Developing building exergy methods through collaboration in the open-data era

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Abstract:

Exergy analysis combines the first and the second law of thermodynamics through a reference state, quantifying energy quality. Although exergy methods are a relatively recent development in applied thermodynamics, many classical engineering fields use them successfully to optimise their processes. A deeper understanding of quality and degradation of energy resources would be beneficial for the built environment too, but designers do not use exergy assessments yet, and building exergy analysis is still limited to research institutions. Classical exergy assessments of buildings are conducted on a steady-state basis, but the building behaviour is intrinsically dynamic in most cases, which means that dynamic calculations are required for exergy to be meaningful in the everyday life of designers. However, there are three major obstacles to the development of dynamic exergy methods for buildings: the controversial definition of the reference state, the unclear usefulness of the analysis and the lack of simulation tools; these problems are deeply interconnected and difficult to address separately. This research attempts to tackle the obstacles simultaneously by proposing a collaborative approach to exergy methods and simulation software development, and open data as the fulcrum of the connection between academia and the real world. An open-source software for the dynamic exergy analysis of the building envelope, with a user-defined reference state, is partially developed and used to illustrate the process with a research case; detailed building exergy assessments give the opportunity to test different definitions of the exergy reference state and virtually experiment various solutions, which are then discussed with building designers and tested in real cases. Calculations are currently focused on envelope exergy storage. Further developments consider model calibration with measurement of the real case, discussion of software tools, modification and addition of calculations, validation and improved user-experience, and require open collaboration with fast feedback loops among researchers and building designers.

Keywords:
Exergy, Reference state, Building simulation, Dynamic software, Open data.

1. Introduction

The cutting edge of building energy design is nowadays focused on energy conservation. An alternative approach is based on the thermodynamic function exergy, a measure of energy quality combining the first and second law of thermodynamics by means of a reference environment. Exergy of a flows or matter is the product of the corresponding energy (of the flow or the matter) and a "quality factor", a coefficient between 0 and 1 that quantifies the quality of the stream or energy stored in the matter, its capability of producing work when brought into equilibrium with the reference environment. Even in the case of exergy analysis the attention remains focused on the performance of the building under assessment, but the target of energy conservation is now combined with the minimisation of exergy destruction. However, even if a considerable effort - of which [10] and [6] are good examples - has been put in reaching out to building designers, exergy methods are not really adopted in the real world and remain still confined in an academic environment.
Three major obstacles to the adoption of building exergy analysis are the controversy around the reference state definition, the lack of agreement about the real usefulness and meaning of exergy assessments of the built environment and the lack of open and detailed dynamic simulation tools that could constitute a common ground for discussion. Further aggravating the situation is the deep connection between all the major obstacles: the reference state definition determines not only the values but the entire meaning of the analysis, and without common dynamic tools the discussion remains based on a limited amount of data.
In this context, the evolution of building exergy methods and the exploration of new meanings and connections that could disrupt the current energy paradigm is condemned to a slow pace. The cold reaction of building practitioners towards the exergy concepts could be a sign that the current proposal is not having an impact on the solution of real problems, and alternative exergy frameworks should be investigated at the same time. This study proposes a collaborative approach to the investigation and comparison of different exergy methods, and presents an example of an alternative exergy method within the open development process.

2. The problem: truth model and benefits of exergy in buildings

The main problem of exergy analysis is probably its own nature of being a composition of energy and entropy through a reference state, created with the aim of assessing the maximum available work that could be extracted from a system when brought into equilibrium with an environment. If the definition is clear and its use obvious for a power cycle, its interpretation is not directly transferrable to a building.
What are we actually using exergy analysis for, in the case of building design? Certainly not to maximise the work production. Some researchers claim that minimising work consumption could be a reasonable target for buildings, and it is achieved just as the opposite of its maximisation. At the same time, more complicated views and many different opinions can actually coexist, and almost none can be proven wrong. In other words, there is not a truth model that can be taken as a reference to prove if a certain framework is appropriate or not.
However, exergy methods could be compared on the basis of their practical impact and the real problems that they contribute to solve. In this case, the issue is the large amount of data and feedback that needs to be collected from real buildings and energy systems.

3. The idea: collaboration around open data, software development and real cases

How can exergy methods evolve and become part of the common design practice? If the discussion remains within the academic environment, demonstrating the usefulness, applicability and impact of a second-law mindset is challenging, if not impossible, and there is not enough feedback and experimentation to validate the methods. Furthermore, controversies are heated and hard to solve through theoretical discussions. On the other hand, the availability of open data is increasing exponentially and the potential impact on engineering research methods cannot be ignored: if the boundaries between academia and the rest of the population became more fluid, the academic research engineer would not be a rather isolated entity anymore, but more likely the start and end of a process involving an active participation of external subjects and resources.

In the specific case of building exergy analysis, the theoretical framework itself is not mature and, even if various attempts of reaching out to building practitioners have been made in the last decade, the value of exergy methods for the built environment has not been recognised. Although there is a diffuse tendency of blaming the complexity of exergy concepts for the lack of practical applications, the suspect underpinning this study is that the feedback from the real world has not been central so far in the research of exergy meanings and methods, and the benefits of applying current exergy analysis are actually not disruptive enough to justify the effort. The recurring claims of the theoretical thermodynamical superiority of second-law approaches are not sufficient to convince any stakeholder.

The main idea of this work is that controversies on the exergy reference state selection and on the usefulness and meanings of exergy methods could be tackled through a collaborative approach aimed at exploring and comparing alternatives while developing a detailed exergy software on an open platform and sharing open data from real cases that successfully addressed a specific design problem.

4. Minimal working example of the process

In order to demonstrate how a similar process could be carried out in practice, a few key aspects of a real case under investigation are presented. An unpopular and not widely explored reference state is adopted, because of its convenience and potential impact on the exergy analysis meaning. The real problem and key motivation behind the exploration of exergy analysis is the well-acknowledged need of sustainable and low cost thermal storage in order to decouple energy production and demand and exploit more renewable sources. The software tool developed to calculate the relevant exergy values is based on an open-source software; the model and simulated data, the feedback and measured data are made available as soon as produced on an open platform. In synthesis, the method presented in this study, as a minimal working example of the proposed process, is based on the following hypothesis:

- the most convenient reference state is a fixed temperature based on comfort;
- the specific issue under investigation is the decoupling between energy supply and demand;
- the method and software tool developed to address the issue is focused on exergy storage.

Each point is explained in the next section in more detail.

4.1. Reference state

The reference state for building exergy analysis represents a critical controversy [7] and is still worth investigating more deeply, since there is no common agreement in the exergy literature. Not only does it affect the numerical results of the analysis, but impacts the entire meaning of the exergy values [5]. It is thus important to have the option to define the reference state in the simulation tool in a flexible way, by means of a profile which can be constant, time dependent or linked to other conditions (for example change with the season or the building use).
In common terminology, "cold exergy" denotes thermal energy below the reference state T_0, and "warm" or "hot" refers to conditions above T_0 [9]. Although the predominant choice is currently a variable reference based on the fluctuating outdoor conditions [10], which causes the definition of "cold" and "warm" to vary in the same way, this study considers a fixed reference based on thermal comfort as more convenient, as discussed in previous studies [2] and [3].
For the sake of simplicity, the most basic definition of minimum indoor thermal comfort is considered in this research: a dry-bulb air temperature of 18°C for the presented case (requiring heating only) and 24°C for a hypothetical situation requiring cooling. The fixed reference state adopted in the case study 5. is the lower limit of winter comfort: $T_0 = 18°\text{C}$.

4.2. Real problem: decoupling of energy supply and demand

One key idea behind the design method proposed in the minimal working example is the necessity of the distinction between constrained and unconstrained sources of exergy, presented in [1]. Briefly, the term "unconstrained resources" refers to the energy sources that need to be consumed or stored as soon as produced (such as electrical energy from wind turbines) and the "constrained resources" are, on the other hand, the ones that are untapped until needed (like fossil fuels) because naturally stored. In terms of economical value and environmental impact, there are substantial differences between constrained and unconstrained resources, and energy storage systems are generally expensive and not always sustainable and durable. At the same time, the exergy of energy and materials of devices used to produce, store, transform and move energy certainly need to be taken into account in the general equation, but rarely are.
The second key fact is that the building envelope can constitute a low cost and durable energy storage, if designed and controlled appropriately. The inner layers of the envelope have a direct impact on the indoor comfort and controlling their temperature directly could be a feasible option if the constructions allow storage without excessive loss towards the outside.
The third and last key point, which is a well-know fact, is that exergy is a useful thermodynamic function for assessing thermal energy storage. Especially if based on a fixed reference state related to thermal comfort, exergy quantifies the quality of energy and provides information about not just the maximum work available (its theoretical definition) but the actual ability of the matter to exchange heat or remain close to equilibrium. If a thermal mass has an exergy quality factor just above the reference state, for example, it will help maintaining the indoor environment close to equilibrium without the need of being controlled.
These three facts joined together underpin the hypothesis that the mere reduction of building energy and exergy consumptions does not constitute the high priority target, as higher energy and exergy consumptions could decouple supply and demand and thus also, or even better, satisfy economical and sustainability requirements when the bigger picture is considered.

4.3. Simulation tool and exergy storage calculations

The simulation tool produced for the calculation of exergy storage is an extension of the dynamic simulation software ESP-r [4] and produces HDF5 files containing compound data for each node for every timestep of the simulation (code available at [12]). HDF5 files are organised as in figure 1 and can be accessed and modified with any modern language, such as Python or R.

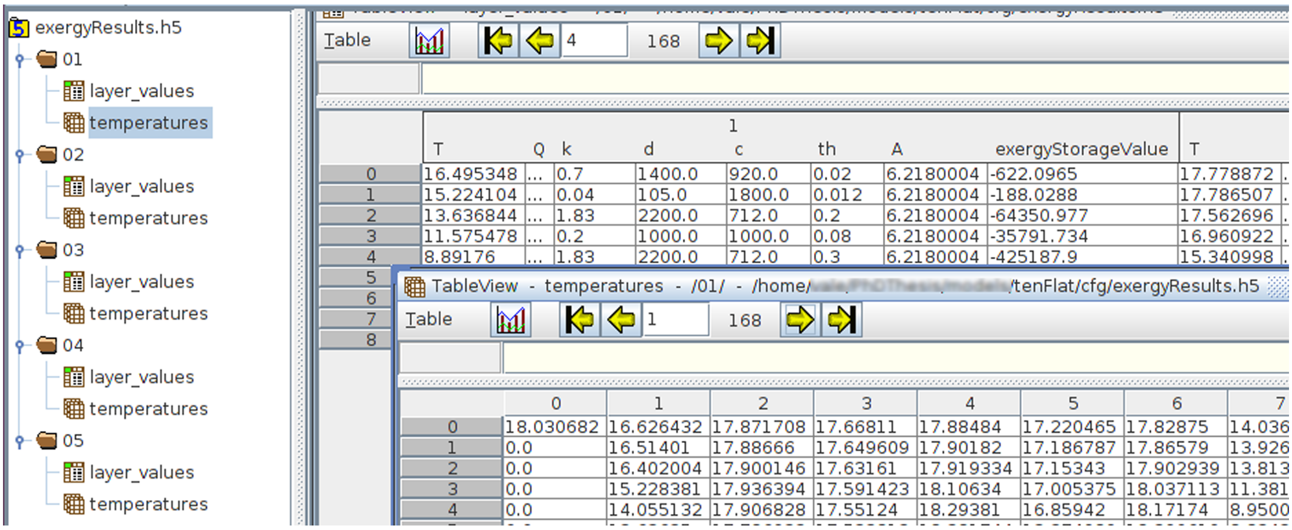


Figure 1: Example of HDF5 file structure with temperatures, thermal properties and exergy storage data obtained for each node and timestep (visualised with HDFView software).

The exergy stored in a generic node n, representing a volume of matter of uniform properties (ESP-r uses a finite volume method), is expressed per unit volume by:

$$ex_n = c_n\rho_n\left[(T_n - T_0) - T_0 \ln\frac{T_n}{T_0}\right] \approx \frac{c_n\rho_n\,(T_n - T_0)^2}{2T_0} \quad , \qquad (1)$$

where c_n is the specific heat, ρ_n the density and T_n the temperature of the volume; T_0 is the exergy reference temperature [8]. Equation (1) is positive for any node temperature and reference temperature because any state that departs from the reference can theoretically produce work. However, the exergy storage has different meanings depending on their mutual relationship:

- if $T_n > T_0$ it is called "warm exergy";
- if $T_n < T_0$ it is called "cold exergy";
- if $T_n = T_0$ the exergy stored is null and the node is at the reference state.

Cold and warm exergy values are both positive, but the sign function *sgn* is applied to (1) in order to distinguish them; a cold exergy is shown as negative (in blue) and a warm exergy storage appears as positive (red) in the graphs where they appear together.

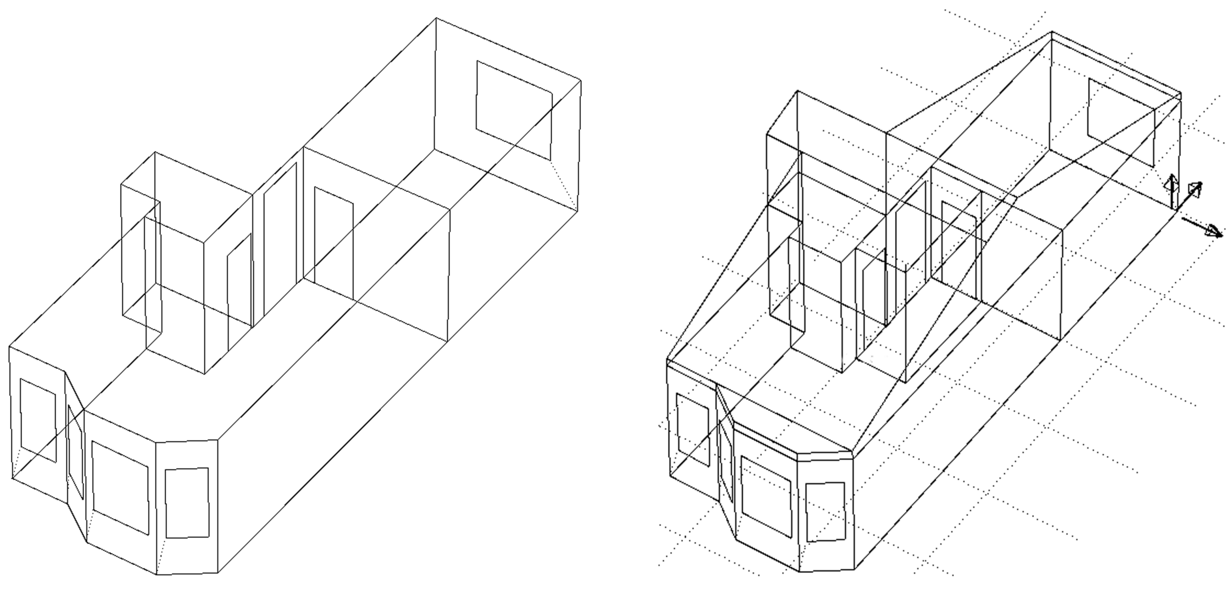
5. Research case study

A simple real case is presented to illustrate the process. The focus of the study is the refurbishment of a typical one-bedroom flat in Glasgow (UK), located at the top floor of a tenement building and requiring heating only. The meaning of each assumption and its relation to the exergy framework and tools development process is explained below in more detail.

5.1. Building model

The flat is modelled with ESP-r, an open-source dynamic software for building energy simulation, and the model has the following characteristics:

- the initial geometry, used to investigate the free floating behaviour of the building, is divided in three thermal zones (figure 2a)
- the model is subsequently partitioned in five thermal zones (figure 2b to increase accuracy (basic energy conservation measures like roof insulation and double glazing for windows are applied at this stage);
- the inner part of the envelope that interacts more directly with the indoor space is roughly estimated through the resistance values of the construction layers (in figure 3a), as explained in 5.3..



(a) *Initial model composed of three zones.* (b) *Final model with five thermal zones.*

Figure 2: *The research case: ESP-r geometry for initial and final model of the building.*

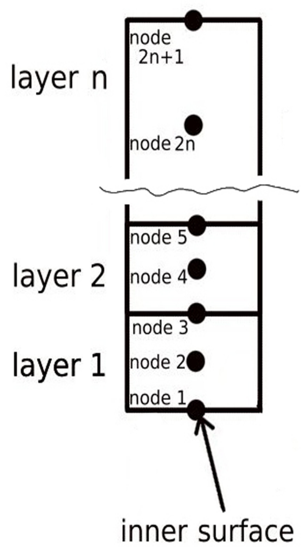
The building materials are typical of the 1920s (stones, bricks, wood, lime plaster, etc.) and the occupancy and internal gains are typical of a residential flat occupied by two adults. All the model files, material properties, construction details, operation and control data are publicly available from the date of the conference proceedings publication in an open repository at [11].

5.2. Reference state selection

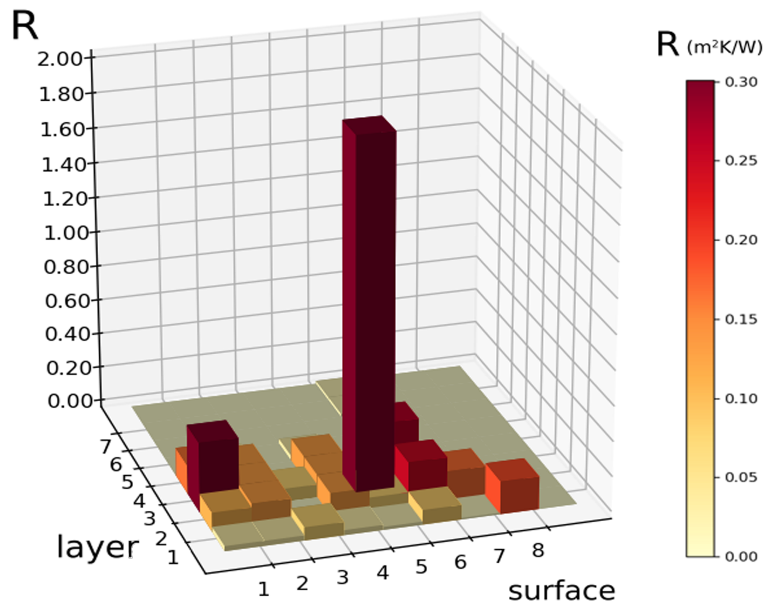
The reference state for this exergy analysis is fixed, as already mentioned in section 4.1.. This allows, independently from the outdoor conditions, to have a fixed criterion to distinguish between "warm" and "cold" exergy, which is particularly convenient when exergy storage is evaluated. In this case, the focus is on heating requirements because the building under assessment does not require cooling at any season. Therefore, the reference state is set to a constant value equal to the lower limit of average comfort conditions, $T_0 = 18°C$. Any thermal storage above T_0 is thus considered as neutral - if very close - or heating source (depending on the specific temperature) and anything below T_0 constitutes a load.

5.3. Definition of envelope inner layers

The particular method here proposed considers the building envelope as the biggest thermal storage that directly affects the indoor environment. Clearly, not every part of the envelope is in direct (or almost direct) contact with the internal space that it encloses, and some layers actually interact more directly with the external environment. Establishing the construction layers (represented in figure 3a) that significantly impact on the indoor zone storage is not a straightforward task. In this work, a simplified strategy is adopted: the number of layers of a particular construction element (wall, ceiling, floor, window or door) that have been included in the "inner part" of the envelope contribute for maximum the 50% of the element total thermal resistance (show in figure 3b). This number varies for each element of each thermal zone and is stored in an array that defines the "inner part" of the envelope before the data analysis.



(a) *Construction layers.*



(b) *Resistance values of each layer of each construction, zone 1.*

Figure 3: *Construction layers and criteria to approximate the "inner part" of the envelope.*

5.4. Envelope exergy storage as a guidance

The exergy stored in the inner part of the envelope (as defined in 5.3.) and the way this part of the building reacts to occupancy, internal gains and different types of heating systems is considered as the guidance of this assessment. The aim is to analyse the starting point (the exergy stored during the free floating behaviour), observe the elements that are most influential in each thermal zone and compare the effect that different heating strategies - in terms of control schedules and actuator locations - have on the exergy storage itself and the resultant comfort and energy consumption patterns.

5.4.1. Envelope exergy storage in free floating mode

The total exergy storage (Wh) of the inner part of each construction element is represented in figure 4, divided per thermal zone, for each timestep (hours) of the two most significant weeks of the year. Exergy storage values are always positive, however warm exergy is coloured in red and cold exergy is represented in blue, and reported as negative value when in the same graph with warm exergy, just to differentiate them. The typical winter week (5th-11th of February of the simulation year, details in [11]) is reported on the left: the elements that have the biggest impact on the zone storage can be easily detected. The typical summer week on the right shows that only the two walls in direct contact with the building staircase (wall 2 of zone 1 and wall 1 of zone 3) store cold exergy; the summer period has less design relevance in this specific case because the free floating temperatures are already within comfort.

5.4.2. Envelope exergy storage with different HVAC strategies

Heating systems, from the point of view of their impact on the envelope and indoor conditions, differ in sensor types and locations, actuator types and locations and actuator schedules. In this case, only two opposite strategies are compared in order to make the discussion simpler and clearer. The main characteristics of system 1, denominated "basic control", are:

- the sensed variable is the air dry-bulb temperature of the thermal zone;
- the heat is injected directly into the zone air node (like an air system);
- the schedule follows a typical request (morning, evening and weekend peaks).

The second system is designed taking into account the constructions that have the highest values of free floating exergy storage per each zone and locating the actuators as radiant surfaces within different layers of those constructions, in feasible positions. The schedule restricts active periods at night times and the system is off during the entire day. The design of actuator locations is iteratively repeated until satisfactory indoor conditions are achieved and the heat injection is completely decoupled from the demand; system 2, denominated "unconstrained control", is briefly characterised by the following:

- the sensed variable is the surface temperature of the heated element;
- the heat is injected within a layer of: wall 2 (zone 1), wall 8 (zone 2), wall 1 (zone 3);
- the heat supply is decoupled from the request and can happen at any time as far as is sufficiently capable of replenishing the exergy storage.

The diffent impact of these systems on the envelope exergy storage can be observed in figure 5.

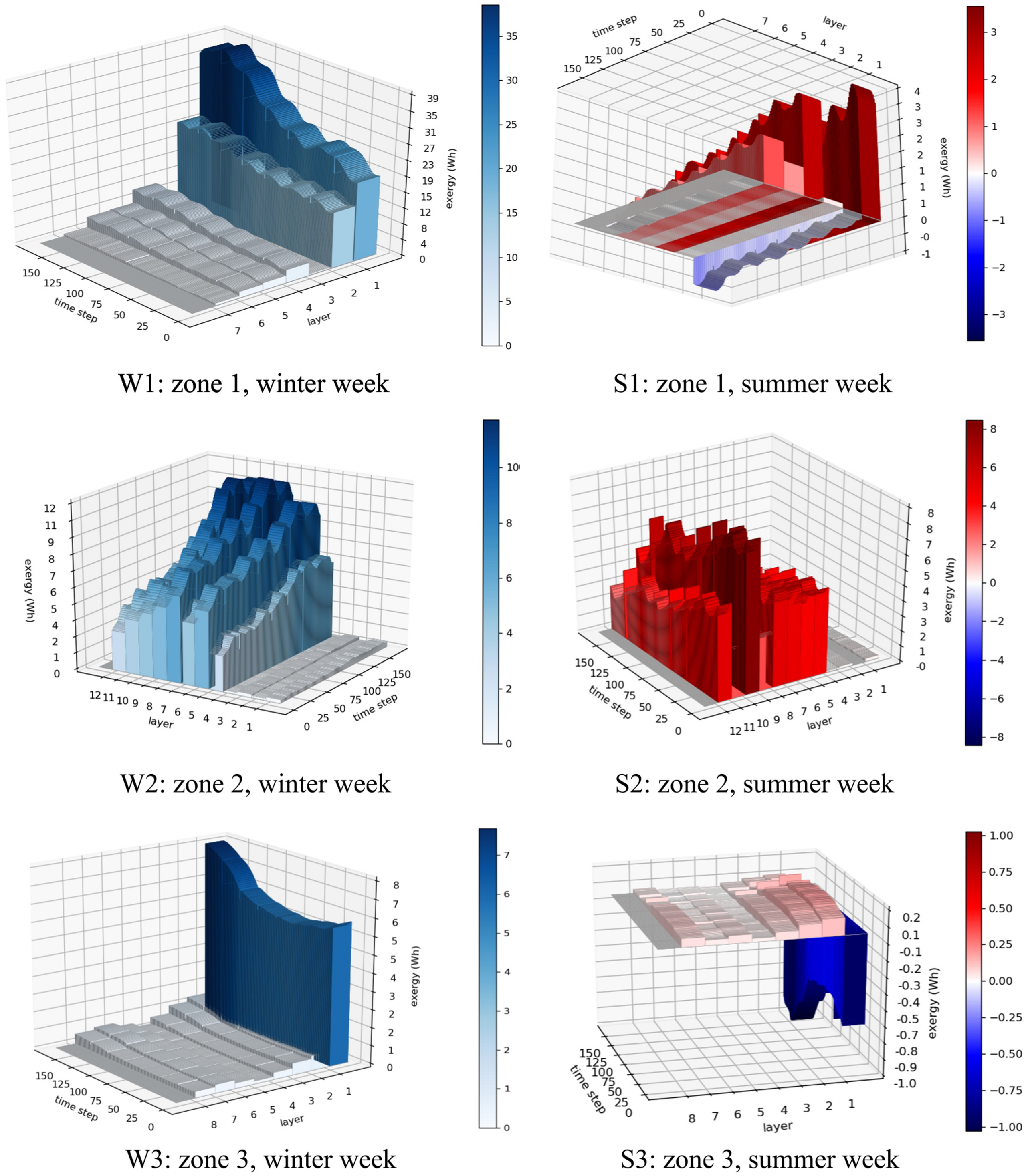
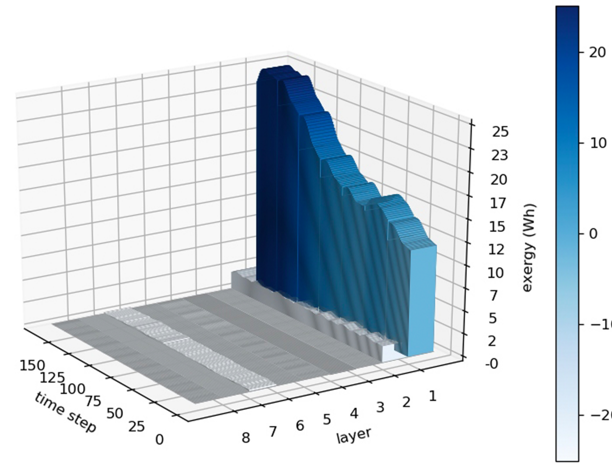
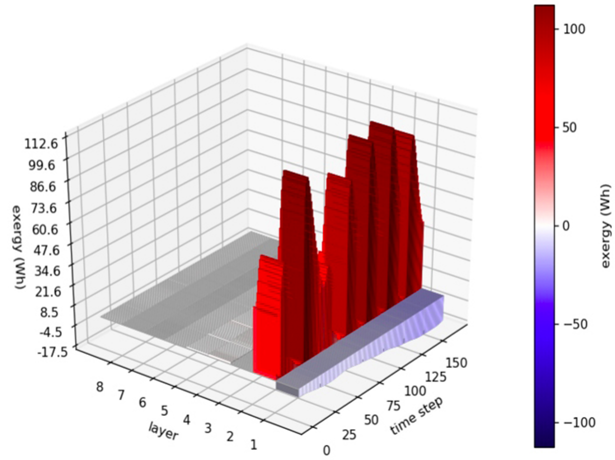


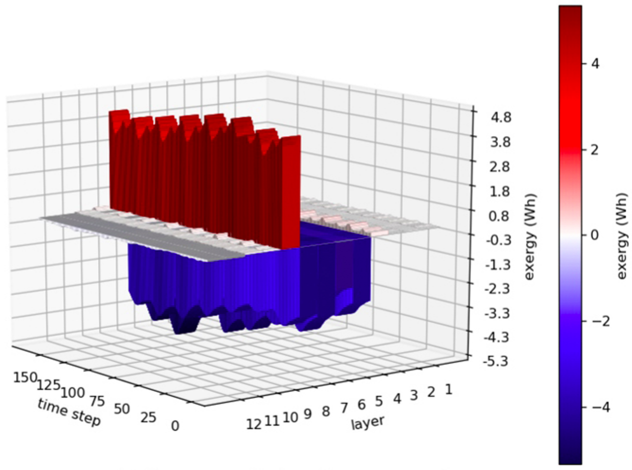
Figure 4: Inner exergy storage (Wh) of each construction surronding each zone during two typical weeks (time steps in hours) in winter (5th-11th of February) and summer (17th-23rd of July). Exergy storage values are always positive, but negative values are used to distinguish "cold" exergy from "warm" exergy where needed (graphs S1 and S3).



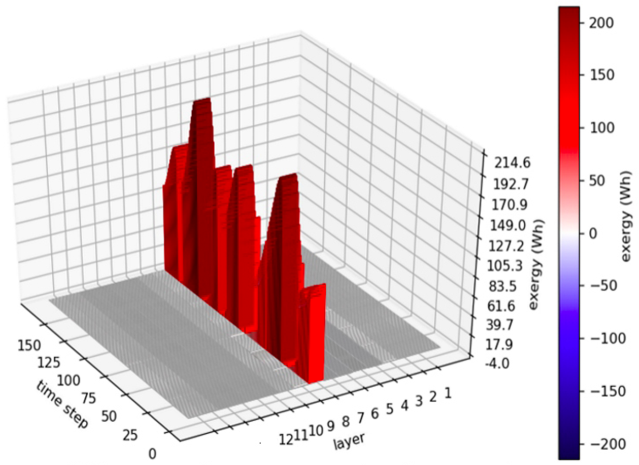
B1: zone 1, basic control



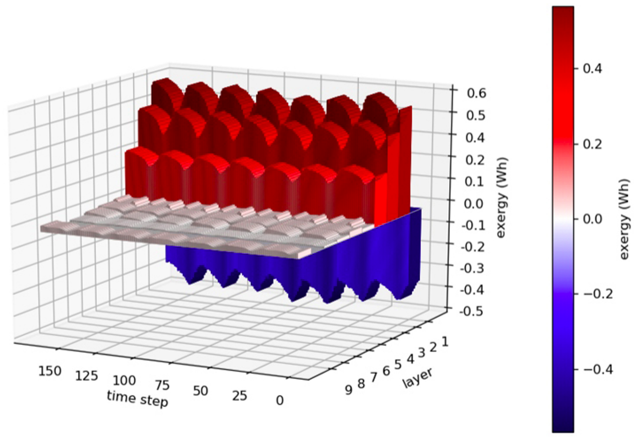
U1: zone 1, unconstrained control



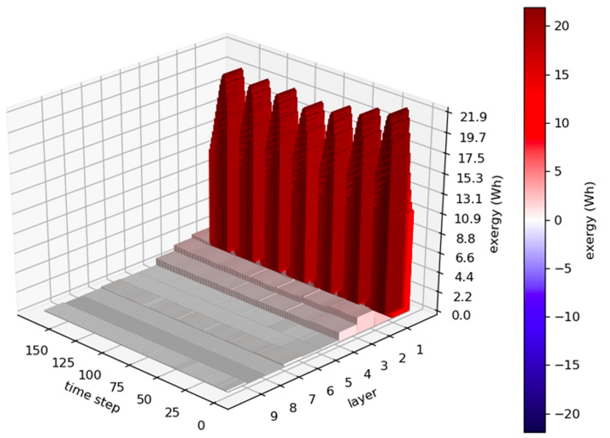
B2: zone 2, basic control



U2: zone 2, unconstrained control



B3: zone 3, basic control



U3: zone 3, unconstrained control

Figure 5: Inner exergy storage (Wh) of each construction surronding each zone during two typical weeks (time steps in hours) in winter (5th-11th of February) and summer (17th-23rd of July). Exergy storage values are always positive, but negative values are used to distinguish "cold" exergy from "warm" exergy where needed (graphs S1 and S3).

5.5. Impact of HVAC strategies on energy consumption and comfort

But what is the meaning of the different exergy storage trends reported in figure 5? Going back to zone air temperatures and energy consumptions, easier to visualise and understand, the different impact of the two opposite (and rather extreme) strategies is clear from figures 6 and 7. System 1 is fast, the air db temperature of the zones goes up quickly when it is switched on, and down when off; the heating loads are low and strictly follow the schedule of comfort request. System 2 is slow and decoupled from the demand, at the price of more than doubled peak loads and slightly higher overall consumption.

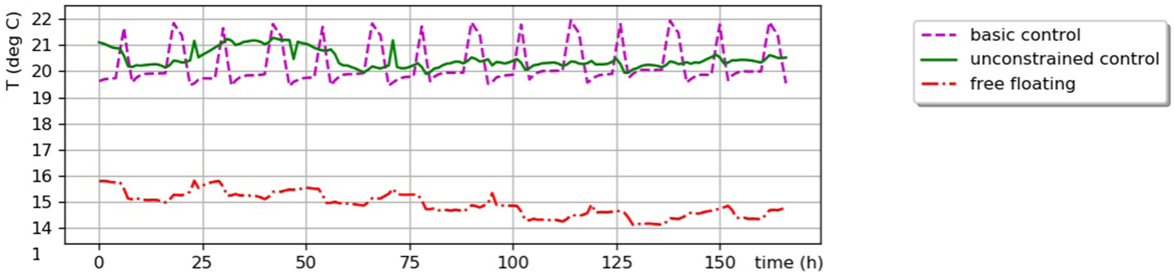


Figure 6: Zone 1 air dry bulb temperature, typical winter week, with different HVAC strategies.

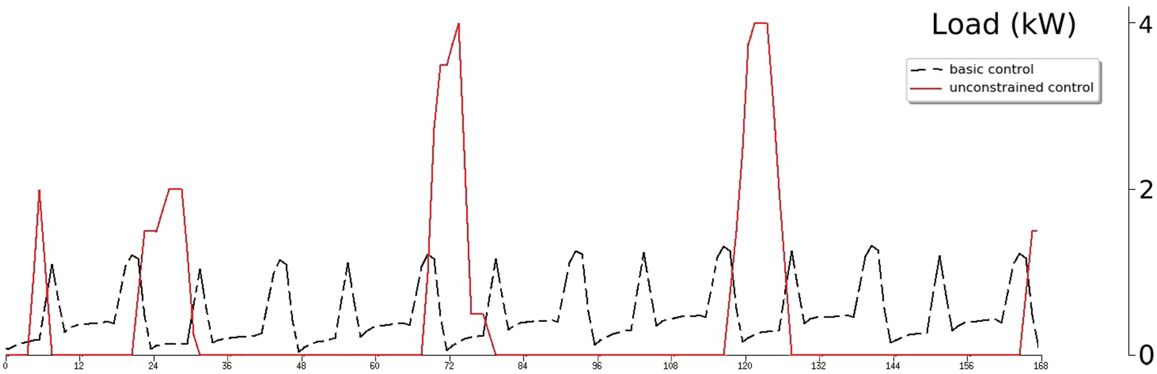


Figure 7: Aggregate loads for the building, typical winter week (5-11 Feb)

6. Conclusions

Building design choices need to compromise many factors, especially in order to achieve sustainable and resilient yet affordable solutions, and none of these factors can be considered in isolation. Unfortunately, the reduction of building energy consumption is often regarded as a detached design step without a wider view on quantifiable sustainability targets, and no distinction is made between external and local resources. On the contrary, design choices should result from a balance between the available exergy budget (local energy and material resources) and the exergy demands of both energy and materials. Exergy could provide a more comprehensive framework and include most of the different aspects in a single equation, but building exergy assessments are far from mature and their development requires an open collaboration around common tools and open data, of which this study is a minimal example.

Acknowledgments

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