AiCARR Journal

2016, 37, 60-67bis

Research paper

AiCARR
Cultura e Tecnica per Energia Uomo e Ambiente

RAPID EXPLOITATION OF BUILDING ENERGY DESIGN THROUGH COMPACT TRNSYS MODELING

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ABSTRACT

This paper presents the development of a new modeling support tool able to simulate, with a reasonable workload, 36 integrated building-plant systems with different scales and resolutions, in order to support architects and HVAC designers/engineers in their modeling efforts, providing them with an extremely flexible, guided and accurate tool which does not require specific expertise during its use. The starting point is represented by a detailed model created with the calculation engine TRNSYS, which allows for dynamic and integrated simulation of the building envelope, heating plant subsystems, and plant components related to the production of the domestic hot water. The paper explores the strategies and simplifications that can considerably reduce the number of necessary inputs for the simulations, thus minimizing the modeling, implementation and simulation runtime of the model, still maintaining a very high degree of accuracy with respect to the computational results and real energy consumptions. The protocols are applied to different case studies, first for the detailed modeling and progressively enhancing the level of simplification. The results show that the accuracy of the most simplified model in terms of heating loads and efficiencies is always below 16% with respect to the most detailed model, but with up to 90% modeling and simulation workload reductions. In this way the dynamic simulations could become an everyday working tool, with a greater amount of outputs in order to avoid plant oversizing and design errors.

Keywords: dynamic energy simulation, building-plant system energy performance, decision tool, TRNSYS.

1. Introduction

The general problem addressed in this paper is the integration of building performance analysis tools in building design processes. Although Building Performance Simulation (BPS) discipline has reached a high level of maturation, the actual application of analysis tools to support building design decisions still does not fully live up. In fact simulation tools are not playing an important role yet in the selection of energy conservation measures, since they require high workloads and expertise, and are considered not compatible with the professional needs (manual data entry process is too slow and error-prone, outputs are not always clear and need to be heavily post-processed).

However, there are compelling motivations to strive for a better integration of the building analysis tools into the building design process, from first to last phases.

For example in an era where international consensus seems to be settling on the goal of Net or Nearly Zero Energy Buildings, there is a great need for building performance analysis and simulation tools. In such very complex

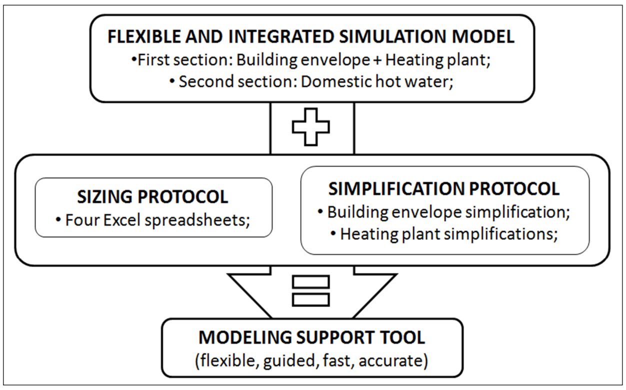


Fig. 1 - Modeling support tool

buildings, the geometry, envelope and many sub-systems interact, thus requiring a high level optimization of the combination of building envelope and HVAC systems.

Now, all these reasons must meet also with the needs related to the design process and the structure of the design team.

The two most important needs for the design process are time and accuracy. Accuracy is an essential prerequisite: if the analysis is not accurate the results could be misleading and the decisions could hardly be optimal. The problem is that an accurate dynamic analysis of a building is not an easy task and requires long times and heavy workloads for the creation and validation of the model.

Regarding the needs related to the composition of the design team, the latter requires building performance tools easy to use, easy to learn, allowing alternative comparisons, applicable during all the integrated design phases, able to give result in a clear form, flexible and fast enough to facilitate changing representations of innovative design concepts.

Hence, is it possible to develop a modelling support able to foster an easy-to-use and flexible model of the building-plant system, on one side simplified enough to avoid the use of not yet available data, and, at the same time, enough complete to guarantee an adequate level of accuracy – even higher than the current standard of stationary methods - at all stages of the integrated design?

In order to answer the last question, one of the most flexible and detailed software tools available for transient simulations of building service systems, TRNSYS, has been reverse-engineered, resulting in the creation of a "pre-casted" building-plant system simulation model, able to carry out the dynamic and integrated simulation of a very large number of integrated building-plant systems. The tailoring of such dynamic simulation model to specific cases is supported via two different protocols, a sizing and a simplification protocol. Together with the TRNSYS model, they build a complete modeling support tool for a fast building-plant system design (Figure 1).

The tool can be used to evaluate, from an energetic and economic point of view, different building-plant-system configurations for residential or commercial applications, with different scales and resolutions. The construction of a "prearranged" simulation model and protocols make the tool, together with its flexibility and guided structure, able to be immediately used by all HVAC designers, who may not have specific skills and knowledge in terms of dynamic simulations or use of TRNSYS.

2. Tool development

2.1 Detailed and integrated simulation model

The detailed dynamic TRNSYS model consists in a flexible building-plant system simulation model created in the main general TRNSYS interface "Simulation Studio", able to carry out dynamic simulations of a very large number of integrated building-plant systems, including the simultaneous simulation of the Building envelope, Heating plant with all its subsystems (HS), Domestic hot water system (DHW).

In particular the whole model can be divided into two different sections, the first related to the production of the DHW, while the second including the building envelope and the heating plant. Figure 2 shows an extracted view of the model, where the dynamic operation of the heating plant is modeled through the TRNSYS components called "Types", all connected according to an input – output logic.

In TRNSYS each Type elaborates algorithms able to describe the behavior of the single component starting from user-defined parameters and inputs, and produce outputs (Figure 3). The inputs of the Types downstream are constituted by the outputs of the Type upstream and these input-output interconnections enable to perform the dynamic simulation of the whole system composed of multiple Types.

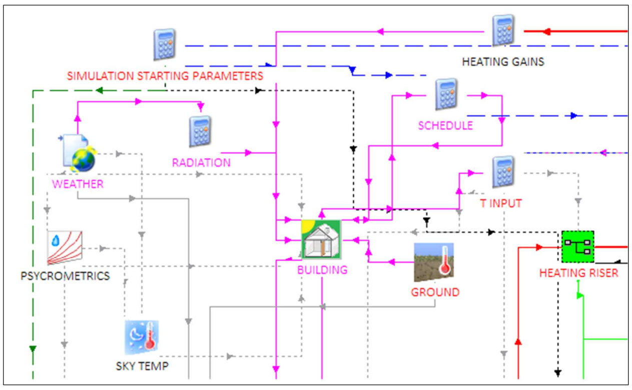
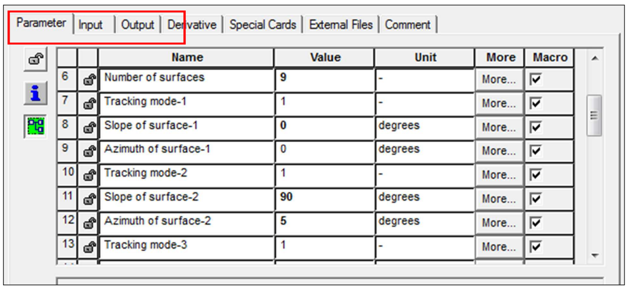


Fig. 2 - Extracted view of the TRNSYS detailed HVAC model



		Name	Value	Unit	More	Macro
6		Number of surfaces	9	-	More...	☑
7		Tracking mode-1	1	-	More...	☑
8		Slope of surface-1	0	degrees	More...	☑
9		Azimuth of surface-1	0	degrees	More...	☑
10		Tracking mode-2	1	-	More...	☑
11		Slope of surface-2	90	degrees	More...	☑
12		Azimuth of surface-2	5	degrees	More...	☑
13		Tracking mode-3	1	-	More...	☑

Fig. 3 - Internal configuration of the TRNSYS Types

The simulation model can be defined "prearranged" in terms that the users do not have to add any Type or interconnections during the simulations, but only have to introduce in each Type the inputs and parameters automatically defined by the sizing protocols (see Section 2.3). The only exception is constituted by the Type regarding the building envelope, for which the definition of a large part of input and parameters is performed through the use of two "easy to use" TRNSYS plug-in.

In the specific plug-in called "Trnsys3d", a three-dimensional representation of the entire building can be created, while to thermally characterize the various zones the plug-in "TRNBuild" is used.

The most important feature of the model is its multiple flexibility.

In fact the energy model presents a:

- Hydraulic scheme flexibility, with 36 different plant schemes available;
- Plant components flexibility, with multiple options for all the subsystem's components;
- Building scale flexibility, with different scale and resolutions for the representation of the building.

About the hydraulic scheme flexibility, all the possible combinations can be summarized in Table 1, generating 36 different hydraulic schemes ready to be simulated by only one TRNSYS dynamic and integrated simulation model.

The model can simulate, for the domestic hot water an:

- instantaneous production, with priority (Prior);
- storage production, with or without priority;
- solar integration (Solar);

While for the heating system, a:

- direct heating system (no hydraulic separator or storage);
- heating system with hydraulic separator or storage between the generation and distribution subsystems;
- going to the second kind of flexibility, the plant components flexibility, it can be stated that, for each hydraulic combination, component variations are allowed.

For example for the Emission and internal Control subsystems, it can be alternatively simulated the behavior of radiators, radiant panels, fan coils, district heating heat exchangers.

Concluding with the third and last kind of flexibility, the integrated and dynamic model can be used in the following three different scales and resolutions for the representation of the building:

- small scale & High resolution, for simulations where one thermal zone is composed by only one room;
- medium scale & medium resolution, for simulations where each thermal zone is equal to one apartment or one floor;

Tab. 1 - Hydraulic scheme combinations

			DOMESTIC HOT WATER (DHW)					
		No DHW	Instantaneous production		Storage production			
			No solar	Solar	No solar		Solar	
			Prior	Prior	Prior	No prior	Prior	No prior
	No HS	/	A1	A2	A3	/	A4	/
HEATING SYSTEM (HS)	Direct HS	A5	A6	A7	A8	/	A9	/
	Separator HS	A10	A11	A12	A13	/	A14	/
	Storage HS	**A15**	A16	A17	A18	/	A19	/
	Direct HS &DHW	B1	/	/	B2	B3	B4	B5
	Separator HS &DHW	B6	/	/	B7	B8	B9	B10
	Storage HS &DHW	B11	B16	B17	B12	B13	B14	B15

- large scale and small resolution, for simulations where each thermal zone is respectively equal to one building (district heating);

2.2 Strengths and Weaknesses

The strength of the dynamic model is surely the multiple levels of flexibility with fixed input/output connections. In fact, the whole detailed model is composed by 221 Types, which require, without connections, a great number of parameters (1537) and inputs (1137), and a modeling workload of weeks should be considered every time. A model with fixed input-output connections permits to extremely reduce the number of inputs to be set (from 1537 to only 17) and the modeling workload associated (from 160-320h to 80-120h), still maintaining a very high flexibility and a great number of outputs (1773). On the other side, the major weakness is that the modeling and simulation workloads, around 80-120h and 4-20h respectively for the tested cases, are still too long for a design support.

So, in order to improve these times, novel sizing and simplifications protocols have been defined and implemented.

2.3 Sizing protocol

The sizing protocol is the protocol created in order first to do the complete and automated sizing and characterization, in terms of inputs and parameters, of all the TRNSYS Types involved in the dynamic model, and, second, to allow the energy and economic analysis of the main simulation results.

The sizing protocol is divided into the following four different Excel spreadsheets, conveniently indicated with SZp for internal reference:

1. SZp1 - DHW sizing: sizing of each component related to the production of the domestic hot water;
    a. First section - DHW simulation: dynamic energy simulation of the DHW plant, using the first section of the TRNSYS integrated model (simulation time-step 1min);
    b. Second section - Building ideal load simulation: dynamic energy simulation of the building envelope, using the only part of the second section of the dynamic model related to the latter;
2. SZp2 - Building ideal load and DHW simulation results analysis: Analysis of the results of the simulations previously performed, in order to define the overall thermal energy demand;
3. SZp3 - Heating plant sizing: choice of the hydraulic scheme and complete sizing of each component of the heating plant;
    a. First + Second section – complete DHW + HS simulation: dynamic and integrated energy simulation of the whole building-plant system (simulation time-step 1min);
4. SZp4 - Integrated simulation results analysis: energy and economic analysis of the simulation results.

For SZp1, SZp2 and SZp3, the structure of each sizing protocol spreadsheet has been shaped in such a manner that, with the minimum number of possible inputs, they directly return all the TRNSYS Types inputs. For SZp4, it is used to assess the technical and economic feasibility of the simulated solution.

For this reason its inputs are constituted by the main outputs coming from the dynamic model, i.e. the most important performance indicators, such as the building and plant subsystems internal temperatures, building energy needs and power curves and finally the plant subsystems efficiencies.

2.4 Sizing protocol advantages

The sizing protocol, in particular through SZp1 and SZp3, allows an important reduction of the number of TRNSYS parameters to be set for the simulations (from around 1500 to around 330), hence another reduction of the modeling workload (from 80-120h to 40-80h for the tested cases) is possible, commencing to make the new modeling support tool more compatible with the design times of stationary softwares.

2.5 Simplification protocol

The simplification protocol allows applying specific simplifications, which can further reduce the modeling implementation and simulation runtime of the dynamic model, still maintaining a high degree of accuracy of the results.

It is composed of two different main kind of simplification, indicated with SMp for internal reference:

1. Building envelope simplification (SMp1);
2. Heating plant simplifications (SMp2);

In particular SMp2 can be divided into three independent and different possible simplifications:

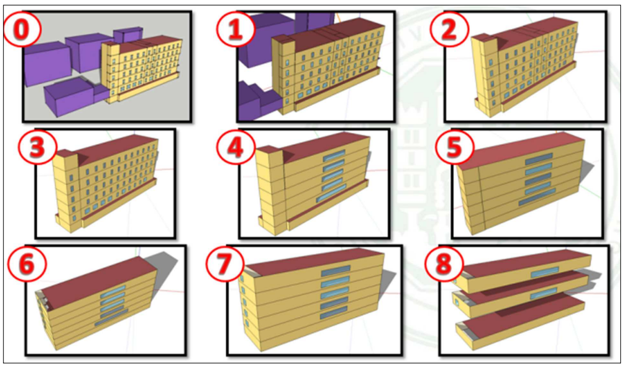


Fig. 4 - Building envelope simplification

- heating plant resizing (SMp2.1);
- emission control with ideal energy load (SMp2.2);
- standard efficiency for emission and control subsystems (SMp2.3).

The first simplification, related to the "Trnsys3d" and "TRNBuild" modeling phase of the tool, is composed of eight consecutive, optimised steps to generate a simplified building model from a detailed building model, as shown in Figure 4 (Picco et al., 2014).

The simplification "Heating plant resizing" is closely related to the building envelope simplification previously described.

In fact the reduction of a high number of real zones to a low number of thermal zone through the steps of SMp1 is necessarily accompanied by a new sizing of the plant, in particular of the emission and distribution subsystems.

The simplification "Emission control with ideal energy load" involves the replacement of the component related to the simulation of the building behaviour (Type 56 Building) with a TRNSYS Type constituted by an external data file. This text file gives, at each time-step, the ideal thermal useful energy demand of each zone considered, allowing the control of the heating system in terms of power required. The last simplification, "Standard efficiency for emission and control subsystems", allows characterizing the different kind of emission and control subsystems with only their standard efficiency values. With this last simplification no time should be spent in order to tune the control subsystem.

2.6 Advantages of the simplification protocol

The best advantage given is actually the very large reduction of both the modeling workload (from 40-80 hours to 12-24 hours) and the simulation workload, that can now range from 0.1 to maximum 3 hours for the most complex cases, far less than the 20h previously required. The accuracy of the most simplified dynamic model in terms of energy needs, power curves and subsystems efficiencies (the simulation results extracted from SZp4) is very high, with a difference from the most complete model always below the 16% for all the outputs.

3. Case studies and results

Among the many different case studies (CS), a selection of only two cases is given in this paper.

CS1 is a single residential unit located in a semi-detached existing house, subjected to renovation, and has been used for the development of the tool, applying the latter to buildings with common concrete structure and medium energy performances.

CS2 is a recently built apartment condominium comprising 15 flats, three of which subjected to a complete monitoring of all energy consumptions and uses. For this last case study, two different approaches have been followed. The first approach CS2.1 provides the dynamic simulation of the whole building-plant system for each single unit with monitored activities and consumptions. It has been used in particular for the validation of the tool modeling and simulation process, applying it to a real monitored and complex building with excellent energy performances. The second approach CS2.2 provides the dynamic simulation of the building-plant system for the entire apartment building, supposed to have a heating and domestic hot water central plant. It has been used for the application of the whole modeling and simulation process (DHW included).

3.1 Case study 1 - stationary and dynamic tools

3.1.1 Stationary simulation model

For the first case study not only a dynamic simulation has been carried out, but also a stationary simulation, with a Italian commercial software, TerMus by ACCA Software, in order to test the differences between the two kind of simulations. The software, based on standard values and conditions, with the plant subsystem efficiencies given as an input, does not consider the possible presence of a storage tank. It generates, as main output, only maximum thermal powers (for each room) and monthly/annual energies (for the whole unit).

3.1.2 Dynamic simulation model

Through the specific plug-in "Trnsys3d", the three-dimensional detailed model of the entire building has been created (Figure 5), while in the plug-in "Trnbuild" all the zones have been characterized.

The simplification protocol has been applied in consecutive simulations where all the simplifications constituting the protocol has been used (except for SMp2.3), progressively enhancing the level of simplification.

3.1.3 Simulation cases and results

8 different annual simulations have been identified and carried out, as depicted in Table 2.

The comparison of the results for all the simulations carried out, in absolute values and percentage differences compared to the reference Simulation 5 (highest degree of detailed simulation for both the building envelope and the heating plant) is summarized in the following Table 3 and 4 and Figure 6.

Considering the results just shown, it can be stated that:

- all the thermal power curves (to be clear, this curve cannot be obtained using stationary models) related to the annual profile of the useful thermal power Q_h have a similar trend;
- the value of the annual heating useful energy demand of the apartment has a maximum variation of 6%;
- except for the emission and regulation efficiencies (η_e*η_c), the others are almost constant and only for the stationary simulation 4 they assume different values. The product (η_e*η_c) is overestimated in those simulations where the SMp2.2 has been applied;

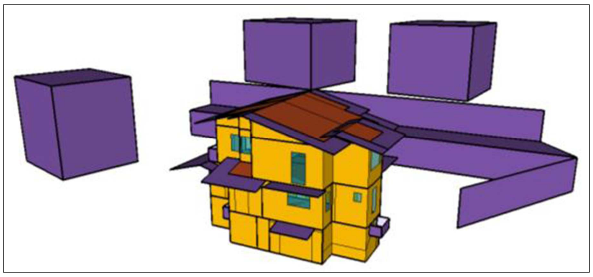


Fig. 5 - CS1 "Trnsys3d" detailed model

Tab. 2 - CS1 simulations. The colums represent the kind of envelope model, while the rows represent the different HVAC models. Both stationary (TerMus) and dynamic simulations are present. Most complete and detailed simulation: 5. Most simplified simulation: 8

SIMULATIONS		ENVELOPE		
		TerMus	TRNSYS	
		DETAILED	DETAILED	DETAILED +SMp1
HVAC	IDEAL LOADS	1	2	3
	DETAILED	4	5	/
	DETAILED+SMp2.2	/	6	/
	DETAILED+SMp2.1	/	/	7
	DETAILED+SMp2.1+SMp2.2	/	/	8

Tab. 3 - CS1 results: absolute values

CS1	UM	1	2	3	4	5	6	7	8
Time step	h	744	1.00	1.00	744	0.08	0.08	0.08	0.08
Q_h	kWh	8151	8243	7739	8151	8243	8243	7739	7739
EP	kWh	8151	8243	7739	9266	10049	9403	9562	8864
$\eta_e \cdot \eta_c$	/	1.00	1.00	1.00	0.94	0.90	1.00	0.90	0.99
η_d	/	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00
η_s	/	1.00	1.00	1.00	1.00	0.91	0.90	0.90	0.90
η_g	/	1.00	1.00	1.00	0.97	0.97	0.97	0.97	0.97
Mod Wload	h	20	28	8	24	48	40	32	24
Sim Wload	h	0.02	0.08	0.05	0.03	4.50	0.18	1	0.1

Tab. 4 - CS1results: percentage values

CS1	UM	1	2	3	4	5	6	7	8
Q_h	kWh	99%	100%	94%	99%	100%	100%	94%	94%
EP	kWh	/	/	/	92%	100%	94%	95%	88%
$\eta_e \cdot \eta_c$	/	/	/	/	105%	100%	111%	100%	110%
η_d	/	/	/	/	96%	100%	100%	100%	100%
η_s	/	/	/	/	110%	100%	99%	99%	98%
η_g	/	/	/	/	100%	100%	100%	100%	100%
Mod+ Sim Wload	h	42%	58%	17%	50%	100%	83%	67%	50%

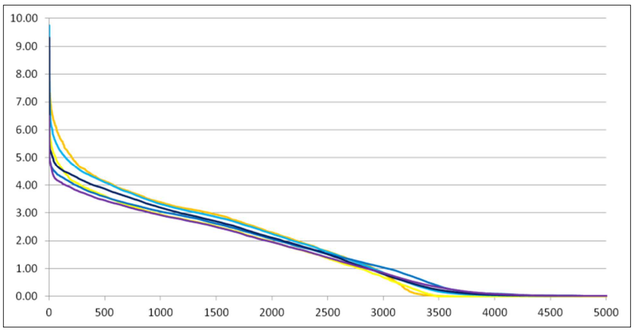


Fig. 6 - CS1 thermal power curves (kW$_t$ against yearly hour)

Considering the results just shown, it can be stated that:

- all the thermal power curves (to be clear, this curve cannot be obtained using stationary models) related to the annual profile of the useful thermal power Q_h have a similar trend;
- the value of the annual heating useful energy demand of the apartment has a maximum variation of 6%;
- except for the emission and regulation efficiencies ($\eta_e \cdot \eta_c$), the others are almost constant and only for the stationary simulation 4 they assume different values. The product ($\eta_e \cdot \eta_c$) is overestimated in those simulations where the SMp2.2 has been applied;
- the primary energy demand of the building has a fairly limited variability for all the 8 simulations, with an underestimation of up to 12% for the most simplified one;
- the time required to perform a simplified dynamic simulation of the entire building-plant system becomes equal to the time required to perform a stationary simulation.

3.2 Case study 2.1 – tool validation

The building analyzed in the case study 2 is an apartment building comprising 15 flats, built in 2012 and situated in Torquay, UK. It consists of four floors, the basement for the car park, ground, first and second floors intended for residential purposes and each composed of five apartments along a central hallway. It has layers designed to have the best thermal, hygrometric and acoustic performances (average transmittance of the diabatic surfaces equal to 0.12 W/m^{2}K). The HVAC plant provided for each apartment is composed by an independent mechanical ventilation system and an independent radiator heating system powered by a combined condensing natural gas boiler, used also for the instantaneous production of the domestic hot water.

3.2.1 Monitored data

The first approach CS2.1 provides the dynamic simulation of the whole building-plant system for each of the three single units with monitored activities and consumptions. All located to the second floor, although they have the same structure and size, the three apartments are characterized by very different energy consumptions, due to a very different use by the tenants. In addition to the outside temperatures and relative humidity, the Occupancy, Window opening, Balcony door opening, Internal Temperature and Relative Humidity, Total gas and electricity consumptions have been monitored for each apartment with 5 min time steps.

3.2.2 Dynamic simulation model

As shown in the Figure 7, the three-dimensional modeling of the entire building has been created in "Trnsys3d".

In particular every room has been modeled for the three apartments while only one thermal zone has been created for the other apartments and boundary zones. The comparison with the monitored data has been proceeded for:

- trend of the average internal temperature during the winter season (controlled temperature) and during the summer season (uncontrolled temperature);
- monthly gas consumption for heating.

A representative extract of the results obtained is shown in Figure 8.

Considering the results for all the three apartments, it can be stated that the simulation trend of the average internal temperature reflects in a very reliable way the monitored data.

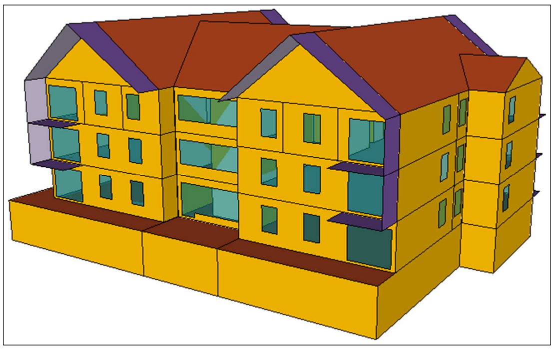


Fig. 7 - CS2.1 Trnsys3d building modeling

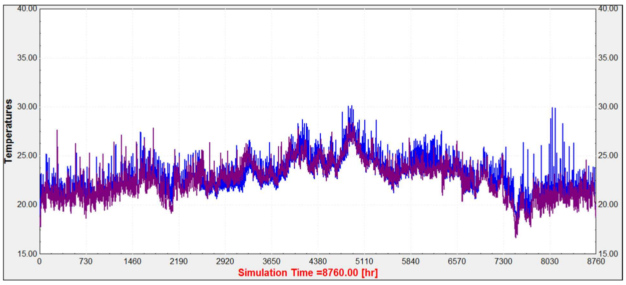


Fig. 8 - Apartment 2 internal simulated (bluish) and monitored (purple) average temperatures (°C)

Even the trend of the monthly gas consumption between the simulated and monitored data is similar for all apartments (Figure 9). In particular the average annual consumption coming from the simulation is at most overestimated by 16% compared to the real one.

Considering that (i) the simulated building is characterized by very high thermal performance and low energy consumptions, (ii) the heat balance of each unit is very sensitive even to small variations of a single HVAC component, (iii) the apartments are characterized by very different consumptions, the results obtained through the application of the tool can be considered extremely positive in terms of its validation, as it is able to predict the behavior of the whole building-plant system for extreme cases such as the one presented above.

3.2.3 Case study 2.2 – whole tool application

The second approach for CS2 provides the dynamic simulation of the building-plant system for the entire building described in Section 3.2 supposing to have now a heating and DHW central plant (with the hydraulic scheme called B15 and represented in Figure 10). The heating and DHW system is composed by a 80 kW natural gas boiler and a heating storage of around 1000l, able to satisfy the heating and domestic hot water demand for the 15 flats. Moreover, storage of 2000l is provided, with a solar integration composed of 35 square meters collectors.

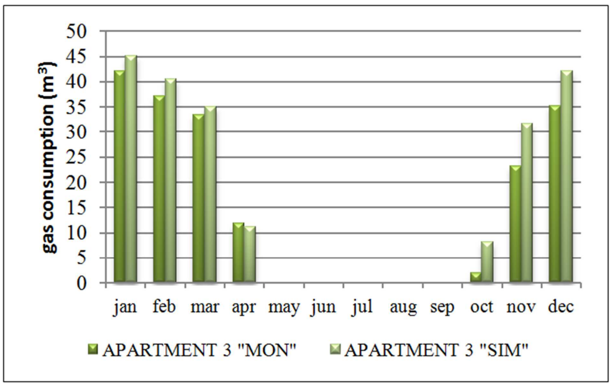


Fig. 9 - Apartment 3 monitored and simulated monthly gas consumption (m^3)

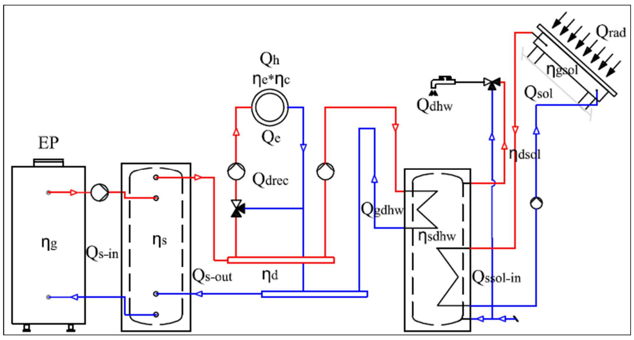


Fig. 10 - Hydraulic scheme B15

Tab. 5 - CS2.2 simulations. The colums represent the kind of envelope model, while the rows represent the different HVAC models. Most complete and detailed simulation: 3. Most simplified simulation: 8

	SIMULATIONS	**ENVELOPE**	
		DETAILED	DETAILED +SMp1
HVAC	IDEAL LOADS (NO DHW)	1	2
	DETAILED	3	/
	DETAILED + SMp2.2	4	/
	DETAILED +SMp2.2+SMp2.3	5	/
	DETAILED + SMp2.1	/	6
	DETAILED + SMp2.1+SMp2.2	/	7
	DETAILED + SMp2.1+SMp2.2+SMp2.3	/	8

Instead of a competitor stationary model, the simplification SMp2.3 is included. Simulation 3 is now the most complete and detailed simulation, taken as the reference case, while the 8 is again the most simplified simulation (Table 5).

Considering the results in Table 6 and Figure 11:

- passing from the most detailed model to the most simplified model, there are noticeable workload reductions;
- the value of the annual ideal heating energy demand (Q_h) has a very low change (2%);
- the total primary energy demand EP is 4% overestimated in the most simplified simulation case, while the highest percentage difference is related to the standard emission and control efficiencies of the heating service, with a 7% difference totally acceptable;
- the heating power curves, related to the an-

Tab. 6 - CS2.2 results: absolute values

CS2.2	**UM**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Time step	min	60.0	60.0	1.00	1.00	1.00	1.00	1.00	1.00
Q_h	kWh	11266	11545	11266	11266	11266	11545	11545	11545
EP	kWh	11266	11545	47471	47607	48724	48043	48132	49296
$\eta_e \cdot \eta_c$	/	1.00	1.00	1.00	1.00	0.93	1.00	1.00	0.93
η_d	/	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99
η_s	/	1.00	1.00	0.98	0.98	0.98	0.98	0.98	0.98
η_g	/	1.00	1.00	0.96	0.97	0.97	0.97	0.97	0.97
Mod Wload	h	64	8	80	78	76	24	22	20
Sim Wload	h	0.66	0.05	19.0	5.00	6.50	3.25	2.50	2.75

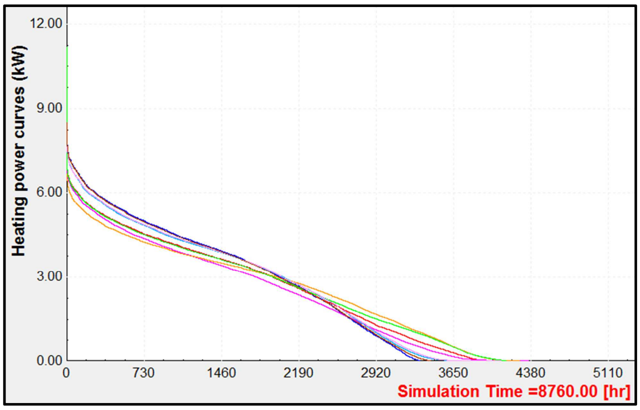


Fig. 11 - CS2.2 thermal power curves

nual trend of the useful thermal power Q_h introduced in the whole building, have a similar trend for all the simulations.

4. Conclusions

The general problem addressed in this paper, the integration of building performance analysis tools in the building design process, have been answered with the creation of a new modeling support tool validated for different cases. The tool, composed by a TRNSYS dynamic simulation model, an EXCEL sizing protocol and a simplification protocol can actually be defined flexible, guided, fast and accurate. It has the potential to indicate a good strategy for the integrated design of building, and the use of dynamic simulations with the same workload of the standard stationary simulations.

References

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