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Can constructal law and exergy analysis produce a robust design method that couples with industry 4.0 paradigms? The case of a container house

Michele Trancossi[1]*, Mauro Cannistraro[2], Jose Pascoa[3]

[1] Sheffield Hallam University, Sheffield (S1, 1WB), UK; Ethical Property Management Italia srl, Parma 43125, Italy
[2] University of Ferrara, Ferrara 44121, Italy
[3] Universitade da Beira Interior, Covilla 6201-001, Portugal

Corresponding Author Email: mtrancossi@gmail.com

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ABSTRACT

Constructal law deals with evolution and generation of new configurations of a physical system according to first and the second law of thermodynamics. Constructal law based design allows understanding the basic principles of the evolution of design in nature and to evolve a system through the maximization of its efficiency. On the other side, Digital Twin is a foundational paradigm of Industry 4.0. Digital Twin is the technological framework that allows an effective lifecycle analysis of a system and an effective comparison of different configurations. It allows determining the digital model of a physical system and replicating its evolution. This paper investigates how they can be complementary instruments of engineering and design process inside a knowledge based framework that opens the way through a knowledge-based, holistic and evolutional perspective in engineering. This paper aims to verify if an extended and evolved digital twin model that conforms with a multidisciplinary application of constructal law can be realized through the design of an optimized low-cost container house for social housing. The results demonstrate not only the efficiency and the results of the proposed system and that the results allow an effective improvement of the system performances and that this improvement is realized through an effective design which can be realized as it is with a finite precision, which is the one that is allowed by the real industrial components.

1. INTRODUCTION

1.1 Container housing

Migrations and reduced income of the most fragile parts of middle classes are global problems. In particular, they affect Europe and regard directly the housing politics [1-2].

The reduction of the number of members for each family, the immigration fluxes and the growing age of population are increasing house shortening [3].

Shipping containers are manufactured for complying the necessary specifications for freight transport. After their end of life they are just occupying huge spaces at ports and other places [4], which are increased by the asymmetry of global trade fluxes [5].

Recent construction practices have started the containers for house and commercial building purposes. In particular, Faludi et al. [6] produce a lifecycle assessment of commercial container modular architecture and define some good manufacturing practices.

Kelly [7] analyzed Japanese prefab housing model and determines a preliminary industrial model. Richard [8] defines a sustainable and demountable housing system based on container structures. Smith [9] and Boyd et al. [10] determine industrial models for an efficient off-site manufacturing for apartments. Shoemborn [11] has identified the major constraints and barriers to design innovation in modular construction. An effective architectural overview has been produced by Schwarzer [12].

Modular container housing system and economic offsite manufacturing in a controlled industrial environment allow an effective coupling of house manufacturing with Industry 4.0 evolution.

1.2 Constructal design

Bejan [13-14] has defined constructal law as a unifying principle of nature that governs the evolution in nature: "*For a finite-size flow system to persist in time (to live) it must evolve such that it provides greater and greater access to the currents that flow through it.*" Consequently design evolves with the flows through the physical domain.

This process generates new configurations that facilitate the flow [15-16], such in the case of tree-shaped river basins and deltas [17], vegetation and all forms of animal mass flow (running, flying, swimming) [18-19], heat transfer systems [20-21].

If constructal law could be applied to industrial design it is expected to produce new configurations of physical systems based on first and second law of thermodynamics [22-23]. Most of related literature insists on hydraulic and thermodynamic systems.

From the tree shaped system discretization presented by Zamfirescu and Bejan [24], Trancossi has defined the possibility of adopting it into general industrial design [25-

26]. It produced interesting results on evaluation of first and second law efficiency of transports [27].

Trancossi and Pascoa applied it to the design of ground vehicles [28], Coanda effect nozzles [29-30] and aircrafts [31-32]. Pascoa applied it to the optimization of DBD aerodynamic actuators [33-34] and of cyclorotor propellers [35-36].

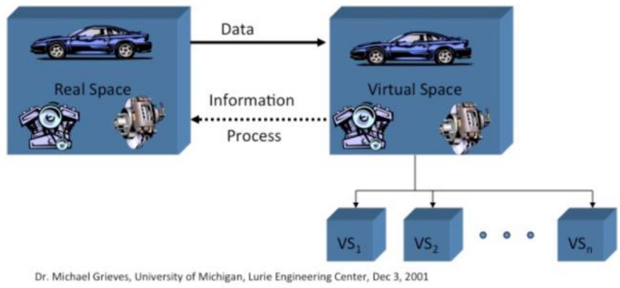

Figure 1. Conceptual ideal for PLM by grieves

1.3 Industry 4.0 and digital twin

Industry 4.0 is a set of digital instruments that allows producing a large set of benefits, such as smarter and cheaper production cycles, improved possibility of lifecycle management and enhanced design cooperation possibilities.

It is based on Internet of Things and Digital Twin.

Digital Twin concept [37-38] has been introduced by Grieves [39-40] as an evolution of Product Lifecycle Management (PLM) and is presented in Figure 1.

This model was named "Conceptual Ideal for PLM", and contains the key elements that characterize the Digital Twin: real space, virtual space, data and information flow from virtual space to real space and virtual sub-spaces.

The natural consequence is that each engineering system consists of two systems: the physical system that is the real object; a digital system that contains all the information that allows replying the physical one.

Such a process allows creating a twinning process that interconnects the real space to the virtual space and vice versa. The Digital Twin can be defined as a construct by virtual information that describes and allows creating an exact replica of a potential or actual manufactured product.

In particular, it is possible to define four different Digital Twins:

1. Digital Twin Prototype (DTP) – It is a digital prototype that allows describing and reconstructing the physical artifact. The sets of information must include: requirements, 3D models, Bill of Materials (including specifications), manufacturing plans, control codes, Bill of Processes, Services, and Disposal, etc.
2. Digital Twin Instance (DTI) – It links to a specific physical product and remains linked to it throughout the entire lifecycle and describes the use which is required for it. It contains the following information sets: 3D model, General Dimensioning and Tolerances (GD&T) that describes the physical instance and its components, a Bill of Materials (current components and all past components), a Bill of Processes (the necessary operations for creating the physical instance), results of instrumental measurements and tests during the lifecycle, the Service Record (service and maintenance history), operation state as determined by sensors, numerical predictions, etc.
3. Digital Twin Aggregate (DTA) – It is the aggregation of all the DTIs. Unlike the DTI, usually, the DTA is not an independent data set, but is a computing construct that summarizes the performances of all the DTIs and allows interactive queries for service performance estimation such as Mean Time Between Failure (MTBF) of components, prognostic and maintenance plans;
4. Digital Twin Environment (DTE) - It is an integrated, multi-domain physics application space for operating on Digital Twins for a variety of purposes that includes predicting future behavior and performance of the physical product; virtual modeling and testing of prototypes that allows determining the behavior of the designed product, different possible components and their effect on the performances, requirements and specification matching.

1.4 Objectives of the paper

It is evident that the intrinsic nature of constructal law based design and of Industry 4.0 digital twin based holistic design and optimization modes can precisely couple to allow a more effective design that accounts first and second law of thermodynamics into the definition of both product and production system. In this paper it will be assessed an effective design method which derives from constructal design, in the hypothesis of coupling it with modular design and consequently with digital twin according to guidelines defined by Weyer [41] and Rios et al. [42].

This paper will account the design of a container based modular housing system, which can be easily produced off-site and moved on-site with major economic and industrial benefits with respect to traditional building technologies. In particular, it has been conceived specifically as an instrument for robust and limited cost social housing.

The actuality container buildings clearly refer to the dissymmetry of global commercial fluxes a large quantity of shipping containers is sitting and waiting for a possible future reuse [43] and new ones arrives continuously [44]. Some experiences such us UBC-uniform building (USA) [45] and Travelodge (Uxbridge, London) [46] demonstrates that container based modular construction is 40-60% quicker, produces 70% less onsite waste than traditional building methods, requires simpler construction processes and reduces cost substantially. A better planning of constructive sites has the aim of creating a low-cost and zero waste construction [47]. Several experiences of container constructions demonstrate their unique modularity, flexibility and rigidity.

2. METHODOLOGY

2.1 Assessment of the building

Any building requires a defined amount of energy for maintaining the wellness conditions. It can be evaluated by an effective energy balance which is schematized in Figure 2.

The demand is the sum of the energy losses including transmission and ventilation heat losses of the envelope.

The losses can be compensated by the energy gains which are caused by appliances and users as well as solar gains.

Diminish the necessary of heating energy that is needed for heating, lighting, ventilation, and for any other operation of building systems. According to Schlueter and Thesseling [48-49], it is necessary to evaluate six performance indices, that allows understanding the energy performance of the building and producing an effective assessment of the energy performance of the specific design at the maximum temperature difference for a specified location. A similar process allows the evaluation of the structure. The method by Schlueter and Thesseling is presented in Figure 2. It is evident that the structure of data can be easily implemented in a Digital Twin data structure. The analysis requires a complex set of input parameters: geometry and masses, topology; semantic parameters, climatic parameters, materials properties.

Dependencies are automatically introduced into the building information model.

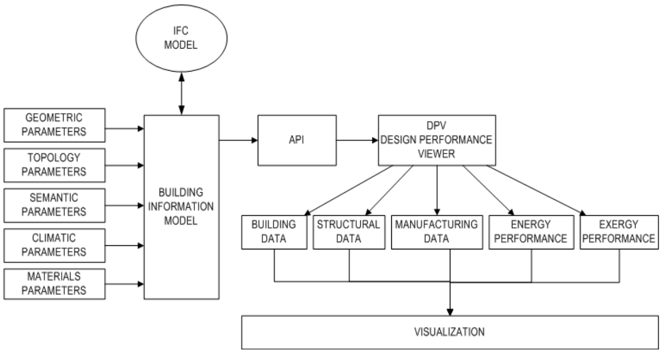

Figure 2. Building assessment process

2.2 First law assessment

Transmission heat losses of the envelope - The real building or the design model allows taking all the information about the geometry of walls, doors, windows, roofs ceilings. From the bill of materials (BOM) it is possible to determine the specific values of U for the elements that exchanges with the exterior environment. T_i is the indoor temperature and Te is the outdoor one, which depends on the location of the building. The total transmission heat loss is the sum of the heat losses of all envelope surfaces. Heat bridges are not considered at this level even if they can be accounted by standardization (i.e. in Italy UNI TS 11300 [50-51])

$$\dot{Q}_T = \sum_j U_i A_i (T_i - T_o) \tag{1}$$

A correction factor can be introduced if some temperature are exchanging with temperatures, which are different from reference external temperature (Fi). It assumes the following reference values: 1.0 for exterior walls and roofs; 0.6 for walls and floors facing the ground [22], 0 for winter gardens, attics and unheated rooms. Equation (1) becomes:

$$\dot{Q}_T = \sum_i F_i U_i A_i (\theta_i - \theta_e) \ \text{[W]} \tag{2}$$

Ventilation heat losses - A simplified formula captures the ventilation heat losses. The volume V is determined from the building model and multiplied by the air exchange rate n_d.

$$\dot{Q}_V = (0.34 \cdot n_d \cdot V) \cdot (T_i - T_o) \ \text{[W]} \tag{3}$$

It is assumed the specific heat capacity of air (0.34 Wh/mK).

Solar heat gains through windows - Solar irradiance is a function of location and orientation of the windows.

Solar radiation that heats the building is calculated for each window in dependence of the area A.

The total solar transmittance of the windows g defines the energy input of solar radiation passing through a specific glass.

$$\dot{Q}_S = \sum_i (I_{s,j} A_{w,i} g_{L,i} F_{F,i} F_{W,i} F_{C,i} F_{S,i}) \ \text{[W]} \tag{4}$$

The data for calculation can be determined by BOM. The F symbols indicate the correction factors: F_F (windows framing); F_W (angle of incident solar radiation); F_S (shading by surrounding buildings and vegetation); F_C (shading devices). The correction factors are usually cumulated in a standard value of 0.567 according to the standardization.

Internal heat gains -Internal heat gains caused by humans are a static parameter within the occupancy number no of the room. The heat gain per person is considered to be

$$\dot{Q}_P = 80W / person$$
$$\dot{Q}_O = \dot{Q}_P \cdot no_0 \quad \text{(W)} \tag{5}$$

The specific heat gain by electrical appliances $\dot{Q}_E$ is defined on the basis of the building location. This static value can be adapted as a function of the building type, area and usage.

$$\dot{Q}_A = \dot{Q}_E \cdot A_n \tag{6}$$

Specific lighting power/lighting power - The specific lighting power changes as a function of different national regulation. The specific lighting power can be defined as:

$$p_{Li} = \frac{E_{vm} p_v}{\eta_V \eta_{Lo} \eta_R} \quad [\text{W/m}^2] \tag{7}$$

Consequently, lighting power is:

$$\dot{Q}_{i,L} = p_{Li} \cdot A_n \ \text{[W]} \tag{8}$$

Resulting heating demand - The above cited terms allow to determine the energy needs of the building according to the first law of thermodynamics

$$\dot{Q}_h = (\dot{Q}_T + \dot{Q}_V) - (\dot{Q}_S + \dot{Q}_O + \dot{Q}_A + Q_{i,L}) \tag{9}$$

2.3 Second law exergy assessment

The analysis of energy flows in buildings requires an effective second law assessment. An exergy assessment [52-53] is performed.

The exergy assessment into building processes has been introduced by Wall [54] and Rosen [55]. In particular, the analysis which is performed will consider Shukuya [56] and Schmidt [57] and in particular Schlueter and Thesseling [49] models. Schlueter and Thesseling work presents a certain interest, even if it presents some lacks, which refers to the idea of exergy demand, and not of exergy dissipation that is more coherent on thermodynamic point of view (Figure 3).

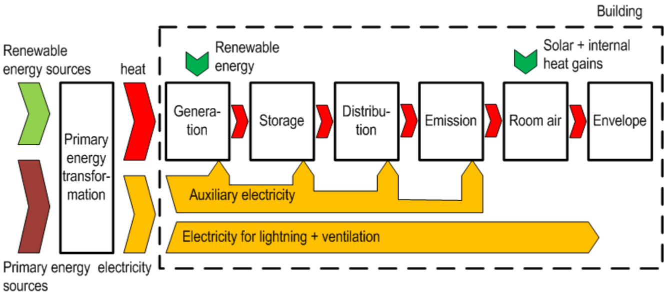

Figure 3. Exergy dispersions (derived and corrected from 49)

2.3.1 Envelope

The amount of exergy that will be dissipated for acclimatization is estimated by the heat demand with the quality factor of the room F.

This quality factor is estimated by calculating the Carnot efficiency calculated by outside and inside temperatures:

$$Ex_{envelope} = \dot{Q}_h \cdot F_{q,envelope} \tag{10}$$

2.3.2 Acclimatization

Exergy dissipated by acclimatization accounts the quality factor of the heater surfaces $F_{q,heat}$, which have been calculated by the Carnot efficiency using the temperature of the heater and reference outdoor one.

$$Ex_{envelope} = \dot{Q}_h \cdot F_{q,heat} \tag{11}$$

2.3.3 Emission subsystem

The heat losses of the emission subsystem $\dot{Q}_{loss,E}$ account the efficiency of the emission system.

Exergy is extimated by three reference temperatures: inlet (T_{in}), return (T_{ret}) and outside(T_0).

$$\Delta Ex_{emis} = \frac{\dot{Q}_h + \dot{Q}_{loss,E}}{(T_{in} - T_{ret})} \left\{ (T_{in} - T_{ret}) - T_o \ln\left(\frac{T_{in}}{T_{ret}}\right) \right\} \tag{12}$$

The exergy disruption by the emission system is:

$$Ex_{emis} = Ex_{heat} + \Delta Ex_{emis} \tag{13}$$

2.3.4 Distribution subsystem

The calculation of the exergy dissipated by the distribution subsystem is calculated in the same way of the emission subsystem. The following temperatures are considered: mean design temperature (T_{dis}); the return temperature is equal to the design temperature minus the temperature drop ΔT_{dis}.

$$\Delta Ex_{dis} = \frac{\dot{Q}_{loss,D}}{\Delta T_{dis}} \left\{ \Delta T_{dis} - T_o \ln\left(\frac{T_{dis}}{T_{dis} - \Delta T_{dis}}\right) \right\} \tag{14}$$

The exergy dissipation is consequently:

$$Ex_{dis} = Ex_{heat} + \Delta Ex_{dis} \tag{15}$$

2.3.5 Energy storage

Energy storage subsystem is present when using renewable energies to partially satisfy the needs of the building. The exergy dissipation of the storage subsystem, by considering the mean storage design temperature T_{dis} is used as inlet temperature, the return temperature is the design temperature minus the temperature drop ΔT_{sto}.

$$\Delta Ex_{sto} = \frac{\dot{Q}_{loss,S}}{\Delta T_{sto}} \left\{ \Delta T_{sto} - T_o \ln\left(\frac{T_{dis} + \Delta T_{dis}}{T_{dis} + \Delta T_{dis} - \Delta T_{sto}}\right) \right\} \tag{16}$$

The exergy dissipation is consequently:

$$Ex_{sto} = Ex_{sto} + \Delta Ex_{sto} \tag{17}$$

2.3.6 Exergy dissipation in the generation subsystem

The generation subsystem satisfies the demand of all subsystems. It also considers, when present, the thermal solar power with a solar fraction Fs.

$$\dot{Q}_{Ge} = \left(\dot{Q}_h + \dot{Q}_{loss,E} + \dot{Q}_{loss,D} + \dot{Q}_{loss,S} \right) \cdot (1 - Fs) \cdot \frac{1}{\eta_G} \tag{18}$$

The requested energy of generation therefore is

$$Ex_{Ge} = \dot{Q}_{Ge} \cdot F_{q,S} \tag{19}$$

The exergy load of building service components (lighting P_L, and ventilation P_V) depends on an electric plant quality factor

$$Ex_{plant} = (P_L + P_V) F_{q,electricity} \tag{20}$$

2.3.7 Exergy dissipated by renewable energy

Assuming that heat is extracted from the environment, the exergy dissipated by renewable energy production is

$$Ex_{renew} = Ex_{environment} + \dot{Q}_{Ge} \cdot F_{renew} \tag{21}$$

2.3.8 Exergy dissipated by primary energy

Exergy dissipated by primary energy is:

$$Ex_{prim} = \dot{Q}_{Ge} F_P + \left(PL + PV + \sum P_{aux} \right) F_{P,electricity} \tag{22}$$

in which F_p is the primary energy factor that can be considered around 3 for a large part of EU countries.

Exergy balance: it is possible to evaluate the total exergy necessary to the building.

$$Ex_{tot} = Ex_{prim} + Ex_{renew} \tag{23}$$

3. BUILDING MODEL

This paper analyses and optimizes the design of a new container house. It has been assumed that the reference building is the one has the following characteristics.

This paper considers a container house with one flat constituted by two container modules (Table 1) and an internal surface of 62 m^2 (Table2 and Figure 4).

Table 1. Measures of a 40' container

external dimension	length (m)		Width (m)	height (m)	
	12.192		2.438	2.591	
internal dimension	length (m)		Width (m)	height (m)	
	12.032		2.352	2.385	
door opening	length (m)		Width (m)		
	2.343		2.28		
Internal volume	67.5	m^3	Max gross weight	30.4	kg
empty weight	3.8	kg	max net load	26.6	kg

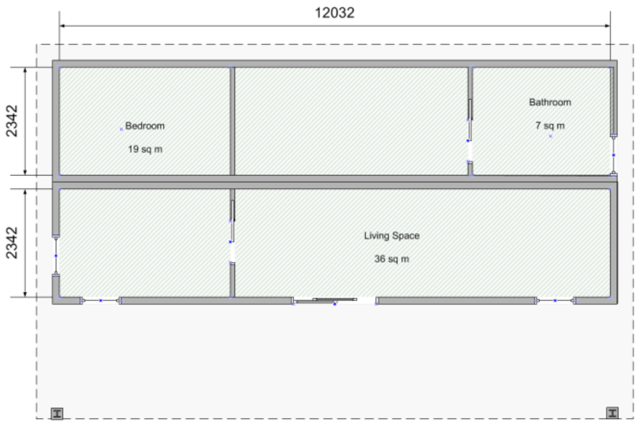

Figure 4. Preliminary plant of the reference building

It has a flat ceiling and is placed on a concrete floor. Reference climatic and solar radiation data have been assumed in Bologna (Italy) and are reported in the Annex [58].

Reference temperatures are defined by E.U. standards [59]:
Int. Ref. Temp.: Summer 26 °C; Winter 20 °C;
Ext. Ref. Temp.: Summer 35 °C; Winter -5 °C.

Table 2. Building properties

Gross surface area	58,5	m^2
Gross volume	151,5	m^3
S/V ratio	0,9	-

3.1 Digital twin implementation

A complete BOM and a digital model of system configurations have been implemented.

It has been the basis for the following analysis and configuration design.

3.2 Consideration on wall structure and insulation

The objective of the design is to meet passive house requirements. The insulation is the fundamental aspect of design, as observed by Bowley [60].

It is necessary to insulate the container with an adequate thermal resistance and limiting thermal bridges.

Two different strategies are possible:

Insulated wall outside the container – It allows some advantages, i.e. using costless and greener materials with higher thicknesses to meet energy requirements and avoid thermal bridges. Otherwise it requires a structural frame around the container to support the wall and some cladding to for environmental protection, with additional costs, and needs of a more accurate design for moisture management and avoiding the degradation of insulation.

Insulation inside the containers' frame - It takes advantage of the protection by the weatherproof container exterior skin, and keeps the container aesthetics, but insulation can will reduce the interior space. Closed cell foam insulation requires around 230 mm to attain an adequate resistance. An alternative is the use of vacuum insulated panels (Figure 5) VIP/foam combination for exterior surfaces. According to Bowley, VIP panels can be layered with half inch foam board on either side.

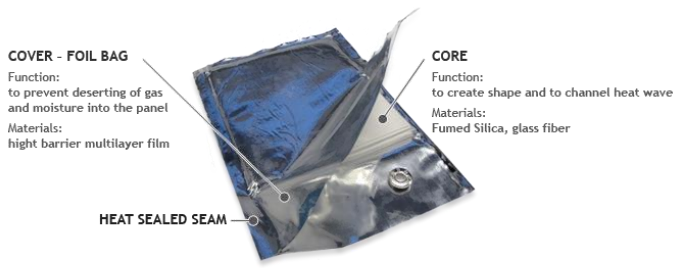

Figure 5. Structure vacuum insulated panels

Table 3. Comparison of different materials

Material	λ (W/mK)	U (w/m²K) at thickness D (mm) 5	10	15	20	30	40	50	60	70	80	90	100
VIC*	3.5	0.70	0.35	0.23	0.18	0.12	0.09	-	-	-	-	-	-
Rockwool	35	7.00	3.50	2.33	1.75	1.17	0.88	0.70	0.58	0.50	0.44	0.39	0.35
PUfoam	22	4.40	2.20	1.47	1.10	0.73	0.55	0.44	0.37	0.31	0.28	0.24	0.22
EPS	36	7.20	3.60	2.40	1.80	1.20	0.90	0.72	0.60	0.51	0.45	0.40	0.36
XPS	32	6.40	3.20	2.13	1.60	1.07	0.80	0.64	0.53	0.46	0.40	0.36	0.32

* Turvac FG vacuum insulated panels with fumed silica core. [61]

Table 3 presents conductivity of different construction materials. It shows the much higher performance of VIC with respect to any other material.

Table 4 presents the possible insulated wall structures. Areas and dispersions of external dissipating surfaces are determined in Table 4.

Table 4. Properties of wall layers

n.	Mat.	*s* *[mm]*	*ρ* *[kg/m³]*	*K* *[W/(mK)]*	*A* *[W/(m²K)]*	*C* *[J/kgK]*
	Ext.				25	
1	**Steel**	1	8000	17		500
2	**PU**	12.5	40	0.022		1600
3	**VIC**	20÷40	180	0.0041		500
4	**PU**	12.5	40	0.022		1600
5	**Steel**	1	8000	17		500
	Int.				7.7	
Overall heat transfer coefficient				0.16÷0.09 W/(m^{2}K)		

It can be observed that use of VIC allows reducing the thickness to maximum 67.5 mm and consequently that it limits the space losses.

Double glassed windows with Argon gas allow a U value in the range (0.7÷1.1W/(m^{2}K)).

Table 5. Building external surfaces geometry and emissions

	Gross Area	Wall	Heat flux	Window	Heat flux
	[m^2]	[m^2]	[W]	[m^2]	[W]
South	31.59	25.11	56.7÷102.0	6.48	113.0÷178.0
North	31.59	31.59	71.4÷128.0	0.00	
East	12.63	11.37	21.8÷46.0	1.26	25.2÷31.4
West	12.63	11.37	21.8÷46.0	1.26	25.2÷31.4
Area	88.45	79.45		9.00	

3.3 Preliminary building design

Climatic data and solar irradiation in Bologna is reported in the Annex and is accounted in the calculations of building performances. The proposed building configuration with most of the glassed area on one surface works optimally with south orientation. The expected performances are evaluated on a monthly base and reported in Table 5.

It has been assumed a gas heating plant with a condensation boiler and an overall seasonal efficiency 0.4.

Heating plant is constituted by large low temperature radiant panels. Temperature regulation is performed by coupled indoor sensors with temperature capability and environmental outdoor sensors.

Table 6. Building energy initial performance

Heating	Jan	Feb	Mar	Apr	Oct	Nov	Dec	
Transmission dispersions	162,3	127,3	100	28,6	29,1	102,6	146,1	kWh
Ventilation dispersions	181,0	140,7	107,2	28,4	28,3	110,6	161,8	kWh
Internal contribution	184,5	166,7	184,5	89,3	101,2	178,6	184,5	kWh
Solar contribution	104,2	131,7	174,2	77,1	91,2	115,3	98	kWh
Net energy Needs	55,4	2,4	0	0	0	0	28,9	kWh
Heating need	*17.5*	*kWh/m^2*	*CO_2 emissions*	*2.75*	*kgCO_2/m^2*			
Cooling needs	May	Jun	Jul	Aug	Sep	kWh		
Transmission dispersions	73,7	36,0	17,6	23,2	53,0	kWh		
Ventilation dispersions	76,0	31,6	9,4	16,1	51,8	kWh		
Internal contribution	184,5	178,6	184,5	184,5	178,6	kWh		
Solar contribution	202,3	203,3	223,4	214,2	216,1	kWh		
Net energy Needs	237	314,5	381	359,2	289,9	kWh		
Cooling need	*36.0*	*kWh/m^2*	*CO_2 emissions*	*5.95*	*kgCO_2/m^2*			
Appliances								
Water heating	*23.2*	*kWh/m^2*	*CO_2 emissions*	*3.83*	*kgCO_2/m^2*			
Lightning system	*7.5*	*kWh/m^2*	*CO_2 emissions*	*1.24*	*kgCO_2/m^2*			

The energy performance during winter appears excellent. It is worst during summer, but can be improved by a mobile solar shading appliance.

In addition, water heating performance can be improved.

3.4 Digital twins and first law improvements

The improvement process starts from considering different improvements and add-ons that can be applied.

Application of a solar shading device on south façade.

If a shading device is installed, it can be reduced the solar heating during summer, when the solar angle is higher than 45°. Wintertime solar contribution reduces but the acclimatization needs are reduced during summertime.

The adoption of a mobile device allows keeping constant winter shading and reducing the solar charge during summertime.

Table 7. Building with mobile solar shading

Heating need	17.5	kWh/m^2	CO_2 emissions	2.75	kgCO_2/m^2
Cooling need	23.4	kWh/m^2	CO_2 emissions	3.87	kgCO_2/m^2
Water heating	23.2	kWh/m^2	CO_2 emissions	3.83	kgCO_2/m^2
Lightning system	7.5	kWh/m^2	CO_2 emissions	1.24	kgCO_2/m^2

Adding a 3 m^2 of solar water heating panels with 0.2 m^3 heat storage for hot water and heating contribution, allows producing a dramatic reduction of the needs for water heating and environment heating. The high temperature heating source during summer allows increasing the cooling efficiency during summer.

Table 8. Building with solar panels and mobile solar shading

Heating need	17.5	kWh/m^2	CO_2 emissions	1.07	kgCO_2/m^2
Cooling need	23.4	kWh/m^2	CO_2 emissions	3.87	kgCO_2/m^2
Water heating	2.5	kWh/m^2	CO_2 emissions	0.41	kgCO_2/m^2
Lightning system	7.5	kWh/m^2	CO_2 emissions	1.24	kgCO_2/m^2

Further improvements are obtained by adding a PV plant to achieve the complete energy neutrality.

3.5 Second law based improvements

Exergy analysis deals with the quality of the energy. The traditional plant made by a winter condensation boiler and a summer air conditioning can be easily substituted by a heat pump with a nominal COP 2.5. In particular the following options have been considered with respect to the climatic conditions in Bologna (Table 9 and Figure 6).

Table 9. First a second law efficiency of different kinds of acclimatization plants [62-63]

Energy source	*Acclimatization system*	*First law eff. η*	*Second law eff. E*
natural gas	Gas boiler + radiator	0,86	0,040
natural gas	condensing gas boiler + radiant panels	1,05	0,051
Italian electrical mix	air-to-water heat pump	0,90	0,062
Italian electrical mix	air-to-air heat pump	1,21	0,071

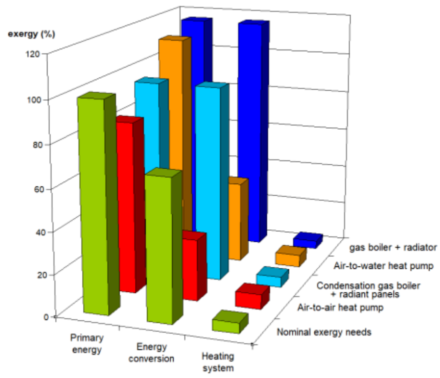

Figure 6. Simplified representation of exergy efficiency of different heating technologies

The above compared acclimatization plants allow an effective definition of the best technical solution for the building. It is then evident the increase in terms of efficiency that has the maximum levels of benefits in both terms of first and second law is the air to air heat pump.

The reduced charge for units allows thinking to a centralized acclimatization plant that serves 8/10 modular apartments.

4. CONCLUSIONS

This paper has demonstrated that industry 4.0 Digital Twin model can perform properly allowing an effective holistic optimization process of a building. In addition it also demonstrates that a building configuration can evolve according to constructal law in the direction of increasing its efficiency. The building system can be consequently designed as an evolutional system that can increase its performances according to the increase of the performances of the components. Starting from an actual container house it demonstrates that it can evolve in the sense of maximizing both first and second law efficiency. The final configuration in terms of envelope and plants, including solar shading can reach an A+ class with an accurate design process. The results for the best possible configuration have been verified by the energy efficiency module of RetScreen [64] and have been reported in table 9. The results have been encouraging up to the point to encourage the authors to start the development of specific software for building design according to constructal law and industry 4.0 semantic and holistic approaches.

Table 10. Best configuration annual performance

	Winter	*Summer*	
Dispersions by transmission	12,4	12,4	kWh/m^2
Dispersions by Ventilation	13,5	13	kWh/m^2
Internal contribution	19,5	28,8	kWh/m^2
Solar contribution	14,1	18,4	kWh/m^2
Time constant	336,3	336,3	h
Net Energy Need	1,5	18	kWh/m^2

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NOMENCLATURE

A_i	area of element of envelope i, m^2
$A_{w,i}$	area of generic window i, m^2
A_n	area of rooms with apparels, m^2
E_{vm}	illuminance of each room, W/m^2
Ex_{heat}	exergy dissipated by heating system, W
Ex_{emis}	exergy dissipated by the emissions, W
$Ex_{envelope}$	exergy dissipated by the envelope, W
Ex_{Ge}	exergy dissipated by generation system, W
Ex_{heat}	exergy dissipated by heating system, W
Ex_{sto}	exergy dissipated by storage, W
F_i	temperature correction factor, -
$F_{C,i}$	solar correction factor due to shading devices,-
$F_{F,i}$	solar correction factor due to windows framing,-
F_p	primary energy factor, -
$F_{q,S}$	quality factor of the energy generation, -
$F_{q,heat}$	quality factor of the heater surfaces, -
$F_{q,envelope}$	quality factor of the envelope, -
$F_{q, electricity}$	quality factor of electric uses, -
$F_{S,i}$	solar correction factor due to surroundings, -
$F_{W,i}$	Correction factor due to solar angle, -
$F_{S,tot}$	overall solar correction factor, 0,567
p_{Li}	specific lighting power, W/m^2
P_L	exergy load for lightening, V
P_V	exergy load for ventilation, V
$\dot{Q}_A$	heat contribution by apparels, W
$\dot{Q}_E$	unitary heat contribution by apparels, W/m^2
$\dot{Q}_{Ge}$	heat for energy generation, W
$\dot{Q}_{i,L}$	heat gain by lighting, W
$\dot{Q}_O$	heat gains by occupants, W
$\dot{Q}_P$	heat gain per person, W
$\dot{Q}_S$	solar heating flux, W
$\dot{Q}_T$	heat loss from the envelope, W
$\dot{Q}_V$	ventilation heat losses, W
T_i	indoor temperature, K
T_{in}	inlet temperature of heating system, K
T_o	outlet temperature, K
T_{ret}	return temperature of heating system, K
U_i	global heat exchange coefficient, W/m^{2}k
V	volume of the building
$g_{L,i}$	energy input of solar radiation
n_d	Air exchange rate
No_0	number of occupants

Greek symbols

$\Delta Ex_{envelope}$	exergy variation through the envelope
ΔEx_{emis}	exergy variation though the emissions
ΔT_{dis}	Temperature drop in distribution system, K
η_{Lo}	lamp efficiency
η_R	specific room lightening characteristics
η_v	specific lightening efficiency, -
Te	outdoor temperature, K
Ti	indoor temperature, K
ρ_v	Illuminance ageing factor, -

Table A.1. Reference climatic data in Bologna (Italy)

Month	Air temp.	Rel. Humid.	Daily solar radiation-horizontal.	Atm. Press.	Wind speed	Earth temp.	Heat. degree days	Cool. degree days
	°C	%	kWh/ (m^2d)	kPa	m/s	°C	°C-d	°C-d
Jan.	2.5	82.0%	1.22	98.8	1.7	3.2	481	0
Feb.	4.4	75.2%	1.91	98.7	1.9	4.5	381	0
Mar	9.2	70.0%	3.12	98.5	2.4	9.1	273	0
Apr	12.9	70.8%	4.38	98.1	2.6	13.2	153	87
May	18.2	68.0%	5.45	98.3	2.5	19.2	0	254
Jun	22.3	65.5%	6.08	98.4	2.6	23.1	0	369
Jul	25.1	63.4%	6.15	98.4	2.5	26.0	0	468
Aug	24.6	66.0%	5.26	98.4	2.4	25.7	0	453
Sept	20.2	70.6%	4.04	98.5	2.2	21.2	0	306
Oct	14.7	80.3%	2.55	98.6	1.8	15.4	102	146
Nov	8.2	83.9%	1.39	98.5	1.7	8.8	294	0
Dec	3.8	83.0%	1.05	98.7	1.8	4.6	440	0
Annual	13.9	73.2%	3.56	98.5	2.2	14.6	2.124	2.083
Meas. at	m				10.0	0.0		

Table A.2. Solar radiation in Bologna (MJ/m^2)

	ORIZZ.	NE	E	SE	S	S	O	NO	N
January	4.5	1.8	3.5	5.8	7.4	5.8	3.5	1.8	1.7
February	7.9	3.2	6.1	9	10.7	9	6.1	3.2	2.6
March	12.1	5.4	8.8	11	11.6	11	8.8	5.4	3.8
April	17.3	8.5	11.9	12.6	11.2	12.6	11.9	8.5	5.5
May	21.0	11.1	13.8	12.7	10.2	12.7	13.8	11.1	7.9
June	23.6	12.8	15.2	13.1	10.0	13.1	15.2	12.8	9.7
July	25.6	13.6	16.8	14.7	11.1	14.7	16.8	13.6	9.5
August	21.0	10.5	14.3	14.3	12.0	14.3	14.3	10.5	6.6
September	15.4	7.0	11.1	13.1	12.9	13.1	11.1	7	4.3
October	9.9	4.1	7.6	10.7	12.4	10.7	7.6	4.1	3.0
November	5.3	2.1	4.2	6.8	8.5	6.8	4.2	2.1	1.9
December	4.1	1.6	3.3	5.7	7.2	5.7	3.3	1.6	1.5