmission, and consumption [25]. Hicham et al. discuss the increasing attention electric vehicles have received due to stricter global emission policies. This article presents the initial phase in the design and development of a test bench for the powertrain of an electric vehicle, with the dual objectives of supporting research activities and serving educational purposes. The methodology employed is MBSE, specifically through the CESAM architecture and modeling framework. This methodology enabled the conceptualization and formalization of an operational architecture for the powertrain test bench, serving as a pivotal step in the preliminary design phase of the system [26].

The main objective of this study is to design and implement an automated test bench to optimize flocculation-thickening processes, which are critical in wastewater treatment. The tasks performed include (1) identifying stakeholder requirements, (2) developing a system architecture using MBSE and SysML, (3) designing the mechanical and electrical components of the bench, (4) programming the control system, and (5) evaluating the performance of the bench for various industrial and educational applications.

2. Challenges of Flocculation-Thickening Testing

2.1. Flocculation-Thickening Testing Systems

The efficiency of flocculants in water treatment is influenced by several challenges, including the variability of sedimentation velocity measurement techniques. Methods like visual observation and sludge height measurements lack precision and depend on subjective assessment. Turbidimetry and gravimetric analysis, while more quantitative, are resource-intensive and sensitive to external factors. Jar Test is a classic and widely adopted method for evaluating flocculant performance. Advanced techniques, such as optical monitoring and laser diffraction, provide high accuracy but require significant financial and technical investment, limiting their accessibility. These challenges underscore the need for innovative, cost-effective, and scalable solutions for testing flocculants and optimizing flocculation-thickening processes. A summary of the key principles and challenges of each method is presented in Table 1.

Table 1. Principles and challenges of flocculation-thickening testing methods.

Method	Principle	Challenges	Ref.
Visual Observation	Visually tracking the descent of flocculated particles in a graduated cylinder.	Low precision, subjective variability	[27]
Turbidimetry	Measuring the reduction in turbidity with a turbidimeter to estimate sedimentation velocity.	Sensitive to dissolved substances or coloration	[28]
Sludge Height Method	Measuring the height of settled particles at the bottom of a cylinder after flocculation.	Ineffective for fine particles or heterogeneous suspensions	[29]

Table 1. *Cont.*

Method	Principle	Challenges	Ref.
Gravimetric Analysis	Weighing flocculated particles after collection and drying.	Time-consuming, requires meticulous sample preparation	[30]
Optical Monitoring	Tracking optical density at different heights within the container.	Expensive, sensitive to optical interference	[31]
Laser Diffraction	Analyzing the diffraction pattern of a laser beam passing through the suspension.	High cost, complex setup	[32]
Jar Test	Mixing various doses of flocculants, observing sedimentation, and measuring residual turbidity.	Time-consuming, lacks precision for sedimentation velocity analysis	[33]

2.2. Limitations and Drawbacks

The measurement of sedimentation velocity is crucial for assessing flocculation performance in various environmental and industrial processes. However, each method has specific limitations and drawbacks that can affect the accuracy and applicability of the results. Table 2 presents the primary sedimentation velocity measurement methods along with their limitations and drawbacks.

Table 2. Sedimentation velocity measurement methods: limitations and drawbacks.

Sedimentation Velocity Measurement Methods	Limitations	Drawbacks	Ref.
Direct Visual Observation	Limited precision, subjective variability, not suitable for small flocs.	Lacks quantitative rigor; unsuitable for complex suspensions.	[34,35]
Turbidimetry	Measures turbidity only; sensitive to interference.	Requires specialized equipment; infers sedimentation velocity indirectly, leading to potential inaccuracies.	[36,37]
Sludge Height Method	Ineffective for fine particles; assumes uniform sludge.	Gross estimation of sedimentation; unsuitable for slow-settling particles.	[38,39]
Optical Monitoring	Expensive, sensitive to external interference.	High operational costs; requires expertise; unsuitable for opaque suspensions.	[40,41]
Gravimetric Analysis	Time-consuming; lacks real-time tracking.	Requires specialized equipment; unsuitable for dynamic processes.	[42]
Laser Diffraction	Expensive instruments; measures particle size only.	Complex setup; requires highly trained personnel; unsuitable for sedimentation process analysis.	[43]
Jar Test	Provides semi-quantitative results; lacks precision for velocity analysis.	Time-consuming; may not replicate real-world conditions; high reagent cost for multiple iterations.	[44]

2.3. Problem Statement

Flocculation represents a fundamental process in sediment management and water treatment, playing a pivotal role in the removal of suspended particles across diverse environmental and industrial applications. The effectiveness of flocculation is strongly influenced by the sedimentation velocity, making the accurate measurement of this parameter essential for optimizing treatment processes. However, existing methods for measuring sedimentation velocities present several challenges, including variability in precision, cost, equipment requirements, and adaptability to different types of suspensions and real-world conditions. To address these challenges, an innovative test bench has been designed, offering a comprehensive solution that significantly contributes to the domain of wastewater treatment. This test bench serves a versatile platform for research, education, and industrial application, enabling the systematic optimization of the flocculation process. The system is

designed to be robust, efficient, and user-friendly, ensuring that it meets the needs of both researchers and practitioners.

The test bench offers six distinct services. First, it enables the testing and comparison of different flocculants to assess their performance in removing suspended solids. Second, it facilitates the optimization of key flocculation parameters, including the dosage of flocculant and settling time, to maximize the efficiency of solid removal. Third, it provides an evaluation of the settling characteristics of various solid types, such as clay, inorganic matter, and, organic matter, thereby informing the design of an effective treatment process. Fourth, the experimental bench enables the systematic scaling-up of the flocculation process to industrial-scale applications, ensuring the transferability and robustness of the optimized parameters under large-scale operational conditions. Fifth, it serves as a precision tool for continuous quality assurance, providing real-time monitoring and assessment of the performance and efficiency of the flocculation-thickening process over extended operational periods. Finally, it functions as a research platform for the development of new flocculants and the study of flocculation and thickening mechanisms. Despite these advancements, there remains a critical need for a thorough evaluation of the various sedimentation velocity measurement methods. Traditional methods, such as direct visual observation, while cost-effective, often lack the precision required for complex suspensions. More advanced techniques, such as laser diffraction and optical monitoring, offer greater accuracy but are associated with high costs and technical complexity. Meanwhile, methods like turbidimetry and sludge height measurements, though widely applied, can be affected by external factors such as dissolved substances or high turbidity, leading to potential inaccuracies in their results.

The goal of this study is to systematically evaluate and compare these sedimentation velocity measurement methods using the newly developed test bench. This evaluation will focus on finding a balance between cost, precision, equipment requirements, and real-world applicability. Ultimately, this research aims to enhance the efficiency and effectiveness of flocculation processes, making the test bench not only a tool for optimizing wastewater treatment but also a valuable platform for education and scientific research.

3. Model-Based System Engineering

Entities within a system interact and establish connections in accordance with a defined set of governing principles, while simultaneously interfacing with their external environment [7]. A complex system is defined by intricate dependencies, interactions, competition, and connections both among its components and with its environment. These interrelationships give rise to emergent properties, including nonlinearity, adaptability, developmental dynamics, stochastic behavior, and multifaceted interactions. A practical approach to modeling such systems involves the use of networks, where nodes represent individual system components and edges capture the interactions between them. MBSE offers a structured approach for designing, evaluating, verifying, and validating complex systems. MBSE emphasizes the use of models instead of traditional document-based methods in system design [14]. In document-based systems engineering, various documents are independently authored to represent the perspectives of diverse stakeholders, including system behavior, software, hardware, safety, and security. In contrast, Model-Based Systems Engineering (MBSE) leverages digital modeling to generate multiple system views from a unified set of components, resulting in a single, cohesive source of system information. This modeling paradigm facilitates the automatic detection and resolution of design inconsistencies while ensuring adherence to a standardized framework by all stakeholders [25].

MBSE offers substantial advantages compared to traditional methodologies, particularly in the domain of digital modeling and system representation. By employing a consistent methodology for documenting the system according to established standards, the risk of errors is reduced compared to the document-based approach. MBSE facilitates effective communication of changes, updates, or design considerations across disciplines to all stakeholders, which helps in reducing development risks when applied correctly [26]. MBSE integrates key concepts such as frameworks, tools, models, processes, systems engineering, and systems thinking. Models are simplified representations of real-world systems, expressed through diagrams, physical structures, or mathematical formulas. These models facilitate the analysis of complex systems by simplifying their structure and behavior, contingent upon their accurate representation of the system and thorough validation.

System thinking, a fundamental principle of MBSE, conceptualizes a system as an integral component of a broader ecosystem rather than considering it in isolation. This perspective goes beyond strategy implementation or data collection and requires a holistic approach. Systems engineering integrates engineering and management principles to effectively design and manage complex systems throughout their lifecycle. Anchored in systems thinking, this interdisciplinary approach organizes extensive knowledge and fosters collaboration among diverse components to achieve cohesive and functional system designs. Complex or large-scale projects frequently encounter challenges such as requirement analysis, system stability, logistics, interdisciplinary team coordination, testing, maintenance, and risk management. To overcome these obstacles, systems engineering employs structured methodologies, optimization techniques, and risk mitigation strategies, bridging the gap between technical and human-centric considerations. A process, within this context, is defined as a structured sequence of logical steps aimed at achieving a specific objective, while allowing adaptability across various decision-making levels [45,46].

The process framework defines the objectives and tasks to be achieved, focusing on the "what" while deliberately omitting detailed instructions on "how" each task should be executed [47]. Essentially, any method is a sequence of tasks that must be completed, and the distinction between "how" and "what" becomes clearer as tasks are implemented. Tools, whether physical or software-based, are essential in improving the efficiency of processes. A tool simplifies the "how," enhancing both the process execution and outcomes on a broader scale [48]. To effectively apply the MBSE approach, a framework is needed to organize and guide the design of a system from various perspectives. This framework functions as a reference and strategic roadmap, providing coherence and guidance throughout the design process.

3.1. System Engineering Methodology: MBSE and SysML

Systems engineering is a comprehensive and iterative approach to problem-solving, beginning from the highest conceptual level and progressively moving towards detailed implementation. This methodology is utilized by integrated organizations to translate needs and requirements into structured processes and detailed system descriptions. These outputs generate critical data for informed decision-making and serve as inputs for subsequent development stages. The approach is implemented incrementally, with each phase delivering increasing levels of specificity and precision [49]. Systems Engineering (SE) integrates both technical and managerial processes, aiming to minimize risks that could compromise project success while ensuring a balance between evolving requirements and development stages. From a technical standpoint, SE involves analyzing, defining, building, and verifying the system's structure to ensure that all components work together to achieve the overarching objectives [50]. From a managerial perspective, Systems Engineering ensures the adherence to established timelines, performance objectives, and budgetary

constraints, while maintaining the flexibility to adapt dynamically to evolving requirements. SE is structured into three main processes: requirements specification, system design, and system verification.

The initial phase of the system design process involves the identification and documentation of system requirements, which are derived from and aligned with the stakeholders' needs and expectations. These requirements are then allocated to the individual components of the system. The second step involves the development, construction, and testing of these components to verify that they meet the specified requirements. Integration and testing activities include assembling the system's modules and validating their compliance with the requirements [51]. These processes are applied iteratively throughout the development cycle, with ongoing feedback from each stage. As systems grow in complexity, they require multiple layers of hierarchical decomposition, beginning at the overarching organizational system level. In certain scenarios, this decomposition process is iteratively refined and adapted during component acquisition or manufacturing, particularly at intermediate stages of design. The present research examines the system design methodology and its associated specifications, emphasizing a structured process comprising critical steps designed to ensure the system meets stakeholder requirements in a balanced and systematic manner. First, stakeholder requirements are gathered and analyzed to understand the problem, establish system objectives, and identify performance metrics. Next, the functional and physical characteristics required to meet these objectives are defined, considering additional quality factors. The third step entails decomposing the system architecture into distinct components that align with the specified requirements, enabling the exploration of multiple system design alternatives. The fourth step entails evaluating these options and selecting the solution that best satisfies the system's needs while enhancing overall effectiveness. Finally, the fifth step ensures that system goals, component specifications, and verification outcomes are clearly defined and traceable, ensuring that all stakeholder requirements are met. This structured process enables systems engineers to develop effective solutions while maintaining alignment with project objectives and stakeholder expectations.

3.2. Design of the System of Interest

This study leverages the CESAM methodology and the MBSE Grid framework to tackle the challenge of designing a flocculation-thickening test bench for research and development applications. The system model is constructed using the SysML and CAMEO tool. One of the critical early stages in the system development process is to identify stakeholder requirements and clearly define the system's scope [52]. The goal of this study is to present an operational analysis of the System of Interest (SOI), which represents the initial stage. This phase focuses on gathering the necessary information to ensure the SOI's objectives are met.

In the initial phase of system development, the primary activities encompass the identification of stakeholder requirements, the construction of a PFMSO diagram (representing Problem, Finality, Mission, System, and Objectives), the determination of system boundaries along with external stakeholders, and the definition of operational use cases. These steps are essential to ensuring alignment between the system and stakeholder requirements, while providing a comprehensive understanding of the problem domain and the system's objectives. By rigorously defining the system's scope and analyzing its operational use cases, a robust foundation is established for the subsequent phases of system design and development.

3.2.1. Identifying the Expectations of the Stakeholders

Various stakeholders and organizations associated with the project may offer distinct requirements. Table 3 presents a comprehensive overview of the various stakeholders, with their needs classified under performance, operational, functional, and constraint categories.

Table 3. The functional and operational needs of stakeholders.

Need ID	Description of Need	Category	Stakeholder
N1	A device designed for ease of use, featuring straightforward setup and operation guidelines.	Functional	End user
N2	The ability to adjust and manage different variables during testing.	Functional	End user
N3	Offers the convenience of remote operation and control.	Functional	End user
N4	Integration of automated systems for effortless data gathering and report generation.	Functional	End user
N5	Capable of handling various sample types and reagents for testing.	Functional	End user
N6	Constructed with high-quality materials that withstand frequent usage and wear.	Constraint	SOI designer and end user
N7	Equipped with safety mechanisms to prevent accidents during operation.	Constraint	SOI designer and end user
N8	Designed for accessibility, accommodating users with physical disabilities.	Constraint	SOI designer and end user
N9	A balance of affordability without sacrificing quality or functionality.	Constraint	End user
N10	Provides real-time insights into the flocculation-thickening process.	Performance	End user
N11	Delivers accurate and reliable results, even with repeated tests.	Performance	End user
N12	Easy to maintain and repair, with widely available replacement parts.	Operational	SOI designer and end user
N13	Easily maintained and calibrated with detailed instructions and support available.	Operational	SOI designer and end user
N14	A fully automated system, reducing the need for manual intervention.	Operational	End user

3.2.2. Specifying the Operational Architecture: PFMSO

The PFMSO diagram is fundamental for aligning a system with its intended objectives, as it highlights the essential requirements needed to fulfill those objectives. Within the framework of the laboratory flocculation-thickening test bench, the PFMSO diagram (illustrated in Figure 1) delineates the system and outlines the requirements defining its mission and overarching purpose. The primary objective of this system is to enable the precise evaluation of the flocculation-thickening process performance under controlled laboratory conditions, thereby providing essential data to support research and development efforts.

The correlation between the system's performance and its mission highlights the critical necessity for the system to fulfill all mission requirements. Furthermore, the derivation link between the mission and the system's purpose indicates that the system's purpose is inherently derived from the mission objectives. To ensure that the system fully accomplishes its mission, the diagram also identifies various sub-missions, each accompanied by its own specific requirements, where applicable.

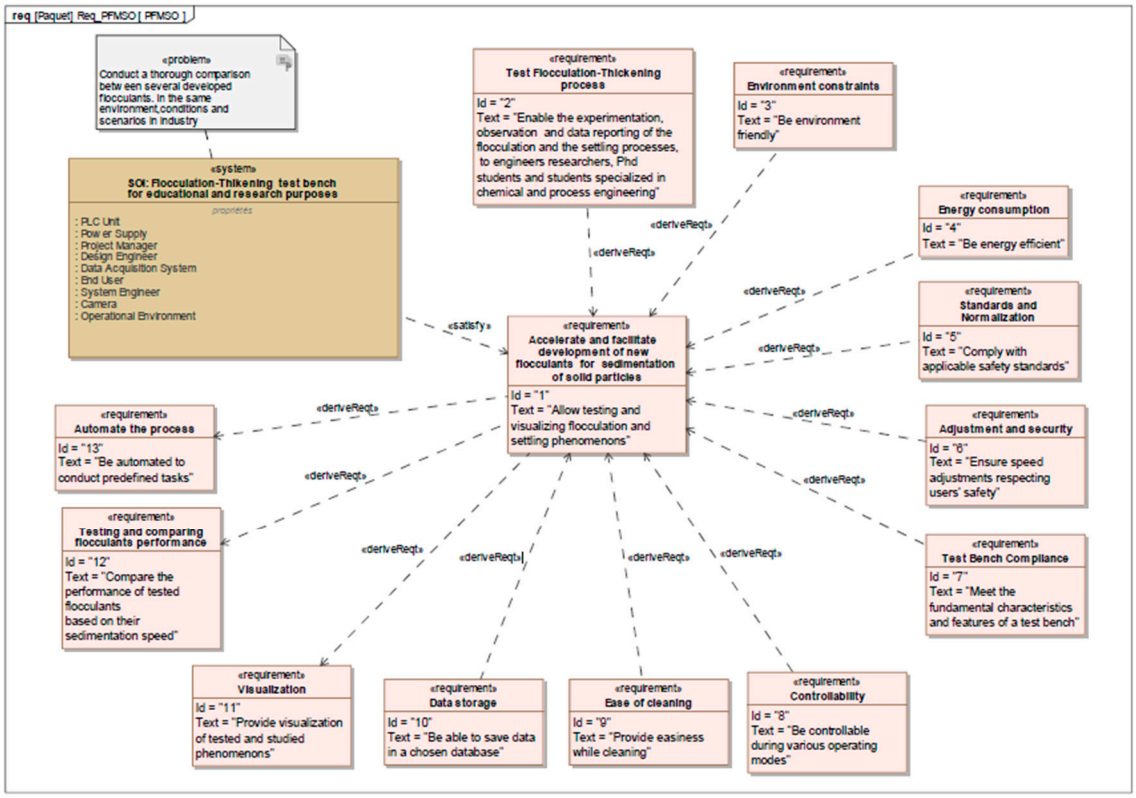


Figure 1. PFMSO diagram representing the architecture of the designed System of Interest.

3.2.3. Defining the System Life Cycle

A thorough understanding of the various phases and the involvement of diverse stakeholders is crucial for comprehending the lifecycle of the laboratory flocculation-thickening system, as illustrated in Figure 2. Table 4 details the key stages of this lifecycle, encompassing planning, design, implementation, testing, and maintenance. Each phase involves distinct stakeholders, including engineers, technicians, researchers, and end users, who contribute through specific roles and responsibilities unique to their expertise.

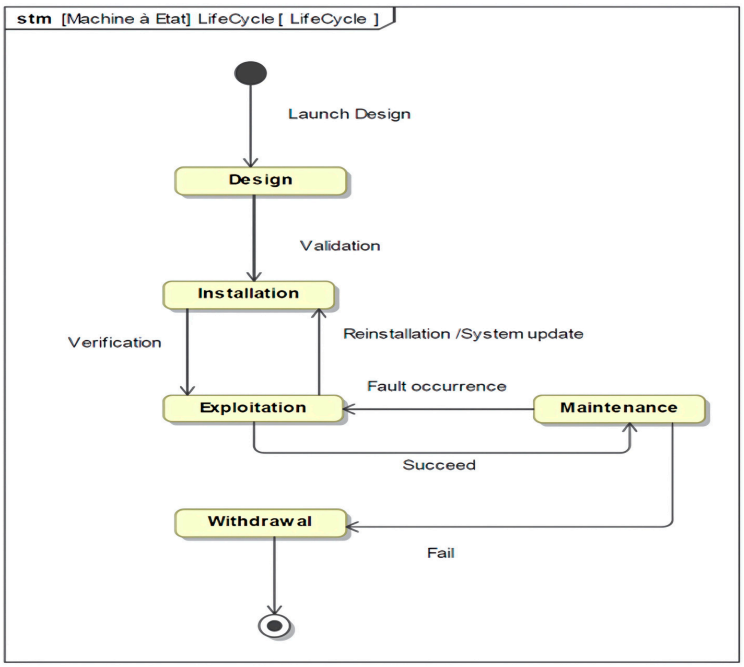


Figure 2. Life cycle diagram of the flocculation-thickening experimental platform.

Table 4. Operational and functional stakeholders' needs.

Lifecycle and Stakeholders	Design	Installation	Exploitation	Maintenance	Withdrawal
Designer	e	e		e	e
End user			e		
Standards	e	e	e	e	e
Maintenance team		e		e	e

The letter "e" in the table represents the participation or active involvement of the stakeholder in the corresponding stage of the lifecycle.

3.3. Flocculation-Thickening Experimental Platform Using MBSE and CESAM Methodologies

This study employs the MBSE grid and CESAM methodologies to address the challenge of designing a flocculation-thickening experimental platform for research and development applications. The system model is constructed using the CAMEO tool (Cameo Systems Modeler 19.0 LTR SP3, Vélizy-Villacoublay, France) and SysML language. The use of MBSE through the CESAM framework and SysML effectively structured the system components while ensuring the traceability of requirements. For instance, integrating the SysML model allowed linking stakeholder needs (such as safety and ease of use) with technical solutions, including the addition of electric brakes and user-friendly interfaces. The initial phase of the system development process is crucial for identifying stakeholder requirements and defining the system's boundaries. This paper focuses on the operational analysis of the System of Interest (SOI) as a foundational step, emphasizing the collection of essential information to align the SOI with its intended objectives. Key activities during this phase include gathering stakeholder requirements, creating a PFMSO diagram (Problem, Finality, Mission, System, and Objectives), delineating system boundaries and external interactions, and defining operational use cases. These steps ensure alignment with stakeholder expectations and provide a comprehensive understanding of the problem domain and system objectives. By clearly defining the system's scope and operational scenarios, this phase establishes a robust groundwork for the subsequent design and development stages.

3.3.1. Defining the System Life Cycle

The practical use cases of the system offer a well-defined framework for identifying the core services it must provide to its users. This step is critical in accurately identifying and defining the requirements of stakeholders. For example, Figure 3 presents the operational use case during the project's exploitation phase, emphasizing the seven primary services the system is designed to deliver to its users. Out of these, six specific services are related to the test bench's functions.

The test bench is designed to provide six essential services that contribute to optimizing the flocculation-thickening process. The first service focuses on testing and comparing the performance of various flocculants in settling suspended solids, enabling a systematic evaluation of their effectiveness. The second service aims to optimize key flocculation parameters, including the dosage of flocculants and settling time, to enhance the efficiency of solid removal. Additionally, the test bench facilitates the analysis of settling characteristics for different types of solids, such as clay, organic matter, and inorganic matter, to support the development of more effective treatment processes. Scaling the flocculation process to industrial levels constitutes the fourth service, ensuring that operations achieve peak efficiency in larger-scale applications. Furthermore, the fifth service establishes the test bench as a quality control tool, enabling the continuous monitoring and assessment of flocculation-thickening performance. Lastly, the sixth service positions the test bench as a research platform, fostering the development of innovative flocculants and advancing the understanding of the underlying mechanisms of flocculation and sedimentation.

These services offer a comprehensive framework for enhancing the overall efficiency and effectiveness of the flocculation-thickening process. In Figure 4, the operational use case diagram shows the interactions between key actors like the end user, system engineer, data acquisition system, and the PLC unit. The diagram highlights the process of adding samples, selecting test scenarios, activating test cycles, and acquiring data. It also demonstrates the automated measurement of sedimentation speed using the camera and data collection through the PLC unit.

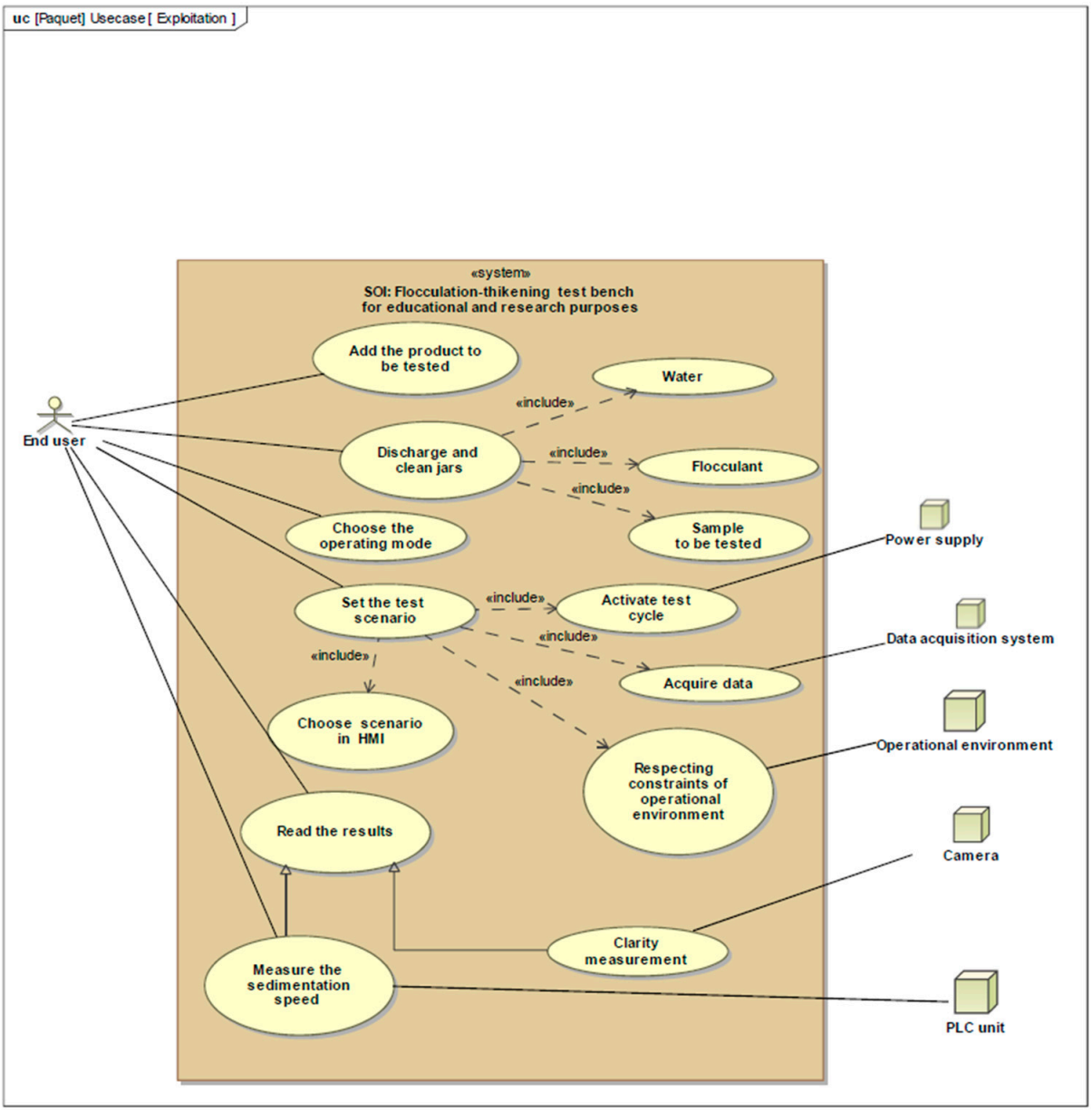


Figure 3. Operational use case diagram of the flocculation-thickening experimental platform.

Figure 4 presents the development use case diagram, illustrating the collaborative roles of the System Engineer, Design Engineer, and Project Manager. The process involves defining system architecture, conducting mechanical and electrical design, and verifying the system's operational compliance.

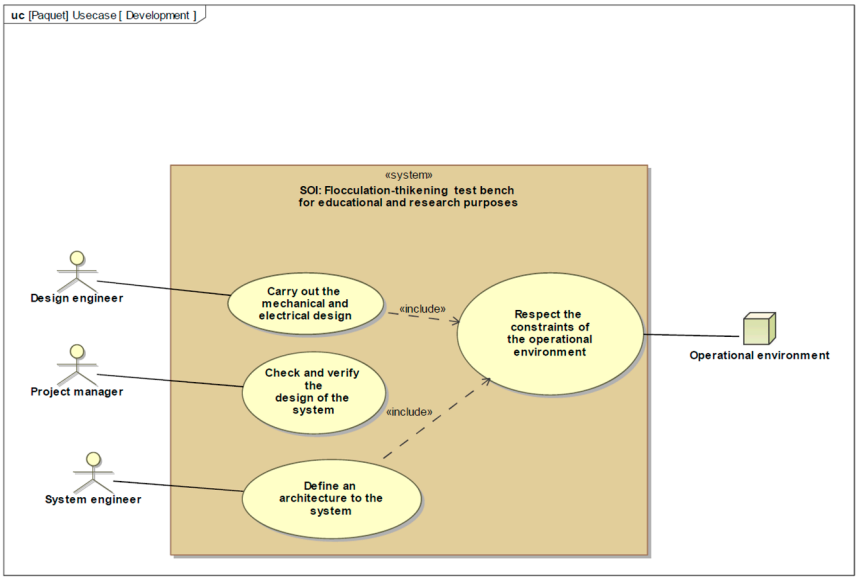


Figure 4. Development use case diagram for the flocculation-thickening experimental platform.

3.3.2. Defining the System Life Cycle

The main goal of this study is to evaluate the system's lifespan while clearly delineating its boundaries and surrounding environment. Figure 5 presents the primary and secondary requirements related to the system of interest (SOI). This requirements diagram serves to formalize the expectations of various stakeholders, both internal and external, concerning the system. It illustrates both functional and non-functional requirements. The purpose of such a diagram is to document these requirements in a way that allows them to be traced to other parts of the model that address them, as well as to the test cases that validate their fulfillment.

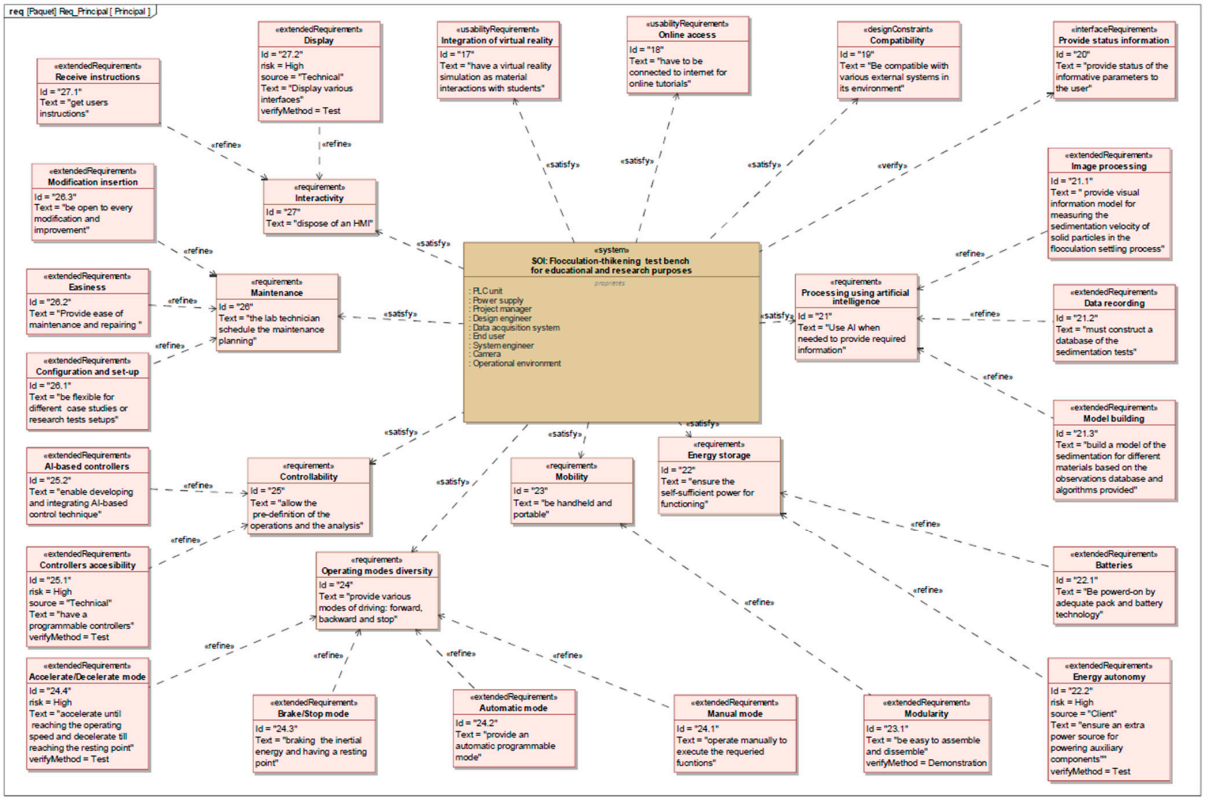


Figure 5. Requirements diagram for the flocculation-thickening test bench.

3.3.3. Defining the System Life Cycle

The system's architecture, illustrated in Figure 6, is composed of various elements, including sensors, control systems, and actuators. This diagram illustrates the interactions between the system's key components, including sensors, the electric motor, and the human–machine interface. Each element is represented to ensure a clear understanding of the data flows and structural relationships within the test bench. The system also includes an electric motor, an emulated load, and a switching mechanism that facilitates the testing of various control strategies. External contributors to the system comprise equipment suppliers, software and hardware providers, regulatory authorities, and academic institutions.

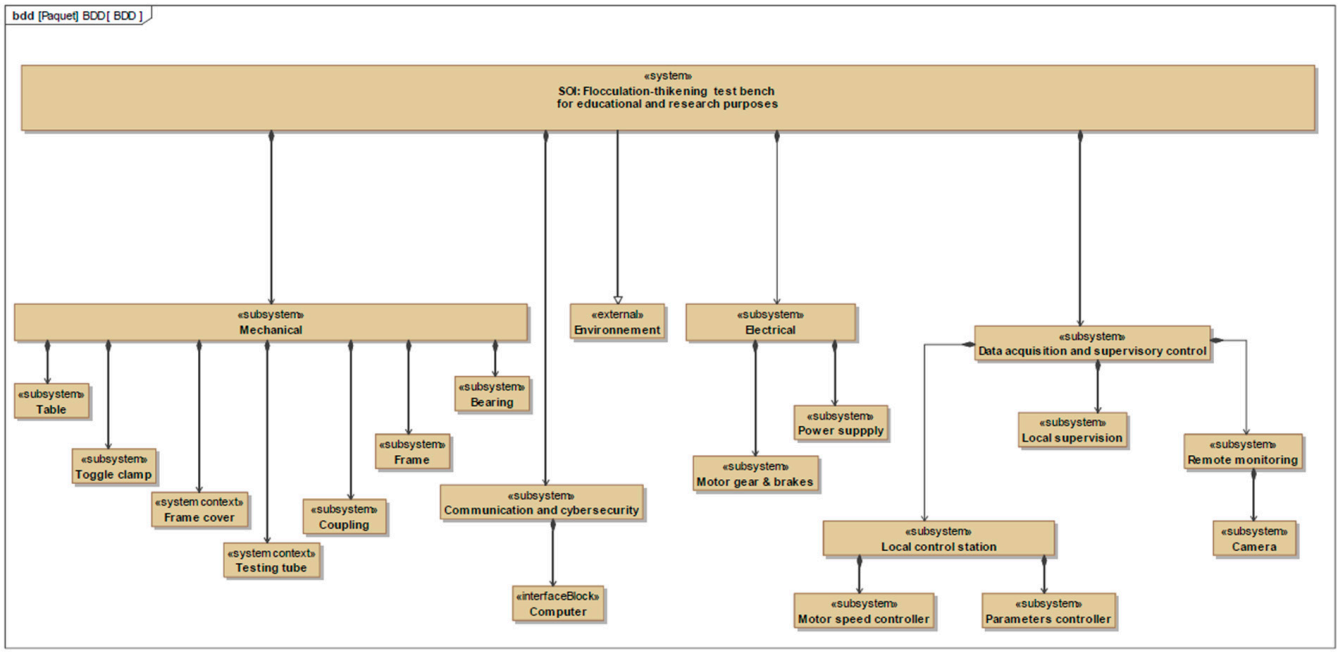


Figure 6. Bloc diagram definition of the proposed system.

4. Design of Proposed System

The flocculation and decantation workbench is designed to serve as a scalable, precise, and user-friendly platform for conducting experiments related to solid–liquid separation processes. This proposed system integrates mechanical, electrical, and control components to optimize the efficiency and accuracy of flocculation and decantation studies, making it suitable for both research and pedagogical purposes.

4.1. Mechanical Design

The mechanical structure of the pilot-scale laboratory workbench is designed to facilitate the study of flocculation and decantation processes through a system that allows the precise manipulation of test parameters. The design was developed using a system engineering approach, ensuring a simple and efficient solution that meets the functional requirements of the experiments. Figure 7 represents the test bench for the study of flocculation and decantation. The designed test bench consists of six test tubes mounted on a rotating frame. The integrated camera enables real-time observation of the decantation process, providing precise visualization of sediment formation.

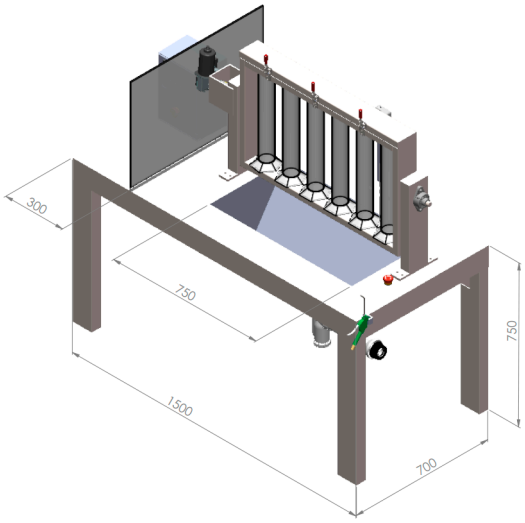


Figure 7. Test bench for laboratory flocculation-thickening process optimization.

Table 5 details the mechanical components of this test bench along with their respective functions, while Figure 8 illustrates the complete system assembly, providing a clear overview of the 3D design. At the core of the mechanical system is a rotating frame that holds six test tubes. This frame is driven by a gear motor equipped with a brake, which ensures controlled and consistent rotation during the mixing of the flocculent with the test substance. The rotation is transmitted via a coupling mechanism and is stabilized by two high-precision bearings, ensuring smooth and reliable operation. The test tubes are secured within the rotating frame using a frame cover, which is designed for easy operation. The cover is connected by hinges and secured with toggle clamps, allowing quick access for loading and unloading samples. These features are critical for minimizing downtime between tests and ensuring a user-friendly interface. Additionally, the workbench incorporates a sink unit and a siphon to assist in draining and evacuating the test tubes after each experiment. A water gun is included in the design for filling and cleaning the tubes, further streamlining the workflow of the testing process. For monitoring purposes, the decantation process is observed using a camera mounted on the workbench. This camera provides real-time visual feedback, allowing for the precise documentation and analysis of the sedimentation process.

Table 5. Components of the system.

ID	Ref	Function	Qty
1	Table		1
2	Frame	Rotates the test tubes	1
3	Frame cover	Closes the opening of the test tubes	1
4	Test tube	Contains the composition to be tested	6
5	Toggle clamp	Easy and fast opening of the frame	3
6	Hinge	Easy and fast opening of the frame	8
7	Gear motor with brake	Rotates the frame	1
8	Coupling	Transmits the rotation	1
9	Bearing		2
10	Camera	Films the decantation process	1
11	Sink unit	Draining/evacuation	1
12	Siphon	Retaining	1
13	Water gun	Filling and cleaning the test tubes	1
14	Protective screen	Made of Plexiglas to protect the electrical cabinet from water	1
15	Electrical cabinet	Contains the control unit and other electrical components	1
16	Human–machine interface	Enters the test parameters, starts the test	1
17	Emergency stop switch		2

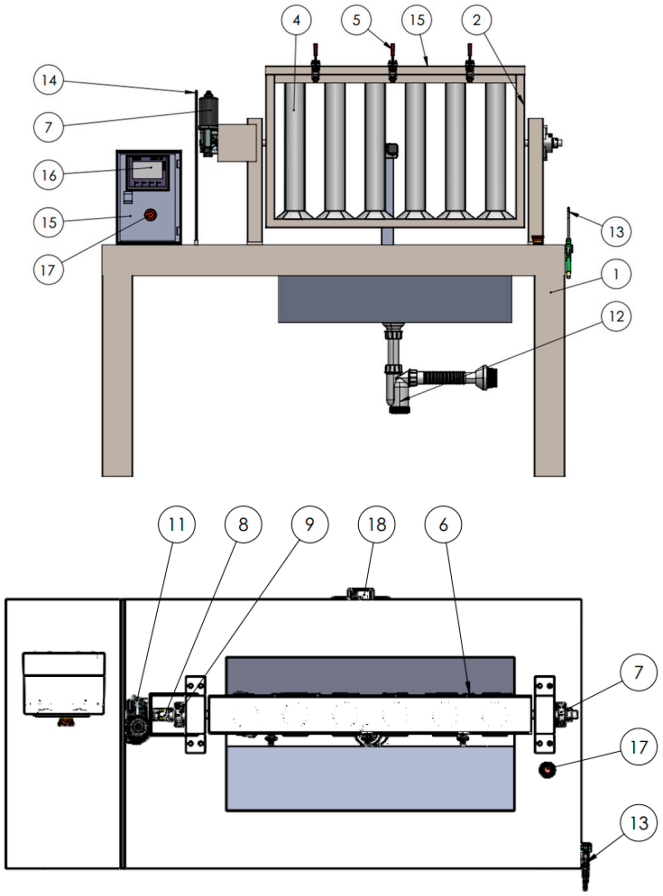


Figure 8. Workbench main components.

To ensure safety and ease of use, the workbench includes an electrical cabinet protected by a Plexiglas screen to guard against water splashes. The cabinet houses the control unit and electrical components, with a human–machine interface (HMI) providing a simple way to input test parameters and initiate experiments. An emergency stop switch is also integrated into the system, providing a safety mechanism to halt the process in case of any malfunction. This mechanical design offers a robust and flexible platform for conducting flocculation and decantation studies, meeting both research and pedagogical needs.

4.2. Electrical Design and Control System Architecture

The electrical design and control system architecture of the pilot-scale laboratory workbench are essential for ensuring the precise operation and control of the flocculation and decantation experiments. This system integrates various components to allow for the safe and efficient management of the mechanical and process functions.

The core of the electrical system is housed within a dedicated electrical cabinet, which contains the control unit and other critical electrical components. This cabinet is protected by a Plexiglas screen, safeguarding the sensitive electronics from water splashes, which is crucial given the nature of experiments involving liquids. The gear motor is electrically driven and provides rotational movement to the frame holding the test tubes. The integrated brake ensures controlled and safe stopping of the rotation when necessary. The motor is connected to the control unit, allowing the system to manage the speed and duration of rotation based on test requirements. A reliable power supply feeds the entire system, ensuring consistent energy delivery to the motor, camera, human–machine interface (HMI), and auxiliary components. Circuit breakers and fuses are installed to protect the system from overload or short circuits, enhancing safety. Two emergency stop switches are

integrated into the electrical design for safety. These switches immediately cut off power to the entire system when activated, ensuring that the workbench can be safely shut down in the event of a malfunction or hazard. The camera, used for monitoring the decantation process, receives its power through a dedicated connection within the electrical cabinet. This ensures a stable power source for consistent video monitoring during the experiment.

The control system of the workbench is managed through a human–machine interface (HMI), which allows the operator to easily input test parameters, monitor the progress of the experiment, and control various aspects of the process. At the heart of the control system is the PLC, which manages the automated functions of the workbench. The PLC is programmed to control the rotation of the frame, adjust the speed of the gear motor, and regulate the timing of the mixing and decantation processes. It also interfaces with the emergency stop switches and other safety features to ensure seamless operation. The HMI serves as the user interface for the operator. It allows for the input of parameters such as rotational speed, the duration of the test, and start/stop controls. The interface is intuitive and designed for ease of use, ensuring that operators can quickly set up and manage tests without complex training. The decantation process is closely monitored by a camera, and additional sensors can be integrated into the system if needed. For example, flow sensors could be added to monitor liquid levels, and pressure sensors could ensure that the system operates within safe limits. Real-time data from the camera and sensors can be fed back to the control system, allowing the operator to make adjustments during the experiment. This closed-loop control ensures that the workbench operates efficiently and that test results are accurate and reliable.

Safety is a critical aspect of control system design. The emergency stop switches provide immediate shutdown capability, and the PLC monitors key operational parameters to prevent overloads or unsafe conditions. The protective screen shields the electrical components from liquid exposure, while the camera allows for visual monitoring without direct interference with the experiment.

5. Conclusions

This study successfully demonstrates the design and implementation of an automated experimental platform for optimizing the flocculation-thickening processes in water treatment, utilizing a Model-Based Systems Engineering (MBSE) approach. By integrating advanced technologies such as PLC programming, sensor systems, and closed-loop control, the bench delivers a highly accurate and efficient platform for studying and optimizing critical parameters in flocculant dosage, mixing speed, and sedimentation time.

The versatility of the test bench allows for the evaluation of various flocculants and their effectiveness in different contexts, offering significant advancements in both research and industrial applications. This is particularly crucial in wastewater treatment where the precise optimization of these processes is necessary to reduce operational costs and improve water quality. Moreover, the test bench provides a scalable solution, making it suitable for both laboratory-scale experiments and larger industrial operations.

Furthermore, the MBSE methodology, incorporating the SysML through the CESAM framework, has proven invaluable in addressing the complexity of system design and ensuring the robust integration of mechanical, electrical, and control elements. The system architecture ensures flexibility and adaptability, enabling researchers to simulate a wide range of operational conditions and gain deeper insights into the underlying mechanisms of flocculation and thickening.

This research opens new perspectives for developing educational and industrial tools in water treatment. In the future, the test bench could be extended to other applications, such as real-time detection of environmental parameters or integration with IoT systems

for remote management. Furthermore, leveraging machine learning to analyze collected data could further enhance the optimization of processes.

The developed test bench stands out as a valuable educational and research tool, offering enhanced capabilities for quality control, process optimization, and the development of innovative water treatment solutions. It represents a critical step forward in advancing sustainable wastewater management technologies by providing an efficient, user-friendly, and scalable platform that can be adapted to diverse operational requirements.

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