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Lazaros Mavromatidis. Coupling architectural synthesis to applied thermal engineering, constructal thermodynamics and fractal analysis: An original pedagogic method to incorporate “sustainability” into architectural education during the initial conceptual stages. Sustainable Cities and Society, 2018, 39, pp.689-707. 10.1016/j.scs.2018.01.015 . hal-02398173

HAL Id: hal-02398173

<https://hal.science/hal-02398173>

Submitted on 4 Jan 2022

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To cite:

Coupling architectural synthesis to applied thermal engineering, constructal thermodynamics and fractal analysis: An original pedagogic method to incorporate “sustainability” into architectural education during the initial conceptual stages, *Sustainable Cities and Society*, Elsevier (IF : 7.587, SNIP : 2.347, SJR : 1.645), pages 689-707, Volume 39, mai 2018, doi:10.1016/j.scs.2018.01.015

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Abstract

This paper describes an original didactic approach to integrate sustainability and building applied thermal engineering methodology with the architectural education. It presents the pedagogical and scientific dimension of a seminar-workshop that has been conceived in order to accomplish the aforementioned objective. Three educational models of architectural synthesis have been

converged to common methodology. According to the present educational program's guidelines complex volumes have been produced, while an evaluation engine was created on the basis of simplified calculation models, in order to provide formal modifications, evaluate the formal solutions and choose the optimum solutions preserving the initial architectural idea. In its final stage, the project featured the refinement of the conceptual architectural design focusing on the energy consumption aspects. As a result of this pedagogical project, it was observed that the adopted methodology produced reliable results for the pedagogical purpose in the nine projects that consisted the direct output of the seminar, while the creativity of the participants has been preserved during the entire process. Furthermore employing constructal thermodynamics we investigated the architectural quality of the produced volumes. However, a direct perspective of the presented approach could be to extend this method until the detail scale in order to offer to it more temporal importance in the schedule of the discipline.

Keywords: bioclimatic design; architecture; constructal thermodynamics; fractal theory; building energy consumption; metastable volumes; low energy building; sustainable architecture; architectural morphogenesis; Gouy-Stodola theorem

1. Introduction and general context

There is widespread acceptance that the Building Sector is one of the most important contributors to climate change. More precisely, many research studies revealed that the Building Sector endows more than the transportation and the industry sectors to the long-term change in the earth's climate, due to an increase in the average atmospheric temperature. For example, the U.S. Energy Information Administration (EIA) recently published a report where it is quantified that *"the Building Sector consumes nearly half (47.6%) of all energy produced in the United States and consequently seventy-five per cent (74.9%) of all the electricity produced in the U.S. is used just to operate buildings. Globally, these percentages are even greater"* [1]. Similarly, in Europe the building sector is assumed to be responsible for about 42% of final energy consumption, 35% of greenhouse gas emissions and 50% of material resources consumption [2]. Additionally, European authorities recognized that we dismantled a turning point in the earth's climate system and consequently the building legislation is conformed to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [3]. Henceforth, a novel institutional framework that introduced new guidelines and directives that impose the adaptation of the entire building industry to new high performance targets for building labeling is

enacted by corroborating the necessity for immediate and sustained action on climate change.

Consequently, we are witnessing the emergence of a new emblematic architecture that responds to the demands of the urban economy and focuses on *"sustainable development"*. As it has been analyzed in the past, this production, which builds its own values, and simultaneously questions their necessity, is not yet able to aesthetically and culturally respond to the growing need to compose an original landscape of symbolic values by producing a new *"radical imaginary"* as it is defined by Castoriadis [4-8]. In previous research [9] it was demonstrated that starting from Maria Kaika's research findings and employing the vocabulary and the philosophical theory of Castoriadis, we could assume that the emblematic architecture, which constitutes an *"urban totem"*, may give form and substance to this real social need for climate change mitigation purposes.

However according to James Wines *"much of the ecologically motivated work today, acclaimed as green or contextual, is nothing more than a catalogue of environmental technology and land conservation systems tacked onto otherwise conventional buildings and landscapes"* [10: p 53]. As we understand, Wines

implies that the imaginary system related to architectural creativity regarding the evolution of architectural forms is always imprisoned in the sterile normative context of every period.

This paper develops the idea that new pedagogic methods and tools are needed to bridge this gap between architectural sustainability and environmental sustainability. There is widespread acceptance among architects – professionals and students- that the formal banality of contemporary bioclimatic architecture, which is confined to the reproduction of proven architectural forms and the procreation of “effective” solutions, has as a result to solely concentrate on the technical aspect of architecture and not on morphogenesis [9]. For this reason the student of architecture seems to be demotivated and do not invest time and effort on the apprenticeship of building thermal engineering practices and the re-invention of the icon due to the climate change context. On the other hand there are many research studies that aim to assist professionals architects in order to conceive in a sustainable way [10-15]; however only few of them are applied to the pedagogy bridging the gap between research and education [16-19]. Through this paper it is claimed that the role of education for re-inventing the sustainability within an exemplary architectural pedagogic framework can contribute to the environmental awareness of the student in architecture and to

the creation of common aesthetic of energy, while architectural production may constitute the effective support for the creation of new collective identity. Nonetheless to achieve this goal current applied thermal engineering practices should be integrated as soon as possible to architectural education in a creative manner with the aim to complete the paradigm of an informed citizen, while simultaneously develop the intellectual, aesthetic and scientific capacities of a future professional.

1.1. Main points and originality of the new pedagogic method in relation to architectural synthesis

A “*professionalist*” pedagogic method for teaching architectural synthesis transmits the necessary tools, the attitudes and a purely professional point of view, to the students of architecture [11]. From this perspective it seems not to be very difficult to integrate within a “*professionalist*” teaching approach a solid scientific background and methodology even if science is oriented towards the discovery of novel paths. However, according to this didactic approach the students and future architects are merely evaluated from the final project (plan, section, elevations of a building, calculation output) that they present. In this case their project should display the traditional characteristics of a professional

project (conformity of the edifice drawn with architectural reference models, constraints of orientation, proportions and quantities of space, circulations between spaces, insertion at the site, etc [11]). Most of the time, this method seems to be considered as a “*black box*” by the students, while the tutor is necessary only in order to provide successive intermediate corrections during the exercise in order to reach an acceptable final result. In contrary, the “*theorized*” approach aims to provide an operational autonomy to the student, in order to construct his own theoretical and methodological framework regarding the architectural synthesis. The aim of this pedagogy is to enable the student to acquire “*a coherent mental construct*” [11].

Ergo, the main concern of the present pedagogic method was to define a common place to conjugate these three phenomenally opposite approaches: professionalist, theorized and scientific. For this reason a concrete exercise of space creation has been conceived in order to conjugate artistic, professional, theoretical and scientific elements around the subject of sustainable development.

The aim of the original pedagogic approach presented in this paper has several characteristics:

- 152 ▪ develop the ability of the students to verify their own choices;
- 153 ▪ develop the awareness of the boundaries between architectural desires
- 154 (poetic and artistic hypothesis, circulation distribution) and architectural
- 155 constraints (the orientation of an edifice according to natural light / the
- 156 energy impact of the conception);
- 157 ▪ develop an attitude of constant self-criticism;
- 158 ▪ develop the capacity to produce architecture based on systematic and
- 159 multiform criteria.

160

161 Additionally and more specifically according to our subject, via this method it
162 was pedagogically managed to :

- 163 ▪ Introduce the notion of metastability
- 164 ▪ Experiment a new design method
- 165 ▪ Define a framework for conceiving and continuously transforming a
- 166 volume placed in an evolving context;
- 167 ▪ Teach the necessary tools to optimize energy potential and / or promote
- 168 interactions with the environment;
- 169 ▪ Provide the necessary ad hoc tools to evaluate the impact of conceptual
- 170 decisions on the energy identity of a complex volume

171

Henceforth, the first aim of the pedagogic research that is presented here was therefore to initially analyze how the students of architecture take into account the energy issues in their practices of architectural synthesis. It was tried to identify when -and on what scale of the project- energy concerns are integrated into the design process and it was realized that energy issues are treated only during the last phases where they examine their projects at the detail scale. Thus, an original process of architectural synthesis was designated through a concrete exercise of volumetric space creation in order to guide the students to produce and simultaneously evaluate at early design stages on the basis of their physical translation a variety of volumetric choices of infrastructures. The main purpose of this pedagogic action was to demonstrate how an informed citizen-professional can contribute to the environmental, social and economic sustainable development through innovative architectural design and how citizen' choices can forward architectural production and aesthetics towards sustainability.

To apply this theoretical pedagogic research a seminar-workshop entitled "*Materiality, envelope and metastable volumes: informed architectural design in the prism of sustainable development*" has been conceived, organized and animated from 19 to 22 January 2016 by the author, in partial fulfillment of the

192 Architecture undergraduate inter-semester program belonging to Department
193 of Architecture of the National School of Applied Sciences of Strasbourg. The
194 pedagogic aim of this seminar was to stimulate students to achieve high-level
195 energy performance results along with expressive aesthetic and functional
196 architectural solutions. The aim of the seminar was to continuously design and
197 transform an architectural object placed in a defined changing context by
198 optimizing it from the point of view of its energy potential and by promoting or
199 limiting appropriate interactions with the environment. More concretely, the
200 seminar aimed to teach participants to evaluate the impact of their conceptual
201 decisions on the energy identity of the designed volume through the use of
202 simple meta-models for assessing its energy impact by defining their own
203 assumptions and approximations. Since the present pedagogic approach has
204 never been applied in the past, the seminar was integrated in the short inter-
205 semester pedagogic framework, while 25 undergraduate students of
206 architecture from the 3rd to the 10th semester voluntarily participated. As a result
207 of the term, it was observed that the adopted methodology produced reliable
208 original and innovative results for the pedagogic purpose in the nine presented
209 projects; nevertheless according to the participants' positive evaluations (95% of
210 fully positive answers) of the seminar the final stage may require more temporal
211 importance in the schedule of the discipline, in order to develop the project up

to the detail scale during an entire semester instead of only three days.
Henceforth, the present paper aims at describing and presenting the theoretical
concepts, the pedagogic methodology and aspects and finally the guided
architectural design process and the output evaluation using constructal
thermodynamics.

2. Pedagogic approach in terms of conceptual innovation: the integration of applied thermal engineering concepts to a training of architects and engineers

The students of architecture are confronted with a wide universe of doubts
during the action of creation. The academic educational program of all the
architectural schools is very condensed and requires lot of personal work since
the tutors are just there to provide advices and guide the student through a
complex universe of choices. Although the architecture courses are exciting,
they also involve so many exceptions and possible misconceptions and
convincingly the students reasonably wonder if eventually there is anything
tangible to learn about architecture. Nonetheless, according to Matthew
Frederic [12] this inherent ambiguity in the teaching of architecture is greatly
needed. The architecture is above all a creative field and for this reason the
difficulties faced by teachers regarding the teaching of their expertise within an

entirely specific pedagogic structure may block the transmission of knowledges because of the fear of imposing unnecessary restrictions on creativity [12]. Ergo, the present pedagogic method was developed by enriching classic architectural conception exercises in order to strengthen the foundation of architectural synthesis providing points, practices and calculation methods on which the design process can rely and thrive around the issue of sustainability. To achieve this objective, the aforementioned general context had to be redefined and a way to introduce an aesthetics of energy employing applied thermal engineering concepts and methods had to be re-invented. Hence, the underlying concepts of the seminar was to revisit the instituted relationship between energy-matter-volume, since these three parameters are the main concern of architecture. Furthermore, the theory had to be completed with a concrete exemple of space creation that enhances the students' creativity while they follow an autonomous but guided waypoint navigation through the univers of coupled architectural creation and energy performance evaluation.

2.1. Step n°1: a little bit of epistemology or the evolution of the complex relationship of the dipole energy-matter in our scientific instituted imaginary

Initially, it was revealed that an upstream issue that has to be clarified within the student's instituted imaginary is the complex relationship of the dipole energy-

257 matter. Even if this issue seems to be obvious, to define force as a "*measurable*
258 *quantity*" we would have needed to wait until 1687 when Isaac Newton
259 introduced the dipole « *force-field* ». At the same time, this kind of
260 interpretation of the nature seems nowadays idealized since any complexity was
261 absent from his equations while the dimension of energy is hidden. Similarly, the
262 instituted approach that strips architecture from its complex dimension and
263 transforms it to a simple conjunction of materials, while sustainability enters to
264 the equation via the post-process application of sterile technical solutions seems
265 to be surpassed. Likewise, with the passing of time, the thermodynamicists
266 introduced the notion of complexity by deciding to deviate from the vision of
267 classical mechanics. Due to the fact that they had to face a fragmented, complex
268 and rich in potential nature, they were doomed to introduce the concept of the
269 "*system*". This systemic vision is a keypoint when we try to integrate
270 sustainability with the architectural education since the students should
271 understand that they are about to design a controlled open system that is
272 composed from matter and space while there is a hidden energy beyond their
273 conceptual choices. Besides, Faraday's work on electromagnetism -and
274 especially his definition regarding "*force fields*"- gave a different existence to
275 the space notion because he deciphered space as an energy field "*travelled by*
276 *line forces*" [13-14]. Thereupon, the space within an architectural volume is not

277 an empty area but an energy field with a hidden potential, and this potential
278 should be explored and optimized via architectural choices. Finally, Einstein
279 throughout his theory of relativity, relinquished a novel interpretation unifying
280 the range of assumptions about the fields, by demonstrating the conversion
281 between matter, energy and space through his famous equation $E = mc^2$. So
282 concretely he instituted throughout his theory of relativity that the matter is
283 nothing more than a "*huge reservoir of energy and that energy is made by*
284 *matter*" [13]. And thus leaving beyond us the dipole "*force-field*" we arrived to
285 the instituted dipole "*matter-energy*" via the mathematization of physical
286 phenomena. Recently Bejan developed an extremely original idea
287 (reinterpreting and proving scientifically the phrase of Heraclitus, the ancient
288 greek philosopher, "*τὰ πάντα ῥεῖ καὶ οὐδὲν μένει*" / English translation: everything
289 flows, nothing stands still) introducing the flow notion to every existing animate
290 and/or inanimate system: everything that moves, whether animate or inanimate,
291 is a flow system [15]. Introducing the constructal law (as we will see later) he
292 managed to give a flow dimension to the complexity of architecture: in every
293 time step there exists only one optimum configuration in accordance to the
294 environing context, while this configuration in order to persist over time should
295 evolve and readapt to the evolved environing context. Thus, for us here the key
296 point to integrate sustainability to architecture deals with the re-invention of this

complex relation between matter and energy by integrating a systemic approach, in order to optimize the inner and outer spaces' potential that is simultaneously seen here as a complex energy field and a flow problem.

2.2. Step n°2: the architecture through the prism of "*sustainable development*" and the concept of a non-expert system under constant evolution

In this paper it is claimed that a novel pedagogic method is necessary in order to imagine a different reading of the eco-efficient architecture, institutionally called "*sustainable*" and/or bioclimatic. Perseveringly, beyond the aforementioned theoretical scheme the main novelty of the present pedagogic proposition subsists through the aim of outlining a radical framework in regard to the design process applied to the conception of eco-friendly architectural forms by binding the design of a space to an evolving energy potential that is attached to the aforementioned dynamic concept of matter and energy. In the institutional context of "*sustainable*" architecture the building notion embodies the architectural form as well as the entire systems (HVAC, heating pumps, renewable energy generators such as PV panels, etc) and is presented, studied and evaluated as an "*expert system*" that is to say, as a system that does not offer at all or offer an insignificant degree of freedom. Nevertheless, the spatial

location of a designed volume (wherefore its position within a specific field consists its context) directly determines the relationship of this volume to a potential available energy balance sheet. Ergo, this relationship is dynamic and evolves over time. Thus, the designed architectural object enacts as a part of a colossal system and this sizable infinite system is not closed and isolated. Besides it is a constantly evolving system.

Moreover, the concept of "*climate change*" indicates a systematic long-term change in the statistical distribution of atmospheric parameters (temperature, humidity, wind) for an extended period (decades or centuries or millions of years). In relation to the aforementioned statement the "*climate change*" era illustrates a rapid changing environment and a continuous change of the dynamic context where an architectural form is implemented. Therefore, the main statement here is that the context in which we place our architectural three dimensional designs inflicts a change in the way of distribution of the already contained by the system energy that is continuously recycled through the notion that we define here as "*energy potential*". And this "*energy potential*" is always constant due to the three laws of thermodynamics. Thence all this reflection guided to focus on the development of an interdisciplinary pedagogic method that attends to implicitly explore the three below fundamental questions:

- 339 ▪ How architectural design can explore the processes that explain the
340 relationship between form, material and energy
- 341 ▪ How these processes can provide significant information regarding the
342 energy potential of an architectural design and continuously transform a
343 specific complex volume to optimize this energy potential through the
344 design via a continuous dynamic transformation of the form
- 345 ▪ How we can evaluate the architectural output from an objective
346 architectural theory point of view without struggle students' liberty and
347 creativity

348

349 Thus, the aim of this pedagogic orientation is to develop a methodology for
350 assisting the design through a process of an informed continuous transformation
351 of an architectural object, placed in a precise context. In a concrete manner, this
352 transformation endeavors to provide changes on the architectural form by
353 optimizing the energy potential of the building form, while promoting or limiting
354 appropriate interactions with the environment. More concretely the
355 methodological output of the present pedagogic approach aims to assist
356 architects (students or professionals) to assess the impact of their design
357 decisions on the energy identity of the designed volume, through the manual

use of simple meta-models for assessing its energy impact by defining their own assumptions and approximations.

To accomplish this task and exasperate the radical imaginary of the students it was needed a philosophical conceptual start point with a strong scientific background. This start point was therefore borrowed from the thermal applied science engineering field by employing the thermodynamic concept of “metastability”, involving also the concept of potential energy of a system. “Metastability” is a concept of thermodynamics that defines the ability of a state to be stable kinetically but not thermodynamically. This concept likewise introduces the concept of potential energy. Thus, energy fluctuations allow a system to adopt different equilibrium structures, that is to say, to continuously transform itself until the system reaches the ground state of lowest energy. In our case, therefore, and using the words of Simondon [14] the form became its volume via the “*stabilization of state [...] that establishes an interior transductive order within a real full of potential system*”. This concept when it is applied to our problem defines that this real full of potential system is the climate context and the specific site of the architectural object, as well as the architectural object that we are going to create. Once we have a given site and specific climatic conditions the architectural object that we are currently designing, sculpting or

transforming is seen here during these early conception stages as a metastable volume since its form is put under constant and continuous transformation in order to reach an optimum equilibrium state from the viewpoint of energy reduction and henceforth "*sustainability*". In other terms, in accordance to Bejan's constructal law, each metastable volume is seen as a finite-size flow system that in order to persist in time it evolved in such a way that provided easier access to the currents that flow through it [15].

In order to achieve the development of such an interdisciplinary approach, it was needed to develop a framework (in a concrete manner a realistic conceptual exercise) that conjugates architectural and applied thermal engineering practices in an implicit way focusing at an early design stage. In general, engineering is a medium that provides an infrastructure that assist us to communicate with each other through various commonplaces, and to understand the world in which we live through the mathematization of physical phenomena [8]. The direct pedagogic objective of this proposal was to enhance the creativity of students of architecture (and/or professional architect-engineers) in the institutional context of "*sustainable development*" and "*eco-efficient bio-climatic design*", which could potentially lead to an informed conceptual innovation via purely scientific parameters, dealing at the same time with what

398 puts forward very complex conceptual issues. Until today, conceptual innovation
399 in "*sustainable*" architecture is still hidden behind "*remarkable*" performances,
400 which are directly related to prefabricated technological devices, whereas it is
401 the technological innovation that has been the source of inspiration and not the
402 innovative way of designing the architectural object [9]. Ergo, the objective of
403 this pedagogic methodology is to provide the tools and an original
404 interdisciplinary approach that architects can use in the upstream phase to assist
405 their conceptual decisions during the processing of a project and
406 exasperate/accompany their inspiration. Approximate, validated, well
407 documented, robust enough and sufficiently precise existing meta-models
408 (derived from detailed and sophisticated applied thermal engineering dynamic
409 simulations [16-19]) are employed in the framework of this study to simulate in a
410 reasonable time, via a Microsoft Excel file a variety of formal solutions. The
411 output of these models is employed to proceed to a classification of a family of
412 different formal solutions towards the goal of finding an appropriate equilibrium
413 for the potential energy consumption of the solution. Different scales, and
414 different representations were account for these interactions towards the
415 objective of developing an energy performance-intuition standpoint and
416 "*reinvent*" the links between material, building envelope and volume, engaging
417 well-defined architectural arguments.

3. Materials and methods

Let's now explain in a concrete way the main elements of the conceptual exercise. From the painting *Auf Weiss II*, by Wassily Kandinsky (<https://www.centrepompidou.fr/cpv/resource/cKaan6A/rRREo7e>), the seminar participants have sketched a form by following the different parts of the table and adopting a certain type of conceptual alignment. This form has been reproduced in 2D employing a wire, and the output of this phase has been illuminated towards a wall with a lamp, in order to enable the students to obtain three projected shadows of different sizes and according to choreography. From these three thicknesses of shadows, they have deduced a plan, where a different material corresponded to each thickness: the thicker the line was, the more thermally inert the illustrated form from this line material was. From the plan and on the basis of repetitive gestures (rotation, folds, extrusions...), the participants constructed a complex volume, which has been three-dimensionally represented by a model. The volume was carved according to energy consumption calculation output to obtain a variety of formal solutions from the same family, testing among others a variety of possible volume orientations, towards the goal of reducing the volume's environmental impact. Thus, an evaluation engine was made on the basis of simplified calculation models, in order to evaluate the

formal solutions and choose the optimum solutions preserving the initial architectural volume.

3.1. Phase 1: Design a Complex Form

Let's enter now in the details of the conceptual exercise that is based on classic pedagogic concepts to introduce the student on the apprentice of the proportions and the rhythms. The entire phase is developed according to 6 distinct steps, while the 4 steps have been developed on the basis of classic introductory conceptual techniques such as them who are presented in the MIT open courses and are available via its internet site (<https://ocw.mit.edu/courses/architecture/4-111-introduction-to-architecture-environmental-design-spring-2014/assignments/>). The main difference and originality of the approach presented here is that in this phase we employed as a start point a Kandisky drawing in order to construct a complex form and we simply used the classic conceptual techniques that are included in the aforementioned MIT exercise in order to develop a rhythm and a set of proportions. In other terms the source of inspiration was the subjective interpretation of the Kandinsky pattern while we translated it into 3D volumes

employing classic architectural techniques. Consequently, the phase 1 has followed the following 6 steps:

- **Step 1:** The participants began the exercise by sketching a shape according to the different parts of the Kandinsky's drawing. This set of formal choices should have some type of conceptual alignment as a set of circumferences or a series of lineaments of the various possible architectural gestures.
- **Step 2:** A scale factor of about *1:100* or *1cm=1m* has been applied to each of the lines. This initial set has been used to start building a complete drawing. The participants started by drawing a main line, then continued drawing a series of rows, at the specified scale, by applying rotations, extrusions or other architectural gestures that follow a specific rule to create a rhythm (for example, clockwise). Each new successive line has been drawn using the previous line as a startpoint, producing a spiraling effect according to a specific rhythm to the final drawing. All the participants were invited to allow the lines to overlap and cut each other, but still maintain the spiral type clockwise direction.
- **Step 3:** Using the drawing produced in the second step, the participants began to carefully bend a steel wire so as to incorporate the design into

its shape. They produced an exact replica of the 2-D drawing with a continuous length of wire, through a series of careful bends.

▪ **Step 4:** Then the participants fastened two perpendiculars to each other cartons (dimension A3). They attached one of the two cartons to a vertical wall. They placed the formed wire against one of the two A3 surfaces attached to the wall and they located a light source in a precise position in front of the shaped wire. Using a pencil they lightly traced the produced shadows exactly as they appear without modifying or reducing shadows. The participants translated the rule they have developed to fold the pattern into a "*choreography*" of movements and rotations. After the accomplishment of three consecutive similar steps they moved the formed wire away from the wall along the path of the choreography while at each step, they traced on paper the shadow that is produced on the vertical carton.

▪ **Step 5:** Once they have finished drawing the shadows, they removed the paper with the traced shadows. A transparent layer has been placed above and the plot has been redrawn by faithfully reproducing the straight lines and angles produced by the shadows respecting with fidelity the fact that each different position of the wire produced shadows of different widths; thence this had been reflected in the weight of the

line used for each position. The resulting accurate and well-design trace clearly showed three different line widths: thin, medium and heavy.

- **Step 6:** Finally a three-dimensional pattern was built on top of the retraced shadow. Three-dimensional shapes matched the shadows by using three different thicknesses of material. The more thermally inert materials were represented by the heaviest lines, and the transparent materials (such as glazing) were represented by the lighter set of lines. Thus a certain materiality was defined. The same logic that guided the participants through the choreographic movement to cast shadows has been reused in order to build a 3D structure as a reproduction of a precise volume in space.

3.2. Phase 2: evaluate the different formal solutions

Once the complex volume has been conceived, the following method developed by Catalina et al [16-18] has been used. The below method allowed to predict the general heating requirement of the entire volume with less than 20% relative error according to [16-18]. Using this method, the heat demand coefficient Q_{LS} in kWh/m^3 was defined as a function of the building heat loss coefficient G (the overall heat loss coefficient in W/m^3K), the SES index (the

south equivalent surface in m^2) and $\Delta\theta$ (the difference between the desired temperature and the sol-air temperature in $^{\circ}C$) according to the following formula:

$$Q_{LS} = 18.454 - 21.498 \cdot G - 1.844 \cdot \Delta\theta + 0.024 \cdot SES + 4.668 \cdot G \cdot \Delta\theta + 0.067 \cdot G \cdot SES + 0.006 \cdot SES \cdot \Delta\theta + 12.352 \cdot G^2 - 0.012 \cdot \Delta\theta^2 - 0.0002 \cdot SES^2 \quad (1)$$

More precisely, and according to this method, the sol-air temperature has been calculated according to the location of the volume employing the mean sunshine coefficient I_h (obtained from Figure 1) and the mean annual temperature θ_0 (obtained from Figure 2). The South equivalent surface (SES) of each volume was calculated according to the glazed area of each facade multiplied by a coefficient according to the orientation of the façade. The building heat loss coefficient G that takes into account the thermal transmission coefficient U_{ma} which is the inverse of the thermal resistance of the envelopes has been also calculated for each volume. To employ this calculation method, we also needed precise information regarding the facade surface i , but also the final volume of our object and the air change rate η that was fixed equal to 0.5 for all the participants. Thus, we employed the following 3 equations :

534

$$535 \quad \theta_{\text{sol-air}} = \theta_0 + \frac{0.06 \cdot I_h}{17} = \theta_0 + 0.0035 \cdot I_h \quad (2)$$

536

$$537 \quad \text{SES} = \sum_{i=1}^n (A_i \cdot C_i) \quad (3)$$

538

539 where A is the glazed area in m^2 , C is the orientation coefficient (see table below

540 and figure 3 with the wind rose) and i is the facade index,

541

$$542 \quad G = \left(\frac{\sum A}{V} \right) \cdot U_{\text{ma}} + 0.34 \cdot \eta \quad (4)$$

543

544

where A is the overall surface area of the volume in contact with the air in m^2 , V

546

is the volume in m^3 , and U_{ma} is the average transmittance of the envelope in

547

WK/m^2 .

548

549 **Table 1** : C_i Coefficients for the calculation of the SES (data source: Catalina et
550 al [24]).

551

Envelope inclination (φ in degrees)	(1) SSE-SSO	(2) SSE-ESE and SSO-OSO	(3) ESE-ENE and OSO-ONO	(4) ENE-NNE and ONO-NNO	(5) NNE-NNO
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85°-90°	1.00	0.85	0.55	0.30	0.20
70°-84°	1.15	0.95	0.60	0.35	0.20
55°-69°	1.20	1.05	0.65	0.35	0.25
40°-54°	1.20	1.05	0.75	0.40	0.30
25°-39°	1.15	1.00	0.75	0.50	0.40
10°-24°	1.00	0.95	0.80	0.65	0.55
0°-9°	0.80	0.80	0.80	0.80	0.80

552

553

554 **Figure 1:** Horizontal global irradiation map for the French territory in order to
555 define the I_h for the sol-air temperature calculation using the equation (2) (source
556 data: NASA surface meteorology).

557

558

559 **Figure 2:** Map of the average daily temperature for the French territory in
560 order to calculate the sol-air temperature from the equation (2) (data source:
561 Météo-France).

562

563

564 **Figure 3:** Wind rose to facilitate the use of table 1.

Finally, in order to define the average transmittance of the envelope, the participants calculated the thermal resistance of each different element according to the following polynomial equation developed by Mavromatidis et al [19] that offered an interactive robust calculation:

$$R = \frac{1}{U} = 0.5708307 + 0.0092552 \cdot \chi - 0.0009931 \cdot \varphi - 1.3967974 \cdot k - 0.000007 \cdot \chi^2 + 0.0000383 \cdot \varphi^2 + 1.21817 \cdot k^2 + 0.0000039(\chi \cdot \varphi) - 0.0094171(\chi \cdot k) - 0.0006031(\varphi \cdot k) \quad (5)$$

where χ is the thickness in m , φ is the inclination in $^\circ$ and k is the thermal conductivity in W / Km . For 3, 4 or 5 layer envelopes, the participants chose the equation with 6 layers and applied the specific boundary conditions of the polynomial equation, or more precisely $x_{min} = 0.02$ and $k_{max} = 0.975$.

4. Results and main points of the methodology

Let's analyze now the output of the aforementioned original educational model developed for the teaching of sustainable architectural design to architects. The particularity of this method is that it aims to incorporate three symmetrical opposite conceptual processes defined as "*professionalist*", "*theorized*" and

584 *"scientific"*. The first consists in transposing empirical models of professional
585 behavior into teaching situation; hence in our case a specific context has been
586 defined in order to proceed to a volumetric study [11]. The second process
587 consists in constructing cognitive instruments [11] while these concepts and
588 methods are being transposed into the didactic situation in order to conserve
589 the artistic dimension of architecture; that's one important reason to use as start
590 point an abstract Kandinsky drawing which provides a variety of linear qualities.
591 The participants were guided, via a classic volumetric exercise, to tame their
592 artistic instinct in order to transform abstract inspiration into architectural form.
593 The third educational process consists in providing the necessary applied
594 thermal engineering tools to analyze the direct energy impact of architecture
595 and henceforth improve and optimize the conceptual output employing a purely
596 scientific methodology. In the past many research works tried to fill this gap
597 linking architectural form and energy optimization; nevertheless these works
598 always focused more on the applied thermal engineering dimension of the
599 problem and less on its creative aspect [20-29]. As we will see now, the design
600 activity of students during the design tasks, which are precisely guided
601 according to the aforementioned education program, provided observable data
602 to analyze this original pedagogic approach.

The participants were divided in 9 distinct groups. During the phase 1, each group worked individually with the aim to conceive an initial volume starting from the painting of Kandinsky and following precisely the guidelines that are presented in the subchapter 3.1. Figure 4, illustrates the variety of traces that each group produced during this phase. Far from being architectural forms, these unconscious abstract traits demonstrate a variety of hidden possible architectural solutions. The post-seminar evaluation (see also next chapter) demonstrated that all the participants appreciated this phase and especially the step n°4 where they were guided to trace the shadows of the initial trait following "*choreography*" (Figure 5).

Figure 4: Output of the 9 different student groups for the phase 1 / conception of a complex form, a) steps 1 and 2- definition of a shape according to the Kandinsky's drawing, b) step 3- production of a replica of the 2-D drawing using a steel wire, c) steps 4 and 5- reproduction of the lines produced by the shadows respecting the different width of each line.

621

622

623 **Figure 5:** Step n°4 of Phase 1 – tracing the shadows according to
624 choreography.

625

626 During the step n°6 we can observe (figure 6) that each team rationalized the
627 contour while a certain materiality starts to be visible since there are 3 different
628 thicknesses for the 2D designs. The next step consisted on the creation of a
629 volume on the basis of these 2D contours. The students are requested to apply
630 an architectural conceptual gesture (for example such as division, extrusion,
631 rotation) in order to give the third dimension to contour (Figure 7).

632

633

634

635

636

637 **(See the original publication for the figure)**

638 **Figure 6:** Step n°6 –Choice of the final contour that will be used in order to
639 build a 3D structure as a reproduction of a precise initial volume.

640

641 **(see the original publication for the figure)**

642 **Figure 7:** Architectural conceptual gestures in order to conceive a 3D volume
643 from the contour : a) division and extrusion (Group 1 : Léonard Gouy - Adeline
644 Duval - J.B.), b) extrusion and vertical rotation (Group 2 : Alex Renard - Cedric
645 Vedlin- Hugo Maurice), c) division, extrusion and horizontal rotation (Group 7 :
646 Nicolas Gautier - Eméline Guillen).

647

648 **(see the original publication for the figure)**

649 **Figure 8:** The initial 3D volumes of each student group as they resulted after
650 the accomplishment of Phase 1: 1) Léonard Gouy - Adeline Duval - J.B., 2) Alex
651 Renard - Cedric Vedlin- Hugo Maurice, 3) Matthieu Bolzer – Anjanaa Devi
652 Sinalapaddi, 4) Camille Lefoul - Brieux Namokel – Steve Meyer, 5) Edwin
653 Lagarde – Camille Rickenbach, 6) Cécile Fritsch – Julien Massotte, 7) Nicolas
654 Gautier - Eméline Guillen, 8) Justine Bernard – Louis Menia, 9) Laurent Boehmer
655 – Marion Moreaux.

656

657 The phase 1 terminated when the initial volume has been identified (Figure 8).

658 The main aim of this phase 1 was to liberate the participants' creativity and re-

659 invent the pleasure of conceiving architecture. Furthermore applying a guided

660 artistic process on the teaching of sustainable architecture re-invented also the

661 dimension of "*sustainability*" since the participants were convinced that the

662 institutional context for climate change mitigation is not a trig to creativity. In

663 contrary, it could be a contingency that re-invents the creative dimension of

664 architecture.

665

666 During the phase 2 all teams worked together in a collaborative manner. A

667 common user interface has been created in order to present all the output in the

668 same manner (Figure 9). The interface was conceived to provide information

669 about the materiality of the volume while a gauge has been introduced near the

670 image of each volume. The height of the gauge indicates the energy

671 consumption of the adjacent volume: the higher the gauge is, the higher the

672 energy consumption is. At this stage, according to the calculation output each

673 group was asked to identify the most influencing parameters and provide

674 volumetric changes in order to minimize the energy impact of the volume within

675 a given climate type of the French territory. Furthermore a variety of possible

orientations have been analyzed in order to correctly position the volume within a potential site. In order to explore a variety of climate types each team located its project at a different climatic zone. Once the volume has been optimized from a volumetric point of view, then the teams worked together and put the volume in the vicinity of each other and then they re-calculated the energy impact and provided further volumetric changes induced this time by the neighboring context (Figure 10).

(see the original publication for the figure)

Figure 9: Creation of common interface to represent and interpret the results after performing the energy consumption calculation. In this figure we can see the output of the Group 5 (Edwin Lagarde – Camille Rickenbach).

(see the original publication for the figure)

Figure 10 : Two different volumes have been put in a vicinity in order to evaluate the impact of the context on the energy calculations and proceed to further modifications. Here we can see the output of groups 5 (Camille Rickenbach – Edwin Lagarde) and 6 (Julien Massotte – Cécile Fritsch).

696

697 Additionally, some groups decided to proceed to a parametric optimization of
698 the volume. Thus, the calculation method presented above has been developed
699 within the Grasshopper™ graphical algorithm editor and provided a parametric
700 modification of the initial volume on the basis of the energy meta-models
701 presented in chapter 3 (Figure 11).

702

703

704

705 **Figure 11:** Automatization of the calculation process employing
706 Grasshopper™ open source graphical algorithm editor, in order to proceed to a

parametric optimization of the initial volume (Group n°3: Alex Renard - Cédric Vedlin- Hugo Maurice).

(see the original publication for the figure)

Figure 12: Final output of the seminar-workshop and creation of a variety of metastable 3D volumes by each student group. Every group delivered after the accomplishment of Phase 2 a variety of volumes that resulted via formal volumetric modifications on the basis of an interactive energy calculation: a) Léonard Gouy - Adeline Duval - J.B., b) Alex Renard - Cedric Vedlin- Hugo Maurice c) Matthieu Bolzer – Anjanaa Devi Sintalapaddi, d) Camille Lefoul - Brieux Namokel – Steve Meyer, e) Edwin Lagarde – Camille Rickenbach, f) Cécile Fritsch – Julien Massotte, g) Nicolas Gautier - Eméline Guillen, h) Justine Bernard – Louis Menia, i) Laurent Boehmer – Marion Moreaux.

In Figure 12a we observe that the main volumetric synthesis was initially divided in 3 distinct parts and then the energy calculation helped to correctly identify the optimum position of each part in a whole volumetric synthesis. The materiality has also been modified in order to correctly suit to the orientation and finally to the neighboring context. Similarly, in Figures 12b and 12c we see

that the automatization of the energy calculation produced a sculptural effect on the final volume. Figures 12d-12f and 12i show that the calculation method helped to improve the impact of the volume via a sculptural process by changing the materiality of several parts and/or by modifying the relation between full and empty parts of the volume. Finally, Figure 12h shows that some teams tried also to create a relation with the surrounding employing solar masks.

5. Discussion of the results

5.1. From a painting to a volume and then to an architectural object

Alan Coluqhun wrote in 1981 that architecture whether refers to a precise meaning through the use of clearly recognizable standardized shapes or remains a meaningless and undetermined process whereas only formalistic choices are illustrated [30]. As we understand, the critical point -from architectural theory point of view- regarding the original methodology previously presented was to overlap the cutting edge that separates pure artistic composition, technical innovation and architecture. Besides, Coluqhun [30] and especially Peponis [31] who analyzed iconic buildings of the history of architecture (La Tourette-Le Corbusier, Villa Rotonda- Palladio, Atheneum- Richard Meier analyzed in [31]) concluded that architecture could be seen as a visual language that

communicates meanings through the use of a precise formal vocabulary,
composed by single simple forms. Furthermore, these single forms are the
bearers of easily recognizable senses. Thereupon, based on the aforementioned
critical observations, we needed at the beginning of the exercise an initial
incentive in order to start from the very early design stage our investigation by
producing a complex drawing based on a simple precise visual vocabulary. We
tried to anon convert this initial 2D design into 3D volume and architecture
according to the method explicitly described in the previous section.

The chosen Kandinsky drawing seemed to be the perfect stimulus for many
reasons. Firstly, Kandinsky is one of the first artists that produced non-objective
art. Peter Fingesten discussed in detail [32] the symbolic nature of creativity and
concluded that an art product could be created in a motif-pattern that was
evocative and rediscovers symbolism in such subjective manner. The nature
paintings of Kandinsky hardly ever seem to depict objects of the world, albeit
being metasymbolical they expand and enhance viewer's perception regarding
space and composition stimulating at the same time creativity and the students'
imaginary.

Secondly, from a pure geometric point of view -independently of aesthetic criteria that are directly related to subjectivity and context-explicit issues- Kandinsky drawings objectively provide an exemplary formal stratification of simple sequences that finally form a complex drawing composed by repeated patterns on the basis of repeated single geometric forms. More precisely, Kandinsky's compositions are based on the marriage of sequences of horizontal, vertical and cyclical segments placed in intuitive manner on the canvas, while they seem to follow a potential linear time algorithm [33]. That's why being inspired from Kandinsky's methodology of composition a so-called Kandinsky model in informatics and discrete mathematics is a model that allows vertices of degree > 4 [34] and is developed to identify orthogonal grid embedding's of plane graphs with the minimum number of bends, solving long-standing open problems [35].

Conclusively, the chosen Kandinsky drawing seemed to resume all the necessary criteria that we needed in the beginning of the exercise in order to produce a complex intuitive 2D drawing according to an explicit methodology. Moreover the intuitive way used by Kandinsky to create space through complex composition and stratification employing simple formal vocabulary patterns

seems to be an optimum manner to create 2D space using the line and the void and augmenting at the same time the potential formal vertices.

In order to avoid blind mimesis of the Kandinsky patterns the step 2 of the phase 1 consisted on the creation of a new pattern based on a specific rule. This step resulted to a 2D contour. However the exercise continued and the steps 3 to 6 added complexity in the 2D form creating stratification and a pattern that has certain characteristics while it is composed by the addition of multiple sub-structures, which are repeated at different scales. At this stage it is important to underline that the students projected the same pattern 3 times according to choreography of movements and rotations varying the distance from the light source (step 4 / phase 1) in order to obtain this stratification effect and create an illegible form that is composed by multiple quasi identical sub-structures of a different scale. Henceforth, we managed to give a fractal dimension to the resulted design, as we will see in the following sub-chapter.

5.2. General mathematical fractal description of the problem

For the economy of space let's focus on one of the seminar output: the work of Cécile Fritsch and Julien Massotte. We can observe in Figure 13 that the followed conceptual methodology guided to a complex 2D pattern where

distinct hierarchically organized structures can be seen. More precisely, as we can observe, several repeated patterns are displayed at different scale and compose the final contour at a preliminary stage. If we consider an elementary structure dimension d we can observe from Figures 13 and 14 that this structure is repeated at different scales as function to a scale factor a according to a rule $ad, a^2d, a^3d, \dots$. This self-similarity of the 2D pattern give as the possibility to provide a mathematical fractal description of the form according to the following classic mathematical expression [36] :

$$\varphi(\alpha d) = \alpha^\eta \varphi(d) \quad (6)$$

where φ is a property of the self-similar structure that in our case is named accessibility (so indirectly refers to different potential circulation paths), and η is the fractal dimension of the problem. Since we study the accessibility we understand that in our case we will examine the internal circulation distribution within the resulted from the painting 2D pattern. Actually, a very important element that is an intuitive indicator as well as an objective element to judge the architectural quality of a form is the circulation distribution [31, 37]. Hence, let's examine how the circulation distribution can be mathematically described within the chosen architectural example and evaluate how it evolved over time

especially due to the energy consumption analysis. In the selected initial form (Figure 13) the number of different circulation paths of size D is hypothesized to follow an “inverse-power law relationship” according to the following general mathematical expression:

$$L(D) = \frac{1}{KD^\eta} \quad (7)$$

where L represents in our case the number of circulation paths within the area and consists a quantifiable measure, D represents the overall size of the circulation paths, K is a constant and η is the fractal dimension of the problem to be determined.

Figure 13: Analyzing the morphing procedure of the contour (work of Cécile Fritsch and Julien Massotte) : a) traces of hierarchically organized structures that remain also in the final solution (fractal dimension of the problem), b) definition of an internal network for circulation, c) internal circulation network within the optimizing building envelope after energy consumption optimization, d) final optimized building form.

Salingaros [38] based on the past research regarding fractal city theory [39, 40] showed that in a given space the number of circulation paths of various finite sizes seem to follow an “inverse-power distribution law” and thus circulation distribution can be correlated to the overall size of these circulation paths through a Power Law statistical model [38]. Additionally, the research of Chen and Zhou [41] on circulation distribution within a given space showed that in order to achieve optimal design the movement need to be developed within central place networks that are abstracted and formulated as multiple geometric series scaling laws, which can be transformed into several power laws. Thereupon, in our example if we consider that D_M is the dimension of the area that is delimited by the sketched contour (thus there is a potential of N circulation paths) we deduce that we can divide the entire area in n elementary pieces of dimension:

$$D_n = \frac{1}{D_M \alpha^n} \quad (8)$$

and according to the equation (6) we can obtain the following mathematical expression:

$$L(D_n) = \frac{1}{KD_M \alpha^{\eta_n}} \quad (9)$$

865

866 The aforementioned general rule shows that the generated complex form is
867 composed by different hidden geometrical patterns solely distributed. These
868 hidden potential circulation paths can be considered as the “*skeleton*” of the
869 form since in architectural design one of the most important things that
870 influence the final volume is the circulation path distribution within the
871 architectural object.

872

873 Let’s examine now how the circulation paths have been indirectly (and
874 unconsciously) optimized after working on the energy performance of the
875 volume and how the entire volume evolved over time due to a creative process
876 of a mathematically assisted volumetric exercise. We observe that the initial
877 volume is composed by a tree-shaped circulation distribution. In the following
878 subchapter we will conduct classic and well-known constructal thermodynamic
879 analysis to identify the reasons for such a particular distribution and to
880 investigate how this distribution has evolved after analyzing the output of the
881 energy performance analysis of the initial volume.

882

5.3. Employing constructal thermodynamics to objectively
characterize the induced architectural quality of the volume

Flow structures in a city scale have been exhaustively studied and analyzed in the past with the use of constructal thermodynamics [42-46]. Constructal thermodynamics provide a complementary view on the understanding of non-deterministic phenomena and can be applied to our case study. In our case we departed from a subjective pattern that is consisted from a composition of a variety of simple shapes. Then according to a specific subjective rule we unconsciously produced a well-defined geometric pattern. Afterwards, we hazardously reproduced this pattern in various scales while these patterns have been merged into new common pattern. This process provided clear fractal dimension on the 2D design as it is analyzed previously. However, now we will use constructal thermodynamics in order to see if the design evolution of the volume was predictable in contrast to non-deterministic fractal models. Moreover we will investigate if the fact of working on the energy consumption of the volume improved in a subjective manner its architectural qualities from a pure architectural theory view.

To conduct this analysis we will employ the constructal law. The constructal law is a physic law that was stated by Adrian Bejan in 1996 as follows: "*For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it.*" [44-46] To transpose this law in our problem we consider that the initial contour establishes the finite-size system while the flow is the circulation distribution within the examined system. Certainly, modeling flows of people is not the same as modeling flows of inanimate fluids, since living systems experience also "*internal*" forces [42-46]. However, many researchers managed to approximate these kinds of flows by modeling the effect of unpredictable bias forces (such as desire, decision, etc) by accounting the resulting entropy generation rate using constructal thermodynamics (for more details on such works see also [44]). In our case, it is very interesting to realize how circulation distribution is correlated to the building envelope and especially how the improvement of the energy consumption of a volume could optimize people's flow within this volume. From energy consumption point of view, circulation paths within a building consist specific thermal zones while it is very important to be placed in strategic areas according to the building layout in order to optimize the overall energy consumption.

922 So let's start by expressing the entropy generation rate within the building
923 volume. We will conduct our mathematical investigation in accordance to the
924 method applied to the city scale presented by Reis [42]. To do so in line with our
925 investigated variable (circulation distribution), we consider W the width of a
926 potential circulation path, while the spatial concentration of individuals is
927 considered ω (people/m²). These individuals flow within the volume with an
928 average velocity u (m/s). At this stage we need to recall that the volume is finite
929 but has the freedom to morph according to our energy consumption analysis
930 that is driven simultaneously. Circulation distribution within a building surface or
931 volume can be considered as a dissipative process while the overall system
932 (building-user) is a complex system that cannot be completely known or
933 described starting from the inside, because it is seldom fully accessible. An
934 approach based just on the Gouy-Stodola theorem has been used, since this
935 approach has been successfully used among other disciplines in economics,
936 urban design and physiology in the past [47]. This approach is based on the fact
937 that lost exergy in a process is proportional to the entropy generation
938 (mathematical proof by Gouy and Stodola [47-55]), while the "*natural*" behavior
939 of complex systems can be scientifically linked to the "*entropy due to*
940 *irreversibility*" [47-54]. According to Lucia [54] and Muriel [55], we formulated

941 the following physical hypothesis in order to use the Gouy-Stodola theorem in
942 our case [53, 54]:

943

944▪ The building volume is considered to be an open irreversible complex system

945▪ Each process of volume modification has a finite lifetime t

946▪ Every intermediate volume is considered as the local equilibrium stage in order

947 to define the global thermodynamic quantities at this time step

948▪ The balance equation of the system regarding circulation flow is a balance of

949 exergy fluxes

950▪ The environmental temperature is always considered constant during each

951 process

952▪ We don't know what happens in each time instant; however we always know

953 what happens after time t (in other terms, we do not know the intermediate

954 stages of volume's morphing over time, but we consider that once a volume is

955 created, this volume consists the geometry of our problem)

956▪ We involve in the equations only the work lost due to irreversibility

957▪ The building volume is considered each time as thermodynamic open and

958 metastable but not completely accessible

959▪ The “wasted heat” is considered here as the “natural interaction-
960 communication” between occupants and their immediate environment that is
961 the building volume.

962

963 The main advantage of this approach is that buildings need very complex
964 models to be described and these models are useful to describe only specific
965 phenomena without endeavoring a global approach regarding the entire
966 dynamic system. Furthermore, specialized approaches cannot describe the
967 interaction inside the system itself. The advantage of this methodology is that
968 we can work solely on the energy consumption reduction of the volume;
969 however at the same time we indirectly and unconsciously optimize the
970 circulation distribution within the volume and thence its subjective architectural
971 quality. As we will see here the energy consumption optimization process
972 coupled to architectural synthesis at the very early design stages offers a great
973 potential to the architects’ creativity.

974

975 Therefore, if we consider the people flow within the sketched contour we can
976 excogitate average mass m and a positive or negative velocity (according to the
977 accelerations or decelerations of the flow) difference Δu and thus the exergy ε
978 lost in the process is calculated as follows:

979

980 $\varepsilon = -\mu(\Delta u)$ (10)

981

982 while according to the Guoy-Stodola theorem we can link exergy to the entropy
983 generation s_{gen} and the ambient temperature T as follows:

984

985 $s_{gen} = -\varepsilon T^{-1} = \mu(\Delta u) T^{-1}$ (11)

986

987 If we consider an elementary control volume w (width), l (length), h (height) we
988 can consider a ϑ_i ratio of people within this control volume with a velocity
989 difference Δu_i and a distance d from each other. Since we work in a 2D system
990 we can assume that h is equal to 1. The total number of decelerations (B), which
991 represents the exergy of the system, can be determined as follows:

992

993 $B = \omega \sum_i \vartheta_i (\Delta u_i) w \frac{1}{d} h$ (12)

994 while the total exergy rate (E/s) is given as follows:

995

$$996 \quad \dot{E} = -B(m_i u) \Delta u_i \quad \Leftrightarrow \quad \dot{E} = -\omega \sum_i \vartheta_i (\Delta u_i) w \frac{1}{d} h(m_i u) \Delta u_i \quad (13)$$

997

998 Applying the Guoy-Stodola theorem we obtain the following expression that

999 correlates the entropy generation rate per people flow rate:

1000

$$1001 \quad \dot{S}_{gen} = -\frac{\dot{E}}{T} \quad \Leftrightarrow \quad \dot{S}_{gen} = \omega \sum_i \vartheta_i (\Delta u_i) w \frac{1}{d} h(m_i u) \Delta u_i T^{-1} \quad (14)$$

1002

1003 If we consider $I = \omega u w$ the intensity of the people flow rate within the potential

1004 circulation path, we can calculate the flow resistance R of the system as a

1005 function of the exergy as follows according to Reis [42, 43]:

1006

$$1007 \quad R = \frac{\dot{S}_{gen} T}{I^2} \quad (15)$$

1008

1009 and then if we consider that wider the circulation path is higher the average

1010 velocity is we have [43]:

1011

$$1012 \quad R = \frac{\dot{S}_{\text{gen}} T}{I^2} \quad \begin{matrix} \dot{S}_{\text{gen}} = \omega \sum_i \vartheta_i (\Delta u_i)^2 w \frac{l}{d} h(m_i u) T^{-1} \\ \Leftrightarrow \\ l = \omega u w \end{matrix} \quad R = \frac{\sum_i \vartheta_i (\Delta u_i)^2 h m_i l}{\omega u w d} \quad \begin{matrix} \xrightarrow{h=1} \\ \xrightarrow{u=\alpha w} \end{matrix} \quad R = \frac{\sum_i \vartheta_i (\Delta u_i)^2 m_i l}{\omega \alpha w^2 d} \quad (16)$$

1013

1014 where a is a constant that correlates the mean velocity to the width of the
 1015 circulation path. In order to simplify the mathematical expression of the flow
 1016 resistance, Reis introduced a specific parameter v that has dimension of viscosity
 1017 and characterizes the people's flow [42] as follows:

1018

$$1019 \quad v = \frac{\sum_i \vartheta_i (\Delta u_i)^2 m_i}{m(\omega l^2 \alpha)} \quad (17)$$

1020

1021 and then after inserting the parameter v into the equation of the flow resistance
 1022 we obtain the simplified expression:

1023

$$1024 \quad R = \frac{v \omega l}{w^2} \quad (18)$$

1025

1026 As we can observe the flow resistivity is direct proportional to the "viscosity" of
 1027 the fluid and inversely proportional to the circulation path width and thence it
 1028 shows the same dependence on channel width as with Hagen-Poiseuille flow

between parallel plates as it is stated by Reis [42]. Thus we can use the results of constructal thermodynamics optimization [41- 43] and especially Bejan's results regarding flow trees for area-to-point flows [46]. In Figure 14 we can observe that we can consider a tree shaped flow regarding circulation distribution within the overall volume and examine how this internal designed evolved over time after imposing the energy consumption calculation that guided to volumetric modifications.

Bejan explicitly mathematically optimized [46] tree-shaped flows by introducing 2 laws relating the ratio and the number of the average consecutive lengths of streams of consecutive hierarchical order by introducing 2 constants R_z and R_N . If we consider Z the length of streams of 1st hierarchical order and N the average number of streams of consecutive hierarchical order we obtain according to Bejan and Reis the two following equations [41-46]:

$$R_z = \frac{Z_n}{Z_{n-1}} \quad (19)$$

and

1048
$$R_N = \frac{N_{n-1}}{N_n}$$
 (20)

1049

1050 Thus, applying this scaling law to the circulation distribution within a city Reis
1051 found that the fractal dimension η is calculated as follows [42]:

1052

1053
$$\eta = \frac{\log R_N}{\log R_z}$$
 (21)

1054

1055 Furthermore Heitor Reis concluded that the fractal dimension must approach 2
1056 for a circulation distribution who has been conceived under the purpose of
1057 optimizing flow circulation [41-46]. The example analyzed in this chapter
1058 provides interesting results from this point of view. Before conducting the
1059 energy consumption calculation, applying the method that was just presented
1060 we calculated a fractal dimension of 2.42. After conducting the energy
1061 consumption analysis as we observe in figure 14 we modified the volumetric
1062 aspect of the object and consequently the internal circulation distribution. We
1063 then recalculated the fractal dimension of the object applying the same method
1064 and we found that $\eta=2.09$.

1065

Figure 14: Tree shape analysis of the internal circulation distribution network (work of Cécile Fritsch and Julien Massotte): a) initial solution before energy performance optimization with the presence of the building envelope trace, b) final solution after energy performance optimization with the presence of the building envelope trace, c) initial solution before energy performance optimization without the presence of the building envelope trace highlighting the hierarchy of the internal circulation paths, d) final solution after energy performance optimization without the presence of the building envelope trace highlighting the hierarchy of the internal circulation paths.

1076

1077 Even if a systematic study on this methodology applied to architectural design
1078 would be needed to fully confirm that we can apply the Constructal Law during
1079 the early conceptual stages of architectural design to optimize architectural
1080 creativity, however we can assume that working on energy consumption during
1081 the early design stages, not only improves the energy impact of the building but
1082 optimizes also the internal circulation distribution and hence the aesthetic
1083 rendering from pure architectural theory point of view. In two words the
1084 methodology presented here aims to generate an architectural design
1085 according to the principle of "*optimal distribution of imperfection*" [42-46].

1086

1087 Decisively, after analyzing the final output of the seminar-workshop, we can
1088 observe that a variety of formal solutions have been evaluated and departing
1089 from an initial volume we progressively improved the energy impact of the
1090 volume preserving but optimizing its main formal characteristics. Simultaneously
1091 the participants realized that finally the energy calculation assisted them not only
1092 to identify the energy impact of their conception but also to define the correct
1093 volumetric proportions, optimize the internal circulation distribution and
1094 transform an arbitral volumetric study into a harmonic structure with a high-
1095 energy performance potential.

1096

1097 In guise of conclusion we may say that the main novelty of this pedagogical
1098 method was that it introduced a new vision for treating the problem of
1099 sustainability via architectural design. Artistic, theoretic, professional and
1100 scientific approaches converged into a common concrete exercise in order to
1101 achieve a quadruple objective:

1102

- 1103 i) Develop an environmental architectural intuition via a process of creation.
- 1104 ii) Identify the parameters that significantly influence on the energy
1105 consumption of a building form and hence realize the impact of conceptual
1106 choices and decisions.
- 1107 iii) Simultaneously optimize the circulation distribution within the volume and
1108 thence improve its architectural arguments form architectural theory viewpoint.
- 1109 iv) Realize that constructal thermodynamics may be a very important tool
1110 that can assist architects during the early design stage under the purpose to
1111 operate complexity at an early design stage.

1112

1113 The final output of the seminar, as well as, the seminar's evaluation (see also the
1114 subchapter 5.4. Post-seminar anonymous auto-evaluation) by the participants
1115 confirmed that the main objectives have been achieved with success since we

1116 can see that there is no formal banality on the architectural production and an
1117 intuitive optimization methodology on the basis of a scientific calculation has
1118 been instituted in the imaginary of the participants. In figures 15 we can observe
1119 the main methodological novelties of the paper in terms of informed sustainable
1120 architectural conception.

a)

b)

Figure 15: Flowchart of the methodological process regarding the coupling of architecture and applied thermal engineering processes in the framework of sustainable development: a) existing linear explicit methodology, b) proposed in this paper implicit ad hoc optimization starting at the early conceptual stages.

Henceforth, the need to continue the process of the exercise until the detail scale is the next step to radicalize the way of teaching sustainability in the schools of architecture and further explore the constructal law's applicability.

5.4. Post-seminar anonymous auto-evaluation

1133 At the end of the seminar-workshop, the participants were invited to fill an
1134 anonymous auto-evaluation form in accordance to the European commission
1135 guidelines in order to appraise the pedagogic content and form of the seminar.

1136 Thus, the aim of this anonymous post-evaluation was:

- 1137 ▪ to check if the goals set at the beginning of the seminar-workshop have
1138 been met
- 1139 ▪ to determine whether the organization and content of the event met the
1140 needs and expectations of the participants in accordance to their training
1141 as architects and/or engineers
- 1142 ▪ to make adjustments or modifications to future similar pedagogic acts
- 1143 ▪ to provide quantitative and qualitative information that can be
1144 disseminated in order to evaluate the impact of the original pedagogic
1145 method that has been employed during the seminar-workshop

1146

	strongly agree	agree	disagree	strongly disagree	Total
Question 1: Do you perceive the interest of this seminar - workshop for your training as architect – engineer	8 (44.4 %)	9 (50 %)	1 (5.6 %)	0 (0 %)	18 (100 %)
Question 2: The seminar - workshop corresponded to what you expected	7 (38.8 %)	9 (50 %)	1 (5.6 %)	1 (5.6 %)	18 (100 %)

Question 3: The subjects and notions addressed during the seminar – workshop as well as the double approach architectural design / energy calculation in the upstream project phase inspire you to deepen this subject	10 (55.6 %)	7 (38.8 %)	1 (5.6 %)	0 (0 %)	18 (100 %)
Total (%)	25 (46.3 %)	25 (46.3 %)	3 (5.6 %)	1 (1.8 %)	54 (100%)

Table 1: Output of the post seminar anonymous auto-evaluation phase (Questions 1-3).

The post-seminar evaluation form contained in total 7 questions; the first 3 were multiple choice questions while the following 4 questions invited the participants to freely express their thoughts and comments. The responses of the participants regarding the first 3 questions are tabulated in Table 1 and in Figure 16. These 3 questions invited the participants to evaluate the overall impact of the seminar. As we can see from Table 1 and Figure 16 the positive responses (strongly agree and agree) reach the 92.6 % (whereas the very positive responses reach the 46.3 %).

Figure 16: 3-D bar summarizing the output of the post seminar anonymous auto-evaluation phase (Questions 1-3).

On the other hand, as we can understand from table 2 (where selected responses on questions 4 to 7 are tabulated) the participants were satisfied from the pedagogic act while they underlined its several original aspects and they proposed some improvements for the future. They also acclaimed more pedagogic time in order to deepen this subject. Thus, from this point of view we can assume that the original pedagogic method presented here was successfully addressed during this seminar-workshop while the seminar was inspiring since it brought science (physics) into the practice and the pedagogy of architecture coupled with sustainable design and applied thermal engineering.

Question 4: Describe in two words the most concrete result of the seminar - workshop	<ul style="list-style-type: none"> - The interesting formal result based on the thermal aspect and potential of the architectural form - The form's evolution on the basis of the energy calculation - The volume's optimization process on the basis of its energy potential - The influence of the architectural choices on the energy impact of the volume
Question 5: How this seminar - workshop should evolve the following years	<ul style="list-style-type: none"> - Have more time in order to deepen on the thermal calculation in relation to architectural conception

	<ul style="list-style-type: none"> - Employ thermal calculation software - Extend this approach to more detail scales and employ it during a complete architectural project
Question 6: Describe the original aspects of this seminar - workshop	<ul style="list-style-type: none"> - Being creative and design a form taking into consideration its energy potential - The way of conceiving the volume and how this volume evolved over time - The way that the seminar-workshop couples architectural design to applied thermal engineering - Transform an art painting into architectural volume by employing applied thermal engineering tools - The mathematical process during architectural creation - How we passed from a 2D drawing to a 3D volume employing applied thermal engineering tools - How we started from an abstract phase to arrive to a concrete result
Question 7: Do you have any comments or do you want to propose any improvements	<ul style="list-style-type: none"> - Employ specialized software instead of manual calculation - Employ more sophisticated calculations and extend this approach to more detail scales - Increase the number of constraints - Work on a very precise geometrical context - Simplify the applied thermal engineering process - Augment the considered parameters

Table 2: Output of the post seminar anonymous auto-evaluation phase (Questions 4-7).

5. Conclusions and perspectives

Being the target of environmental reform, architecture lost its Modernist dimension of being able to design an environment and has been transformed to a discipline that aims to produce an environment by design [56]. However the contemporary era instructs the de-disciplining of architecture shifting the

1185 architectural conception from a sociocultural project to a technological
1186 specialization while the sustainable subculture where technology can apparently
1187 solve all problems becomes the governing doctrine. According to theorists of
1188 architecture we are actually living a de-disciplining by shrinkage that also affects
1189 architectural education.

1190

1191 In the past many research works validated spatial typologies of traditionally
1192 inherited passive heating and cooling strategies [57]. Other works focused on
1193 the architectural student's attitude towards building energy modeling with the
1194 aim to improve integrated building design education [58]. Thus, in a
1195 complementary manner, the purpose of the present paper consists on
1196 reinventing the architectural conception incorporating applied thermal
1197 engineering methodology during the initial conceptual stages. The main
1198 difference regarding past works on the same subject is that architecture is
1199 simultaneously seen here as an independent discipline and an operational tool.
1200 Furthermore, the main aim and originality of the present contribution consists on
1201 bringing science (physics) into the practice of the 'sustainable' or 'green' and the
1202 pedagogy of architecture. As a consequence, the objective of the present
1203 paper is to introduce a novel and original multidisciplinary methodology that
1204 preserves creativity and develops 'sustainable' culture preserving the artistic

dimension of architecture. Furthermore the present paper puts in the forefront of the scene the clearest and most consistent articulations of the relationship between technology, architecture, art, science (physics) and the environment.

To achieve this a conceptual exercise initiated the workshop whereas from the same point of departure different student groups have produced totally different volumes. After a suitable applied thermal engineering computational study, significant improvements have been made both volumetrically and in terms of energy performance and architectural quality. Constructal thermodynamics and fractal analysis have been employed in order to evaluate the forms from purely objective viewpoint focusing on circulation distribution within the architectural volumes. The choice of employing stressing morphogenesis (the constructal law) is key in the understanding of this contribution. Bejan and Errera reviewed the central concepts and words that underpin the physics of evolutionary design today [59]. Additionally, Bejan employed the constructal law and studied nature from all the possible aspects regarding information, knowledge, evolution, change, pattern, organization, drawings, complexity, fractal dimension, object, icon, model, empiricism, theory, disorder, second law, the "any" system in thermodynamics, morphing freely, [59-60]. In this paper, we deal with many of the aforementioned concepts while

1225 the complexity regarding sustainable architectural design is evaluated
1226 employing the constructal law.

1227

1228 The main positive output of the present pedagogic method is that the energy
1229 treatment of a building can be no longer seen as a constraint but as a
1230 fundamental element that contributes to the aesthetic development of formal
1231 solutions. As it has been revealed from post experiment constructal optimization
1232 the work on the energy impact of the volume improved also its architectural
1233 quality. In fact this seminar-workshop managed to transform energy calculations
1234 and present them as an operational tool that assists the volumetric and
1235 architectural conception, while an environmental architectural intuition can be
1236 developed on the basis of such parametric design. The polynomial method
1237 employed during this workshop can be replaced by any other method since it
1238 has been used as a simple operational tool and not as the main element to
1239 obtain "*sustainability*". The research core of this paper is resumed in the fact
1240 that architecture when it is combined with science without losing its artistic and
1241 creative dimension provides huge potential and can adequately respond to the
1242 constraints of "*sustainability*" regenerating its iconic dimension. Furthermore, a
1243 direct perspective of this work is to try generalizing the incorporation of
1244 constructal optimization techniques into architectural conception. For all the

1245 aforementioned reasons it will be very interesting to extend this approach to the
1246 detail scale, since we will be able to study in detail the building based on
1247 enriched dynamic heat transfer models that include much more parameters than
1248 those who are available at an early design stage.

1249

1250 **Acknowledgements**

1251 I would like to acknowledge my colleagues Louis Piccon, architect and Director
1252 of the architecture department of the National Institute of Applied Sciences of
1253 Strasbourg, Christelle Gress, civil engineer and chief of the specialization of
1254 architecture at the INSA Strasbourg and Frank Guêné, architect and Pedagogic
1255 Responsible for the content of the AI1 educational cycle, for supporting and
1256 giving me the opportunity to integrate the aforementioned pedagogic approach
1257 to a concrete pedagogical situation. I am also grateful to Anke Vrijs, colleague
1258 and talented artist, and Jean-Jacques Viroth, architect and art theory expert for
1259 their friendship and support. Furthermore, I would like to thank all the
1260 participants of the seminar for their participation and for giving me their written
1261 permission to diffuse their works.

1262

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