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A Model-Based Constructivist Approach for Bridging Qualitative and Quantitative Aspects in Teaching and Learning the First Law of Thermodynamics

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Abstract
Teaching and learning introductory thermodynamics has drawn considerable research attention over the last two decades, especially in several disciplines of higher education. Under particular investigation is the First Law of Thermodynamics (FLT), which offers an expression of energy conservation in thermodynamic systems, as the evidence shows that students struggle with this fundamental principle. At the upper secondary education level, existing research on this issue is rather limited. This study is concerned with the above, presenting epistemological and cognitive perspectives on the FLT and, based on these, proposes a constructivist approach for its teaching and learning. We place a special focus on the meaningful bridging between thermodynamic processes and a suitable constructivist model (Energy Chain Model) that can accurately describe the mathematical expressions of the First Law. To accomplish this, we implemented a teaching and learning sequence (12 45-min lessons) in the second year of the upper secondary school (ages 16–17). A significant part of the sequence (six lessons in 2 weeks) employed a model-based educational simulation (Ideal Gas Educational Simulation), which was designed and developed for this particular purpose. In this study ($N = 19$), the results indicated gradual improvement in students' representations of thermodynamic processes, wherein they were able to more accurately describe these processes in terms of energy chains and mathematical expressions of the First Law. Some barriers that students could not seamlessly bypass were detected, which are in line with the findings of the existing literature for tertiary education students.

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1 Introduction

Over the past two decades, a growing body of research in the field of thermodynamics has shed light on several deficiencies of student understanding regarding the most prominent principles of the field, particularly the First Law of Thermodynamics (FLT) (e.g., Georgiou & Sharma, 2015; Kautz et al., 2005a, b; Leinonen et al., 2009; Meli et al., 2016). In the contexts of physics, engineering, and chemistry, this law is considered fundamental enough to be taught during early university years or even in upper secondary school (Christiansen & Rump, 2008).

As Zemansky (1937, p. 50) states in the first edition of his seminal textbook *Heat and Thermodynamics*, the FLT is "the principle of conservation of energy applied to a thermodynamic system and its surroundings." In the FLT, only three energy concepts are taken into account: heat (Q), work (W), and change in internal energy (ΔU). As a mathematical expression, the FLT can be presented as follows (e.g., Çengel & Boles, 2011, p. 73; Planck, 1903, p. 43; Zemansky & Dittman, 1997, p. 79):

$$\Delta U = Q + W$$

The above mathematical formalism is not considered especially difficult and students demonstrate the capacity to easily reproduce it. However, accurate mathematical expressions do not necessarily reflect a qualitative understanding of the described phenomena, nor do they reflect a meaningful comprehension of the theory that generates the formulae (Kautz, et al., 2005a, b). Additionally, students hang on to their intuitive linear causal reasoning and project alternative frameworks of the FLT that can be related to energy or not, thus forming a distorted picture of the respective phenomena and theory in their understanding (Rozier & Viennot, 1991).

We suggest that a constructivist instructional approach of introductory thermodynamics can address these issues and lead students towards a more substantial understanding of the FLT. In this respect, we employ an intermediary constructivist model, the Energy Chain Model (ECM), and explore how it affects upper secondary school students' representations of the FLT. Through the operationalization of the ECM for various thermodynamic processes, we aim to improve, on the one hand, these students' qualitative and semi-quantitative representations, and, on the other hand, their quantitative and mathematical expressions for the thermodynamic systems under study. Most importantly, we hypothesize that the ECM can efficiently guide students towards meaningful connections between the observed phenomena and their formalistic interpretations.

For the development and application of the ECM, we take into consideration students' prior knowledge of introductory classical thermodynamics (Section 2.1), while focusing on the development of instruction across the interrelated levels of theory, models (with emphasis on the ECM), and phenomena (Section 2.2). For the integration of the model in our instruction, we employ a simulation (IGasES: Ideal Gas Educational Simulation), developed rather recently (Energy in Education Group, 2017) (Section 2.3). We use this tool as a key component of a teaching and learning sequence used in the second year of upper secondary school (16–17-year-old students) in Greece. As mentioned above, our main goal is to examine if and how the ECM facilitated students in constructing solid representations of the FLT that reflect a sufficient level of understanding of both qualitative and quantitative aspects of the Law (Section 2.4). We describe the research methods used in terms of research sample (Section 3.1), implementation of the research (Section 3.2), research strategy (Section 3.3), data collection and classification (Section 3.4), data analysis (Section 3.5), and methodological limitations (Section 3.6). We present qualitative and quantitative results regarding students' graphical energy representations (energy chains) (Section 4.1), mathematical expressions (FLT formulae) (Section 4.2), and their correlations (Section 4.3). We discuss our results in light of the existing related literature (Section 5). In this context, we indicate possible implications and future directions for this educational research field (Section 6).

2 Theoretical Framework

2.1 Students' Representations of the First Law of Thermodynamics

Students' representations regarding introductory thermodynamics have been under investigation since the 1980s and active interest on this subject continues up to this day across different scientific disciplines. While research conducted up to the 2000s focused on the understanding of basic concepts, such as heat and temperature (e.g., Arnold & Millar, 1994; Erickson, 1979; Kesidou & Duit, 1993), recent literature engages in more advanced topics, such as the Ideal Gas Law and Laws of Thermodynamics (Kautz et al., 2005a, b; Leinonen et al., 2009, 2015; Meli et al., 2016). This more recent research focuses on reasoning patterns and conceptual frameworks that arise during the negotiation of thermodynamics problems by upper secondary school students (e.g., Meli et al., 2016) and first- and second-year university students (e.g., Kautz et al., 2005a, b; Leinonen et al., 2009, 2015). These populations have a common denominator when it comes to thermodynamics because the content of the courses is similar and students' reasoning trails are comparable (Rozier & Viennot, 1991; Tiberghien, 1994).

Students demonstrate a variety of representations regarding the FLT, which can be classified as energy-related, pre-energy, and non-energy representations. Within the first energy-related class, students offer many alternative frameworks that connect mainly with the energy concepts included in the FLT and these concepts' role in the qualitative and quantitative interpretation of the Law. The explanations provided within the second and the third class, of pre-energy and non-energy representations respectively, are surprisingly homogenous and work complementarily, or instead of an energy-related representation of the FLT. For the sum of the invalid representations, we can underpin linear causal reasoning as the common thread that leads to different types of "simplifications" through omission or misuse of the variables involved in the tasks.

2.1.1 Students' Linear Causal Reasoning

Students' alternative frameworks for the FLT find common ground in the reasoning pattern that gives rise to them. According to Walton (1990, p. 404), "*reasoning* can be defined generally as a sequence of steps from some points (premises) to other points (conclusions)." Linear causality is a reasoning pattern reflecting the most basic form of connecting a cause to a result. Because of its simplicity, linear causal reasoning is commonly deployed by students in the first and secondary years of tertiary education as the justification of their answers (Tiberghien et al., 1995). In the context of linear causality, a change in a variable considered to be "independent" corresponds directly to a change in a variable perceived as "dependent." While this reasoning pattern is sufficient for pre-school and primary education students (Delegkos & Koliopoulos, 2018; Koliopoulos, 2012), it is often inefficient for the more complex tasks that older students usually deal with, as in these cases, causes can more frequently lead to a chain of events that connect in linear and/or nonlinear ways (Halbwachs, 1971).

In a study explicitly focused on linear causality in thermal physics, Rozier and Viennot (1991) note that university students deploy this reasoning pattern at large and consequently "simplify" the given tasks by (a) neglecting variables, (b) using preferential relations between two variables, and/or (c) ignoring the symmetry between variables. These conclusions agree with more recent research findings in university (e.g. Kautz et al., 2005a, b; Leinonen et al., 2012) and upper secondary school students (e.g., Meli et al., 2016).

2.1.2 Students' Energy-Related Alternative Frameworks for the First Law of Thermodynamics

Linear causal reasoning and the consequent misuse of the energy concepts used in the FLT as variables are evident in students' interpretations even within the alternative energy-related framework, which approximates scientifically acceptable explanations. Research reveals students' difficulties with heat, work, and change in internal energy, namely the three energy concepts that compose the FLT. These energy concepts are often a source of confusion (Millar, 2014), as students have a problem differentiating between the two sides of the same (energy) coin: (a) heat and work as the "only ways in which a system may interact with its surroundings" and (b) change in internal energy that takes place in the system "only by virtue of an interaction with the surroundings" (Zemansky, 1937, pp. 46–47). In addition, these terms have colloquial counterparts; therefore, students may attempt to conceptualize them through personal experience rather than within the context of thermodynamics.

Heat is probably the most problematic concept for students, among the three under discussion. Students often consider it to be a property of the system rather than an energy concept that depends on the system's interactions with its surroundings (Meltzer, 2004, 2007; van Roon et al., 1994). This representation may foster a "conservation of heat" perception that could interfere with the establishment of the concept of energy conservation through the FLT. Students' handling of the concept of heat as if it was a property of the system affirms the longstanding research on the thin line between heat and temperature (Arnold & Millar, 1994; Erickson, 1979; Johnstone et al., 1977; Kesidou & Duit, 1993). Heat is very often interchangeable with temperature or, at least, is in a privileged relationship with temperature. Problems with adiabatic and isobaric processes even reveal that students consider this relationship exclusive: heat transfer means a change in temperature and vice versa. Thus, a relationship between change in internal energy and temperature difference is, to a great extent, out of the picture (Kautz et al., 2005a, b; Leinonen et al., 2009, 2013; Meltzer, 2004; Meli et al., 2016).

Students also perceive work as a property of the system, interchangeably with the ill-perceived "property" of heat (Hadfield & Wieman, 2010; Meltzer, 2004; van Roon et al., 1994). Therefore, they also ignore it during adiabatic processes, as a transfer of heat seems, to them, to be a more plausible cause for the change in internal energy within the system (Loverude et al., 2002; Meltzer, 2004). According to van Roon et al. (1994), their students were eager to accept the conversion of heat to work and vice versa, completely dismissing the change in internal energy in non-isothermal processes. Once again, conservation of energy, as expressed through the FLT, may be threatened by the adoption of an alternative "conservation principle:" the heat-work equilibrium. A different issue with work concerns its "direction," namely its transfer from the system to the surroundings or the opposite (Greenbowe & Meltzer, 2003; Leinonen et al., 2013; Moore, 1993). Difficulty in determining the "direction" of work results in incorrect algebraic values in the FLT. The calculation outcome changes and, therefore, students may draw inaccurate conclusions regarding changes in the quantity of other energy concepts as well (e.g., increase or decrease in internal energy).

As a principle, energy conservation involves complex representations that present a challenge for young students (Herrmann-Abell & DeBoer, 2014, 2018), and they usually fail in using it as a tool for the prediction of simple physical phenomena. Kautz et al. (2005a, b) highlight that the correct application of the FLT formula does not always reflect an accurate interpretation of the related phenomena. In fact, some researchers support that the concept of energy conservation cannot settle before certain stages of cognitive development (Liu & Collard, 2005; Liu & McKeough, 2005; Neumann et al., 2013).

2.1.3 Students' Pre-energy and Non-energy Alternative Frameworks for the First Law of Thermodynamics

Pre-energy explanations are mostly related to students' personal experiences and therefore they depend on students' age. In the case of thermodynamic systems, students may perceive energy as a quantity that can be stored in an object, work as a fuel-like source, and/or flow as fluid between objects (Duit, 2014; Lemeignan & Weil-Barais, 1994; Koliopoulos & Ravanis, 2001). These naïve representations of energy distribution can be seamlessly apprehended through linear causal reasoning patterns.

For the complex concept of energy conservation, pre-energy explanations may be displaced or hindered by non-energy explanations which can offer a more amenable, yet insufficient, understanding of the FLT. The most common alternative frameworks reported in the literature relate to the ideal gas law and microscopic/chemical models (Kautz et al., 2005a, b; Leinonen et al., 2009, 2012, 2013; Loverude et al., 2002; Meltzer, 2004; Meli et al., 2016). These alternative frameworks can stand alone in students' explanations of thermodynamic phenomena; however, they often coexist with each other, or with energy-related frameworks of the FLT.

Although ideal gas law can offer accurate results for many thermodynamic phenomena, it cannot describe adiabatic processes, and therefore does not have the universal power of the FLT. Linear causality thrives in this context, as the change in one state variable directly influences another. Both upper secondary and university students find ideal gas law very appealing, and they prefer dealing with state variables (temperature, volume, and pressure) than with energy concepts in describing thermodynamic processes, consequently neglecting the fact that this law does not apply to all cases (Kautz, et al., 2005a, b; Leinonen et al., 2009, 2012, 2013; Loverude et al., 2002; Meli et al., 2016).

Students also deploy micro-level and chemical frameworks as "ultimate" explanations for the changes a thermodynamic system undergoes. Although such explanations can be accurate, students can hardly master them because of the vast amount of embedded non-linear causalities in these theories. As a result, students offer an inefficient microscopic interpretation of the related phenomena with noteworthy misuse of variables (Kautz et al., 2005a, b; Leinonen et al., 2009, 2012, 2013; Meltzer, 2004; Meli et al., 2016).

Lastly, there is a framework that appears to a great extent in the secondary school student population, although it has not been reported for university students. This framework includes phenomenological or tautological explanations, that are more descriptive rather than interpretive of the phenomenon (Meli et al., 2016).

2.2 A Constructivist Approach for the First Law of Thermodynamics

The above frameworks may reflect the results of the traditional instructional approaches that are usually deployed in both secondary and tertiary education. From an epistemological perspective, these approaches follow the direction given by standard general physics textbooks (i.e., Young & Freedman, 2012). In such textbooks, the ideal gas law and the kinetic theory of gases are introduced long before the FLT, thus undermining the explanatory power of the latter (Leinonen et al., 2009; Meli et al., 2016). In addition, work, heat, and the energy conservation principle are first presented in the context of mechanics and are particularly resistant to re-conceptualization. Finally, different physics frameworks are constantly mixed in these traditional contexts, with the most prevailing among them being the entanglement between macroscopic and microscopic explanations (Meli & Koliopoulos, 2019b). From a cognitive point of view, traditional approaches do not take into consideration students' alternative frameworks or the limitations occurring through the extensive use of linear causal reasoning. From a pedagogical perspective, in addition to the juxtaposition of different frameworks, a heavy load of mathematical expressions with limited qualitative explanations, empirical-experimental methodological approaches, and limited use of cultural features determine traditional physics instruction (Koliopoulos et al., 2011).

Contrary to the elements of the traditional approach mentioned above, constructivist approaches put students at the center of instruction. Students' representations are organically integrated into each lesson: they have a significant impact on the formation of educational goals and on the design of teaching and learning sequences. There is a specific need for this particular focus on students' representations, since the latter usually are distant from the scientifically accepted sequences, especially when complex notions are involved, such as the FLT as an expression of energy conservation. It is necessary for students to understand both the qualitative and the quantitative aspects of the energy concepts involved and the conservation principle efficiently, so that they can seamlessly "move" from the phenomena to the formulae (theory) and vice versa (Tiberghien et al., 2009).

To establish an accurate and meaningful interplay between all three levels and make the transitions from one to the other possible, material situations (phenomena or experiments) and theory should communicate through proper models that work as links between the two levels (Tiberghien et al., 1995). Modeling is a standard procedure for physicists when they want to interpret or predict phenomenological (or experimental facts): they don't directly apply the theory to the situation at hand, but instead, use models as intermediaries. Respectively, students construct models too, in order to connect the (perceived) material situation and theory, in an attempt to form interpretations or predictions (Tiberghien, 1994). "Learning by modeling" results in a profound comprehension of the content, the practices, and the problem-solving requirements (Seel, 2014).

One key difference between the expert and the novice learner is that while the theory and the model level are quite distinctive for the former, this is not always the case for the latter: as far as the student is concerned, there are abundant model components that derive directly from the respective theory, and are therefore only vaguely differentiated (Tiberghien et al., 2009). This is particularly true for semi-quantitative models proposed to students in order for them to interpret energy-related material situations, such as the thermodynamic processes examined in the scope of the FLT where specific mathematical formalism is involved. In these cases, the theory-model levels should directly correspond to the phenomenological level so students can immediately link the observed objects and events with the models reflecting the theory, i.e., the mathematical expression of energy conservation. Therefore, this three-level approach has the potential to minimize the "gap" that traditionally occurs in learning between material situations and physical quantities, including their relationships, and their meaning within a physics context (Tiberghien, 1994).

2.2.1 Theory Level

Theory plays an important role in constructing accurate representations of our natural and technological environment. In the context of physics, classical thermodynamics suggests a generic energy theory that communicates the differentiation between energy concepts, as well as specifies the conditions and limits of their quantitative changes during natural phenomena and technical processes. It is a macroscopic theory, independent of the system's specifics and the properties of matter (Baehr, 1973; Zemansky & Dittman, 1997). At the end of the nineteenth century, statistical thermodynamics extended the grounded theory by examining the microscopic properties of thermodynamic systems (i.e., Dalarsson et al., 2011). At the core of thermodynamics is the concept of the system. A system can be defined as "a quantity of matter or a region in space chosen for study" (Çengel & Boles, 2011, p. 10), which is in line with the definition of systems usually adopted in K-12 science education (e.g., Fortus et al., 2019; Papadouris & Constantinou, 2016). With respect to the FLT, systems can vividly illustrate the different energy concepts and properties involved, which may be tangled in a linear or nonlinear way.

The FLT constitutes an expression of energy conservation within thermodynamic systems (and beyond), and it is recognized as a powerful tool for the analysis of the operations that take place in these systems. From a historiographic epistemological perspective, scientists' need to decipher the function of the primitive steam engine (Cardwell, 1971; García, 1987; Kuhn, 1977) and establish a theory that would lead to the improvement of the engine's efficiency was a decisive factor that led to the emergence of the FLT (Meli & Koliopoulos, 2019b). Therefore, the FLT reflects the energy conservation within a system and, at the same time, the changes that each of the involved energy concepts undergoes.

As mentioned in the Introduction, the FLT is usually mathematically expressed as (e.g., Çengel & Boles, 2011, p. 73; Planck, 1903, p. 43; Zemansky & Dittman, 1997, p. 79):

$$\Delta U = Q + W,$$

where ΔU is the change in internal energy (U) of the system, Q is the heat entering or leaving the system, and W is the work done on or by the system (resulting in the change of internal energy). All energy concepts included in the FLT, as physical quantities of energy are usually measured or calculated in Joules (J). In reference to the signs of the suggested FLT formula, we accept that work is positive if done *on* the system and negative if done *by* the system. In this case, the sign of heat follows the same convention.[1]

[1] The alternative mathematical expression of the FLT (e.g., Young & Freedman, 2012, p. 630) is $Q = \Delta U + W$. In this case, work is positive if done by the system and negative if done on the system, while the sign of heat follows the opposite convention.

In the introduction and manipulation of the energy concepts involved in the FLT, most higher education physics textbooks (reference knowledge) operationalize a "forms-based" language (Fortus et al., 2019, p. 1343), identifying different forms of energy. This approach appears to be efficient for expert communication and tertiary education, and even for younger students' understanding of certain energy aspects. However, its effectiveness on secondary school students' accurate energy conservation representations has been called into question (Doménech et al., 2007; Fortus et al., 2019; Nordine et al., 2011) on the grounds that it can distort their conception of energy as a unified concept. Our aim is to introduce a scientifically accurate (reference knowledge), yet pedagogically efficient (school knowledge), theory for the teaching and learning of the FLT as an expression of energy conservation in secondary education. Therefore, we argue alongside Millar (2014, p. 196) that the teaching of energy "should exercise some care over the use of labels for 'forms' or 'types' of energy, restricting these to the different ways in which energy can be stored, and separating these from the different ways in which energy can be transferred from one store to another." In this respect, we take the perspectives of (a) heat and work as the only two ways in which energy can be *transferred* to the system from the surroundings or vice versa, and (b) change in internal energy as the only way energy can be *stored* in the system by virtue of an energy transfer (Millar, 2014; Tiberghien, 1996).

2.2.2 Model Level

In the interpretation of thermodynamic processes, proper model-based constructions precede the direct application of the relevant theory. According to Tiberghien (1994, p. 74), "models consist of qualitative and quantitative functional relations (implying mathematical formalisms) between physical quantities in order to represent the selected aspects of a set of material situations." Models should be properly chosen in order to facilitate coherence between the phenomenological level and the theory that describes the phenomena. Depending on their purpose, models used in physics teaching and learning can be pragmatic, constructivist (Seel, 2014), or both.

The prime aspect of modeling concerns the epistemological features of the model as a reductive representation of reality; this dimension is defined by Seel (2014, pp. 466–467) as a "pragmatic" approach. This approach suggests that the model originates from reality, but it only preserves specific characteristics in accordance with its purposes (Seel, 2014); namely, this refers to creating a "model of" something (Gouvea & Passmore, 2017, p. 51). It is important for students to understand that certain elements of the model have been excluded or modified (Greca et al., 2014). This aspect of a model is significant for the teaching process, as it integrates the appropriate selection of a real situation, the meticulous reduction of its features, and the preservation of those features that should be highlighted, all with regard to the learning goals that nurtured the construction of the pragmatic model in the first place. It should be noted that pragmatic models can be either qualitative or quantitative: qualitative pragmatic models refer to the selected representation of objects and events, while quantitative pragmatic models refer to the mathematical expressions of the targeted theory (Seel, 2014; Meli & Koliopoulos, 2019a).

A "constructivist" approach addresses the explanatory function of the model (Seel, 2014, pp. 466–467). This aspect of models mainly corresponds to the constructed conceptual model that provides accuracy, consistency, and completeness to the natural or technological situation at hand. A satisfactory conceptual model serves the following goals: (a) allows predictions that are in line with the consequent observations, (b) solves problems and offers explanations regarding the phenomena under consideration, and (c) addresses some of the limitations embedded in pre-scientific explanations (Tiberghien, 1996).

We are particularly interested in constructivist models that show the potential to efficiently bridge the gap between qualitative pragmatic models and quantitative pragmatic models. Graphical representations in the form of diagrams that support an energy-based illustration and interpretation of phenomena can take on this role (Kubsch et al., 2020), especially if they adopt a semi-quantitative perspective that explicitly aims for a gradual "quantification" or "mathematization" (Gray et al., 2019, pp. 010129-5) of the implicated energy concepts. Such semi-quantitative graphical representations spring from their respective qualitative representations; in other words, basic symbols and rules emerge out of a qualitative representation, enhancing the model with semi-quantitative elements.

In order to develop a qualitative and semi-quantitative constructivist model that is appropriate for interpreting thermodynamic processes in terms of energy, we use most of the qualitative elements included in the ECM (Cornuéjols et al., 2000; Devi et al., 1996; Lemeignan & Weil-Barais, 1994; Megalakaki & Tiberghien, 2011; Tiberghien, 1996; Tiberghien & Megalakaki, 1995). On the energy chain, all rectangles symbolize the respective reservoirs included in the system, namely the phenomenological (or experimental) field elements that can store energy. An arrow symbolizes an energy transfer between two reservoirs. In addition to the properties of energy storage and transfer, the ECM implies energy conservation since "a complete energy chain starts and ends with a reservoir" and "the initial reservoir is different from the final reservoir" (Megalakaki & Tiberghien, 2011, p. 181).

We have taken some additional steps in order for the ECM to more effectively serve the interplay between the qualitative and quantitative aspects of energy conservation in thermodynamic processes. These enhancements aim for quantification and mathematization of the energy stored or transferred within the ECM. On the one hand, changing energy quantities, that increase or decrease respectively are represented within each rectangle and are also conserved overall. On the other hand, the mathematical symbols of heat and work (for energy transfer) and change in internal energy (for energy storage) make their appearance at the end of each process in their respective place, so all three energy concepts involved in the FLT are clearly indicated within the model.

Taking the above adjustments into account, from an epistemological perspective the ECM offers a qualitative and semi-quantitative constructivist model for the distribution of energy within a system; it restores a dialectical relationship between qualitative and quantitative pragmatic modeling, which facilitates bridging the material situation with meaningful mathematical expressions (Shen et al., 2014). On the one hand, the ECM can provide essential information on the energy concepts playing a role in the phenomenon. On the other hand, it supports the formation of preliminary hypotheses on the quantitative perspective of these energy concepts during the evolution of the thermodynamic process and on the mathematical relations that link them as physical quantities.

To elaborate on the pedagogical characteristics of the ECM that are consistent with our approach, energy chains offer a foundation for the understanding of the conceptual model, as, within it, energy storage and transfer are explicitly represented, while the conservation of energy is also implied. This model supports the idea that students' understanding of energy concepts takes place in an interwoven way, namely that "students make progress by understanding aspects of multiple and interrelated energy concepts at the same time, not by mastering one concept before moving on to the next" (Herrmann-Abell & DeBoer, 2018, p. 70). Additionally, it takes into account the linear causal reasoning that comes naturally to students, while also challenging linear causality by exposing occurring nonlinearities in energy distribution (Rozier & Viennot, 1991; Tiberghien et al., 1995).

In the pertinent literature, one can find alternative qualitative and semi-quantitative graphical energy representations that are, more or less, compatible with the ECM version we employ. For example, Energy Tracking Diagrams (Scherr, Close, Close, et al., 2012, Scherr et al., 2016) present a forms-based approach within which energy is "being conserved, localized, and changing form" (Scherr et al., 2016, p. 96) and also illustrate the "energy flow" between the different system objects. Within the forms-based perspective of energy, one can find models that specifically aim to represent the energy flow throughout a system. Semi-quantitative energy flow diagrams that are similar to the famous *Sankey diagrams* (Kennedy & Sankey, 1898) represent energy as arrows that stem from a set of sources and reach a set of destinations, wherein the amount of transferred energy is relative to the width of each arrow (Hobson, 2004; Scherr, Close, McKagan, et al., 2012). Such models explicitly illustrate the properties of energy conservation, transfer, and transformation. Fortus et al. (2019) introduce the semi-quantitative Energy Transfer Model that is characterized by a transfer-only perspective of energy. In contrast to the forms-based, the transfer-only perspective "does not distinguish between different forms of energy but instead treats energy as a unitary entity" (Fortus et al., 2019, p. 1346). Energy is always transferred from one system to another, therefore both conservation and transfer are implied as energy properties, while transformation is not. In a version presented by Nordine et al. (2018), the model includes Sankey-like arrows of different thicknesses to illustrate the relative amounts of energy being transferred.

2.2.3 Phenomenological Level

The phenomenological level of thermodynamics refers to natural or technological situations that correspond to the respective theoretical field. It includes events, instruments, and measurements (for experiments) or indications (for phenomena observations) (Tiberghien, 1994). The phenomenological field should be relevant to what students usually face, and it should not raise technical challenges. Also, it should not be especially simple, in order for it to cause a "cognitive need" to the audience; namely, it should bring up issues that are impossible for students to solve using their pre-existing knowledge (Devi et al., 1996).

In studying energy conservation through the focal point of the FLT, a broad phenomenological field is that of thermal engines (Cochran & Heron, 2006) and, in particular, steam engines. Focusing on thermodynamic systems and processes, the steam engine motor can serve as an excellent phenomenological field that works either as an autonomous thermodynamic system or as a subsystem that is part of the larger engine system. The motor has an isomorphic analogous with the simple representation of a piston in a cylinder filled with an ideal gas (thermodynamic system under investigation), thus facilitating the didactic transposition (Chevallard, 1985; Christiansen & Rump, 2008) from the engineering reference knowledge to physics school knowledge.

2.3 Model-Based Simulation for the First Law of Thermodynamics: IGasES

Educational technologies, and simulations, in particular, took up the challenge for accurate conceptual knowledge of introductory thermodynamics. Some examples include virtual labs (i.e., PhET, Thermolab) and the representations of natural or technological systems with flexible variables for the user to insert values and export graphs (i.e., Physlets). Although these simulations seem to positively contribute to the teaching and learning of physics (Cox et al., 2003; Finkelstein et al., 2005; Lefkos et al., 2011; Wieman & Perkins, 2006), they usually render a fundamental epistemological issue: the conflation of classical and statistical thermodynamics, mainly through the statistical interpretation of the macroscopic aspects of phenomena. This juxtaposition of different conceptual models is regularly embedded in traditional approaches (Koliopoulos et al., 2011) and results in questionable reality reduction outcomes.

The pedagogical features of the simulations mentioned above notably undermine qualitative pragmatic modeling while focusing on quantitative pragmatic modeling, without the intermediation of proper qualitative and semi-quantitative constructivist models. Additionally, carefully pre-selected digital lab equipment can prompt the novice learner to behavioral practices (Chen, 2010). Finally, these simulations seem to neglect students' linear causal reasoning in that their design does not consider students' existing reasoning patterns, nor the need for them to meaningfully overcome these patterns when they fail to interpret a phenomenon (Chinn & Malhotra, 2002).

In order to avoid the issues that existing computational simulations raise and to utilize the elements of the previously described constructivist approach for teaching and learning the FLT, we developed the IGasES (Ideal Gas Educational Simulation). The main purpose of the IGasES is the meaningful connection between the two aspects of pragmatic modeling (qualitative and quantitative) with the use of constructivist modeling. More explicitly, it attempts to bridge the processes that occur within a simple thermodynamic system (phenomenon) with the mathematical expression of the FLT for a given process (theory), through the use of the ECM as the proper intermediate model. Design principles, layout, and use of the IGasES are described in detail in Meli & Koliopoulos (2019a).

The qualitative pragmatic model embedded in the IGasES corresponds to the graphic representation of a piston with an attached mass that can freely move through a cylinder filled with an ideal gas. There is the option to select between isothermal, isochoric, isobaric, and adiabatic processes, with expansion/compression and heating/cooling regarding what is possible for the selected process. There are indications of change in the volume, pressure, and temperature of the gas, without specific numbers, since the purpose, in this case, is the qualitative representation of the phenomenon and not the conduction of an experiment. Qualitative pragmatic models should precede quantitative pragmatic models, since the first constitute a transparent knowledge form (Tiberghien et al., 1995), while the latter can be very challenging for the students (Bing & Redish, 2009; Meli, Zacharos, et al., 2016). Nevertheless, the IGasES integrates quantitative pragmatic models in the form of the mathematical expression of the FLT, which changes with respect to each process. However, the "screen" that includes the FLT formula is optional: namely, it does not appear when the simulation launches (Fig. 1), but it can be presented later on (Fig. 2). Numerical data for quantitative validation of the FLT can be inserted as optional.

Qualitative and quantitative pragmatic models can connect given that the constructivist model works as a mediator between them. In the IGasES, the ECM works as the constructivist model that attempts to meaningfully link the illustrated phenomenon with the corresponding mathematical expression of the FLT. The energy chain is presented dynamically and simultaneously with the phenomenon (Fig. 3). As soon as the phenomenon concludes, the energy chain isolates the components that play a role in the given process, which includes only the system and the implicated surroundings. It is additionally enriched with the mathematical symbols that represent the energy concepts of the FLT. Therefore, the ECM embedded on IGasES is in touch with both phenomenon (thermodynamic process)

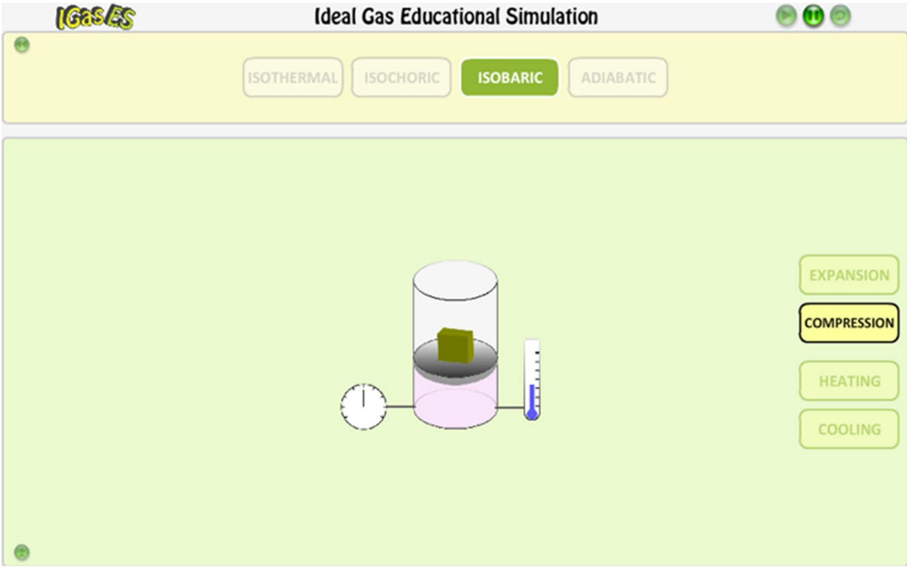


Fig. 1 Screenshot of IGasES during an isobaric compression

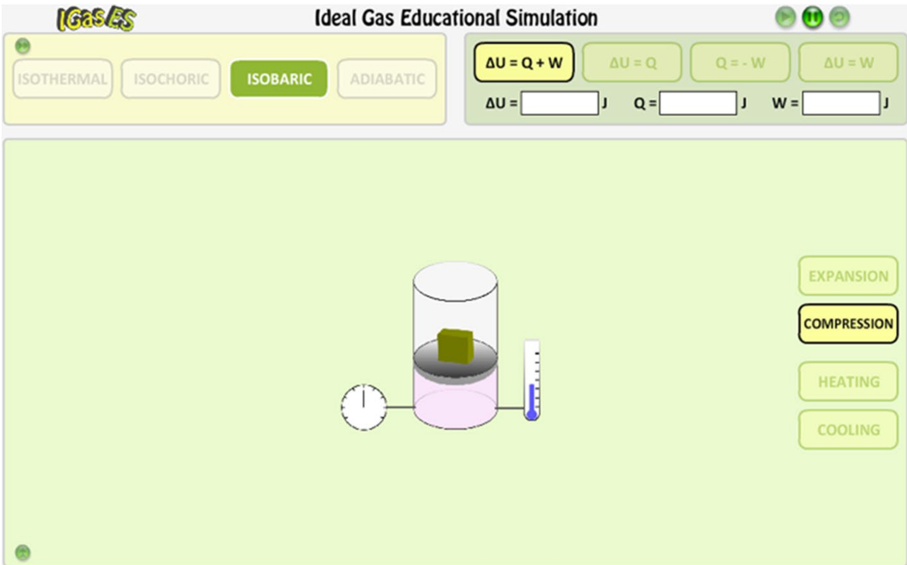


Fig. 2 Screenshot of IGasES during an isobaric compression with the additional appearance of the FLT "screen"

and theory (FLT) simultaneously, thus creating a solid connection between them that can attribute meaning to both levels.

The specific choice of a computational simulation as an educational tool for implementing some basic features of the constructivist approach (mainly the

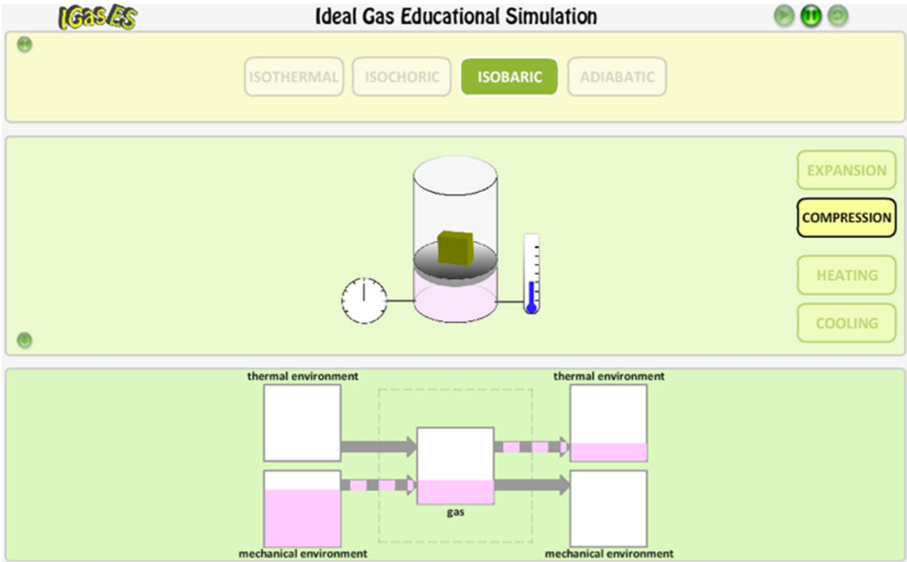


Fig. 3 Screenshot of IGasES during an isobaric compression with the appearance of the ECM "screen"

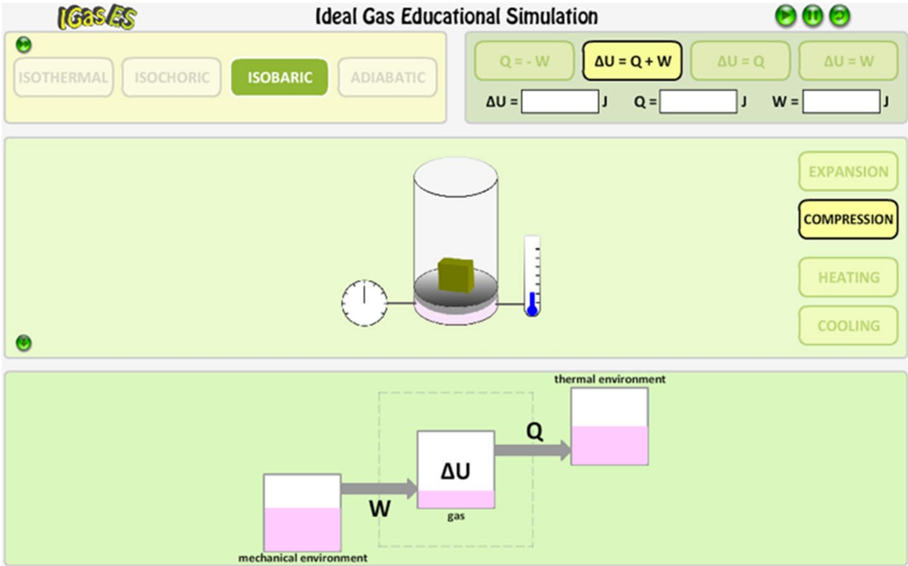


Fig. 4 Screenshot of IGasES by the end of an isobaric compression with all "screens" on

phenomenon-model-theory triplet) is related to its power to seamlessly integrate all the targeted levels of the FLT. The conflation of both pragmatic and constructivist models within a moderately interactive environment is facilitated by the uncomplicated manipulation of these multi-level representations (Greca et al., 2014). Additionally, the dynamically evolving phenomena and their respective energy chains capture the essence of thermodynamics, which is focused on the changes that a system undergoes during a process, rather than on the mere depiction of its initial and final states. Figure 4 presents all “screens” of IGasES open at the same time.

2.4 Research Questions

This research seeks to investigate if and to what extent the use of a model-based simulation, which embeds specific features of the constructivist approach, can help upper secondary school students construct meaningful connections between thermodynamic processes and the respective mathematical expressions of the FLT that accurately describe the phenomena. Our main hypothesis suggests that, when followed by proper constructivist models, the use of qualitative pragmatic models, which represent phenomena from the field of introductory thermodynamics can efficiently lead students towards the accepted scientific theory reflected by the use of correct formulae. In our case, we especially want to test the power of the ECM as the intermediate constructivist model. We integrate the above features in a “tailor-made” simulation (IGasES), as a proper educational technology tool that can accommodate the dynamic nature of thermodynamic processes and models, as well as the need to present the different levels gradually and by choice. Taking the above considerations into account, our research questions are the following:

1. How does the operationalization of the ECM affect students’ qualitative/semi-quantitative graphical representations (energy chains) of thermodynamic processes?
2. How does the operationalization of the ECM affect students’ quantitative/mathematical expressions (FLT formula) of thermodynamic processes?
3. How does the operationalization of the ECM affect the connections students make between graphical energy representations and mathematical expressions of thermodynamic processes?

3 Methods

3.1 Research Sample

The research sample consisted of a maximum of 19 students (8 females and 11 males) and a minimum of 16. All students were between 16 and 17 years old, attending the second year of upper high school in a private school in Athens (Greece). In the Greek national curriculum, students of this age choose between a science-math focus and a humanities-language focus in addition to their common core courses. The students in the sample made up one class out of the four that were in the science-math group. This class was chosen conveniently, as it was assigned to one of the researchers for the instruction of physics. Although the sample was convenient, at the same time its students were placed within it randomly, as the only criterion for being put into this particular class (instead of the other three) was the alphabetical order of students’ last names. Additionally, although they chose this particular focus, some of them did not have a particular preference for physics.

Although students had gone through four consecutive years of physics instruction, they did not have systematic teaching and learning experiences in reference to thermodynamics up to the period of this study. In previous classes, they had limited physics lessons for temperature and heat, as well as chemistry lessons for the ideal gas law. Therefore, students’ prior knowledge of the field under investigation can be considered rather negligible and does not threaten the validity of the research.

3.2 Implementation of the Research

The IGasES was used as a key component of a constructivist teaching and learning sequence for introductory thermodynamics. Educational simulations should be supported by teaching and learning materials that allow educators to seamlessly integrate the respective technological tool into their instruction (Smetana & Bell, 2012). In this study, the sequence was implemented during normal class meetings, in line with the content suggested by the official national curriculum. Nevertheless, a different didactic transposition was used under the scope of the constructivist approach, with its main characteristics being: (a) at the theory level, the presentation of merely macroscopic thermodynamics elements to introduce the FLT (Meli & Koliopoulos, 2019b); (b) at the phenomenological level, the deployment of Newcomen's steam engine and the thermodynamic processes taking place in its motor; (c) at the model level, the extensive use of the ECM embedded in the IGasES to bridge phenomena with theory. As mentioned before in the respective paragraph (2.3), the structure of IGasES also supports this three-level approach.

The design of the teaching and learning sequence was research-based and informed by (a) the epistemology of macroscopic thermodynamics, in the context of historical and textbook analysis; (b) students' cognitive capacity for dealing with energy concepts and properties; (c) pedagogical approaches of the field, based mostly on the comparison between traditional and constructivist instruction (Meli & Koliopoulos, 2019c). Instruction included three broad sections (BS), which were divided into 12 subsections (SS). An outline of the sequence is presented in Table 1. The first broad section worked as an introduction to Newcomen's steam engine and its motor as a thermodynamic system. Taking this engine as a point of reference, the concepts of the thermodynamic system and the energy chain were introduced. The second broad section elaborated on the thermodynamic processes (isothermal, isobaric, and adiabatic) that play a role in the function of the engine's motor and presented the FLT. The final broad section served as an opportunity to synthesize lessons taught on thermodynamic processes in the cyclic process of the motor, and for a short introduction to engines' thermal efficiency. In the table, the "activity problem" column describes the issue students attempted to address throughout each subsection. The "conceptual components" column refers to the thermodynamic concepts and processes that were introduced in a subsection. Finally, the "conceptual negotiation" column mentions the representations that students were expected to construct during the instruction of the subsection. A detailed description of the teaching and learning sequence can be found in Meli & Koliopoulos (2019c).

The IGasES was used during the second section, which included six lessons and lasted three weeks. Each lesson corresponded to a one 45-min teaching period. All lessons had a generally common flow. As a first step, a video of a phenomenon of the pertinent thermodynamic process was presented. Secondly, a worksheet was given to students which asked them to describe the phenomenon and give an example of an energy chain they thought fit. Afterward, the modeled phenomenon was presented in the IGasES, followed by its energy chain; at this point, there was a discussion about the differences between students' graphical representations and the one given by the simulation. Finally, students were asked to give the Mathematical expression, based on the energy chain, again followed

Table 1 Outline of the teaching and learning sequence

	Activity problem	Conceptual components	Conceptual negotiation
BS1	Thermal engines and thermodynamic explanation		
SS01	What is a thermal engine and how does it work?	Structure/function of Newcomen engine	Activation of pre-energy conceptions Qualitative representation of energy distribution Semi-quantitative energy distribution Introduction to the ECM
SS02	How can we explain the function of the Newcomen engine in terms of energy?	Work and heat	
SS03	How does the Newcomen motor work?	Thermodynamic system and surroundings	
BS2	Gas processes and the first law of thermodynamics		
SS04	Why did an ignition take place in the tube?	Adiabatic compression/ Change in internal energy	Qualitative and quantitative representation of energy distribution and conservation: phenomenon ➞ ECM phenomenon ➞ ECM ➞ mathematical expression mathematical expression ➞ ECM ➞ phenomenon Distinction between heat and change in internal energy Overcoming linear causality
SS05	Why was the air in the tube liquified?	Adiabatic expansion/ Work/ FLT	
SS06	Why did the piston move (I)?	Isothermal expansion/ Heat/ FLT	
SS07	Which alternative phenomenon does the expression on isothermal expansion describe?	Isothermal compression/ Heat and work/ FLT	
SS08	Why did the piston move (II)?	Isobaric cooling/ FLT	
SS09	What will happen if we isobarically heat the gas?	Isobaric heating/ FLT	
BS3	Improving a thermal engine: a historical issue		
SS10	Which processes take place in the Newcomen motor?	Cyclic processes	Qualitative and quantitative representation of energy distribution in complex systems Generalization of FLT as an expression of energy conservation Overcoming linear causality: energy dissipation
SS11	What is the efficiency of a Newcomen engine?	Real engine efficiency	
SS12	How can an engine's efficiency surpass Newcomen's?	Theoretical engine efficiency	

Table 2 Question labels for the thermodynamic processes that are required to be represented as energy chains and mathematical expressions

Thermodynamic process	Energy chain	Mathematical expression
	Question label	
Adiabatic compression	C1	
Adiabatic expansion	C2	E2
Isothermal expansion	C3	E3
Isothermal compression	C4	
Isobaric compression	C5	E5
Isobaric expansion	C6	E6

by a discussion regarding the different formulae they proposed. To conclude the lesson, the respective theoretical elements were presented.

In two cases, the students were asked to merely give a graphical representation of an energy chain without a mathematical expression: (a) in the first lesson of the section, which worked as an introduction, and (b) in the fourth lesson of the section, in which the instructional process was diverted, first providing the formula and asking the students to describe a suitable phenomenon. Table 2 presents the thermodynamic processes that students were called to represent as energy chains (C) and as mathematical expressions (E). The energy chain questions requested a graphical representation, specifically a drawing, while the mathematical expression questions requested a symbolic representation, specifically a formula.

3.3 Research Strategy

Considering the size of the research sample and conditions, we use the methodology of quasi-experimental single-case research (ABAB design). As mentioned by Cohen et al. (2007, p. 284), single-case studies carried out in education involve "the continuous assessment of some aspect of human behavior over a period of time, requiring on part of the researcher the administration of measures on multiple occasions within separate phases of the study" and "intervention effects which are replicated in the same subjects over time."

Through this methodological strategy, we seek to draw inferences about the effectiveness of the ECM as a facilitator for students to make accurate connections between thermodynamic phenomena and their respective mathematical expressions of the FLT. IGasES suggests the technological means for bringing targeted characteristics of this constructivist approach into the classroom, in order for students to pursue an understanding of energy conservation. We observe the development of students' understanding of thermodynamics phenomena in terms of the representations of energy chains and the mathematical expressions of the FLT they provide to interpret these phenomena. Examinations of students' graphical representation of the energy chain were conducted six times, while for their symbolic representation of the mathematical expression of the FLT examinations were conducted four times.

We consider the implementation of the constructivist teaching and learning sequence through IGasES as the independent variable, while students' understanding of thermodynamic phenomena and energy conservation is the dependent variable. More explicitly, we expect that IGasES will have an impact on students' representations of energy chains and mathematical expressions of the FLT.

3.4 Data Collection and Classification

As mentioned, students responded to a worksheet during each lesson that specifically required an energy chain and a mathematical expression for each observed phenomenon. Their worksheets were collected at the end of every lesson as deliverables for their in-classroom work. After consultation with the school administration, students gave their informed consent for this data to be used for research purposes anonymously. Their answers were transferred to *NVivo* (v. 12) for qualitative data analysis.

Regarding the energy chain, the categories that were formed reflect students' representations within the field of macroscopic thermodynamics, as presented in the theoretical framework. In the first column of Table 3, we present the four sufficiency levels of the provided representations with reference to the explanation of the phenomenon's degree of accuracy, in terms of energy. As shown in the second column, each sufficiency level summarizes one or more explanation categories that are closely associated with the alternative frameworks presented in the theoretical section The third column provides a short definition of each explanation's category, justifying the awarded level of efficiency. Finally, the fourth column includes specific examples of each sufficiency level/explanation category in reference to the phenomenon of an isobaric compression.

In reference to the mathematical expression of the FLT, the categories were formed in the same spirit, considering the accuracy of the given formula in describing each phenomenon. In Table 4, we present the sufficiency levels with respect to the categories that were formed, along with short definitions, as well as specific examples of each category for the phenomenon of an isobaric compression. At this point, it should be noted that the teaching and learning sequence used the mathematical expression of the FLT in the form $\Delta U = Q + W$.

The validity and reliability of the coding frames were pursued through investigator triangulation and pilot testing (Cohen et al., 2007). Two science education researchers separately read through students' responses and assigned them to a category. This led to a high degree of inter-rater agreement (89%). These particular coding frames have been used in previous research (Delegkos & Koliopoulos, 2018), but have been slightly transformed to meet the needs of the particular context of the FLT. The proposed categories were formed a priori, based on the literature review (students' reasoning patterns and frameworks). During the school year that preceded the one in which the research took place, the coding frame was tested during a pilot version of the teaching and learning sequence, with a sample of approximately 15 students of the same level (not included in the sample of this research).

3.5 Data Analysis

Assigning a numerical value to each explanation category (from 1 to 4, 1 being the lack of an answer and 4 a sufficient answer) allowed for quantitative analysis of the otherwise qualitative data, through descriptive statistics and non-parametric statistical tests for the sufficiency levels of both the energy chains and the mathematical expressions representations. For this analysis, we used *SPSS* (v.21).

Table 3 Classification of energy chain graphical representations in levels of sufficiency. Each level corresponds to one or more explanation categories, with the respective definition and example (for isobaric compression)

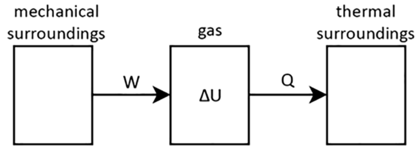
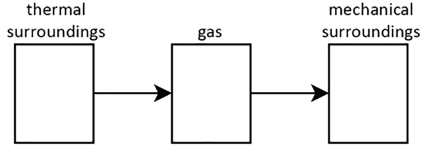
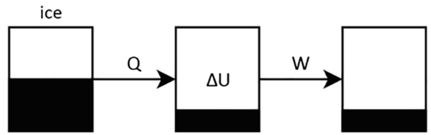
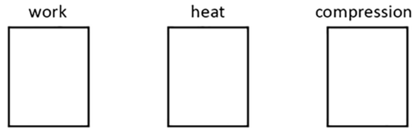
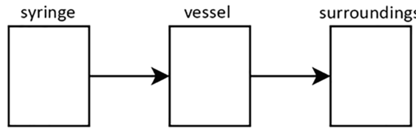
Sufficiency level	Explanation categories	Definitions	Examples (isobaric compression)
Sufficient	Accurate energy chain	Correct and complete presentation of the FLT conceptual components	
Intermediate	Partially accurate energy chain	Correct, but incomplete presentation of the FLT conceptual components	
Insufficient	Inaccurate energy chain	Incorrect presentation of the FLT conceptual components	
	Pre-energy components	Extensive use of pre-energy components	
	Phenomeno-logical or tauto-logical components	Exclusive use of phenomenological or tautological components	
None	No answer	No answer or statement of ignorance	

Table 4 Classification of mathematical expression symbolic representation in levels of sufficiency. Each level corresponds to explanation categories, with the respective definition and example (for isobaric compression)

Sufficiency level	Explanation categories	Definitions	Examples (isobaric compression)
Sufficient	Accurate mathematical expression	Correct and complete form of the FLT mathematical expression	$W = \Delta U - Q$
Intermediate	Partially accurate mathematical expression	Correct form of the FLT mathematical expression, but incorrect signs	$\Delta U + Q = W$
Insufficient	Inaccurate mathematical expression	Incorrect form of the FLT mathematical expression	$U_{\Delta} = \frac{W}{Q}$
None	No answer	No answer or statement of ignorance	

Table 5 Frequencies and relative frequencies (in percentages) for students' sufficiency level in their energy chain graphical representation

	C1	C2	C3	C4	C5	C6
Sufficient	0 (0.00%)	5 (27.78%)	2 (11.11%)	6 (37.50%)	11 (61.11%)	6 (35.29%)
Intermediate	2 (10.53%)	3 (16.67%)	1 (5.56%)	3 (18.75%)	1 (5.56%)	9 (52.94%)
Insufficient	16 (84.21%)	10 (55.56%)	15 (83.33%)	6 (37.50%)	6 (33.33%)	2 (11.76%)
None	1 (5.26%)	0 (0.00%)	0 (0.00%)	1 (6.25%)	0 (0.00%)	0 (0.00%)
Total	19 (100%)	18 (100%)	18 (100%)	16 (100%)	18 (100%)	17 (100%)

We are interested in scrutinizing the development of students' sufficiency level in their qualitative/semi-quantitative and quantitative representations of the FLT, and how they correlate in each phase. Although we present each category separately in descriptive statistics frequency tables, due to the small sample, we have reduced the categories from four to two, in order for the statistical tests to bring additional value. Therefore, throughout the statistical testing, we consider that sufficient and intermediate responses correspond to "adequate" representations of the energy chain and the mathematical expression, while insufficient and no responses correspond to "inadequate" representations.

As a first step, we used Friedman's test, which is the non-parametric alternative to the repeated measures one-way ANOVA. It is used to test for differences among dependent groups when the measurements are ordinal (Field, 2018), as is the case in this study. The Friedman test revealed the existence of at least one statistically significant difference ($p < 0.05$) between two consequently repeated measurements. To further explore this lead, we conducted a Wilcoxon testing, which is the non-parametric alternative to the paired sample *t*-test. It is used to test for differences among two dependent groups when the measurements are ordinal (Field, 2018), and in our case it reveals the specific measurement pairs that have statistically significant differences ($p < 0.05$). The comparisons are between energy chains, mathematical expressions, or both. To calculate the Wilcoxon signed rank test significance, we used the exact test. This method is the most accurate for small samples ($N < 50$) and gives an exact significance value (*p*-value) (Field, 2018).

Due to the relatively small sample size, we also present the effect sizes[2] to indicate the relative importance of each research finding. The reported effect sizes describe the impact that our intervention had during each transition, as they are linked to "the ability of a test to detect an effect of that size (known as the statistical *power*)" (Field, 2018, p. 138). Effect sizes with values greater than 0.3 indicate a medium effect, and those with values greater than 0.5 indicate a large effect (Cohen, 1988; Field, 2018).

3.6 Methodological Limitations

The main methodological limitations of this study are its convenience and small sample size. The statistical power of the test was about 60%, which is only marginally sufficient, while the statistical power that would allow generalization of results is 80% (Cohen, 1988).

[2] The effect sizes were calculated as $r = \frac{z}{\sqrt{2N}}$, where z is the z-score and N is the number of observations (positive differences, negative differences, and ties) implying the sample size. For more details, see Field (2018, pp. 407–414).

Table 6 Summary of Wilcoxon signed rank test results for students' level of sufficiency in their energy chain graphical representation

Comparison	Transition	Negative ranks		Positive ranks		Ties	Effect sizes
		N	Mean rank	*N*	Mean rank	*N*	
Overall	C6–C1*	0	0.00	13	7.00	4	0.62
After each lesson	C2–C1*	1	4.50	7	4.50	10	0.35
	C3–C2*	5	3.00	0	0.00	12	0.38
	C4–C3*	0	0.00	7	4.00	9	0.47
	C5–C4	4	4.50	4	4.50	7	0.02
	C6–C5	0	0.00	3	2.00	13	0.31
To first lesson	C3–C1	2	3.00	3	3.00	13	0.07
	C4–C1*	1	5.50	9	5.50	6	0.45
	C5–C1*	0	0.00	10	5.50	8	0.53
To second lesson	C4–C2	2	3.50	4	3.50	9	0.15
	C5–C2	1	3.50	5	3.50	11	0.28
	C6–C2*	0	0.00	7	4.00	9	0.47
To third lesson	C5–C3*	0	0.00	8	4.50	9	0.48
	C6–C3*	0	0.00	11	6.00	5	0.59
To fourth lesson	C6–C4	2	4.50	6	4.50	6	0.27

A representative sample with more students would increase the statistical power and, therefore, more efficiently detect any effects that might exist (Field, 2018, p. 138). More specifically, for $\alpha = 5\%$ (the probability of type I error) and power equal to 80% ($1 - \beta$, β is the probability of type II error), the sample should include at least 82 participants to detect a medium effect size ($r = 0.3$) and at least 31 participants to detect a large effect size ($r = 0.5$).

4 Results

4.1 Students' Graphical Representations (Energy Chains)

With regard to the thermodynamic processes that students represented as an energy chain (see Table 2), the non-parametric Friedman's test of six related scores revealed statistically significant changes [$x^2(5) = 22.356$, $p = 0.001$]. Table 5 shows the frequencies and the relative frequencies in percentages (within brackets) for the levels of sufficiency in each case.

Table 5 summarizes the development of students' sufficiency level in their graphical representations of the energy chain. Starting from C1 and moving towards C6, there is an overall decrease in insufficient answers. In C1–C3, insufficient answers get the lion's share, while in C4–C6, the percentages of intermediate and sufficient answers become significantly greater. It should be noted that with the exception of one student in C1 and one in C4, all students attempted an energy chain in each question.

Students' first three attempts to give an energy chain for the given thermodynamic process resulted in mainly insufficient explanations. More than 84% answered inefficiently in questions C1 (adiabatic compression) and C3 (isothermal expansion), while at the same threshold in C2 (adiabatic expansion), over 55% of students answered

Table 7 Frequencies and relative frequencies (in percentages) for students' sufficiency level in their mathematical expression symbolic representation

	E2	E3	E5	E6
Sufficient	8 (44.44%)	7 (38.89%)	3 (16.67%)	5 (29.41%)
Intermediate	1 (5.56%)	2 (11.11%)	12 (66.67%)	12 (70.59%)
Insufficient	6 (33.33%)	7 (38.89%)	3 (16.67%)	0 (0.00%)
None	3 (16.67%)	2 (11.11%)	0 (0.00%)	0 (0.00%)
Total	18 (100%)	18 (100%)	18 (100%)	17 (100%)

sufficiently. However, in C2 and C3, both intermediate and sufficient explanations make their appearance, but in low frequencies, at 44% and 16% respectively. Up to that point, it seems students' representations of thermodynamic processes in terms of energy were still unstable, and/or students had not yet become familiar enough with an accurate graphical representation of an energy chain.

In C4 (isothermal compression), answers begin to improve in sufficiency level again. This was clearly a turning point for students' energy representations as expressed through their energy chains. In C5 (isobaric compression), over 67% gave intermediate and sufficient explanations. There is a significant percentage of inefficient energy chain graphical representations (33%), though it should be highlighted that, in this particular thermodynamic process, students confronted all energy concepts (expressed as physical quantities) together for the first time. Finally, in C6 (isobaric expansion), the percentage of inefficient answers is minimized to 11%.

In the following Table 6, we used Wilcoxon's tests to further elaborate on the changes of sufficiency levels in the energy chain graphical representations. Negative ranks in this table were assigned to data pairs that represent sufficiency level decrease and positive ranks were assigned to the opposite case.

The comparison between students' first (C1) and last (C6) attempts to give an energy chain to accurately describe the given thermodynamic process, reveals a statistically significant difference, along with the greatest effect size (0.62) among all transitions reported in Table 6. There is an overall improvement in students' sufficiency levels, with zero negative ranks, suggesting that the entire class notably refined their qualitative and semi-quantitative models of the FLT representations.

Looking at this intervention more closely, we should examine all consequent transitions, namely the differences that occurred between the energy chains that were delivered lesson after lesson. Comparing C1 to C2 (adiabatic processes), there is a statistically significant difference with a moderate size effect toward the improvement in students' sufficiency level. This also seems to be the case for the transition from C2 to C3, with the important exception that there is a trend toward the decrease in sufficiency level. This likely to be the result of the introduction of a new thermodynamic process (isothermal) with which students were not at all familiar. Nevertheless, considering the comparison between C3 and C4 (both isothermal), the previous localized "step back" was soon restored. This pattern is repeated after the introduction of the final process (isobaric) in C5, but with no statistically significant differences and very weak effect size, while for C6 students' qualitative and semi-quantitative representations appear to have improved and stabilized.

As mentioned above, the launch of each new process is challenging for the students. This may be the main reason that there are no statistically significant differences between C1 (adiabatic) and C3 (isothermal), for which students' level of sufficiency was still rather

Table 8 Summary of Wilcoxon signed rank test results for students' level of sufficiency in their mathematical expression symbolic representation

Comparison	Transition	Negative ranks		Positive ranks		Ties	Effect sizes
		N	Mean rank	*N*	Mean rank	*N*	
Overall	E6–E2*	0	0.00	7	4.00	9	0.47
After each lesson	E3–E2	5	5.50	5	5.50	7	0.01
	E5–E3	2	5.00	7	5.00	8	0.29
	E6–E5	0	0.00	3	2.00	13	0.31
Rest of the cases	E5–E2*	1	5.00	8	5.00	8	0.40
	E6–E3*	0	0.00	8	4.50	8	0.50

*Indicates statistically significant change ($p<0.05$)

low. However, this picture improves when comparing C5 (isobaric) to C3, indicating that students tend to respond better to new processes as they get more familiar with the ECM. This conclusion is supported by the lack of statistically significant differences between the second time students encounter each new thermodynamic process (C2 to C4 and C4 to C6).

4.2 Students' Mathematical Expressions (FLT Formula)

As mentioned in the methodological section, as soon as students completed their graphical representations of energy chains, their models were refined through discussion based on the correct representation shown on the IGasES. For the thermodynamic processes that required a mathematical expression (see Table 2), students provided a FLT formula based on the accurate energy chain for the given process. The non-parametric Friedman's test of four related scores revealed statistically significant changes [$x^2(3)=12.0$, $p=0.007$]. Table 7 shows the frequencies and relative frequencies, in percentages, for the levels of sufficiency in each case.

As Table 7 illustrates, the sufficiency level of students' responses for the symbolic representation of the intermediate and sufficient mathematical expressions gradually increased. In questions E2 (adiabatic expansion) and E3 (isothermal expansion), the respective sufficiency percentage is around 50%. These were students' first attempts to formulate—from scratch—a mathematical expression they had never before encountered for the description of energy distribution and conservation during two different thermodynamic processes.

In E5 (isobaric compression), 83% of students' formulae are sufficient or intermediate. Although the percentage of merely sufficient answers is 16%, the lowest among all questions, intermediate answers are quite satisfying in this case. In this particular process, students successfully used all energy concepts in the formula for the first time; however, placing the correct signs was quite challenging for them, especially with reference to the decrease of internal energy. Finally, in E6 (isobaric expansion), there are no answers at the inefficient level. The relatively high percentage of intermediate mathematical expressions (70%) can be explained due to the equivocal sign of heat, which is transferred both to and from the system. It is also noteworthy that, in these final questions (E5 and E6), all students, at least, attempted to provide an answer.

Table 9 Frequencies and relative frequencies (in percentages) for students' sufficiency level in their energy chain and mathematical expression representations (only for the cases that both apply)

	C2	E2	C3	E3
Sufficient	5 (27.78%)	8 (44.44%)	2 (11.11%)	7 (38.89%)
Intermediate	3 (16.67%)	1 (5.56%)	1 (5.56%)	2 (11.11%)
Insufficient	10 (55.56%)	6 (33.33%)	15 (83.33%)	7 (38.89%)
None	0 (0.00%)	3 (16.67%)	0 (0.00%)	2 (11.11%)
Total	18 (100%)	18 (100%)	18 (100%)	18 (100%)
	C5	E5	C6	E6
Sufficient	11 (61.11%)	3 (16.67%)	6 (35.29%)	5 (29.41%)
Intermediate	1 (5.56%)	12 (66.67%)	9 (52.94%)	12 (70.59%)
Insufficient	6 (33.33%)	3 (16.67%)	2 (11.76%)	0 (0.00%)
None	0 (0.00%)	0 (0.00%)	0 (0,00%)	0 (0.00%)
Total	18 (100%)	18 (100%)	17 (100%)	17 (100%)

In the following Table 8, we use Wilcoxon tests to take a broader look at these changes of sufficiency levels in the mathematical expression symbolic representation.

The overall change in the sufficiency level of the mathematical expression symbolic representation, namely the comparison between E2 and E6, is statistically significant and has an effect size that is moderate (0.47). All changes that occurred are positively ranked, suggesting that students had notably refined their quantitative representations of the FLT by the end of the intervention.

However, this progress does not appear to be gradual or stable when assessed in the four individual lessons that required the FLT formula. As mentioned before, the change of thermodynamic process from E2 (adiabatic) to E3 (isothermal) seems to have undercut the students, as the positive and negative transitions are equal. The picture improves for the transition from E3 to E5 (isobaric) with seven positive changes, but still lacks a statistically significant difference between the two sufficiency levels of students' mathematical expressions. Nevertheless, the final transition (E5 to E6) shows stabilization of students' quantitative representations, as the number of ties is considerably large, and an improvement for the rest of the cases.

4.3 Correlation Between Students' Graphical Representations and Mathematical Expressions

It is interesting to examine whether, and to what extent, the sufficiency level of the energy chain graphical representation matches the sufficiency level of the mathematical expression symbolic representation for the cases in which both the chain and the expression are required (see Table 2). In the following Table 9, we present the frequencies and relative frequencies in percentages for each combination, as they derive from the selective merging of Tables 5 and 7.

We anticipated that students' initial energy chains would be proper qualitative/semi-quantitative representations for the consequent construction of the FLT mathematical expression for each thermodynamic process. After the refinement of the model through the discussion based on the correct energy chain presented in IGasES, we expected that the

Table 10 Summary of Wilcoxon signed rank test results for students' level of sufficiency in their energy chain and mathematical expression representations (only for the cases that both apply)

Transition	Negative ranks		Positive ranks		Ties	Effect sizes
	N	Mean rank	*N*	Mean rank	*N*	
E2–C2	3	4.00	4	4.00	11	0.06
E3–C3*	0	0.00	6	3.50	12	0.41
E5–C5	1	3.00	4	3.00	13	0.22
E6–C6	0	0.00	2	1.50	15	0.24

*Indicates statistically significant change ($p < 0.05$)

initial energy chain sufficiency levels would result in improved mathematical expression sufficiency levels. As shown in Table 9, in the first two pairs of questions (C2/E2 and C3/E3), the majority of students start from inefficient energy chains and, in almost equal numbers, form sufficient and insufficient mathematical expressions of the FLT. In contrast, the last couple of questions (C5/E5 and C6/E6) derive all possible sufficiency levels (mostly sufficient and intermediate), and land almost exclusively on sufficient and intermediate symbolic representation of the mathematical expression.

Students' first attempts to give both a representation of the energy chain and mathematical expression resulted in quite mixed results. More specifically, for questions C2/E2, a percentage of 28% of students begin from a sufficient energy chain, while 44% finally present a sufficient mathematical expression. Considering the first group (sufficient energy chain), 40% out of these students held at the sufficient level, while the rest gave an insufficient mathematical expression. From the second group (sufficient mathematical expression), 25% derived an intermediate energy chain and 50% derived an insufficient energy chain. It should be noted that the percentage of students that did not attempt to give a mathematical expression derived merely from inefficient energy chains.

Regarding questions C3/E3, the distribution is quite similar to the previous set, but in this case, all the students who started from sufficient and intermediate energy chains gave mathematical expressions at either level. To be exact, 28% constructed a sufficient energy chain, and 39% reached a sufficient mathematical expression. From the first group, students equally derived sufficient and intermediate mathematical expressions. Students of the second group mostly started by deriving insufficient energy chains (71%), indicating that such representations can be refined through the proper model given by IGasES.

In questions C5/E5, 61% started with a sufficient energy chain, but only 17% landed on a sufficient mathematical expression. Looking into the first group, 18% remained at the sufficient level, while 73% gave an intermediate expression. In the second group, 33% started from an insufficient energy chain. In these questions, the majority of students presented intermediate formulae (67%), starting from sufficient and intermediate energy chains (75%).

For questions C6/E6, 35% began with a sufficient energy chain and 29% gave a sufficient mathematical expression. Within the first group, 33% remained at the sufficient level, while the rest gave an intermediate mathematical expression. For the second group, 40% initially gave an intermediate energy chain and 20% gave an insufficient energy chain. In this case, the results are more consistent, taking into account that most students started from an intermediate level and remained there (41%).

To get a bigger picture of the energy chain-mathematical expression transitions, we conducted a Wilcoxon test for each case. The results are depicted in Table 10.

We expected that there would be few statistically significant differences between the level of sufficiency in the energy chain and in the mathematical expression representations. One of our main hypotheses was that students' initial qualitative and semi-quantitative representations of the FLT, expressed through their energy chain, greatly affect and indicate their forthcoming quantitative representations, given in the form of the mathematical expression. Table 10 indicates that this hypothesis might be on the right path: the ties in sufficiency levels between energy chains and mathematical expressions outnumber the positive and negative ranks in all cases, suggesting that the majority of students maintain their sufficiency level across both qualitative/semi-quantitative and quantitative representations.

Our aim, however, is to use the IGasES in order to improve students' initial representations through the ECM, so that they can ultimately land on a more accurate FLT formula. This is also reflected in the analysis provided in Table 9: the cases that are not ties, are mainly positively ranked. That is, students tend to improve in the sufficiency of their representations after teacher intervention with the use of the IGasES. Although students had initially given an inadequate energy chain, they landed on an adequate mathematical expression. This is vividly sketched particularly for the pair of C3/E3, for which the level of the energy chain sufficiency was rather low, but the correspondent value for the formula increased (see Table 9), resulting in a statistically significant difference (see Table 10).

A case that diverges from the overall set of results is the pair C2/E2, for which the negative ranks are almost as numerous as the positive ranks. This result can likely be explained by the fact that this was students' very first attempt to give a mathematical expression on their own, and at this initial point, had not quite grasped how to use the energy chain for this purpose. The overall results suggest that this skill notably improved by the end of the respective section of the teaching and learning sequence.

5 Discussion

In the present study, we make use of key elements of a constructivist approach for the teaching and learning of the FLT as an expression of energy conservation. For the development and implementation of this approach, we gave prominence to students' alternative frameworks of the FLT in the light of linear causality as a predominant reasoning pattern for young learners (Halbwachs, 1971; Rozier & Viennot, 1991; Tiberghien et al., 1995). The research on secondary school students' representations of introductory thermodynamics concepts and principles has been quite limited up to this point in time (Meli et al., 2016), although these early representations greatly affect their overall perception of energy in educational and social contexts. Although the sample of this study was rather small (max. 19 students) and thus the results cannot be generalized to the entire upper secondary school student population, certain outcomes, regarding particular energy concepts and energy conservation in the form of the FLT, can be indicative for this educational level. To begin with, our results indicate that prior to the intervention, second-year upper secondary school students (16–17 years old) were initially aligned with university students' alternative frameworks of the FLT and the implicated energy concepts (e.g., Kautz et al., 2005a, b; Leinonen et al., 2009; Meltzer, 2004), with the addition of several phenomenological explanations (Meli et al., 2016). However, the strategic choice of purely macroscopic elements of the teaching and learning sequence illuminated all possible micro-level explanations (Kautz et al., 2005a, b), while the immediate introduction of the energy properties of the systems minimized the references to state variables (Loverude et al., 2002). Respective studies for tertiary education students also suggest the careful distinction between macroscopic and microscopic frameworks, as well as the “right timing” for the introduction of non-energy tools, such as the ideal gas law, in upper secondary school so students entering university will have already constructed more sophisticated energy representations for the interpretation of phenomena taking place in the context of thermodynamics (Leinonen et al., 2009, 2012).

In particular, we operationalize the ECM as a proper graphical energy representation for bridging the qualitative, semi-quantitative, and quantitative aspects of the FLT for the interpretation of various thermodynamic processes. When used in instruction, qualitative and semi-quantitative energy representations have been proven useful to help students to develop a better understanding of energy-oriented explanations in physics courses—especially in mechanics, which has been the preferred field for most of these studies (e.g., Fortus et al., 2019; Kubsch et al., 2020; Lemeignan & Weil-Barais, 1994; Neumann et al., 2013). However, the extent to which the different energy representations mentioned in the literature (e.g., Energy Tracking Diagrams—Scherr et al., 2016; energy flow diagrams—Hobson, 2004; Energy Transfer Model—Fortus et al., 2019) work as pragmatic models *of* or as constructivist models *for* the system under examination, is not always clear (Gouvea & Passmore, 2017; Seel, 2014). From an epistemological perspective, almost all the representations mentioned in the literature (with the exception of the Energy Tracking Model) adopt a straightforward forms-based approach that may interfere with students’ understanding of the unified concept of energy (e.g., Fortus et al., 2019; Kaper & Goedhart, 2002a, 2002b; Millar, 2014). More importantly, although students incorporate semi-quantitative elements, they do not actively establish connections between the observed phenomenon (phenomenological level) and the respective energy-related mathematical expressions (theory level). From a pedagogical perspective, common graphical representations implicitly consider students’ linear causal reasoning, but they do not implicate which specific strategies can overcome it.

The qualitative ECM has been used in several educational settings and physics fields, proving to be effective for students’ qualitative modeling of material situations and theories (e.g., Cornuéjols et al., 2000; Devi et al., 1996; Lemeignan & Weil-Barais, 1994; Megalakaki & Tiberghien, 2011; Tiberghien, 1996). In this study, however, in order to address our research question, we went a further step and incorporated semi-quantitative elements in addition to the qualitative ones included in the ECM. In this respect, we employed a tailor-made educational simulation (IGasES) to introduce the ECM, so the semi-quantitative elements were more vividly illustrated. Our hypothesis was that those students adequately representing the observed phenomena through the qualitative and semi-quantitative ECM, can, in the long term, considerably improve their quantitative representations in the form of mathematical expressions (Papadouris & Constantinou, 2016). At the same time, in the short-term, the level of sufficiency in their qualitative and semi-quantitative representations is a strong indicator of what they can achieve in their quantitative representations.

Therefore, we investigated students’ qualitative/semi-quantitative and quantitative representations of the FLT as stepping-stones for the meaningful energy interpretation of several thermodynamic processes. The initial classifications of students’ answers gradually changed throughout the implementation of our teaching and learning intervention and stabilized on more accurate representations that were vastly energy-oriented. It is noteworthy that in a time period of about 2 weeks, our sample of students achieved a considerable level of sufficiency in their interpretations of phenomena they had never before encountered before. Those phenomena were to be interpreted under the scope of the energy conservation principle, which is considered particularly difficult for secondary school students (Herrmann-Abell & DeBoer, 2018). The ECM and the FLT formula were completely foreign to them when the implementation of the sequence started, and yet they managed to construct both adequately. On the one hand, students moved towards sufficient or intermediate (adequate) energy chain representations and, on the other hand, they gave sufficient or intermediate (adequate) mathematical expressions of the FLT for the description of the observed phenomena.

In our point of view, the three-level constructivist approach (theory-model-phenomenon) (Tiberghien et al., 1995) acted as a facilitator for students to generate their own meaningful representations, but also to potentially align gradually with the established scientific viewpoints for thermodynamics. The dynamic nature of IGasES gave us distinct leverage for the operationalization of the ECM since it allowed students to conceive the interplay between the levels of phenomenon, model, and theory directly, and therefore bridge different FLT aspects in thermodynamic processes (Greca et al., 2014). The ECM was embedded in IGasES as the prevailing model level component and its contribution to students' conceptual understanding should be highlighted. For those questions that the explanatory model supports the expression of students' intuitive linear causal reasoning, the results are gradually more satisfying. Ultimately, however, the questions challenge this reasoning pattern, requiring a nonlinear energy chain. As our results indicate, students responded remarkably well to this unexpected turn. The high percentages of sufficient and intermediate (adequate) representations justified the decisions made in the design phase of the sequence, which accounted for students' reasoning patterns and the frameworks that derive from them. To our knowledge, there has been no research evidence so far indicating the overcoming of students' linear causal reasoning in light of a model-based intervention.

It should be noted that a substantial number of students fall under the category of intermediate level of sufficiency with reference to their symbolic representation of the mathematical expression. Given that, in the case of the formula, this level corresponds merely to inaccurate signs of the energy concepts as physical quantities, this suggests that students were able to clearly distinguish between energy transfer and storage but were not able to capture the "direction" of change. This particular issue has been mentioned in the literature (e.g., Greenbowe & Meltzer, 2003; Leinonen et al., 2013; Moore, 1993), but in our case, we can detect an implementation-specific issue: to provide a mathematical expression, students were ultimately working on the final snapshot of the correct energy chain given by the IGasES. Although they observed the energy chain developing for as many times as they had requested, at its final state, it was deprived of its dynamical characteristics and it is possible that students were not able to define the change in internal energy, thus getting the signs inaccurately. This issue pinpoints the need for dynamic representations, such as the ones IGasES can provide, for fields dealing with natural or technical processes and not states. This finding is in line with the limitation that explicitly characterizes other graphical energy representations reported in the literature (Scherr, Close, McKagan, et al., 2012b).

6 Implications and Future Research Directions

In the vast majority of related studies for school levels, energy concepts and energy conservation are initially approached within the physics framework of mechanics (e.g., Fortus et al., 2019; Kubsch et al., 2020; Neumann et al., 2013). This research indicates that there are epistemological and pedagogical reasons for the educational community to reconsider the role that thermodynamics can play in this endeavor: the FLT, in particular, suggests a powerful tool (Papadouris & Constantinou, 2016) and is yet accessible to students for the construction of solid representations of abstract energy concepts, properties, and principles. Beyond thermodynamics, it can also integrate additional systems, and therefore might suggest a valid point of reference for all energy-related instructions.

Considering another research perspective, the results indicate a constant need for the use of qualitative and semi-quantitative constructivist models for physics instruction. More often than not, physics educators struggle to help their students meaningfully connect material situations to the formulae that have the power to interpret the phenomena or experiments. However, traditional approaches, that usually rigorously move from the phenomenological to the theory level with a heavy load of mathematical formalism, do not rise to this challenge efficiently (Kautz et al., 2005a, b). Along with other elements of traditional approaches, such as the juxtaposition of different frameworks (Koliopoulos et al., 2011), the lack of proper constructivist modeling should be addressed.

This research addresses both the content and the form of an instruction that is based on the constructivist approach for the teaching and learning of the FLT. These components should work cooperatively for the seamless integration of targeted elements into the instruction through educational technology, and, on the other hand, for educational technology to meet its purposes and expectations through its proper design and implementation (Meli & Koliopoulos, 2019a). Consequently, teachers and developers should closely collaborate in order to create educational tools that offer user-friendly digital environments with the potential for teaching and learning in any given physics field.

7 Conclusion

This research suggests an addition to the existing literature on the teaching and learning of the FLT in the context of introductory thermodynamics for four main reasons. First, our sample consists of secondary school students, for whom the pertinent research and interventions are quite limited, although tertiary education researchers see a distinct need for such. Secondly, we offer some new insights for students' energy concepts, properties, and principles within the significant field of thermodynamics, that further inform both the educational research and practice since, so far, energy is mostly examined in the context of mechanics. Thirdly, we took into account previous studies' results on students' frameworks and reasoning to develop a research-informed constructivist approach, especially considering the interplay between the levels of phenomena, models, and theories that students typically encounter in their physics courses. Finally, in this respect, we developed and implemented a simulation-enhanced model that sufficiently achieved the bridging of qualitative and quantitative aspects of common thermodynamic processes with the overcoming of students' linear causal reasoning, addressing a pressing need deriving from both secondary and university education for meaningful mathematical representations.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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