

Life cycle efficiency ratio: A new performance indicator for a life cycle driven approach to evaluate the potential of ventilative cooling and thermal inertia



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ABSTRACT

Building envelope design has gained importance as a means to reduce heating and cooling demand related to a building's operational phase. However, in high internal load buildings, such as offices, internal gains can easily lead to overheating. Thermal inertia (*TI*) and night ventilation have a great potential for reducing heat loads and temperature. However, their influence is difficult to predict due to the complex nature of the *TI* phenomenon, which is related to the interactions of multiple factors such as architecture, building physics and external conditions. Moreover, *TI* efficacy has often been studied in relation to energy savings or temperature analysis, overlooking other aspects implicated in buildings' efficiency, such as the embodied energy involved. This paper presents a multidimensional approach to evaluate ventilative cooling and thermal inertia as a sustainable strategy to improve building performances. To that end, several scenarios of night ventilation strategies have been applied to the case study of an experimental double-office room placed in Fribourg (Switzerland). Based on this monitoring, a dynamic software simulation tool has been calibrated and used to analyze the energy savings potential and the life-cycle performance of *TI*. A new ratio index has been introduced to easily evaluate the life cycle efficiency. The results show the importance of balancing operational and embodied impacts when evaluating a design choice. Although high *TI* levels have great benefits on reducing the cooling loads, the results are completely different when a life cycle assessment is applied. Natural ventilation coupled with middle levels of *TI* have been identified as the best strategy to optimize the building's energy and environmental performances, without compromising indoor temperatures.

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1. Introduction

Buildings are responsible for almost 34% of the global final energy use and 15% of total direct energy-related carbon emissions

Abbreviations: CED, cumulative energy demand; CEDnr, cumulative non-renewable energy demand; COP, coefficient of performance; Evc, energy used for ventilative cooling; EI, embodied impacts; EPBD, energy performance of buildings directive; GWP, global warming potential; H, number of hours; HT, high inertia (room); LCA, life cycle assessment; LCER, life cycle efficiency ratio; LCI, life cycle inventory; LT, low inertia (room); OI, operational impacts; Qc, cooling need; Qc_{ref}, cooling need – reference scenario; SEER_{vc}, seasonal energy efficiency ratio for ventilative cooling; SPI, specific power input; TI, thermal inertia; TMY, typical meteorological year.

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worldwide [1], indicating the great CO₂ reduction potential that lies in the building sector. Energy efficiency standards push toward buildings with a very low energy request, such as Nearly Zero Energy Buildings defined by the European Union – EPBD [2]. On the other hand, Switzerland increases the target with the 2000watt-society vision [3], which aims at a drastic reduction of both the energy used and the CO₂ emitted by the construction sector on a life cycle perspective. Life cycle assessment (LCA) [4] is commonly used for assessing buildings' impacts on the environment; it evaluates the impacts produced in the exploitation period of the building, called operational impacts (OI), and the ones involved in the materials production, transportation, manufacturing, building's construction and demolition phase, called embodied impacts (EI) [5].

Considering the operational life, the first step towards energy efficiency is reducing heating and cooling consumptions [6]; the latter has been gaining importance in the last years due to higher

comfort expectations, increasing temperatures caused by global warming and over-insulated building envelopes [7]. This is the case of offices, characterized by high internal heat gains and predominant cooling requests. Cooling loads are highly variable, strictly related to interactions between a broad set of variables [8,9], and closely correlated to climatic and operation patterns [10]. The envelope's design becomes essential to minimize buildings' conditioning load, which are generally related to the dynamic thermal properties of the building enclosure. However, the envelope's dynamic behavior is often overlooked by energy regulations [11], which are more focused on controlling heating needs, offering a semi-stationary evaluation regime [12]. The thermal dynamic properties depend mostly on interactions between insulation, thermal inertia (TI) and ventilation strategies [13], nonetheless their effects are not linear and easily quantifiable. In fact, buildings insulated from the outside and with high thermal mass on the inside seem to have improved thermal behavior [14,15]: insulation acts as a shield for thermal exchanges, while thermal mass increases the inertial properties enhancing the building thermal cycles. Accordingly, buildings with higher TI have more stable indoor temperatures [16,17] and lower cooling needs [18–21]. TI is particularly effective in mild climate, assuring comfort in middle seasons without the contribution of air conditioning [22,23]. It works as a thermal battery, storing heat during the temperature peaks and releasing it later. In offices, night natural ventilation is often used as a cooling technique [24–28], which can dissipate the heat load accumulated during the day. Coupling night ventilation and thermal inertia enhances their cooling effects [29,30], reducing heat peaks and preventing overheating [31].

On the other hand, TI is a critical property when EI is assessed. From a life cycle point of view, in fact, the energy savings induced by a design strategy can be nullified by the related EI , resulting in increasing the overall building impacts. This is the case of TI , usually implemented through the use of massive materials, such as concrete-based materials or bricks, which are proven to have higher EI than other construction techniques [32].

Although LCA has already been applied to buildings materials and components in several applications [33,34], so far only few studies aim at quantifying the environmental performances of a passive cooling strategy, such as TI [35,36]. Usually, LCA -driven approach considers the life-cycle energy [37] or life cycle greenhouse gas emissions [38] of buildings, focusing only on one of the multiple aspects that constitute the life cycle assessment, while few studies consider both. Table 1 lists the main researches containing a double approach to OI and EI , published after the reviews on life cycle emissions [38], life cycle energy [37] and LCA in the construction sector [39].

Table 1 clearly shows that a more comprehensive approach to LCA on the effects of thermal inertia is missing.

This paper quantifies the influence of TI and night ventilation in Fribourg's climate (Switzerland), applying a multidimensional investigation and analyzing the benefits on LCA and energy consumption. The analysis is part of the smart living building research program [51], which aims at the definition of the design brief for an innovative low-carbon building. In this framework, previous analyses highlighted the potential benefits of massive construction achieved with low-carbon materials, such as compressed earth bricks [52,53]. However, a broader comparative study on TI effects on embodied and operational impacts and a reliable way to assess the efficiency on the life cycle scale are missing. This paper introduces a new concept for LCA , based on the balance comparison between EI and OI , which relies on the use of an indicator that can help in understanding the reciprocal influence of these two components of the whole life cycle impacts. This research presents the first exploration on the viability of using this indicator and it is applied to the case of TI and night ventilation strategy, framing a deeper

understanding of the applicability of TI coupled with ventilative cooling for future low-carbon and energy efficient buildings.

2. Methodology

The scope of the paper is to analyze TI performances on a calibrated parametric model in order to understand the potential of TI coupled with night ventilation strategies for passively cooling an office in Fribourg (Switzerland), representing a continental climate with cold winter and warm summer. The novelty of the work lies on the multidimensional approach used for evaluating a passive cooling strategy. Moreover, a new indicator is introduced to evaluate and balance on a life cycle perspective the efficiency of the solution proposed. The methodology used is described by the following consecutive steps:

1. The case study is applied to a double office room in an office building placed in Fribourg, within the smart living building framework;
2. The results of a previous experimental campaign made on a real-scale prototype made up of a double-office room test cell have been analyzed and used to calibrate a virtual model;
3. Six different thermal inertia levels have been designed according to the SIA380/1 [54];
4. Five ventilation strategies have been set for the ventilative cooling options;
5. The TI and ventilation profiles have been combined to create a set of possible scenarios;
6. The scenarios have been simulated in a thermal dynamic software, DIAL+ [55], and on LCA with KBOB database [56];
7. The OI results have been assessed evaluating the potential energy savings due to the ventilation and thermal inertia strategies adopted;
8. The EI results have been assessed with a new indicator: the life cycle efficiency ratio ($LCER$), which weights the operational impacts reduction of a given scenario, on its embodied impacts compared to the reference case.

The calibration was necessary for a comparative analysis of the virtual model results, due to the gap encountered between simulation and real energy performance [57], given the complexity of interactions due to the TI behavior. An accurate calibration of the dynamic software used can substantially reduce these discrepancies [58], increasing the results' reliability.

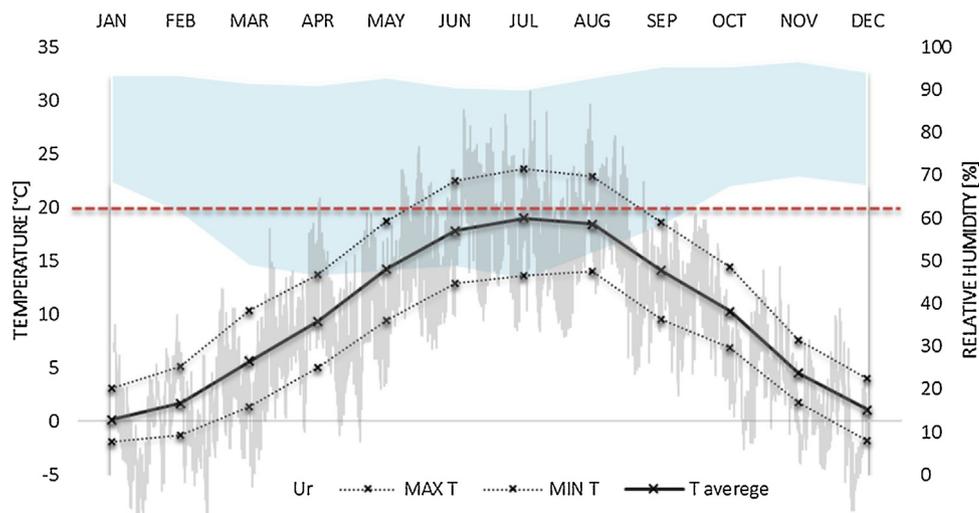
LCA uses several parameters to describe the potential impacts on the environment [5]; among those, the carbon emissions and the primary energy use have been proved to be reliable in evaluating the environmental impacts of a building and describing the trends for all the categories [59–61]. Reducing the indicators needed is essential to simplify the LCA calculation method in regard to its application in the early design stage, considering the high computational time and effort associated to a full LCA [62]. In this study, embodied impacts are expressed for the three main indicators of LCA : global warming potential (GWP), cumulative energy demand (CED), and cumulative non-renewable energy demand (CED_{nr}), according to [3]. The weather file used is the TMY (typical meteorological year) for Fribourg, generated by Meteororm [63].

3. Calibration of the virtual model

The calibration process aims to refine the virtual model in order to better describe the real system building-environment, based on the comparison between real measurements and simulated data. To calibrate the model used for the analysis, an experimental facility has been used as a case study.

Table 1
Summary of the research balancing operational and embodied impacts.

REF	RESEARCH	CASE STUDY	INDICATORS STUDIED
[40]	Giordano et al. (2017)	High rise office building	Operational and embodied primary energy
[41]	Macias et al. (2017)	Model detached dwelling	Operational and embodied primary energy
[42]	Wang et al. (2016)	Two green buildings	Greenhouse gas emissions life cycle
[43]	Praseeda et al. (2016)	16 urban dwellings	Operational and embodied primary energy
[44]	Hong et al. (2015)	Podium of a residential building	Embodied greenhouse gas emissions
[45]	Giordano et al. (2015)	Single family detached house and apartment building	Operational and embodied primary energy
[46]	Rossello-Batle et al. (2015)	Single family detached house	Embodied energy and thermal energy demand
[47]	Rauf and Crawford (2015)	Detached residential building	Embodied energy and recurrent energy
[48]	Brown et al. (2014)	Broad sample of residential buildings (1400)	Operational primary energy and embodied greenhouse gas emissions
[49]	Stephan and Stephan (2014)	Four-storeys apartment building	Operational, embodied and transport primary energy
[50]	Cellura et al. (2014)	Three-storeys apartment building	Operational and embodied primary energy



Graph 1. Climatic condition for Fribourg (CH). Hourly temperature (grey line), monthly average temperature (black line), monthly daily average temperature (dotted line), monthly night average temperature (dotted line) and relative humidity range (light blue zone) are shown. The red line indicates the value of 20 °C (temperature side) and 60% (humidity side). Acronyms used: Ur (relative Humidity), MAX T (monthly average of the maximum daily temperatures), MIN T (monthly average of the minimum daily temperatures), T average (monthly average of the average daily temperatures). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Source: Meteonorm [63]

3.1. Real scale prototype case study

The 1:1 scale test facility is a small experimental building made of two double offices, placed in a free area in Fribourg (Switzerland). It has been designed according to the Swiss norms to better represent a typical high efficient office building in Switzerland.

Fribourg is characterized by a continental climate with average cold winter and warm summer. Graph 1 shows the average monthly temperature and the extreme values, which range from almost -10°C (January) up to 31°C (July). However, the average temperature is always below 20°C and the daily average below 26°C . This means that normally Fribourg has warm summer but hot spells are frequent and can achieve critical temperature, leading to overheating and indoor discomfort situations. On the other side, Fribourg is characterized by high relative humidity: the average is above 60%, classifying Fribourg as humid-continental city.

The two rooms are 36m^2 , indicated by SIA2024 [64] as the typical dimension for offices, and they are separated by an anteroom that contains the technical facilities and the building equipment (Fig. 1). The construction is a wooden lightweight construction with a highly-insulated envelope, which reaches U-values lower

than $0.15\text{W}/(\text{m}^2\cdot\text{K})$. Table 2 shows the prototype's constructive elements.

In one of the rooms, the longer walls are covered with compressed earth bricks, identified as an interesting strategy for an environmental efficient *Tl* application [52]. For this reason, the rooms were called High-Thermal inertia room (*HT* room) and Low-Thermal inertia room (*LT* room).

Large windows are placed on the shorter walls of each room, facing south-east and north-west. Natural ventilation is made through a single hopper opening part of the windows, which allows to achieve a net opening surface of 0.1m [2]. During the monitoring phase a thin black plastic layer was added to the external part of the windows, covering the whole glazed facade. This expedient allowed to cut down all the solar contribution in order to reproduce the same heat gains patterns for each measurement. The internal gains were generated through artificially controlled lighting systems, which were switched on and off following a standard schedule, according to the SIA indications [64]. This system produced heat through the energy dispersion of incandescent bulbs (efficiency 10%).

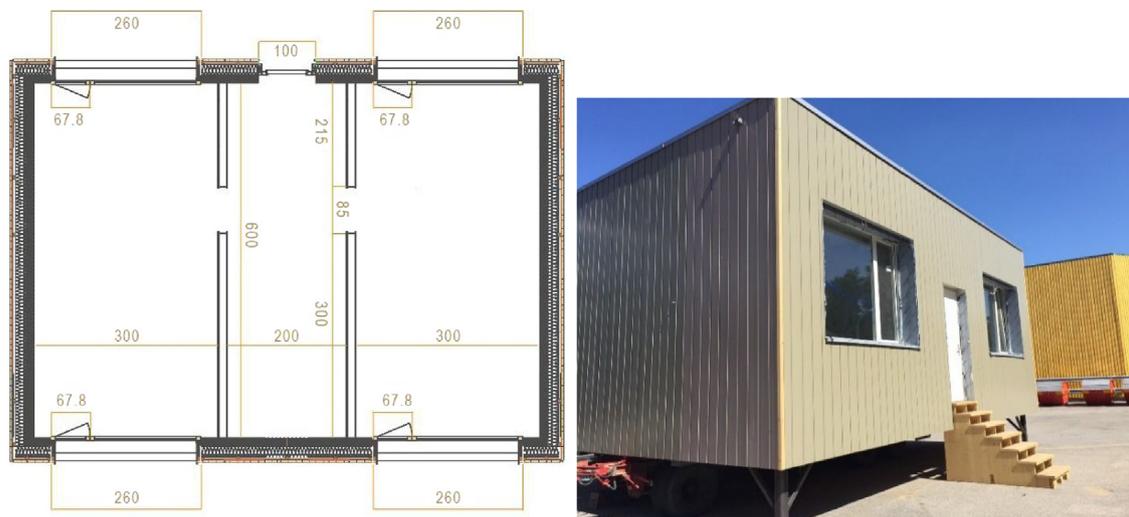


Fig. 1. Architectural plan (quoted in cm) and side view of the prototype used for calibrating the virtual model.

Table 2

Description of the composition of the prototype's architectural elements. For each element, the materials and the relative specific thermal properties are specified.

COMPONENTS	MATERIALS	Thickness [mm]	Conductivity λ [W/(m·K)]	Density δ [kg/m ³]	Heat capacity C [kJ/(kg·K)]
ROOF	Bitumen elastomeric membrane	4	0.2	875	4.5
	Insulation polyurethane	180	0.031	15	1.116
	Vapour barrier	0.22	0.4	500	1.8
	OSB panels	25	0.13	600	2.15
FLOOR	Linoleum	3	0.17	1200	1.47
	Cement screed (fiber reinforced)	50	0.8	1400	1
	Acoustic insulation	9	0.15	556	1.7
	OSB panels	25	0.13	600	2.15
	Insulation glass wool	350	0.032	28	1.03
	Wooden panels	60	0.047	250	2.1
	Wooden structure	140	0.13	471	1.6
WALLS – LT (Low Inertia)	Vapour barrier	0.22	0.4	500	1.8
	Insulation polyurethane	180	0.031	15	1.116
	Permeable membrane	0.45	0.17	900	1.8
	Ventilation chamber	50	–	–	–
	Wooden cladding	24	0.15	450	1.8
	Compressed earth bricks	140	0.79	1900	1.1
	Wooden structure	140	0.13	471	1.6
WALLS – HT (High Inertia)	Vapour barrier	0.22	0.4	500	1.8
	Insulation polyurethane	180	0.031	15	1.116
	Permeable membrane	0.45	0.17	900	1.8
	Ventilation chamber	50	–	–	–
	Wooden cladding	24	0.15	450	1.8

3.2. Virtual prototype

The virtual model has been developed using DIAL+ [55], a Swiss thermal dynamic simulation tool created by the Estia Company. Its thermal model has been validated with respect to the European norms [65–67]. Thanks to a meteorological station directly mounted on the prototype, it has been possible to re-create the specific weather file for the calibration, reproducing the same conditions encountered during the monitoring phase. The calibration is a way to fine tuning the accuracy of the virtual prototype [68], reducing the errors and the standard deviation between the real case and the virtual results [69].

3.3. Calibration process

The calibration process was made on two scenarios: during the day from 08:00 to 20:00 mechanical ventilation was active with an air-flow of 80 m³/h; during the night (from 20:00 to 08:00 am of the successive day) there was either natural ventilation (scenario C2) or no ventilation (scenario C1). The scenarios lasted two consecutive

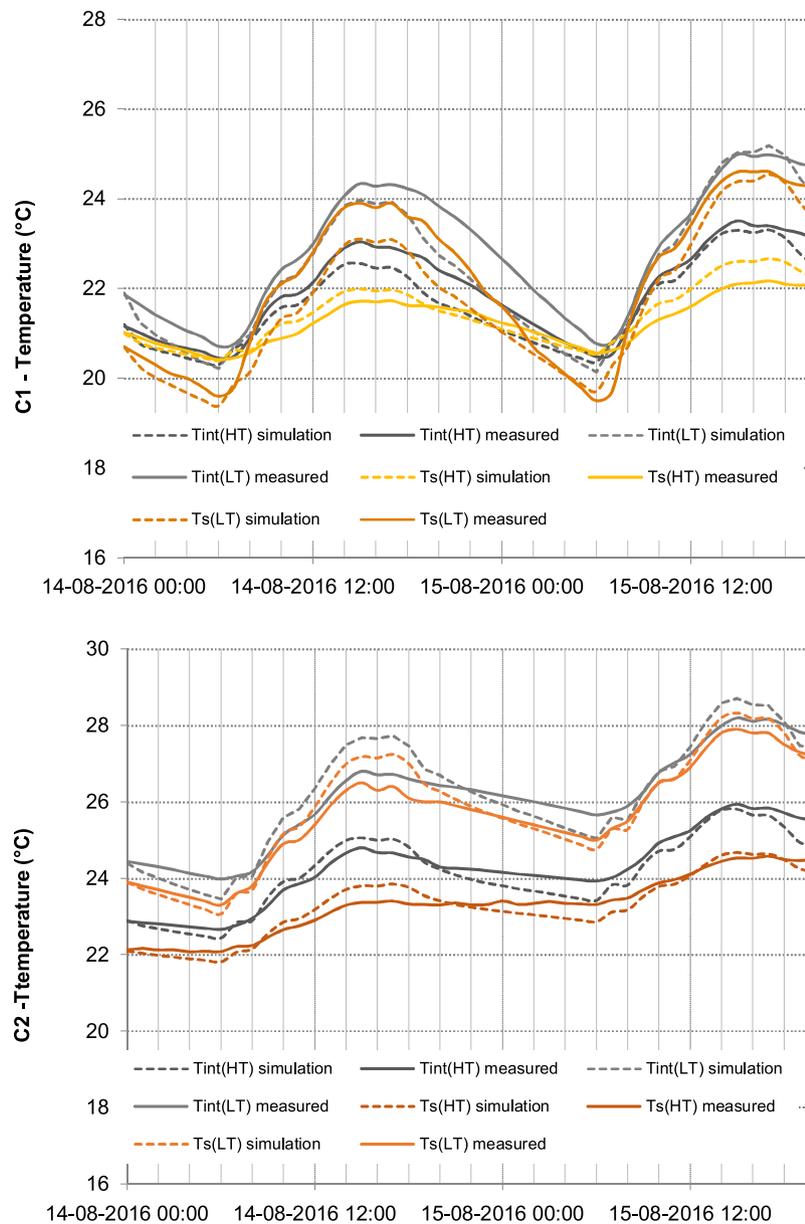
Table 3

Description of the scenarios used for the calibration. The calibration process compared results monitored from a prototype and taken from thermal simulations. Scenarios, building's geometry and physical properties and climates were identical.

SCENARIO	DAY ventilation 08.00/20.00	NIGHT ventilation 20.00/08.00	HEAT GAINS
C1	80 m ³ /h	–	Standard by SIA
C2	80 m ³ /h	natural	Standard by SIA

days and were performed during August 2016. Scenario C1 on the 4th and 5th, while scenario C2 on the 12th and 13th (Table 3). An ideal calibration should be done on both summer and winter periods, however in this paper only the summer calibration has been done since that the free-running mode is allowed only during the warm period, as the analysis is focused on the cooling capacity of TI.

Scenario C1 is used to gather information about the night thermal losses through the envelope, the thermal gains due to the internal gains profile applied and the stability of the airflow. Scenario C2 shows the importance of night ventilation.



Graph 2. Surface temperatures (left) and internal temperatures (right) for the two rooms (HT and LT) in the calibration scenarios (C1 and C2). Dashed lines represented the simulated data in the virtual model, continuous lines the monitored in the prototype. It is possible to notice that there is a difference between the two measures, in particular, for scenario C1 simulations have higher temperatures than the real monitored, while for C2 is the opposite.

The calibration process involves the comparison of two variables: internal air temperature (Tint) and surface temperature (Ts), considered as the mean value of the longitudinal walls. While in simulations it is possible to easily set an output with the two variables, for the prototype, some sensors were used. A Vaisala GMW93R transmitter (one for each room) placed on half of the longer wall logged the air temperatures and some calibrated thermocouples type K were placed along the longitudinal walls for logging the surface temperatures. Among the various calibration models available [70], in this paper we followed a manual hourly-based process [71], aimed at defining the confidence interval of the simulation results.

Graph 2 shows the temperatures logged and simulated as function of time.

The analysis highlights a slight difference between the simulations and the data collected, Table 4 shows the standard deviation and the maximum error calculated for the two scenarios, referring both to internal air temperature and the surface temperature.

Table 4 shows that the max errors encountered in the simulations is below 1.5° , which can be considered an acceptable threshold for the accuracy of the model used [69].

In the first scenario, it is possible to notice a decay of the simulated night temperatures. The reason is most likely due to the windows' coverage: the black plastic layer traps static air, which contributes to insulate the envelope. A higher resistivity in the enclosure means fewer losses during the night and, therefore, slower temperature decrease. In scenario C2, instead, no significant difference is detected between simulated and measured temperatures.

4. Simulation scenarios

The calibrated virtual model has been used as case study to perform the simulation of different scenarios, aiming to define the benefits of TI and ventilative cooling in Fribourg's climate. The

Table 4

Standard deviation and max error calculated between the simulation results and monitored data. The variables used are the internal air temperature and the mean surface temperature of the longitudinal walls. Results are shown for both rooms (characterized by high inertia and low inertia).

	SCENARIO C1		SCENARIO C2	
	STD Deviation (°C)	Max Error (°C)	STD Deviation (°C)	Max Error (°C)
HT – Ts	0.26	0.45	0.22	0.52
HT – Tint	0.27	0.66	0.24	0.78
LT – Ts	0.32	0.90	0.38	1.12
LT – Tint	0.48	1.01	0.38	1.11

geometry has been kept identical and the lightweight room is used as reference case. Its thermal properties have then been changed according to the scenarios applied.

Six different thermal inertia levels (scenario *TI*) have been used, defined by different construction typologies. To each *TI* level, five ventilative cooling strategies (scenarios *V*) have been applied. These crossed scenarios (scenarios *TI* + *V*) help to define the suitable technical strategies for an office placed in Fribourg, to maintain indoor comfort while improving the environmental efficiency of the building. Moreover, four additional risk scenarios (scenarios *R*) have been evaluated to understand the criticisms related to the ventilative cooling strategy.

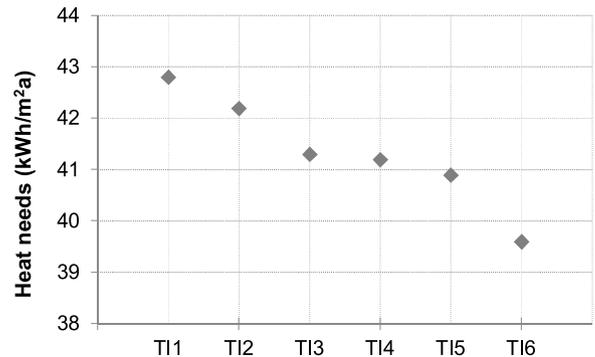
4.1. Thermal inertia levels

In the analysis, we created six different *TI* levels, varying from very light to very heavy in order to better represent the possible solutions used in offices. The choice of having these scenarios was driven by the only previous study aimed at balancing *OI* and *EI* of different *TI* levels [36], where four construction typologies are defined. Based on that, we modeled two more scenarios, in the medium-weight construction ranges with different materials, as the goal of the analysis was to determine *TI* impacts on both operational and embodied impacts and, therefore, the variation in the materials implemented to achieve the desired heat capacity is essential.

TI levels are classified according to the specific Swiss norm on thermal properties of building elements [54]. Accordingly, the levels have been chosen ranging from very light to very heavy and referring to typical Swiss construction typologies exemption made for *TI*4, which is modeled as the prototype used for the calibration (Table 5).

4.2. Ventilation profiles

Ventilative cooling can be a useful strategy to reduce cooling loads during summer in buildings with high internal heating gains, such as offices. For this reason, different ventilation scenarios have been tested, in order to understand the potential of these strategies in relation to the case of the Smart Living Building [51]. The scenarios have been created starting from scenario *V*1, considered as a reference case. *V*1 only includes the minimum requested rate of hygienic ventilation during occupancy [54,64], equal to 46.3 m³/h. The other scenarios integrate the hygienic ventilation with ventilative cooling strategies during the night (scenario *V*2), occupied hours (scenario *V*4) or all day long (scenario *V*3 and scenario *V*5). Therefore, the scenarios have been created as *V*1 plus and adjunctive ventilation strategy. As said, *V*1 represents a critical profile, as it includes only the minimum requirements for hygienic purpose and, therefore, it is not sized for cooling purpose. *V*5 represents instead the critical profile on the opposite directions, as overcooling might occur when external temperatures are too low. The other three profiles have been designed starting from these two extreme situations and representing the ventilative profiles most commonly used in offices: night ventilation (*V*2), temperature-driven auto-



Graph 3. Heating needs for ventilation scenario *V*1, expressed as function of thermal inertia. Please, note that the vertical axis is not starting from 0 but 38 kWh/m²a.

matic ventilation system (*V*3), and users-driven ventilation profile (*V*4) (Table 6).

4.3. Scenarios used for simulation

Once the ventilation profiles and the *TI* levels have been defined, a cross matrix that merges these two aspects has been created. Each *TI* level has been simulated with each ventilation profile, creating a set of possible and feasible solutions that are commonly used in the Swiss construction context.

5. Simulation results

5.1. Operational impacts: energy savings

Ventilation scenarios are designed to maximize the ventilative cooling effects; they are applied accordingly on thermal simulation only during the Swiss cooling period (16th April to 15th October), while during the heating period the hygienic airflow rate is the only one considered. Therefore, the heating requirements' analysis is addressed only for the ventilation scenario *V*1, regarding the six *TI* levels.

Results (Graph 3) confirm the state of the art: the heating needs decrease when higher levels of *TI* are considered.

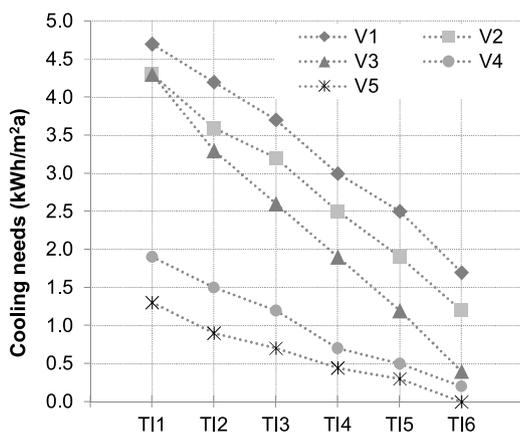
A massive construction (*TI*6) requires almost 7% less heating than a lightweight wooden one (*TI*1), reducing the heating needs from 43 kWh/m²a to 40 kWh/m²a. However, the percentage reduction from one *TI* level to the other averages between 0.2% (from *TI*3 to *TI*4) and 3.2% (from *TI*5 to *TI*6), indicating that the winter thermal performances of the envelope are not driven by *TI*. On the contrary, the extent of *TI* influence on the reduction of cooling needs increases when summer time is considered (Graph 4). These results clearly confirm the previous studies done on thermal inertia and its effect on cooling and heating in continental climates [52,53]. *TI* has a bigger potential when no mechanical system is used [15]. Therefore, in cold continental regions such as Switzerland, where mechanical heating is essential to assure indoor comfort, *TI* importance is mostly related to its influence during summer as natural cooling strategy.

Table 5
Thermal Inertia scenarios used for the analysis. TI levels are calculated with SIA380/1 and described by the heat capacity of the room. This depends on the thermal properties of each surface delimiting the room itself. The type of construction considered is reported in the table.

SCENARIO	LONGITUDINAL WALLS	SHORT WALLS	ROOF	FLOOR	Heat capacity C [kJ/(kg K)]
T11	Light- wooden	Light – wooden	Light – wooden	Light – wooden	39.1
T12	Wooden + synthetic rendering	Wooden + synthetic rendering	Light – wooden	Light – wooden	46.2
T13	Light – wooden	Light – wooden	Light – wooden	Wooden + cement screed	50.4
T14	Wooden + compressed earth bricks	Light – wooden	Light – wooden	Light – wooden	58.7
T15	Wooden + compressed earth bricks	Light – wooden	Light – wooden	Wooden + cement screed	70
T16	Concrete + internal mortar rendering	Concrete + internal mortar rendering	Concrete + internal mortar rendering	Concrete + cement screed	94.4

Table 6
ventilation scenarios used for the analysis. The scenarios enhanced the ventilative cooling potential and were defined as integrative strategies applied on the reference case, represented by scenario V1.

SCENARIO	BASIC AIRFLOW	+	MECHANICAL VENTILATION	NATURAL VENTILATION
V1	46.3 m ³ /h during occupancy	+	–	–
V2	as reference scenario	+	46.3 m ³ /h from 2am to 6am	–
V3	as reference scenario	+	46.3 m ³ /h if Tint-Text > 2 °C and Tint > 21 °C	–
V4	as reference scenario	+	–	Open windows during occupied hours
V5	as reference scenario	+	–	Open windows 24/24h



Graph 4. Cooling needs of ventilation scenarios, expressed as function of thermal inertia.

TI's potential in reducing overheating lies in fact on the dynamic capacity of storing heating during the day and releasing it later. Graph 4 displays the cooling requirements associated with the ventilation scenarios in relation to the TI levels. The cooling requirements have been evaluated according to SIA [54] using a comfort threshold of 26.5 °C.

Cooling requirements for the case study are relatively small, due to the continental climate of Fribourg; however, overheating during hot days can occur, making necessary the use of mechanical cooling [53]. TI contributes to decrease cooling requirements and reduce indoor temperatures in all the scenarios, however, the extent of the contribution varies according to the ventilation strategy applied: the reduction between lightweight and heavyweight scenarios (from T11 to T16) ranges between 60% – when the minimum hygienic ventilation rate is considered (V1)– up to 100% – when natural ventilation is used (V5). The results of mechanical ventilation scenarios V2 and V3 clearly indicate the low efficiency of these ventilative cooling profiles, which are not able to dissipate the accumulated internal heat, even when activated all night long (scenario V2). In this case TI property is essential to reduce the cooling need and its difference among ventilation profiles. In fact,

in scenario T16 the cooling needs associated to V3 (mechanical ventilation temperatures-driven) differ of less than 0.5 kWh/m² from the needs of V5.

These results show the importance of TI as a means to balance under-estimated airflows for ventilative cooling purposes.

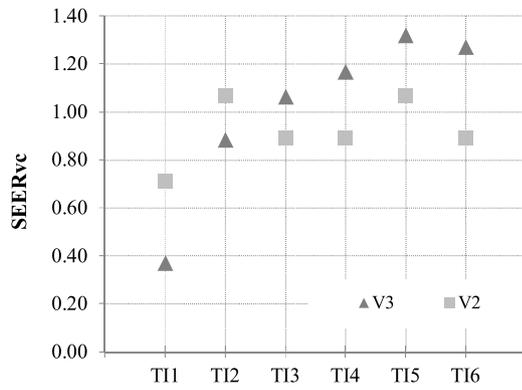
Graphs 2 and 3 underline three major points:

1. TI reduces both heating and cooling needs, even if its efficiency is higher in the latter
2. The ventilative cooling potential is affected by TI
3. The extent of the interactions between TI and ventilative cooling is strongly dependent from the typology of ventilation profiles considered

Moreover, from the operational savings analysis it is possible to conclude that natural ventilation – either active all day long or only during occupied hours – is the most effective solution to reduce cooling needs independent from the TI levels considered. If mechanical ventilation is considered instead, a temperature-dependent system (V3) is more efficient than a time-scheduled one (V2). In fact, the latter does not encompass the effective cooling properties of the airflows, which depends on physical properties of the external environment as well as the relative indoor and outdoor temperature's differences.

5.2. Operational impacts: seasonal energy efficiency ratio

In the previous section, a consistent difference between mechanical ventilation scenarios in regard to the energy saving potential has been shown. As said, mechanical ventilation based on temperature's gradient (scenario V3) is more effective than mechanical ventilation based time schedule (scenario V2), especially for high TI where the difference is more significant – Graph 3. To better define this difference, the seasonal energy efficient ratio for ventilative cooling (SEER_{VC}) has been assessed. This parameter has been introduced by EBC Annex 62 [72] and is useful for evaluating the ventilative cooling potential associated with a specific mechanical ventilation profile, allowing the comparison with any real cooling machine.



Graph 5. Seasonal energy efficiency ratio for ventilative cooling (SEER_{vc}), expressed for mechanical ventilation scenarios (V2 and V3) for TI levels. Mechanical ventilation based on temperatures gradient (V3) shows higher SEER_{vc} than mechanical ventilation based on time schedule (V2). TI influences V3 almost linearly: the effects of scenario V3 are maximized by high TI levels.

It is evaluated for both scenarios V2 and V3 and it is calculated as the cooling need difference between the specific scenario with and without the mechanical cooling system:

$$SEER_{VC} = \frac{Q_{Cref} - Q_C}{E_{VC}} \quad (1)$$

SEER_{VC} seasonal energy efficiency ratio

Q_{Cref} is the cooling need of the scenario without ventilative cooling kWh/m²

Q_C is the cooling need of the scenario with ventilative cooling applied kWh/m²

E_{VC} is the energy used to apply ventilative cooling, calculated as:

$$E_{VC} = SPI \times \vartheta \times H \quad (2)$$

Where:

SPI is the specific power input of the ventilation system, expressed in W/(m³/h)

ϑ is the airflow rate of the mechanical ventilation in m³/h

H is the number of running hours of the ventilation system for cooling purposes in h.

A negative SEER_{VC} means that the strategy evaluated has negative impacts on the overall cooling demand. If positive, it means that there are benefits associated to the ventilative cooling profiles in terms of reduction of cooling needs. However, when SEER_{VC} is positive but lower than 1, it means that the cooling needs savings are lower than the energy spent for running the mechanical ventilation system. In these three cases, ventilative cooling is not recommended. On the contrary, when the value is positive and greater than 1, the ventilative cooling strategy chosen has overall energy benefits, and it is an effective way to reduce a building's energy needs.

In the case study, we considered an SPI of 0.4 W/(m³/h), airflow rate of 46.3 m³/h, and the number of hours from the virtual simulations related to each scenario. With these assumptions, Graph 5 shows the SEER_{VC} related to scenarios V2 and V3 for each TI level.

It is interesting to see that for both scenarios – T11 and T12 (low TI levels) – the ventilative cooling strategies V2 and V3 are not effective. SEER_{VC} for V2 is always lower than 1.1, indicating that the balance between the energy requested by the mechanical system, and the energy savings induced by the ventilative cooling is not optimal.

Graph 5 shows that the SEER_{VC} behavior for scenario V2 is highly unstable, probably due to the high cooling needs, which requires a more efficient and powerful ventilation system than the one assumed.

Nevertheless, when ventilation is controlled by the temperature difference (scenario V3), SEER_{VC} increases with higher TI levels and stabilizes around 1.3. Therefore, V3 is efficient only if coupled with massive constructions. These results confirm the potential associated with the two mechanical ventilation scenarios in relation to TI and they classify the extent of the overall benefits and highlight the most effective strategy for reducing cooling needs in an office building in Fribourg using mechanical ventilation.

5.3. Embodied impacts: life cycle efficiency ratio

Embodied impacts assessments are usually done by evaluating not only the impacts of the building's construction but also those of every single material. Due to the complexity of the calculation, a simple visualization method is needed when comparing two or more different solutions. For this reason, a new indicator has been introduced in this paper: the life cycle efficiency ratio (LCER). This indicator has been defined following the SEER_{VC} methodology: it compares the operational savings of a given scenario with the referenced ones, weighted on the difference of embodied impacts implied in the two considered scenarios.

$$LCER = \frac{OI_{ref} - OI}{EI - EI_{ref}} \quad (3)$$

OI_{ref} are the operational impacts of the reference scenario (CED and CEDnr in MJ-eq and GWP in kgCO₂-eq)

OI are the operational impacts of the scenario analyzed (CED and CEDnr in MJ-eq and GWP in kgCO₂-eq)

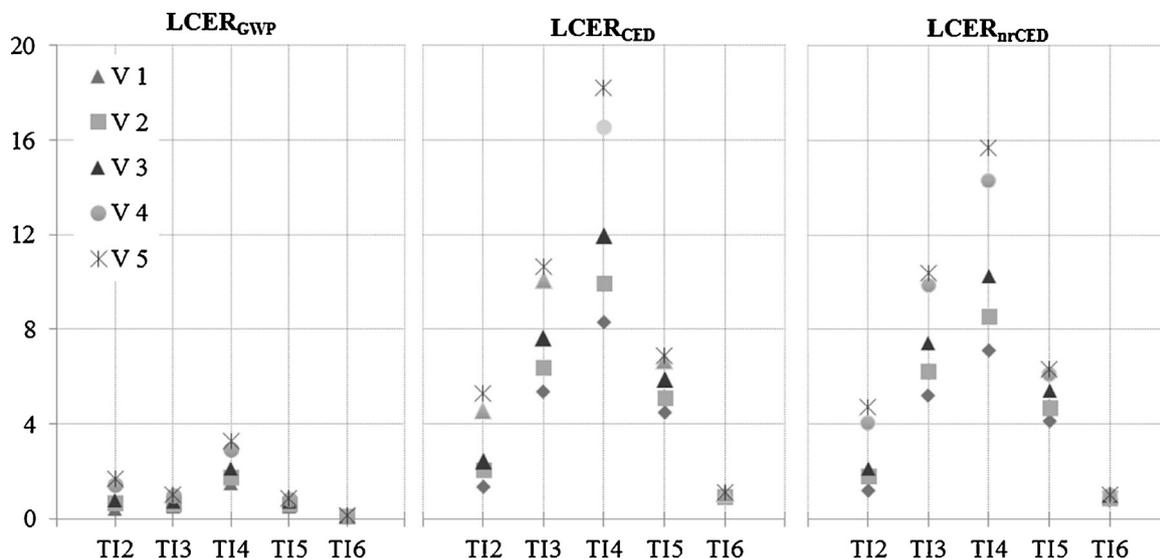
EI_{ref} are the embodied impacts of the reference scenario (CED and CEDnr in MJ-eq and GWP in kgCO₂-eq)

EI are the embodied impacts of the scenario analyzed (CED and CEDnr in MJ-eq and GWP in kgCO₂-eq)

This indicator relies on the ratio between the two main aspects of LCA, embodied and operational impacts, which are usually summed up to obtain the life cycle impacts of a specific building. In this case, we identify the environmental performance with a sole number, given by the ratio between the two components (EI and OI), instead of using either the sum or two separate numbers. In this way, the multidimensional comparison of multiple scenarios is easier and faster. Operational and embodied impacts are calculated following the standard LCA procedure given by norm [4,5]. LCER can be applied for each LCA indicator analyzed, in this case the impacts considered would be the specific ones assessed. In this analysis LCER is assessed for global warming potential (LCER_{GWP}), cumulative energy demand (LCER_{CED}), and non-renewable cumulative energy demand (LCER_{nrCED}). As for the previous indicator, when LCER is negative – meaning that the embodied impacts are higher than the operational savings, or when it is lower than 1 – the scenario analyzed does not introduce benefits in comparison with the reference one. On the contrary, the greater the indicator, the higher the life cycle benefits.

5.3.1. Embodied impact: LCA method applied

LCA is strictly dependent on the life cycle inventory (LCI) principles used [73,74] and to the method used [75]. Three main methods are used for compiling the inventory: the process-based method, the input-output method, and the hybrid method [76]. The process-based approach was the first methodology introduced to compute the environmental impacts. It follows the actual process flow [75] and it usually assumes that a production process produces one material (or energy), materials and energy flows do not have loops and the connections between process is linear (each process takes one input and generates one output) [77]. Generally speaking, all production processes in a supply chain are connected to one another, bringing in the LCI process-based method to a necessary truncation to a certain degree of the chain [78,79]. The



Graph 6. Life cycle efficiency ratio for ventilative cooling in relation to TI. The parameter is expressed for GWP, CED and CEDnr.

input-output method is instead a top-down technique, based on macro-economic interdependencies of industrial sectors [77–79]. This latter approach is not affected by the truncation errors, but still presents problems in the macro-scale of the study [80], the data age and the industry aggregation [77]. Based on the fundamental gaps found in the two methods, more recent hybrid approaches have been developed [81–83], combining the strength of the two methods with different degrees of integration [76]. In literature, different studies aimed at understanding the differences between the approaches: generally, there is a big gap between the input-output and the process-based methodology [84,85], even if it has also been found that the order of magnitude could be the same [86,87]. In our study, we used the KBOB database [56], which is a process-based LCI database that contains information about building materials and components and relies on the ecoinvent database [88,89]. In the KBOB, the energy indicators are evaluated according to [90] and [91], while the emissions are calculated according to the impact assessment method described in IPCC 2007 [92].

We calculated the embodied impacts of the scenarios as a comparison: considering the reference scenario TI1 + V1, embodied impacts are assessed only for the additional layers. Exception is made for TI6, where concrete substitutes the wooden structure. In this case, wooden EI are subtracted and replaced by concrete EI. For this reason, the underestimation embedded in the truncation adopted in the process-method LCI is considered to be negligible and not affecting the result added-value in supporting the design process.

In general, the following assumptions have been made for the LCA:

- materials EI are considered for production, transportation, and end of life;
- thermal energy is provided by a heat pump COP 4;
- final energy is transformed directly in primary energy factors according to the KBOB database. Final energy is directly converted into the primary energy impacts directly using the factors given by KBOB database for the final energy delivery system used. The factors indicated for the heat pump chosen are: CED: 1.57 MJ-eq, CEDnr: 0.709 MJ-eq, GWP: 0.0153 kgCO₂-eq [56,93,94], per unit of final energy in MJ;
- cooling loads are considered: an ideal mechanical cooling system is used to supply the cooling needs that the ventilative cooling strategy cannot satisfy;

- transportation distance is considered similar for all products;
- the additional massive layers are considered to have an impact only on the thermal properties of a building, overlooking the structural impacts;

Graph 6 shows that V5 has always the highest LCER, underlining the great potential of this ventilative cooling profile and confirming the results obtained from the operational savings analysis. However, LCA completely changes the conclusion previously obtained when considering the thermal inertia levels. LCER shows that TI is interesting if middle levels are considered (TI3, TI4, TI5), highlighting that high levels of TI are not efficient from a life cycle point of view, due to the materials involved to increase the building's thermal capacity.

This trend can be detected also in low-energy-consumption buildings, where the energy spent in creating an efficient envelope increases the embodied impacts of the construction [95,96].

On the contrary, the extremely high value achieved by TI4 is given by the relatively low EI of the compressed earth bricks, used as massive layer in that scenario.

The analysis points out the benefits of CEB on the life cycle of a building and, in the same time, highlights the necessity to consider EI when implementing TI. GWP has the lowest values among the three indicators, indicating that the carbon emissions related to a building's life are the critical parameters to consider when looking at its life cycle performances. The LCA analysis underlines that:

1. including embodied impacts when evaluating the benefits of a cooling strategy might change completely the results; in the case study the optimal solution to minimize the building impacts passed from very heavyweight to middle thermal inertia levels;
2. material with an optimal balance between thermal properties and embodied impacts, such as compressed earth bricks, have higher benefits;
3. LCER is an easy way to understand the life cycle impacts of a cooling solution and should be integrated to the operational savings evaluation when deciding for the optimal design solutions;
4. Natural ventilation has the highest benefits both on OI and EI if compared to mechanical ventilative cooling.

6. Discussion

In this paper, we applied a multidimensional approach for evaluating the benefits of different ventilative cooling strategies in relation to the thermal properties of the building's envelope. This means that the influence of the scenarios is considered under different points of view to understand *TI* effects on multiple dimensions.

The test facility constructed in Fribourg was used to calibrate the simulation software, small deviations have been found between simulated and measured data, given by the methodology applied in the experimental campaign.

DIAL+ was then used to simulate with the standard conditions (SIA 2024) the influence of ventilative cooling on offices with different thermal capacities.

For the test facility constructed in Fribourg, it is possible to conclude that:

- *TI* has a smaller influence on heating requirements, up to 7%, compared to the influence on cooling requirements, ranging from 60% up to 100%.
- Mechanical ventilation based on temperature differences has more effects in reducing cooling loads than mechanical ventilation based on time schedule. The first ventilation strategy has a seasonal energy efficiency ratio 1.5 time bigger than the second one; its SEER_{VC} increases with higher *TI* levels and stabilizes for heavyweight constructions (maximum value 70 Wh/(m²·K));
- Middle levels of *TI* are more efficient from a life cycle point of view than lightweight up to a factor of 2 (*GWP*), 3.5 (*CEd*) and 3 (*CEd_{nr}*). In comparison with high *TI* levels instead: 25 (*GWP*), 16 (*CEd*) and 15 (*CEd_{nr}*);

The approach adopted in this paper highlights the importance of introducing a holistic method to the early design phase, where the possible efficiency strategies have been evaluated. The benefits of a given passive strategy – in this case thermal inertia (*TI*) and ventilative cooling might change in relation to the parameters considered. High thermal inertia and natural ventilation strategy have been defined as the best way to prevent overheating in an office building placed in Fribourg (CH), according to the previous results obtained [53]. However, if *LCA* is considered, the results show that high *TI* levels correspond to high embodied impacts (*EI*), due to the materials involved for the additional mass in the construction. These *EI* are often higher than the savings induced on the operational impacts (*OI*), given by reduced cooling needs. This observation confirms the results already found in literature [95,96], however the methodology presented in this paper aimed at testing a new indicator to balance the two aspects – embodied and operational impacts – during the building design stage. It is possible to conclude from the results that middle *TI* levels (50 kJ/(kg K)) coupled with natural ventilation optimize the balance when natural materials are used. The results also show the interesting potential for maximizing *TI* benefits of natural materials, as compressed earth bricks (*CEB*). The low *EI* incorporated in these materials' typology increases the overall benefits of implementing *TI* through *CEB*. The numerical results are strictly dependent on the assumptions made and, in particular, on the scenarios analyzed and the *LCA* approach. As discussed, the life cycle inventory method used is a process-based approach, which brings a truncation error in the data used. This error results in underestimated total value of the environmental impacts considered. However, in this study, we calculated the differential impacts between scenarios and we used the *LCER* indicator, based on the ratio between embodied and operational impacts, always referring to a comparison more than the absolute value. In this way, the truncation effect is minimized, as the comparative results might not change.

Alongside the results on *TI* and ventilative cooling, the first viability assessment on the use of *LCER* as new indicator has been addressed. This performance indicator is a balanced ratio between the operational and embodied impacts of a given solution and it aims at defining a method to quantify the environmental benefit of a given design choice, based on the effects of the whole life cycle. In this study, only the case of the smart living lab has been addressed, as preliminary exploration on the feasibility of using *LCER* as design guide. Future research development aims, however, at better investigating its reliability in regard to a broader application on several case studies. This first results show clearly that *LCER* can have a big potential as an evaluation parameter during the design phase. Usually we evaluate the quality of a project based on energy indicators (e.g. heating needs), the results of this analysis open the possibility to replace those indicators with the *LCER*, which evaluates a project from a global perspective.

In the framework of the smart living building research program, the conclusions help to define an optimal solution for designing its future environmental efficient building [51], including in the design brief the mandatory requirement of balancing *OI* and *EI*. *LCER* indicator will be incorporated into the design brief as a design compass for the architectural competition that will serve as a decision-making tool to help designers provide more environmentally efficient solutions.

Further development of this research could better focus on an extensive use of this parameter to quantify the environmental efficiency embedded in the commonly used passive design strategies. We expect the results to draw some criticism in relation to an *OI*-driven design, which is the approach suggested by energy efficiency standards.

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