Energy Systems Pedagogy with Thermoptim

An Innovative Approach Based on Established Pedagogical Theories

Introduction

Over the past twenty-five years, we have developed a new pedagogy for applied thermodynamics and thermodynamic energy conversion, now used in over one hundred and twenty higher education institutions, both at undergraduate and graduate levels (engineering schools, universities) as well as in professional training.

The objective of this note is to present this new approach from the perspective of the pedagogical theories underlying it.

After a first section recounting the genesis and evolution of the pedagogy, its theoretical foundations are presented. The following section describes the main functionalities of the Thermoptim simulator. We then explain the three complementary implementation modes of this pedagogy according to learners' scientific level, then detail the pedagogical resources it employs, before addressing the results of its implementation. We then return to the key principles used, likely transferable to other disciplines.

However, before addressing these different points, a brief overview of the impact of a tool like Thermoptim on teaching will help illustrate our point.

From the traditional course on the gas turbine to the one with Thermoptim

The gas turbine, also called combustion turbine, is a heat engine that is currently very popular, given its excellent performance (efficiency greater than 35% when used alone, and 55% in combined cycle). This machine is composed of three elements: a compressor, a combustion chamber, and a turbine[1].

Let us take a look at the difference between a classic presentation of a gas turbine model and how it can be done with Thermoptim.

The screen of Figure 1 shows the 22 main equations which must be introduced in order to study, with reasonable accuracy, the performance of the simplest gas turbine in a conventional curriculum. It is of course possible to simplify, but the model becomes a caricature.

[1] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/turbines-gaz.html

Equations describing the compression appear at the top left, and those for expansion in the upper right. These are the simplest.

The more complicated ones are at the bottom left: they determine the composition of exhaust gases at the combustion chamber outlet.

And yet, for simplicity, we have firstly considered here a very simple fuel and secondly have omitted to give the equation for calculating the end of combustion temperature, which is an implicit equation including an integral, one of the bounds of which is unknown.

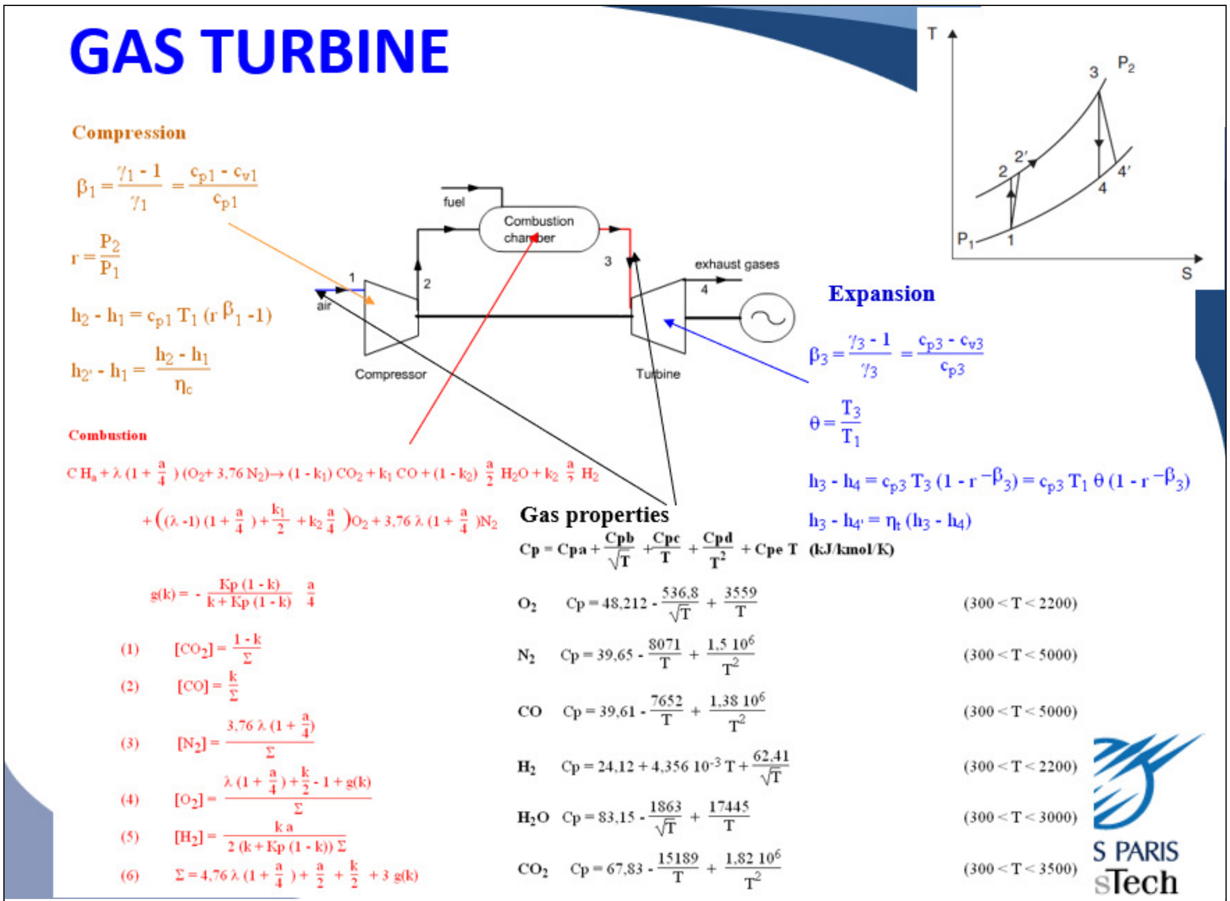

Figure 1: Conventional modeling of a gas turbine

In all cases, the gas properties require equations of the kind presented at the bottom of the figure. They are needed to calculate the energy properties of fluids put in.

All things considered, it is at least forty equations that must be taken into account to obtain a realistic model of the gas turbine.

Of course, even if each of the equations is known, the risks of error are numerous in the development of the model and its resolution, especially since they are interconnected and the resolution of some of them must be done iteratively.

Building a gas turbine model with Thermoptim is radically different from that which was traditionally implemented: we favor a qualitative approach of phenomena, the calculations required for quantitative studies being conducted by software tools in a transparent manner for the learners, i.e. they have no need, at least initially, to know the details.

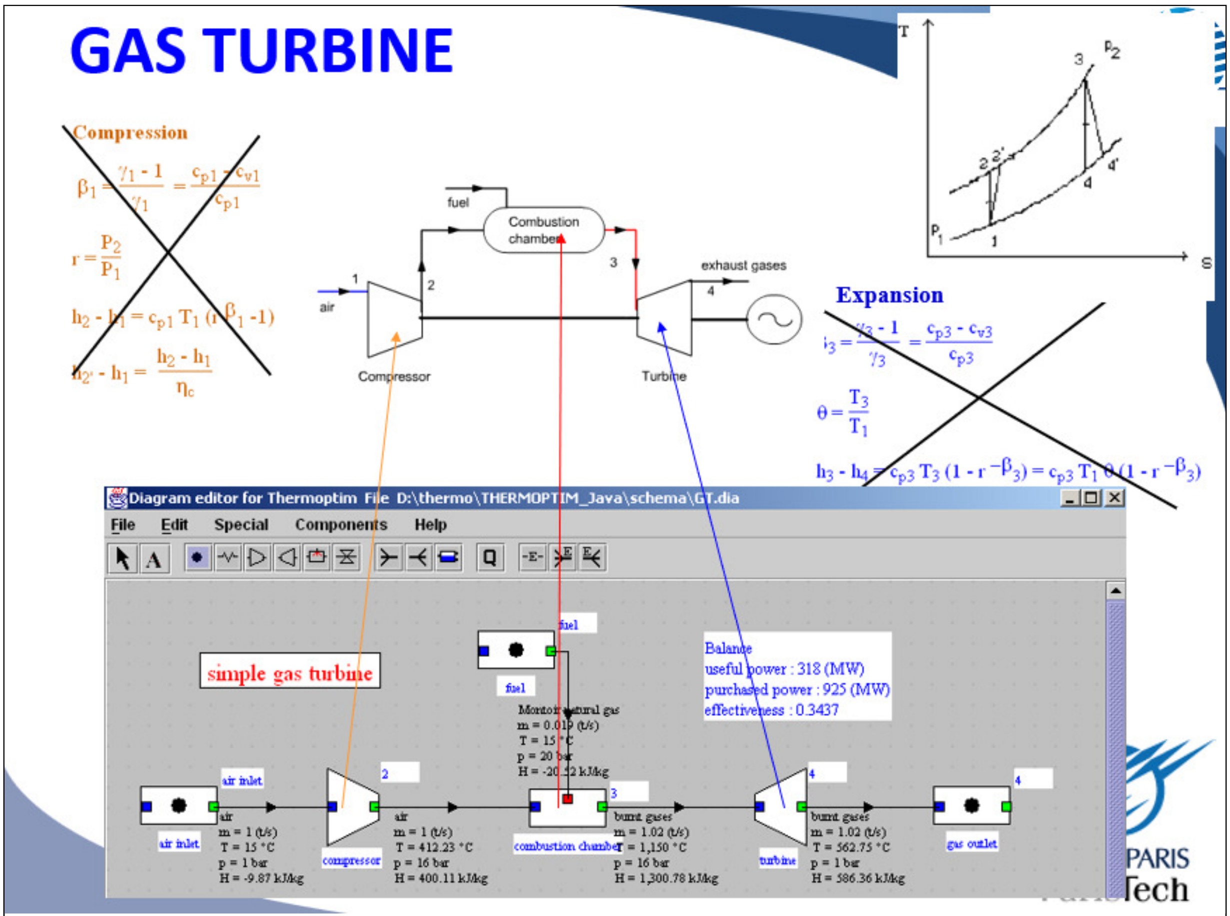

Figure 2: Modeling with the new teaching method

The use of equations is reduced to a minimum when introducing the discipline, the cognitive effort being mainly devoted to understanding concepts and technologies as well as their implementation, and it is only once the learner has acquired sufficient knowledge of the subject that we consider the writing of equations becomes possible if relevant.

Specifically, as shown in Figure 2, the model is constructed by assembling icons placed on a diagram editor working plan, the machine architecture being very close to its physical sketch.

Each component is then set with a small number of characteristic values. The thermodynamic properties of fluids being encapsulated in the software, computing performance presents no difficulty, giving much greater precision than with the traditional approach.

Using a tool like Thermoptim, the time to calculate a thermodynamic cycle is reduced to one-fifth or one-sixth of before, and once the model established it is possible to perform sensitivity analysis and resolve in minutes what would take hours by conventional methods.

In addition, there is no risk of programming error or incorrect reading of properties. This results in considerable time savings on one aspect of things not essential at the educational level, namely solving computational problems. Besides the time saved, the arduous nature of the work is greatly reduced, resulting in a significant gain in learner motivation, as they are no longer put off by cumbersome and tedious calculations.

Moreover, considerable gains in precision are obtained and thus in calculation likelihood: there is no need to resort to oversimplifying assumptions for the sole purpose of making possible the calculations.

A typical example: in almost all lessons taught in undergraduate and graduate courses in the world, internal combustion engines are analyzed with the assumption that the technical fluid is air, itself assumed to behave as a perfect gas. How with such assumptions could we hope motivating learners who today are concerned about the environmental impact of these technologies: an air engine has never polluted and will never pollute!

Genesis and Evolution of the Pedagogy

The process of developing this new pedagogy has been long, as we had to imagine and develop numerous digital resources and test them with various categories of learners.

Three Key Development Periods

Systemic Foundations and Computational Relief

The first phase from 1997 to 2001 corresponds to the creation of Thermoptim from the first drafts in 4D already allowing students to be relieved of computational difficulties, through its porting to Java and the development of the schema editor which enabled adopting a systems approach in developing energy technology models. This approach led to a fundamental observation: applied thermodynamics is much simpler qualitatively than quantitatively.

Extensions and Advanced Features

The second phase, from 2001 to approximately 2007, saw the development of numerous advanced features. The external class extension mechanism enabled expanding the number of systems addressed and tackling complex subjects like technological dimensioning studies and off-design operation.

During this period, the implemented pedagogy benefited from rich exchanges with numerous colleagues:

- First within the Grande École Virtuelle project of the Écoles des Mines
- Then during LIESSE workshops organized for preparatory class teachers (CPGE)[2]
- Within the ALET Club (Software Tools for Teaching Thermodynamics)[3], which we plan to reconvene after a 15-year hiatus
- Finally during meetings of the French Navy's Energy Teaching Network

These exchanges taught us that we progress better together, by comparing our approaches and sharing our failures as much as our successes, and that comparing different pedagogical contexts enables particularly fruitful perspectives.

Adaptation and Pedagogical Streamlining

Initially developed within our teaching at École des Mines de Paris, our approach proved to interest a much broader audience, not only at university level, but also for training learners without as substantial a scientific background as our students, such as operators of propulsion systems and refrigeration and air conditioning installations in the French Navy, or professionals in continuing education.

During the third software development phase, from 2007 to 2017, we therefore sought to lighten the scientific content of teaching as much as possible, emphasizing understanding of physical phenomena rather than studying the equations describing them. This evolution follows a well-established pedagogical orientation in didactics: **minimalist instruction** by Carroll (1990)[4], according to which cognitive load on learners should be limited to what is strictly necessary to achieve objectives. Concretely, this meant in our case:

- Favoring learning through action (guided explorations) rather than exhaustive theoretical exposition
- Not teaching entropy and exergy from the outset
- Introducing these concepts only when they become indispensable

In parallel, new tools were developed, notably during preparation in 2016 of our two MOOCs on Thermodynamic Heat Conversion (THC), so learners could work autonomously, since supervision is necessarily reduced in this context. These include self-assessment

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[2] https://direns.minesparis.psl.eu/Sites/Thopt/fr/co/stages-liesse.html

[3] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/module_Enseignement_3.html

[4] Carroll, J. M. (1990). The Nurnberg Funnel: Designing Minimalist Instruction for Practical Computer Skill. MIT Press, Cambridge, MA, USA.

activities on one hand, and guided explorations of models created with Thermoptim on the other, which allow learners to progressively learn to model numerous energy systems.

Here too, exchanges with colleagues from multimedia units brought their share of complementary insights, essentially on online course pedagogy and creating the Thermoptim-Unit portal which will be discussed later. Moreover, we were fortunate that several benefactors took an interest in these developments and decided to support them: Mines Paris PSL, the UNIT Foundation, and Institut Mines Télécom. We thank them warmly for their confidence and support.

In terms of features, the main addition was exergetic (or productive) structures, enabling automatic generation of exergy balances for numerous systems.

The third edition of the book *Energy Systems* published by Presses des Mines reflects these various evolutions. In particular, while the two previous editions contained numerous sections with advanced equation developments, these have been removed. We will detail its content in section 4.1.

1. Theoretical Foundations of the Pedagogy

1.1 Cognitive Load Theory (CLT)

Our approach is primarily based on cognitive load theory, developed by John Sweller and colleagues[5]. This theory provides a scientific explanation for difficulties observed in traditional teaching and proposes concrete solutions.

Fundamental Principles of Working Memory

Short-term working memory is limited: we can process simultaneously only a few elements and must assign them meaning in a very brief time[6]. This limitation imposes significant constraints on human learning. Two mechanisms help circumvent this difficulty:

1. **Schema acquisition**: Constructing appropriate explanatory mental models allows decomposing information into meaningful memorable elements. This is the fundamental process of knowledge structuring. Well-formed schemas enable learners to recognize structures and process complex information as comprehensible units.

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[5] Sweller, J. (1985). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, 12, 257-285.

Sweller, J. (1989). Cognitive load theory and instructional design: Recent developments. *Australian Journal of Educational Technology*, 5(2), 108-124.

[6]Miller, G. A. (1956). The magical number seven plus or minus two: Some limits on our capacity for,processing information. Psychological Review, 63, 81-97.

2. **Task automation**: Once schemas are well structured, automation results from practice and allows retaining appropriate work methods. Automation frees working memory resources.

The "Split Attention" Phenomenon and Its Consequences

Cognitive overloads appear when too much disparate information must be simultaneously considered by the mind. The "split attention" phenomenon occurs when elements that can only be understood together are presented separately. An example is presenting two parts of explaining the same concept on two slides, and saying: "As you saw in the previous slide...". To avoid this mechanism, it is important to simplify educational materials content as much as possible.

This has direct implications for our pedagogy: rather than presenting abstract equations first, then applications, it is notably preferable to show how concepts work on concrete and visual examples before introducing mathematical formalization[7].

Implications for Pedagogical Structuring

According to this theory, it is fundamental that students begin by structuring their knowledge according to appropriate schemas. They must be explicitly guided in this task, while being aware that it is not intuitive, and knowing there is a dialectical difficulty: students must construct their schemas themselves, but cannot be left completely on their own. Pedagogies centered on learners and sufficiently open to allow meaning construction must be found.

Cognitive load theory affirms that **worked examples** play an essential role at this level. Memorizing key examples, made possible through successive impregnations during practical activities, allows students to anchor their field culture in concrete reality[8]. This is why we recommend using what Sweller calls "worked examples": examples solved step by step that allow learners to discover how calculations can/should be performed[9]. This is precisely the role of guided explorations we make available to them.

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[7] Sweller, J., & Cooper, G. A. (1985). The use of worked examples as a substitute for problem solving in learning algebra. *Cognition and Instruction*, 2(1), 59-89.

[8] Giordan, A. (1999). *Apprendre : une alchimie complexe*. 10e Entretiens de la Villette, Cité des Sciences et de l'Industrie.

[9] Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive Load Theory*. Springer. Chapter on Worked Examples

1.2 Conceptual Framework: The RTM(E) Model

Articulation Between Cognitive Load and RTM(E) Model

Cognitive load theory teaches us *how* to organize learning to avoid overloading working memory. The RTM(E) model complements this approach by specifying *what* to teach and in what order. These two frameworks are complementary:

- **CLT** guides the **form** of presentation (avoid split attention, use worked examples)
- The RTM(E) model serves as a guide for **content** and **sequencing** (start with Reality and Examples before addressing more abstract Theory)

This synergy forms the foundation of our progressive and iterative pedagogical approach.

The RTM(E) Model: A Taxonomy of Knowledge

The pedagogical design of our approach is based on a detailed analysis of what must be taught. We developed the RTM(E) model[10], a taxonomy of scientific knowledge to transmit that distinguishes four major interrelated categories:

The Four Components of the RTM(E) Model

- **Reality (R)**: The real world as it concretely exists—nature and technology, observed facts, matter, the field, fluid properties. For energy, this means understanding real technical constraints of machines, physical phenomena occurring in components, like state changes, etc.

- **Theory (T)**: An explanatory framework emerging from studying and observing Reality. It highlights similarities between different observations and explains them coherently, simply, and generically. For applied thermodynamics, theory is now well stabilized, based on the first two principles and energy balances.

- **Methods (M)**: Operational tools and procedures for solving practical problems. These methods apply theoretical principles in specific contexts, essentially involving know-how. Thermoptim is an example of a method: it encapsulates calculation procedures in an accessible environment.

- **Examples (E)**: Concrete applications illustrating how to solve specific problem classes. These are commented and detailed examples that play a fundamental role in learning. Links between Reality, Theory, and Methods are most clearly explained around them. Basic examples here are the steam power plant, gas turbine, and refrigeration machine, to which summer and winter air conditioning cycles can be added.

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[10] Gicquel, R. (2004). Utilisation pédagogique des simulateurs : Volet 1 : éclairages de la didactique. *Bulletin de l'Union des Professeurs de Physique-Chimie*, 868, 1611-1620.

Articulation and Pedagogical Implications

Theory constitutes both a reading grid for Reality and a guide for developing Methods. This structure joins the concept of "disciplinary matrix" proposed by Thomas Kuhn, representing what a group of scientists has in common and constituting the foundation for training their students[11].

Our pedagogical approach frees students from tedious calculations, enabling two major innovations:

- On Examples: Realistic and complex cases can be immediately addressed.
- On Theory: Its pedagogical approach can be strongly renewed (visualization, experiential learning, progressive concept introduction), making it more intuitive and better assimilated.

Choice of pedagogical supports depends on the nature of knowledge to transmit[12]:

- **For Reality**: visits, presentations, slideshows, videos, films, readings, disassembly/reassembly, practical work
- **For Theory**: Digital resources (Diapason modules, videos, MOOCs) for self-learning, contextual theoretical contributions ("Just-in-time") triggered by modeling needs, and a posteriori conceptual syntheses
- **For Methods and Examples**: studying detailed solved examples, practical exercises and especially simulations, guided explorations

RTM(E) Model and Evolution of Theoretical Presentation

While fundamental thermodynamic laws (Theory's core) are stable, their didactic transposition has radically evolved in our approach.

Contrary to the traditional axiomatic approach (which starts from principles to reach applications), we developed an inductive and functional approach:

- **The CFER approach (Components, Functions, Reference Evolutions)**: After simply introducing the first principle in closed and open systems, rather than parachuting state equations, we start from technological analysis (Reality) to identify **functions** (compression, expansion...), which define **reference evolutions**. Theory then arises from the need to model these evolutions.

- **The light and progressive presentation**: A major theoretical innovation consists of deferring introduction of abstract concepts (like entropy or exergy) to present them

[11] Kuhn, T. S. (1972). *La structure des révolutions scientifiques* (2e édition française). Flammarion. p. 215.

[12] Gicquel, R. (2004). Implications pour l'enseignement : utiliser des médias adéquats. *Bulletin de l'Union des Professeurs de Physique-Chimie*, 868, 1619-1620.

only when they become indispensable for problem solving (often in a second phase or for advanced cycles).

- **The pedagogical spiral**: Theory is no longer a prior monolithic block, but a corpus visited repeatedly with increasing depth (Light Approach → Progressive → In-Depth).

1.3 Complementary Cognitive Models

Several other theoretical frameworks enrich and consolidate this pedagogical approach.

The SRK Model (Skills, Rules, Knowledge)

This model, developed by Rasmussen in cognitive ergonomics, distinguishes three levels of cognitive control corresponding to increasing stages of expertise[13]:

- **Knowledge**: Approach based on declarative knowledge, characterized by conscious analytical processing. This is the initial stage where learners must consciously think through each step.

- **Rules**: Application of memorized rules, intermediate approach where behavior is governed by learned rules. This is the stage where learners react effectively while still being conscious of their cognitive processes.

- **Skills**: Automated performances, characterized by fluid automation of complex behaviors. This is the expertise stage where reactions become fluid and intuitive.

Our pedagogy seeks to guide learners through these three levels, starting with simple rules (guided explorations) before progressing toward more deeply integrated knowledge.

A Minimalist Pedagogy

Carroll (1990) developed the concept of “minimalist instruction”[14], a pedagogical approach rejecting the traditional exhaustive instruction model in favor of light presentation. Key principles being:

- Start with realistic but simplified tasks
- Reduce cognitive load by presenting only essential information
- Favor active exploration and controlled trial-and-error learning
- Accept that learners discover progressively rather than teaching everything in advance

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[13] performance models. *IEEE Transactions on Systems, Man and Cybernetics*, 13(3), 257-266.

[14] Carroll, J. M. (1990). *The Nurnberg Funnel*. MIT Press. Minimalist instruction principles

This is exactly the philosophy we adopt: a "light pedagogical presentation" that introduces concepts when they are truly necessary.

The Allosteric Model of Learning

Giordan (1999) emphasizes that learning is a dynamic process where different mental structures can form or transform according to context and learner experiences[15]. This model recognizes the complexity of learning processes and the importance of creating favorable environments for this transformation, rather than assuming simple knowledge transmission.

Gardner's Multiple Intelligences

Finally, Gardner (1983) showed that several distinct forms of intelligence exist[16]. Proposing several approaches appealing to various forms of intelligence is a major asset for unlocking learner misunderstandings. Thus, Thermoptim mobilizes:

- Visual and spatial intelligence (through diagrams and schematics)
- Practical intelligence (through manipulation and simulation)
- Logical-mathematical intelligence (through equations and calculations)

This is all the more important as psychological blocks regarding the discipline often exist among learners due to difficulties encountered in their prior training.

2. Thermoptim: An Educational Technology Response to Pedagogical Difficulties

2.1 Origins and Simulator Development

Thermoptim was developed from 1997 in response to serious difficulties we encountered in traditional applied thermodynamics teaching. The objective was to make students capable, at course completion, of tackling contemporary energy challenges: reducing environmental impact of technologies, modeling innovative systems, improving efficiency under acceptable economic conditions. With classic pedagogies, this objective was unattainable.

After experimenting with spreadsheets so students could perform calculations for studied systems, it became clear that using a single versatile tool encapsulating professional knowledge was preferable. Thermoptim was therefore developed to fill this gap and gradually emerged as a pedagogical and professional standard.

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[15] Giordan, A., & De Vecchi, G. (1987). *Les origines du savoir*. Delachaux et Niestlé. Allosteric learning model.

[16] Gardner, H. (1983). *Frames of Mind: The Theory of Multiple Intelligences*. Basic Books, New York

2.2 Dual Systemic and Analytical Approach

One of Thermoptim's main assets is its dual systemic and analytical approach[17][18].

- **Systemic dimension**: Systemic representation allows visualizing connections between components of a complex energy system. An intuitive graphical environment facilitates constructing and understanding the system's global structure. This approach is particularly useful qualitatively because it can be done visually and allows understanding each component's role in the complete system. This separation between qualitative system understanding (its structure) and quantitative study of its components considerably reduces cognitive load.

- **Analytical dimension**: For each component, detailed and possibly customized analytical models can be defined. Thermoptim thus ensures coherence of complete multi-component system models, while drastically reducing error risks in generating equation sets. Modeling is both facilitated and secured. Note in passing that once the model is established, Thermoptim can export all corresponding equations, which can then if desired be solved in other environments, notably by generic solvers.

2.3 Conceptual Structuring

Thermoptim is based on distinguishing elementary concepts called **primitive types**:

Hierarchy of Primitive Types in Thermoptim:

Project

├── SUBSTANCES (fluid properties)

│ ├── POINTS (thermodynamic states: P, T, other variables)

├── PROCESSES (extensive calculations with mass flow rates)

│ ├── Compressions

│ ├── Expansions (with or without work)

│ ├── Combustions

│ ├── Heat exchanges

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[17] Gicquel, R. (2004). Apports de Thermoptim : structuration conceptuelle et approche visuelle. *Bulletin de l'Union des Professeurs de Physique-Chimie*, 869, 1783-1810

[18] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/Model_syst_simples_complexes.html

├── NODES (fluid networks)

│ ├── Dividers

│ ├── Mixers

│ └── Phase separators

└── HEAT EXCHANGERS (coupling two fluids)

This structuring is inscribed in a "Project" that encapsulates all these elements. Meticulous design of corresponding screens, performed in collaboration with numerous teachers in the field, ensures they are both simple and complete, with formalism very close to that used in practice. This attention to pedagogical interface design is fundamental: it reduces the attention bias (split attention) mentioned above.

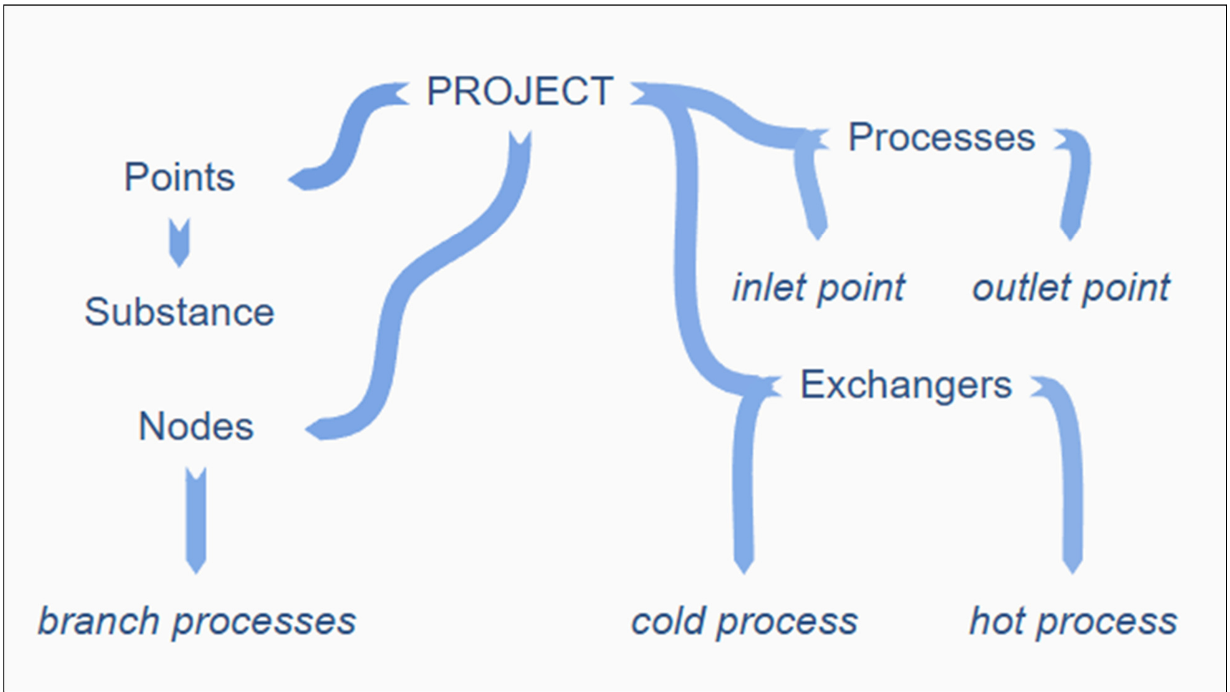

Figure 3: Thermoptim Structure

2.4 How Thermoptim Reduces Cognitive Load

Thermoptim reduces learner cognitive load in several ways, directly consistent with Sweller's theory[19]:

1. **Eliminating tedious calculations**: By handling most quantitative aspects, students can focus on acquiring the discipline's thinking patterns. Automation operates at the conceptual rather than computational level.

2. **Encapsulating vocabulary and concepts**: Screens are carefully designed so content is as simple as possible. Once this vocabulary is learned, cooperative learning with peers and teachers is strengthened.

3. **Reducing split attention**: The schema editor gathers all relevant information about a thermodynamic cycle on a single screen (structure, interconnections, state variable values, global balances).

4. **Worked Examples as starting point**: The best and fastest way to learn using Thermoptim is to start with the four getting-started examples, which are treated step by step according to pedagogical recommendations from scientific literature. Guided model explorations make this easy.

5. **Increasing problem-solving capacity**: Thermoptim places task automation at a higher conceptual and methodological level. For learners, there is not only cognitive load reduction, but also significant increase in problem-solving capacity.

6. **Motivations and operability**: By providing a professional learning environment (the software is used by CEA, EDF, Framatome...), Thermoptim makes students truly operational, which is a major factor in their motivation and attention.

3. Three Modes According to Learner Level

3.1 The Light Pedagogical Presentation

The set of developments in digital resources and pedagogical tools has as we said led to an evolution of our pedagogical approach integrating these new tools as well as concern for lightening scientific prerequisites as much as possible. We then speak of **light pedagogical presentation**.

As a result, our pedagogical approach can today be implemented in three complementary modes according to learners' scientific level.

[19] Gicquel, R. (2006). Place des simulateurs dans la conception d'environnements pédagogiques virtuels : réflexions méthodologiques. *SIMO 2006 - Systèmes d'information, modélisation, optimisation en génie des procédés*, Toulouse, 11-12 octobre 2006

3.2 Synthetic Table of Three Modes

Criteria	Mode 1 (Light)	Mode 2 (Progressive)	Mode 3 (In-Depth)
Target audience	Continuing education, MOOC, reduced scientific background	Undergraduate, active professionals	Master's, engineering schools
Theoretical concepts	Without entropy/exergy	Entropy + Carnot cycle + exergy balances	All advanced concepts
Diagrams	(h,P) only	(h,P) + (T,s)	All + Mollier (h,s)
Pedagogical tools	Simple guided explorations, Slideshows or videos	GE + Diapason modules	Advanced GE + autonomous construction
Approach	From concrete to abstract, immediate examples	Spiral: revisit concepts with increasing complexity	Classical disciplinary presentation possible
Autonomy	Maximum	Guided progressively	Semi-autonomous with projects
Prerequisites	Minimal	Moderate	Solid
Version	2.5	2.5, 2.6	2.5, 2.6, 2.7, 2.8
Available Fr	MOOCs	2023 Edition, Course 2023	Training modules
Available En	Course 2022	2021 Edition, Course 2022	Old modules

3.3 Mode 1: Light Presentation (MOOCs, Continuing Education)

The first mode, **light presentation**, addresses needs of those with reduced scientific background. It implements the **CFER** approach: what are the **Components** involved in energy technologies, what are their **Functions**, and what **Reference Evolutions** do they correspond to in thermodynamic diagrams?

Practical exercises use guided explorations of simple models, and the only type of thermodynamic diagram used is the enthalpy-pressure diagram. This mode uses neither entropy nor exergy.

Usage context: This mode typically corresponds to courses offered in our Thermodynamic Heat Conversion (THC) MOOCs and is particularly suited for continuing education.

Underlying pedagogical principles:

- Maximum cognitive load reduction
- Progression from concrete (solved examples) to abstract (concepts)
- Exclusive use for initiation of realistic and immediately comprehensible examples

- Maximum learner autonomy

3.4 Mode 2: Progressive Approach (Undergraduate, Professionals)

The second mode, which can be called **progressive**, addresses undergraduate learners or active professionals, not particularly motivated by theoretical aspects while capable of following them if necessary.

Structure: It starts with light presentation which is progressively completed by introducing a cycle improvement approach relying qualitatively on comparison with the Carnot cycle in the entropic diagram and quantitatively on exergy balances.

Underlying pedagogical principles:

- Spiral progression where concepts are revisited at increasing complexity levels
- Alternation between visual and quantitative approaches
- Progressive completion of modeling projects of increasing difficulty
- Regular feedback through self-assessment

3.5 Mode 3: In-Depth Approach (Master's, Engineering Schools)

The third mode is intended for master's or engineering school students familiar with theoretical developments. It differs from previous ones in three important points:

Point 1 - Disciplinary presentation: These students are accustomed to "Cartesian" and disciplinary presentation of their teachings. Nothing prevents starting by presenting all theory before moving to applications, according to their pedagogical expectations. However, the **CFER** approach can also be used.

Point 2 - Powerful mathematical tools: Since using entropy poses no problem for them, entropic diagrams (T,s) or Mollier (h,s) as well as exergy and exergy balances can be very quickly introduced. These powerful tools offer a rigorous basis for cycle optimization.

Point 3 - Complete resources: Practical exercises use both guided explorations, including those using Thermoptim's advanced features, and Diapason modules where learners build their models themselves.

Underlying pedagogical principles:

- Systematic construction of rigorous schemas fitting within prior training continuity
- Use of exergy balances as analysis and optimization tools
- Development of original and complex models
- Access to advanced features (dimensioning, off-design operation, pinch method optimization)

4. Course Structure and Pedagogical Resources

The 2022 Online Course on Energy Systems[20] develops step by step the implementation of this pedagogy for **first mode** and the second edition of the book of the same name published in 2021 by CRC Press[21] uses this pedagogy for **second mode**.

4.1 Energy Systems: 3rd Edition Architecture

The work comprises three volumes totaling approximately 800 pages, enabling coherent progression:

First volume (275 pages): Introduces essential concepts and three basic energy technologies (steam power plant, gas turbine, refrigeration machine). CFER approach (Components, Functions and Reference Evolutions): architecture descriptions → main function identification → fluid reference evolutions.

Second volume (280 pages): Classical thermodynamic installations. Shows how to use powerful tools (entropy, exergy, exergy balances) to improve performance. Guiding principle: irreversibility reduction.

Third volume (240 pages): Innovative low environmental impact systems. Advanced cycles, Stirling engines, nuclear reactors, oxycombustion cycles, renewable energies, etc.

4.2 Complementary Digital Resources

Guided Explorations (GE)

Nearly 45 guided explorations of models of approximately 30 different energy systems enable progressive and secure discovery of most existing technologies. GEs propose different activities to learners: finding values in simulator screens, reparameterizing models to perform sensitivity analyses, visualizing cycles in thermodynamic diagrams.

Guided explorations are "worked examples" type learning in Sweller's sense: they allow learners to understand structure without being overwhelmed by calculations or manipulation errors.

Narrated Diapason Modules

About thirty narrated Diapason modules (Pedagogical Animated and Narrated Slideshows) complement guided explorations. These modules allow following courses or learning to build models. The multimodal approach combines image, text, and sound for better understanding and retention.

[20] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/module_Enseignement_4.html

[21] https://direns.minesparis.psl.eu/Sites/Thopt/en/co/secondEditionEnerSyst.html

For THC MOOCs, several of these Diapason modules were recorded in video format, often appreciated by learners.

Self-Assessment Activities

Approximately 70 online self-assessment activities are offered. Their main objective is to allow each learner to verify their understanding of different concepts presented immediately after viewing a Diapason module or video. Five exercise types have been developed:

- **Drag-and-drop on image (DDI)**: Verify positioning in a diagram or graph
- **Gap-fill texts (GFT)**: Reformulate presented concepts
- **Categorization exercises (CAT)**: Organize elements and distinguish their characteristics
- **Single-choice questions (SCQ)**: Test knowledge quickly
- **Multiple-choice questions (MCQ)**: More global but less user-friendly approach

Digital Pedagogical Resources (DPR)

Over one hundred realistic examples of cycles modeled with Thermoptim offer readers models whose structure or parameters they can customize. The Thermoptim-Unit portal (www.thermoptim.org) centralizes most of these resources, with access to solutions sometimes reserved for teachers only.

4.3 Thermoptim-Unit Portal

To facilitate access to these digital resources, a dedicated portal was created (www.thermoptim.org). This portal contains:

- Over 900 pages of pedagogical resources
- An integrated search engine to navigate among resources
- Links to guided explorations
- Access to Diapason modules
- Model examples with pedagogical comments

5. Assessing with Thermoptim

5.1 The Pedagogical Contract

To reduce anxiety and eliminate any ambiguity about what is expected, we find it preferable to distribute at course beginning a pedagogical contract detailing different knowledge categories to acquire:

1. Knowledge: clearly distinguishing what must be memorized from what must simply be understood.
2. Know-how (practical skills).
3. Analytical and synthesis aptitudes.

Each of these categories must be precisely described, and final assessment must conform to this contract.

Indeed, many teachers do not think to carefully explain their course's pedagogical objectives, considering them obvious when this is rarely the case. As a result, they are not very sure of themselves or what they expect from their students, and students are anxious because they have not been sufficiently told what is expected of them.

From this perspective, one asset of online teaching is that it leads to explicating a set of teaching-related elements rarely explicated in classic courses. This should however be done if implementing a true quality approach in this domain is desired.

Establishing a trust relationship between teacher and students seems to us a prerequisite for the course to proceed under good conditions. One constraint is that the teacher is often a researcher who has a teaching "load" to fulfill. Moreover, when beginning, they are generally isolated to perform this task and must manage alone, whereas for their research activity they benefit from laboratory support. Their pedagogical training is at best limited and their available time is counted.

5.2 Summative Assessment and Fighting Fraud (Role of Oral Examination)

For online courses and given generative AI existence, assessment requires special precautions.

- **Oral Examination**: This is the assessment mode providing the best guarantee against cheating. The teacher addresses the student directly, making it very easy to realize their knowledge level. Our experience indicates that a duration of about 15 minutes is sufficient to assess a student. In person as by videoconference, keeping an examination recording as reference in case of grade contestation may be desirable.

- **AI and Cheating**: Generative AI allows students to obtain very elaborate answers, making personal reflection work superfluous. In pedagogies like *enquiry-based learning*, it is therefore preferable to assess students orally several times to verify their personal involvement.

- **Know-How Assessment (Simulators)**: To assess learners' ability to use a simulator like Thermoptim, one solution is to have them solve a simulation problem requiring parameter change to an existing model (Guided Exploration). Results are then verified by MCQ or SCQ, ensuring operational know-how assessment. Since AIs cannot yet perform these simulations, cheating risk is reduced.

6. Implementation and Pedagogical Results

6.1 Usage Flexibility According to Pedagogical Contexts

Pedagogically, the Energy Systems book and Thermoptim can be used in various contexts, both in a traditional approach (neo-behavioral or objectivist) and in a more recent constructivist approach.

Use in Conventional Approach

For proponents of a conventional approach, Thermoptim allows enriching classic presentation with precise simulations and having students work on multiple realistic examples. Results are more accurate than those obtained with manual calculations and learners can quickly study many cases.

For teachers favoring the Anglo-Saxon method and wanting their students to write system equations themselves, it is possible using Thermoptim to build them graphically and generate all corresponding equations to then analyze and solve them independently of the software.

Use in Constructivist Approach

In a constructivist approach, the book and software are additionally tools enabling students to work autonomously to explore a broad field and analyze very open subjects:

- **For beginners**: It's a structured environment reducing cognitive load while facilitating acquisition of vocabulary and basic concepts encapsulated in screens. Once this vocabulary is learned, cooperative learning with peers and teachers is strengthened.

- **Quickly**: It becomes possible to work on realistic and non-caricatured problems (for example, cycles using real fluids rather than perfect air). Moreover, during internships, students using Thermoptim are fully operational in the company where they work, which is very motivating and leads them to engage more deeply.

- **For confirmed users**: Thermoptim allows them to study very complex systems (for example, Framatome used Thermoptim to optimize combined cycles and cogeneration cycles coupled with high-temperature nuclear reactors).

6.2 Observed Empirical Results

Experience accumulated over more than 25 years and more than 120 higher education institutions (from undergraduate to engineering schools) demonstrates:

- **Increased student motivation**: Transformation of relationship to the discipline, passage from initial reluctance to adherence
- **More active participation**: Students engage much more than before
- **Work at own pace**: More assiduity and personal involvement

- **Rapid tool mastery**: Software learning time is very reduced, especially using guided explorations
- **Better assimilation**: Deeper and more lasting concept understanding
- **Requests for deepening**: Initially reluctant students often request complementary theoretical developments once their blocks are overcome: they want to "understand what's under the hood."
- **Increased teacher satisfaction**: More interesting and personalized contacts with learners
- **Greater involvement and responsibility**: Students working on realistic examples feel responsible

6.3 Professional Pedagogical Applications

Beyond academic teaching, Thermoptim has been used for over 10 years by the French Navy for training operators of propulsion systems for nuclear submarines and the Charles de Gaulle aircraft carrier. Previously, many among them were resistant to classic equation approaches, leading to demoralization and dropouts. The Thermoptim-based approach, which prioritizes conceptual and visual understanding before equations, has transformed this situation.

6.4 Thesis in Education Sciences

A thesis in Education Sciences was defended on February 3, 2016, by Ms. Atika MOKHFI, to obtain a doctorate from Aix-Marseille University.
Its title is: "Study of an Open Access Distance Learning System on the Web: A Didactic Approach to Teaching Work in Higher Education. The Case of the Thermoptim-UNIT System at MINES ParisTech School."
This thesis is notably based on surveys conducted with teachers and students in the field using the Thermoptim system, carried out through questionnaires and interviews, whose testimonies confirm the validity of the approach.

7. Key Methodological Principles for Implementation

7.1 From Axiomatic Approach to Pragmatic Approach

What proved most effective is adopting a progressive pedagogical paradigm based on cognitive load theory results.

The Problem of Classic Axiomatic Approach

Traditional teaching often starts with complete theory (First Principle, Second Principle, fluid properties, state equations...) and then assumes students will be able to apply it. However, this creates massive initial cognitive load for learners: they must first memorize numerous abstract concepts before seeing how to use them concretely. Moreover, reduction in hours devoted to technical teaching means students no longer have time to train by this method while putting acquired knowledge into practice on realistic examples.

The Proposed Progressive Pedagogy

Conversely, we propose a progressive and pragmatic approach:

1. **Phase 1 - Immersion in Reality**: Start by showing students how Thermoptim allows them to “do thermo painlessly” and obtain very accurate results without writing a single equation. Students thus acquire vocabulary and basic concepts, anchored in concrete and visual examples.

2. **Phase 2 - Lifting Psychological Blocks**: Once initial reluctances are overcome and they have assimilated vocabulary and basic concepts, it becomes possible to take a new step and progressively introduce more equations. Students, having seen how this knowledge can be put into practice, become much more receptive to Theory.

3. **Phase 3 - Theoretical Deepening**: As soon as psychological blocks set up by overly axiomatic presentations fall, students become much more receptive to equations, probably because they no longer fear finding themselves unable to put them into practice. It then becomes possible to study difficult problems like technological dimensioning and off-design behavior.

Importance of Understanding Real Technological Constraints

We also find it fundamental that learners understand technological constraints existing in different machines (steam power plants, gas turbines, internal combustion reciprocating engines, refrigeration machines, etc.), otherwise they risk reasoning disconnected from reality. This is why we give in courses and throughout the book detailed technological explanations on machine operation, often elided by teachers.

7.2 Modeling as Bridge Between Knowledge and Know-How

Thermoptim illustrates the importance of modeling as a bridge between knowledge and know-how, between declarative and procedural knowledge. Modeling is the translation of symbolic generalizations (Theory) in a particular context, to solve a puzzle (a problem). It’s a fundamental act connecting theory to practice.

7.3 Transposition to Other Disciplines

Although developed specifically for applied thermodynamics, the pedagogy based on Thermoptim and its underlying principles are certainly transferable to other disciplines. Methodological milestones based on:

- Cognitive load theory for pedagogical organization
- The RTM(E) model for knowledge structure
- Scientific simulators for practical application

...should be applicable to process engineering and probably other scientific and technical domains, with appropriate adaptations of course.

R. Gicquel January 2026

Conclusion

Energy systems pedagogy based on Thermoptim represents a radical and scientifically grounded reconception of applied thermodynamics teaching. By integrating solid theoretical foundations (cognitive load theory, RTM(E) model, complementary cognitive models) with innovative technological tools (Thermoptim simulator, Diapason modules, guided explorations, self-assessment activities), this approach has transformed the learning experience for over 120 higher education institutions worldwide. Results are clear: improved student motivation, better concept assimilation, positive transformation of relationship to the discipline, rapid acquisition of operational professional skills, and satisfaction of teachers and user companies. Beyond the specific field of energy, the developed pedagogical principles offer promising perspectives for other scientific and technical disciplines. The progressive approach (from simple to realistic, from qualitative to quantitative), cognitive load reduction, mobilization of multiple forms of intelligence, structuring of learner schemas, and creation of professional learning environments constitute the pillars of effective and motivating pedagogy, coherent with current state of knowledge in cognitive sciences and didactics.