PROBLEM-BASED LEARNING WITH VIDEO ANALYSIS: THE CASE OF THE VARIABLE-MASS ATWOOD MACHINE

APRENDIZAJE BASADO EN PROBLEMAS CON ANÁLISIS DE VIDEO: EL CASO DE LA MÁQUINA DE ATWOOD DE MASA VARIABLE

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This study applies Problem-Based Learning (PBL) to teaching advanced mechanics in undergraduate physics, focusing on variable mass systems through the Atwood machine with chains. Using the Hmelo-Silver PBL model, a structured sequence guided students in problem analysis, hypothesis generation, self-directed study, experimentation, and reflection. The case study combined Newtonian and Lagrangian modeling with experimental validation via Tracker video analysis, enabling students to connect theoretical derivations with accessible empirical data. Results showed strong consistency between theoretical predictions and experimental measurements, despite minor discrepancies from chain oscillations, link impacts, and video resolution limitations. The approach demonstrated how low-cost tools can effectively support experimental inquiry in physics education. Beyond content knowledge, PBL fostered research-oriented skills such as autonomous planning, problem-solving, and collaborative inquiry. The proposed framework provides a replicable model for integrating abstract theory with experimental practice, strengthening active learning and advancing the role of inquiry-based methodologies in STEM curricula.

Este estudio aplica el Aprendizaje Basado en Problemas (ABP) a la enseñanza de mecánica avanzada en la física universitaria, centrándose en sistemas de masa variable a través de la máquina de Atwood con cadenas. Utilizando el modelo ABP de Hmelo-Silver, se guió a los estudiantes mediante una secuencia estructurada de análisis del problema, generación de hipótesis, estudio autodirigido, experimentación y reflexión. El estudio de caso combinó el modelado newtoniano y lagrangiano con una validación experimental mediante análisis de video con Tracker. Los resultados mostraron una consistencia entre las predicciones teóricas y las mediciones experimentales, a pesar de pequeñas discrepancias debidas a las oscilaciones de la cadena, impactos entre eslabones y limitaciones en la resolución del video. El enfoque demostró como herramientas de bajo costo pueden apoyar eficazmente la indagación experimental en la enseñanza de la física. Mas allá del conocimiento de contenido, el ABP fomentó habilidades orientadas a la investigación, como la planificación autónoma, la resolución de problemas y la indagación colaborativa. El marco propuesto ofrece un modelo replicable para integrar la teoría abstracta con la practica experimental, fortaleciendo el aprendizaje activo y promoviendo el papel de las metodologías basadas en la indagación en los programas STEM.

Keywords: Teaching methods and strategies (métodos y estrategias de enseñanza), Research in physics education (Investigación en la educación en física), Formalisms in classical mechanics (Formalismos en la mecánica clásica), Problem-based Learning (Aprendizaje basado en problemas); Variable mass systems (Sistemas de masa variable).

I. INTRODUCTION

In the field of educational innovation, Problem-Based Learning (PBL) has become one of the most influential active learning methodologies due to its student-centered design, which fosters meaningful learning through the resolution of real-world problems [1, 2]. PBL promotes the active construction of knowledge, critical thinking, autonomy, and the ability to solve complex challenges in authentic contexts [3, 4]. However, its application has rarely extended to unconventional and demanding topics such as variable mass systems in Physics, which combine theoretical depth with experimental complexity [5, 6]. This gap underscores the potential of PBL to expand its scope into areas of high theoretical significance yet limited classroom use [7, 8].

In recent years, PBL has shifted higher education from lecture-based instruction to collaborative and reflective practices that position students as active agents [9]. It has addressed motivational barriers by integrating gamification into disciplines such as computing and design [10] and has proven especially suitable for STEM fields, where it strengthens engagement, knowledge integration, and soft skills including metacognitive reasoning [11], intrinsically motivated collaboration [12], and real-world problem-solving [13]. In the natural sciences, PBL has been applied to Physics and Mathematics through methods such as PODS (Prediction, Observation, Discussion, and Synthesis), supporting experimental topics like fluid mechanics and electromagnetism [14–16] and cognitive development in mathematical problem-solving [17, 18].

Despite its effectiveness, PBL integration with other emerging methodologies remains limited [19–21]. Challenges include the absence of concrete interdisciplinary STEM models, insufficient teacher training [22], a scarcity of resources for experimental contexts [23], and weak evaluation criteria for learning outcomes [23]. These limitations are particularly evident in Physics and Chemistry, where experimentation is central yet PBL adoption is sporadic. The lack of structured models complicates the design of activities that connect theoretical concepts with laboratory practice, reducing the transformative potential of PBL in these fields [14–16].

The Tracker software has become a powerful and accessible tool for teaching physics, enabling video analysis to obtain precise and low-cost experimental data [24]. In this study, Tracker is employed in the analysis of a variable mass system using an Atwood machine with chains, allowing Newtonian and Lagrangian models to be contrasted with experimentation. This integration promotes active learning and strengthens research competencies in university contexts [25].

This study addresses these limitations by applying a Hmlo-Silver PBL model tailored to university science educators, focusing on variable mass systems. Using the Atwood machine with chains—a low-cost but powerful apparatus—the framework integrates Newtonian and Lagrangian modeling with direct experimentation. Unlike conventional PBL applications, this proposal offers a systematic teaching guide that links rigorous theory with empirical validation.

Students explore how Newton's and Lagrange's formulations complement one another, while experimental verification reinforces critical thinking and research-oriented skills [26,27]. The main contribution is an integrative PBL-based case study that demonstrates how complex mechanics topic's can become accessible and engaging when theory and experimentation are coherently combined. The paper presents the PBL framework (Section II), the case study design (Section III), implementation results (Section IV), discussion (Section V), and conclusions (Section VI).

II. PROBLEM-BASED LEARNING METHODOLOGY

Problem-Based Learning is a student-centered educational methodology in which participants acquire knowledge on a given topic through collaborative group work aimed at solving an open-ended problem. This problem serves as the driving force behind both the motivation and the learning process [28, 29]. According to Norman and Schmidt, PBL is rooted in experiential learning theory, which emphasizes practical experiences during the learning process [30]. Given the nature of the problem-based scenario proposed in this study, the Hmelo-Silver model [27] is an appropriate choice. This model provides a structured framework that enables students not only to investigate and understand a problem but also to apply their knowledge in an experimental context and critically reflect on the outcomes. Table 1 outlines the details of the selected methodology.

Stage	Step	Description
Formulate and Analyze the Problem	**Step 1: Problem Scenario**	Students face a contextualized problematic situation supervised by a tutor, within a group setting, fostering an initial approach to analysis and understanding.
	Step 2: Identify Facts	Students examine the information provided in the scenario to identify relevant data that can help them better understand the problem.
	Step 3: Generate Hypotheses	Based on identified facts, students propose possible explanations or preliminary solutions that will guide the direction of the investigation.
	Step 4: Identify Deficiencies	The group determines areas of knowledge that need reinforcement to advance in solving the problem, identifying gaps in their understanding
Self-Directed Study	**Step 5: Search for New Information**	Students conduct independent research to gather the additional information needed to address the problem in a well-founded manner.
	Step 6: Define Strategies	Using the collected information, the group plans specific strategies and organizes to apply the knowledge in solving the problem.
Application and Evaluation	**Step 7: Apply Knowledge**	Students implement strategies and apply the acquired knowledge to solve the problem, integrating theory and practice.
	Step 8: Discussion and Evaluation	The group analyzes the obtained results, assesses the effectiveness of strategies, and reflects on the process to identify learning and improvement opportunities.
	Step 9: Conclusion	Students summarize their findings, document conclusions, and present their work.

Table 1. Structure of Problem-Based Learning.

III. CASE STUDY

Health Prof. Educ. This case study addresses a realistic and contextualized problem within the framework of analyzing physical systems with variable mass. The situation is designed as a didactic scenario that fosters the development of critical thinking and problem-solving skills, while simultaneously promoting collaborative work and evidence-based decision-making. Furthermore, it encourages active inquiry through the application of the Problem-Based Learning (PBL) methodology, thereby consolidating a formative environment that integrates theory and practice in the construction of scientific knowledge.

III.1. Formulate and Analyze the Problem

III.1.1. Step 1: Problem Scenario

Problematic situation

At one university, faculty members have identified that many upper-level students lack the necessary skills to investigate and plan autonomously when confronted with real-world problems, which limits their ability to apply knowledge in practical contexts. To address these deficiencies from the early semesters, they consider Problem-Based Learning (PBL) as a promising methodology to strengthen these competencies. However, they face challenges due to the lack of detailed case studies that can serve as a guide for its implementation. In this context, you and your group are required to propose a case study that serves as a reference for both teachers and students, focused on the analysis of variable mass systems—a scarcely addressed topic—using PBL together with the Tracker video analysis tool as a pedagogical strategy.

When addressing the problem situation, interesting and challenging aspects can be identified that guide the case study approach. the case study approach can be identified.

Interesting: The application of variable mass systems in physics, since it is a topic that is not often addressed and seems to offer a direct connection with real situations such as the design of rockets or advanced mechanical systems.

Challenging: Integrating a pedagogical approach such as PBL with a technical subject, as it requires understanding both physical concepts and designing a case study that is effective for other students

III.1.2. Step 2: Identify the facts

In this stage, a preliminary search for information relevant to the problem scenario is conducted, with the purpose of establishing a theoretical and contextual framework to support the subsequent analysis.

The objective is to identify relevant data that will serve as a basis for a deeper and more accurate understanding of the situation presented. This process allows distinguishing between hard facts and assumptions, thus facilitating the formulation of key general and specific questions and the identification of areas that require further investigation.

Guiding Questions for the Initial Exploration

1. In what real-world situations are variable mass systems studied?
2. What physical principles govern the behavior of variable mass systems?
3. What experimental system to implement to study variable mass systems using accessible resources and free software for data collection and analysis?

III.1.3. Step 3: Generate hypotheses

The following hypotheses address different aspects of the problem and seek to guide the development of the research.

Hypotheses

1. Analyzing a case study on variable mass systems using PBL will improve research and autonomous planning skills when facing real-world problems.
2. The use of the video analyzer will allow obtaining data consistent with Newtonian and Lagrangian theory applied to a variable mass system, demonstrating its viability as an educational tool.

III.1.4. Step 4: Identify deficiencies

In Table 2, knowledge gaps are identified, detailing prior knowledge and the knowledge that needs to be reinforced to address the problem.

Knowledge area	Previous knowledge	Knowledge to be reinforced
Physics	Exercises of systems with constant mass.	Exercises of systems with variable mass.
Mathematics	Fundamentals of differential and integral calculus.	Ignorance of the Lagrange equation.
Research	Basic information search.	Planned search process.
TICs in education	Use of homemade components to perform experiments.	Use a video analyzer for experimental analysis.

Table 2. Knowledge gaps: prior knowledge and knowledge to be reinforced

III.2. Self-Directed Study

III.2.1. Step 5: Search for new information

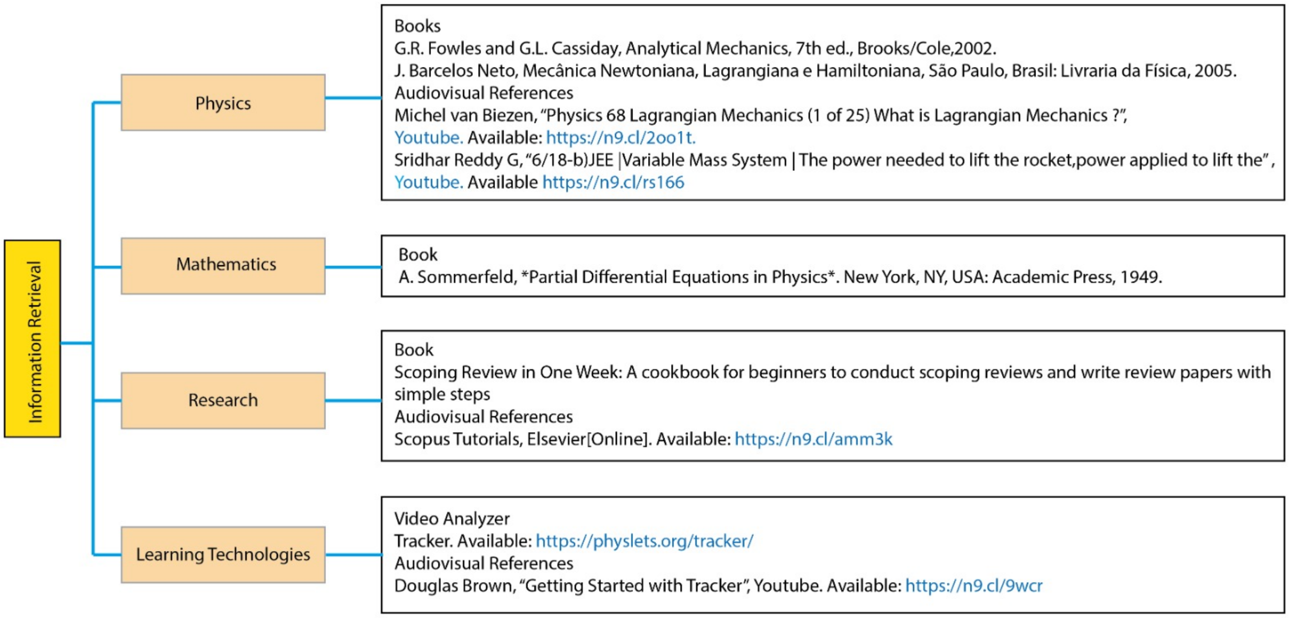

Figure 1. Resources consulted to strengthen the problem analysis.

To strengthen the problem analysis, specialized resources on Lagrangian formalism and differential calculus were consulted to address the weakness identified in step 4 of the PBL process. Additionally, an academic database search was conducted on the use of Problem-Based Learning in physics education. Finally, tutorials on the Tracker video analyzer were reviewed to enhance the acquisition and processing of position and velocity data. The organization of the most relevant resources is presented in Figure 1.

III.2.2. Step 6: Definition of strategies

At this stage, based on the information collected, the concrete strategy was planned (Figure 2). This stage is crucial, as it establishes the foundation for practical implementation.

IV. RESULTS

IV.1. Step 7: Apply New Knowledge

At this stage, we put into practice the acquisition of new knowledge gained during the planning and research process.

IV.1.1. Experimental setup

The system consists of a pulley fixed to the wall, through which an inextensible wire passes. One end of the wire holds a block m hanging vertically, while the other end is connected to a chain of mass M and length L.

Ascent of the chain: the chain is fully coiled on the ground, connected to the string at one end (Figure 3(a)). When the system is released, the block descends under the action of gravity, which causes the chain to begin to lift off the ground. As the chain rises, the effective mass acting on the system increases progressively, modifying the dynamic conditions.

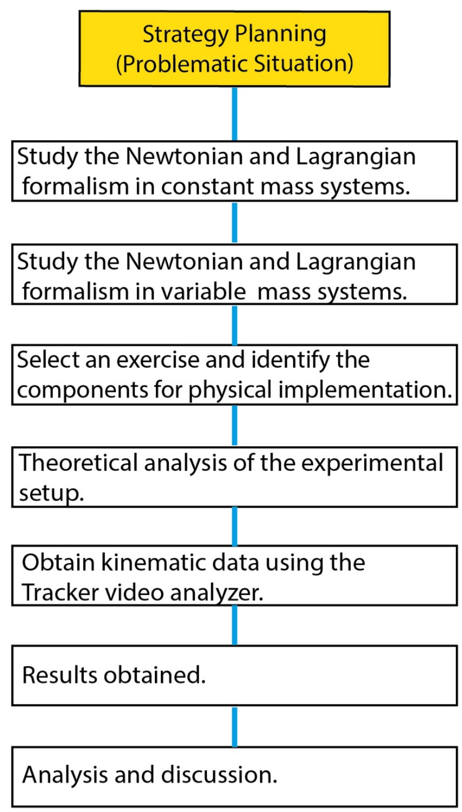

Figure 2. Strategy planning diagram.

Chain descent: initially, the chain hangs vertically from one end of the string, while the block hangs from the other end (Figure

3(b)). When the system is released, the chain begins to slide downward due to gravitational force, while the block ascends. In this case, the effective mass of the moving system varies continuously as the length of the suspended chain changes with time.

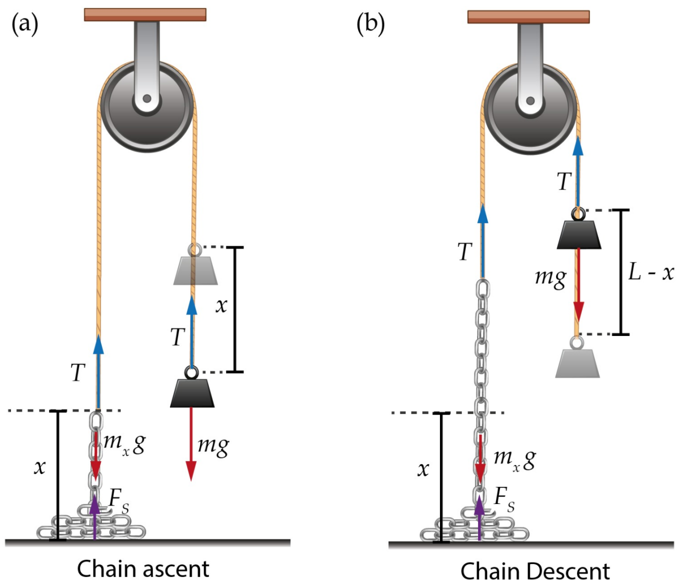

Figure 3. Illustration of the system with variable mass.

For the theoretical analysis, the system is modeled under several assumptions:

- The inertia of the pulley and the friction of its shafts are negligible.
- The mass of the yarn is negligible, and it lacks elastic properties.
- The influence of air resistance is ignored.
- Both the chain and the rope have a constant mass density along their length.
- The experiment is conducted in one dimension, meaning oscillations of the rope or the chain, as well as any effects, are not considered.

In both situations, the behavior of the kinematic quantities of one end of the chain will be studied. Instruments and materials used in the implementation of the experiment is shown in Figure 4.

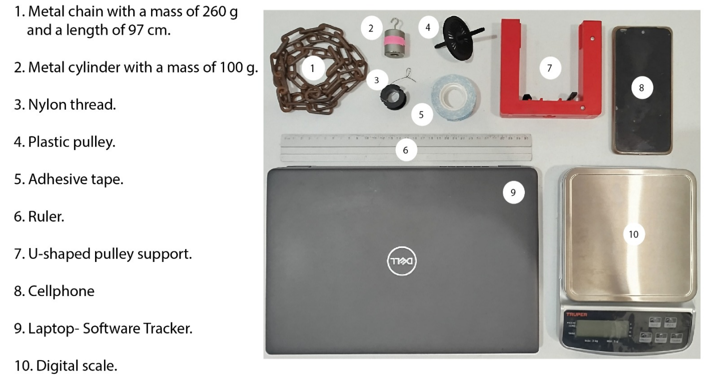

Figure 4. Instruments and materials used in the implementation of the experiment.

IV.1.2. *Acquisition of kinematic parameters*

For data measurement, the open-source software Tracker was used, which allows for the precise analysis of the chain's position and velocity as functions of time (Figure 5).

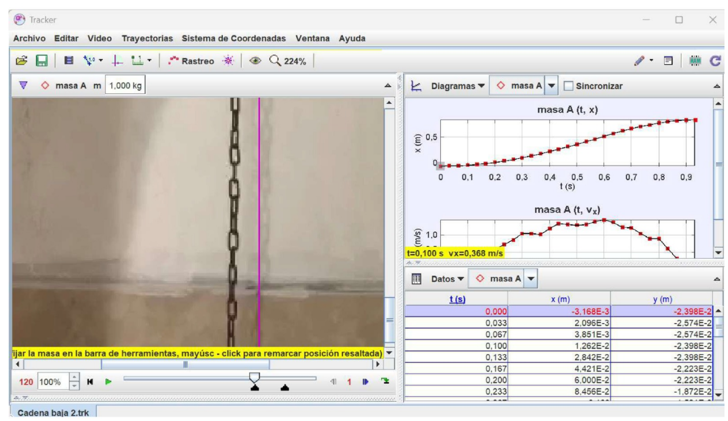

Figure 5. Tracker software interface.

IV.1.3. *Theoretical analysis*

At the ascent of the chain, From the free body diagram (Figure 5a) for the hanging block m, we obtain the dynamic equation:

$$mg - T = m\frac{dv}{dt} \tag{1}$$

According to the momentum and quantity of motion theorem, the net force F_{net} acting on the chain is equal to the rate of change of its quantity of motion $m_x v$, where the upward mass is equal to $m_x = Mx/L$:

$$F_{net} = \frac{dp}{dt} = \frac{d(m_x v)}{dt}$$

$$T - \frac{M}{L}xg = \frac{M}{L}v^2 + \frac{M}{L}v\frac{dv}{dt} \tag{2}$$

Eliminating the tension T from the system of equations and expressing the nonlinear differential equation in terms of the position, we have:

$$\frac{d^2x}{dt^2} = \frac{1}{\left(\frac{m}{M}L + x\right)}\left[\left(\frac{m}{M}L - x\right)g - \left(\frac{dx}{dt}\right)^2\right],$$

$$t = 0, x = 0, \frac{dx}{dt} = 0 \tag{3}$$

Equation (3) shows how the distance traveled varies as a function of time. It is possible to express the velocity as a function of chain height by rewriting (3) in terms of the velocity:

$$\frac{dv}{dt} = \frac{1}{\left(\frac{m}{M}L + x\right)}\left[\left(\frac{m}{M}L - x\right)g - (v)^2\right] \tag{4}$$

$$\frac{dv}{dt} = \frac{dx}{dt}\frac{dv}{dt} = \frac{1}{2}\frac{dv^2}{dx}$$

$$\left(\frac{m}{M}L + x\right)^2\frac{dv^2}{dx} + 2\left(\frac{m}{M}L + x\right)v^2 = 2\left(\frac{m}{M}L + x\right)\left(\frac{m}{M}L - x\right)g \tag{5}$$

By changing the variable $z^2 = \left(\frac{m}{M}L + x\right)^2 v^2$ and integrating, we obtain:

$$\int_0^z dz'^2 = 2g\int_0^x \left[\left(\frac{m}{M}L\right)^2 - (x')^2\right]dx'$$

$$z^2 = 2g\left[\left(\frac{m}{M}L\right)^2 x - \frac{x^3}{3}\right]$$

$$v^2 = 2g \cdot \frac{\left(\frac{m}{M}L\right)^2 x - \frac{x^3}{3}}{\left(\frac{m}{M}L + x\right)^2} \tag{6}$$

We notice that when the block stops, the chain rises at $x = \sqrt{3}\frac{m}{M}L$.

At chain descent, as Figure 3(b), a similar analysis to the case of the ascent ($v < 0$) is performed for the block.

$$mg - T = m\frac{dv}{dt} \tag{7}$$

During the fall, the ground applies a force to stop the chain links. At a time dt, a mass dm whose velocity is v, collides inelastically with the ground, causing a decrease in linear momentum. Therefore, the ground force will be:

$$F_s = v\frac{dm}{dt} = \frac{M}{L}v^2 \tag{8}$$

The new force F_{net} acting on the chain is equal to the rate of change of its quantity of motion $m_x v$.

$$F_{\text{net}} = \frac{dp}{dt} = \frac{d(m_x v)}{dt}$$

$$T - \frac{M}{L}xg + \frac{M}{L}v^2 = \frac{M}{L}v^2 + \frac{M}{L}x\frac{dv}{dt} \tag{9}$$

Eliminating the stress T from the system of equations and expressing the differential equation in terms of the position, we have:

$$\frac{d^2x}{dt^2} = \left[\frac{\frac{m}{M}L - x}{\frac{m}{M}L + x}\right]g, \quad t = 0,\ x = L,\ \frac{dx}{dt} = 0 \tag{10}$$

By solving equation (9) by numerical methods we obtain the distance traveled as a function of time of the highest link in the chain. Using (4) we rewrite the equation in terms of the distance-dependent velocity.

$$\frac{dv^2}{dx} = 2\left[\frac{\frac{m}{M}L - x}{\frac{m}{M}L + x}\right]g$$

We integrate,

$$\int_0^{v^2} dv'^2 = 2g\int_L^x \left[\frac{\frac{m}{M}L - x'}{\frac{m}{M}L + x'}\right]dx'$$

$$v^2 = 2\left[L - x + 2\frac{mL}{M}\ln\left(\frac{\frac{mL}{M} + x}{\frac{mL}{M} + L}\right)\right]g \tag{11}$$

From the Lagrangian perspective the dynamics of the masses is determined by equation (11), where the difference between the kinetic energy T and the potential U energy defines the Lagrangian ($\mathcal{L} = T - U$) of the system and Q_x represents the external non-conservative forces.

$$\frac{d}{dt}\frac{\partial\mathcal{L}}{\partial\dot{x}} = \frac{\partial\mathcal{L}}{\partial x} + Q_x \tag{12}$$

The energy and force expressions for the variable mass system are:

$$T = \frac{1}{2}m\dot{x}^2 + \frac{1}{2}\left(\frac{M}{L}x\right)\dot{x}^2$$

$$U = -mgx + \frac{1}{2}\left(\frac{M}{L}\right)gx^2$$

$$\mathcal{L} = \frac{1}{2}m\dot{x}^2 + \frac{1}{2}\left(\frac{M}{L}x\right)\dot{x}^2 + mgx - \frac{1}{2}\left(\frac{M}{L}\right)gx^2 \tag{13}$$

Developing each term of (12), we have,

$$\frac{\partial \mathcal{L}}{\partial x} = \frac{1}{2}\frac{M}{L}\dot{x}^2 + mg - \frac{M}{L}gx$$
$$\frac{\partial \mathcal{L}}{\partial \dot{x}} = \left(m + \frac{M}{L}x\right)\dot{x}$$
$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{x}} = m\ddot{x} + \frac{M}{L}\dot{x}^2 + \frac{M}{L}x\ddot{x}$$

Applying the Lagrangian for variable mass systems is not very usual and care must be taken with the analysis of Q_x to maintain the result using the Newtonian formalism. The derivative $\partial\mathcal{L}/\partial x$ contains a term that depends on $\dot{x}$, so we must consider the average linear momentum loss due to mass change. Therefore:

$$Q_x = -\frac{1}{2}\frac{dm}{dt}\dot{x} = -\frac{1}{2}\frac{d}{dt}\left(\frac{M}{L}x\right)\dot{x} = -\frac{1}{2}\frac{M}{L}\dot{x}^2$$

$$\left(m + \frac{M}{L}x\right)\ddot{x} + \frac{M}{L}(\dot{x})^2 = \frac{1}{2}\frac{M}{L}\dot{x}^2 + \left(m - \frac{M}{L}x\right)g - \frac{1}{2}\frac{M}{L}\dot{x}^2 \qquad (14)$$

By multiplying equation (14) by Health Prof. Educ.L/M, equation (3) is obtained. This shows that both approaches are effective in analyzing the dynamics of the problem.

IV.1.4. Experimental Results

Tracksuber software was used to record the velocity and position data as a function of time for the assembly in Figure 5. During the experiments, the variations in the velocity and position of the block while the chain was ascending (Figure 6) and during the descent (Figure 7) were analyzed. In addition, a graph of velocity as a function of position was obtained, which made it possible to observe the relationship between both magnitudes throughout the movement. To validate the experimental results, mathematical analyses were performed using the Newtonian and Lagrangian approaches, from which the corresponding theoretical equations were derived. These equations were compared with the experimentally obtained data, evidencing the consistency between the theoretical models and the measurements obtained with Tracker.

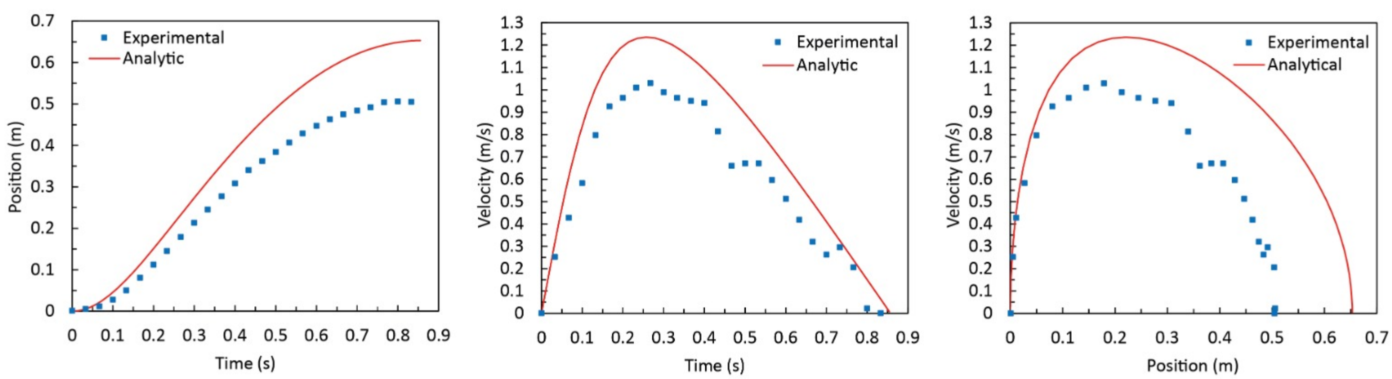

Figure 6. Experimental results obtained with Tracker (experimental) and the theoretical equations (analytical) for the motion of an Atwood's machine system with the chain in ascent.

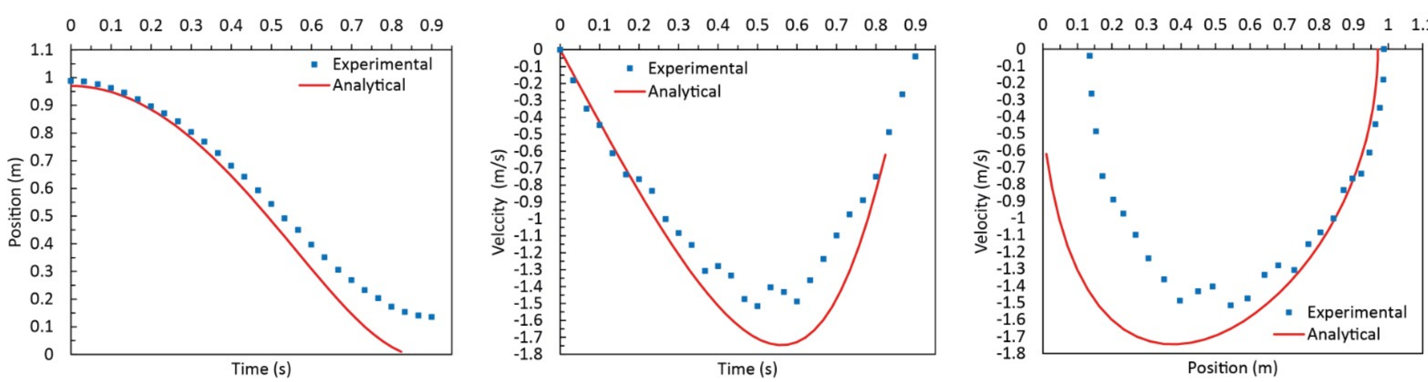

Figure 7. Experimental results obtained with Tracker (experimental) and the theoretical equations (analytical) for the motion of an Atwood machine system with the chain in descent.

V. DISCUSION

V.1. *Step 8: Discussion, evaluation and limitations*

Problem-Based Learning (PBL) has been consolidated as an effective methodology to improve physics teaching [31], highlighting its ability to promote critical thinking, problem solving, and the connection between theoretical concepts and practical situations [32]. However, its implementation continues to pose a challenge for many teachers, as it requires careful preparation in designing relevant problems and facilitating learning without compromising student autonomy [33, 34]. In this context, the present article was developed with the purpose of providing a practical guide to help teachers implement PBL effectively in their courses. This guide not only assists educators in overcoming the inherent difficulties of this methodology but also offers students a clear structure of activities and deliverables for each stage of the process [35, 36]. In doing so, the aim is to optimize learning outcomes and foster a comprehensive and collaborative educational experience.

In the results for the variable mass system, a comparison between experimental measurements and theoretical predictions is observed for the ascent and descent of the chain. In the ascent (Figure 7), the position and velocity plots show a general trend that closely follows the theoretical predictions, although the experimental data show a slight discrepancy, especially in the initial phase of the motion. As time progresses, both position and velocity show a larger discrepancy compared to the theoretical, implying energy loss. The main factor for this discrepancy is that the mathematical model does not consider the undulations of the chain during the ascent, while the friction in the pulley has a negligible contribution. In the descent (Figure 7), the graphs show a better agreement between the experimental and theoretical results in terms of the shape of the curves. However, the experimental velocity presents a more pronounced deceleration than the theoretical one, which is attributed to the absence of undulations in the chain during its descent. Another influencing factor is the impact of the links during the fall, which is considered mathematically, but even so, a loss of energy is observed that is not contemplated in the model. Therefore, the results confirmed hypothesis 2, since it was evidenced that the use of the Tracker video analyzer, with the support of a cell phone, captures in a good way the behavior of the movement and its statistical analysis. In addition, it stands out as an excellent educational tool, since it does not require the acquisition of commercial kits, allowing students to perform experiments in an accessible and economical way.

Among the main limitations identified, one of the most significant was the use of a mobile phone with a capture rate of 30 frames per second (fps) for experimental analysis. This configuration limits the accuracy of the Tracker software in tracking the motion of the chain, particularly in phases that require more detailed data. It is recommended to use devices with higher resolution or high-speed cameras to improve precision in future experiments. Another limitation identified was the lack of bibliographic material that thoroughly addresses the analysis of variable mass systems using the Lagrangian approach. Although numerous resources develop Lagrangian analysis for constant mass systems, a significant gap was observed in specific information regarding its application to variable mass systems, both in textbooks and in the reviewed articles and videos.

VI. CONCLUSION

VI.1. *Step 9: Conclusions*

This study demonstrates that applying a structured Problem-Based Learning (PBL) model to variable mass systems provides an effective framework for linking academic training with research practices. Using the Atwood machine with chains as a case study, the proposal shows how integrating theory and experimentation strengthens critical thinking, research skills, and the communication of results. Consequently, this approach stands as a practical guide for both instructors and students, contributing to the expansion of PBL in university physics education.

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