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CO-SIMULATION BETWEEN ESP-R AND TRNSYS: MORE HIGHLY RESOLVED MODELLING OF INTEGRATED BUILDING AND ENERGY SYSTEMS

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ABSTRACT

The analysis of innovative designs that tightly integrate architectural and energy systems presents a challenge for existing building performance simulation (BPS) tools. No single BPS tool offers sufficient capabilities and the flexibility to resolve all the possible design variants of interest. The development of a co-simulation between the ESP-r and TRNSYS simulation tools has been accomplished to address this need by enabling an integrated simulation approach that rigorously treats both building physics and energy systems. The application and capabilities of this new modelling environment are demonstrated in this paper.

INTRODUCTION

The need for integrated modelling

Future buildings must become less energy intensive to address the pressing issues of energy security and the environmental consequences of energy consumption. In the past, reductions in building energy intensity have been achieved through improvements to components: increasing fabric insulation, reducing air leakage through the envelope, employing fill gases in glazings, increasing combustion efficiencies, etc. With a few exceptions, solutions which integrate the building structure and active energy systems have not been sought. Further improvements will be more difficult to achieve using such strategies—e.g. the diminishing returns that can be realized from additional insulation and the cost of lost floor area due to thicker walls are limiting factors; combustion efficiencies are nearing achievable limits; the risk of overheating inhibits greater exploitation of passive solar gains.

Consequently, more complex designs are increasingly being sought, ones which more tightly integrate architecture and active energy systems. Examples include: building-integrated photovoltaic systems with thermal recovery (PV/t); hydronic-floor systems recovering excess passive solar gains and coupled to active stores; automated blinds controlled by central systems to control overheating; thermal storage in the building structure that is charged and discharged through HVAC systems; buried seasonal stores that thermally influence the house through the ground. With such concepts there is a tight coupling between the building fabric, occupant behaviour, energy systems, and controls.

Some of the earlier building performance simulation (BPS) tools (starting from the 1960s) subdivided the problem domain, mainly because computing resources were limited, slow, and extremely expensive (see, for example, Sowell and Hittle, 1995). The so-called *Loads-Systems-Plant* modelling strategy was commonly employed in these early approaches, it subdividing the simulation of the building into three sequential steps which essentially decouples the treatment of the architecture and energy systems. Although such sequential approaches can lo longer be justified for reasons of computational efficiency, the ethos of segregating the treatment of building physics from energy systems persists in the BPS field. For example, it is not uncommon for users to calculate building loads with one tool for some assumed indoor environmental conditions and set of occupant interventions, and then to sequentially predict the performance of energy conversion and storage equipment with another tool through an imposition of these loads. For the reasons argued above, however, integrated approaches must be advanced in order to accurately appraise the multi-variate state of buildings and their systems, an argument eloquently expressed by Clarke (1999).

The benefits of coupling

As argued by Trčka et al. (2009), no single BPS tool offers sufficient capabilities and the flexibility to enable the treatment of the types of integrated systems mentioned above in an accurate and time-efficient manner. State-of-the-art building performance (BPS) simulation tools such as ESP-r possess strengths in modelling building physics. ESP-r possesses highly resolved and well validated methods for modelling the interactions between the indoor and outdoor environments and the building fabric. Although it possesses domains for treating HVAC and electrical systems in a dynamic and integrated fashion, ESP-r's libraries of component models for these domains is wanting and the development of new components requires considerable expertise and knowledge of the program's source-code structure. In contrast, TRNSYS, which was originally developed for modelling renewable energy systems, possess a structure and suite of component models that facilitate the simulation of renewable and other energy systems. Although components exist for modelling building physics, TRNSYS currently lacks the rigour and detail found in state-of-the-art BPS tools in this regard.

One option for more integrated and highly resolved simulation is to add further capabilities to existing tools. This approach requires considerable expertise and resources, and, unfortunately, a duplication of effort as code is rarely reused from one code base to another, many times due to copyright and licensing restrictions. A second option is to integrate the source code of one tool into another, and many such examples exist (e.g. Aasem, 1993; Dorer and Weber, 1999; Huang et al., 1999). A more ambitious approach is to develop new BPS tools drawing upon new simulation paradigms. This is a hugely complex and resource-intensive undertaking, and furthermore it fails to capitalize upon the decades of effort that have been invested in code development, testing, and validation.

More recently, initiatives have been taken to couple complementary tools at run-time, enabling them to exchange data as they march together through time. This offers the possibility of a more highly resolved and accurate treatment of complex systems. This technique, commonly referred to as *co-simulation* in the literature (Trčka et al., 2009), allows practitioners to draw upon the tremendous strengths of existing tools. Various co-simulation techniques have been assessed and demonstrated in the buildings domain (Janak, 1997; Djunaedy, 2005; Trčka et al., 2009; Wetter, 2011).

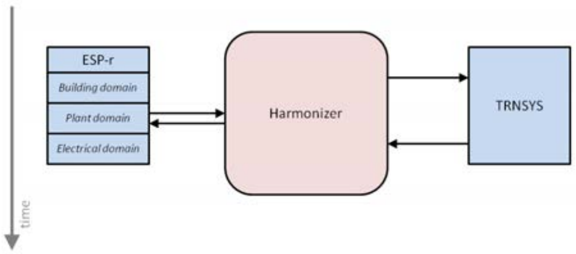

Figure 1: Co-simulation program and data flow

Co-simulation between ESP-r and TRNSYS

A co-simulation has been effected between ESP-r and TRNSYS using methods that have been inspired by the aforementioned authors, yet in a unique fashion. With this, ESP-r treats the building domain, and potentially a portion of the mechanical and electrical energy systems; and TRNSYS resolves most or a portion of the mechanical and electrical energy systems. The design is both general and extensible and exploits the substantial capabilities of both ESP-r and TRNSYS. Importantly, the design enables what is termed a *strong* or *onion* coupling involving the exchange of data during the time-step for the treatment of mechanical systems. This is illustrated conceptually in Figure 1, which shows how a newly developed middleware—called the *Harmonizer*—manages the co-simulation.

Importantly, this is not a prototype or proof-of-concept. Rather, the co-simulation capabilities are supported in the release versions of ESP-r and TRNSYS[1]. An important aspect of the design is that the two simulation tools can continue to evolve their capabilities independently without disrupting the co-simulation functionality. A detailed description of the methodologies employed by the ESP-r / TRNSYS co-simulator and a situation of its approaches relative to those adopted by others is provided elsewhere (Beausoleil-Morrison et al., 2013).

Outline of paper

This paper describes the operation of the ESP-r / TRNSYS co-simulator from the user's perspective. The next section briefly discusses how the two simulators exchange information as they march forward through time to co-simulate a complete building and energy system concurrently. It then describes how the user configures both ESP-r and TRNSYS for co-simulation by focusing upon a case study. This includes a detailing of the application of the new ESP-r and TRNSYS components that were created to support co-simulation. It then demonstrates the types of analyzes that have been enabled by the co-simulator by examining the performance of a number of design variants aimed at improving the performance of the case study house and systems.

CO-SIMULATION APPROACH

There are significant differences in the simulation methodologies employed by ESP-r and TRNSYS, and this informed the design of the co-simulator.

Referring to Figure 1, the Harmonizer controls the overall co-simulation, instructing each BPS program to march through time in a synchronous fashion. ESP-r employs a partitioned solution approach wherein customized solvers treat each modelling domain (building thermal, nodal air flow, HVAC plant, electrical, etc). Once ESP-r's HVAC plant domain has converged a solution for the current time-step, it communicates data to the Harmonizer through new plant components that have been designed for this purpose. The Harmonizer then passes these data to TRNSYS, where they are received by a new type, Type 130. Through TRNSYS's standard input-output mapping approach, these data are then communicated to the normal TRNSYS types and the TRNSYS simulation proceeds as usual for the given time-step. However, before the Harmonizer allows ESP-r and TRNSYS to march forward in time, it assess the state of data passed between the two simulators. If it concludes that these data have not stabilized, it imposes further *invocations*[2] within the time-step.

[1]The co-simulation capabilities require ESP-r version 12.0 or higher and TRNSYS version 17.1 or higher. The Harmonizer is freely available under an OpenSource license.

[2]Each simulator is forced to rewind its solution to the beginning of the time-step and repeat its solution process with the newly passed data from the other simulator.

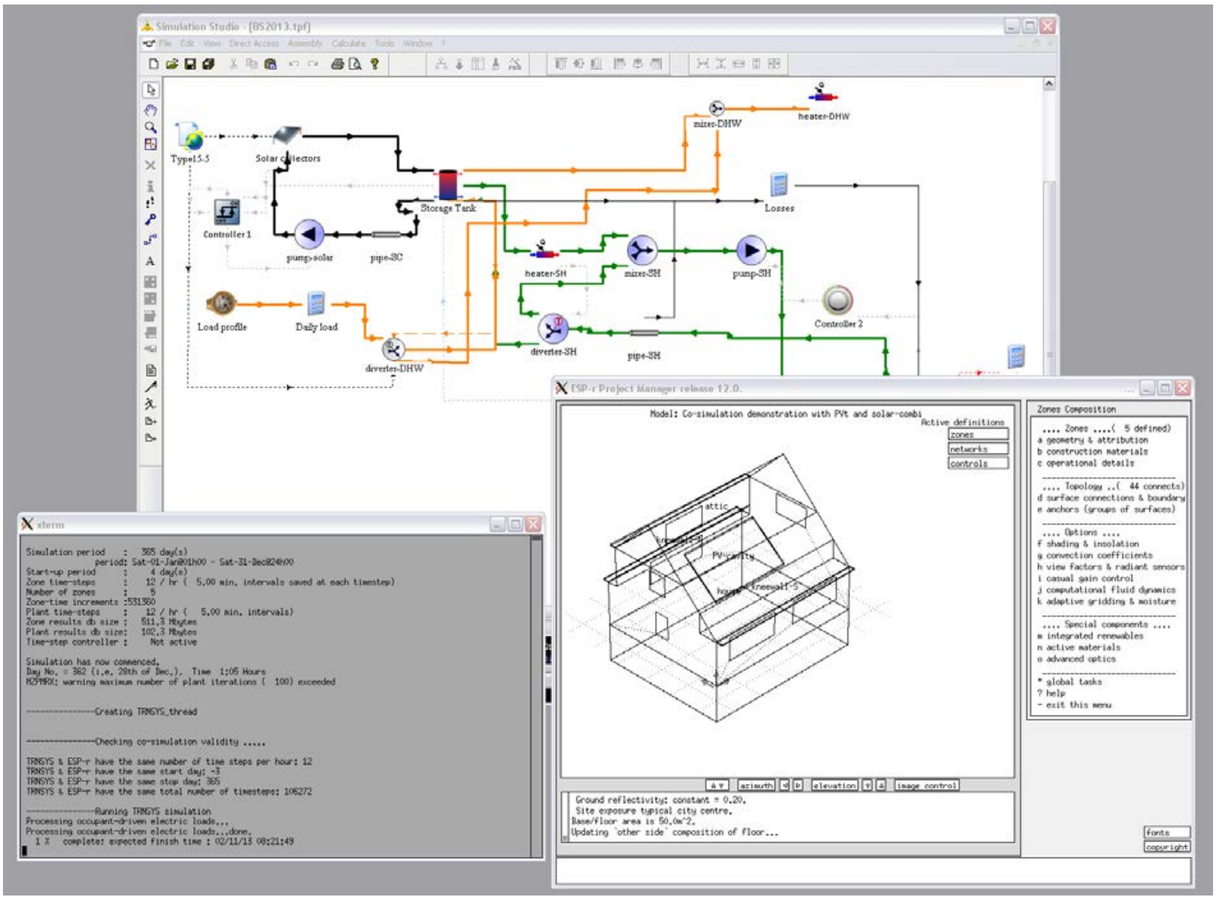

Figure 2: Co-simulation session: model inputs created through TRNSYS (top) and ESP-r (bottom right) interfaces with a co-simulation running in a Cygwin xterm (bottom left)

With this design, the user creates models using both the ESP-r and TRNSYS interfaces and then invokes the co-simulation using the Harmonizer. This process is illustrated in Figure 2. As such, the user does not interact with the graphical interfaces of ESP-r and TRNSYS in the usual fashion to launch the simulations. Consequently, the user cannot examine the progress of the simulation through the *monitoring* function of ESP-r's Building and Plant Simulator module, or through TRNSYS's *online plotter* types. Rather, the Harmonizer invokes each simulator through a command window such as the Windows CMD prompt or a Cygwin xterm (see Figure 2).

CONFIGURING A CO-SIMULATION

The process employed by the user to effect the couplings between ESP-r and TRNSYS is demonstrated through a case study that is described in detail elsewhere (Beausoleil-Morrison et al., 2013). This involves a low-energy house that is heated with a solar-thermal combination space heating and hot water system (solar combi-system), and by a photovoltaic/thermal (PV/t) system.

With the co-simulator, ESP-r treats the building domain. Consequently, an ESP-r model was configured to represent the building's geometry and the thermal characteristics of the building envelope, including air infiltration, air flow through opened windows (an algorithm controls window openings in response to indoor and outdoor conditions to control overheating), contact with the ground, and the shading due to external blinds (actuated in response to indoor conditions).

A schematic representation of the mechanical and electrical systems is shown in Figure 3. The co-simulator design allows ESP-r and TRNSYS to collaboratively model these systems using an approach that is tightly coupled at the time-step level. With this, some components are treated in ESP-r while others by TRNSYS and data is exchanged between the simulators to predict the performance of the complete system and its interaction with the building. In this case ESP-r treats the PV collector and its thermal interactions with the enclosure through which air is ducted. ESP-r also modelled the two fans, the water-air heat exchanger, and the fresh-air heat-recovery ventilator. These components are coloured light organge in Figure 3.

The air-air heat exchanger between the PV/t loop and the conditioned air loop was modelled in TRNSYS as were the dampers to allow the warmed air exiting the PV/t collector (from ESP-r) to bypass the the air-air heat exchanger. A user-defined equation was config-

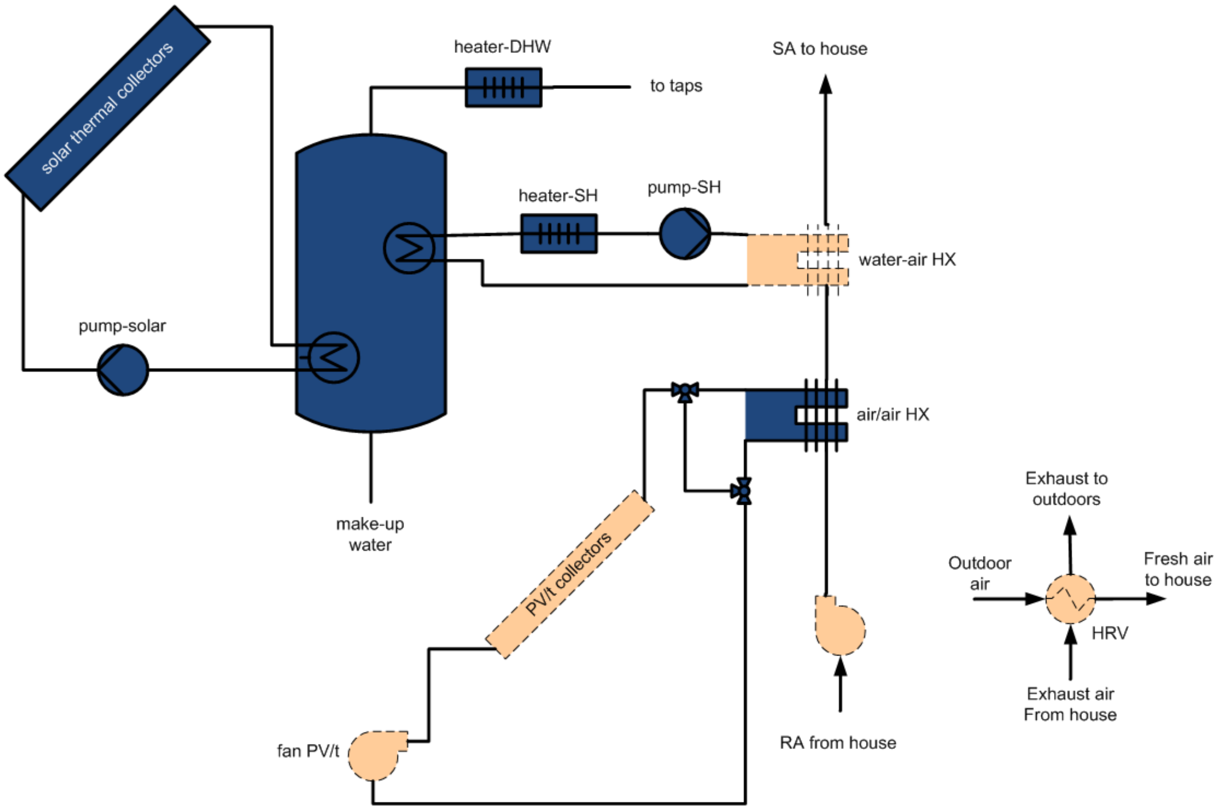

Figure 3: Collaborative simulation of solar and mechanical systems by ESP-r (components shown in light orange) and TRNSYS (components shown in dark blue)

ured in TRNSYS to take a control decision on the position of these dampers. Based upon the sensed conditions of the house's indoor air (from ESP-r) and the temperature of the ducted air exiting the PV/t collector (also from ESP-r), this controller would actuate the dampers in TRNSYS to ensure that heat was only transferred from the PV/t loop to the house (and not the reverse) and only when the house had a need for this thermal energy.

The solar collectors and associated pump and controller were represented in TRNSYS. This pump and the mixing valves on the hydronic space heating and DHW loops were controlled by components within TRNSYS that received sensed inputs from other TRNSYS components. The pump circulating water through the hydronic space-heating loop was controlled by a TRNSYS type based upon the house's air temperature predicted by ESP-r. An ESP-r controller was used to modulate the variable-speed fan that circulated return air through the air-air and water-air heat exchangers. This fan was cycled to high speed when the house demanded heat from the hydronic space-heating loop. Otherwise, it continuously circulated air at a lower rate (and thus at a lower power draw) from October 1 through April 30 in order to pick up heat from the PV/t system, when available.

From the user's perspective, the co-simulation is first configured by creating separate models in ESP-r and TRNSYS (see Figure 2). A TRNSYS network was created using the Studio; types corresponding to the dark blue components in Figure 3 were added and connected in the usual manner. The new Type 130 was also added to the network to support the coupling to ESP-r and this type was connected to the other types, as can be seen in Figure 4. For example, consider the pump that circulates hot water from the tank and auxiliary heater to the water-air heat exchanger in Figure 3. This is represented in TRNSYS by a connection from *pump-SH* to Type 130 in Figure 4. And the cooled water returning from the water-air heat exchanger is represented in TRNSYS by a connection from Type 130 to *pipe-SH*.

The model of the house was constructed with ESP-r's Project Manager interface in the usual manner, and a plant network configured to represent the light orange components in Figure 3. The new plant components designed for coupling with TRNSYS were then inserted and connected to the other components. Consider again the pump that circulates hot water from the tank and auxiliary heater to the water-air heat exchanger. From ESP-r's perspective, this is seen as a stream of hot water that is received from TRNSYS. The new *hydronic coupling component* was added to the ESP-r plant network to represent this stream of hot water and it was connected to ESP-r's water-air heat exchanger. This can be seen in Figure 5, where the

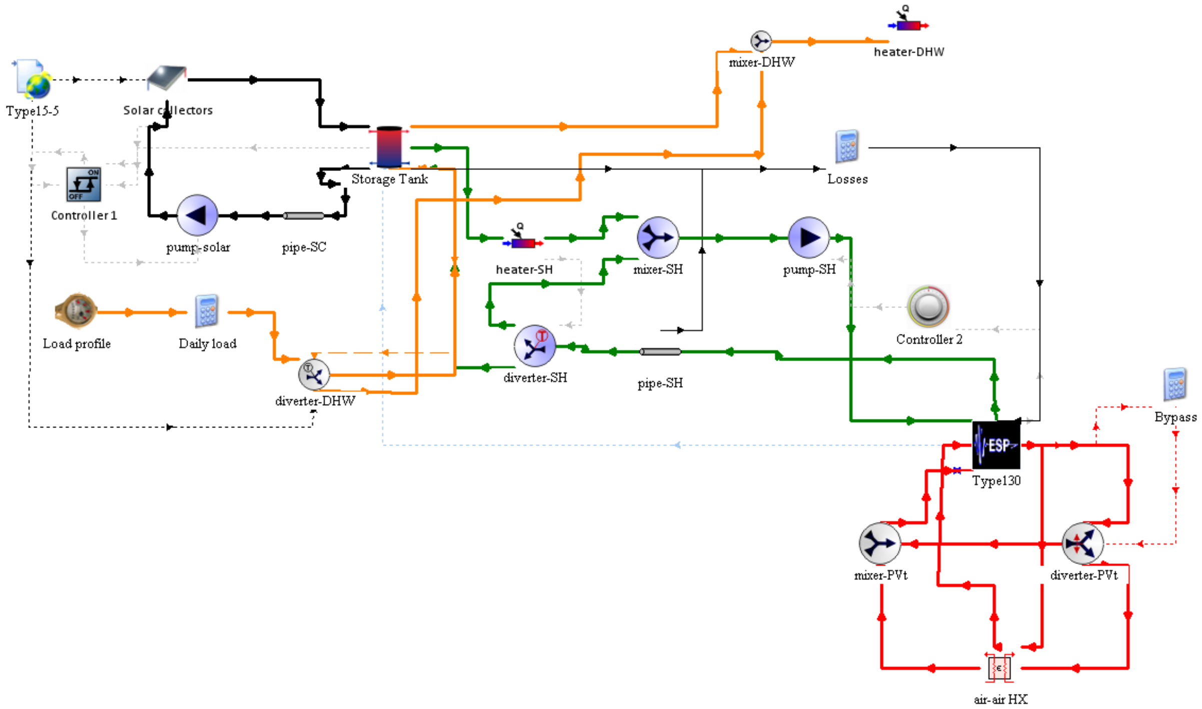

Figure 4: TRNSYS network including Type 130 for coupling to ESP-r

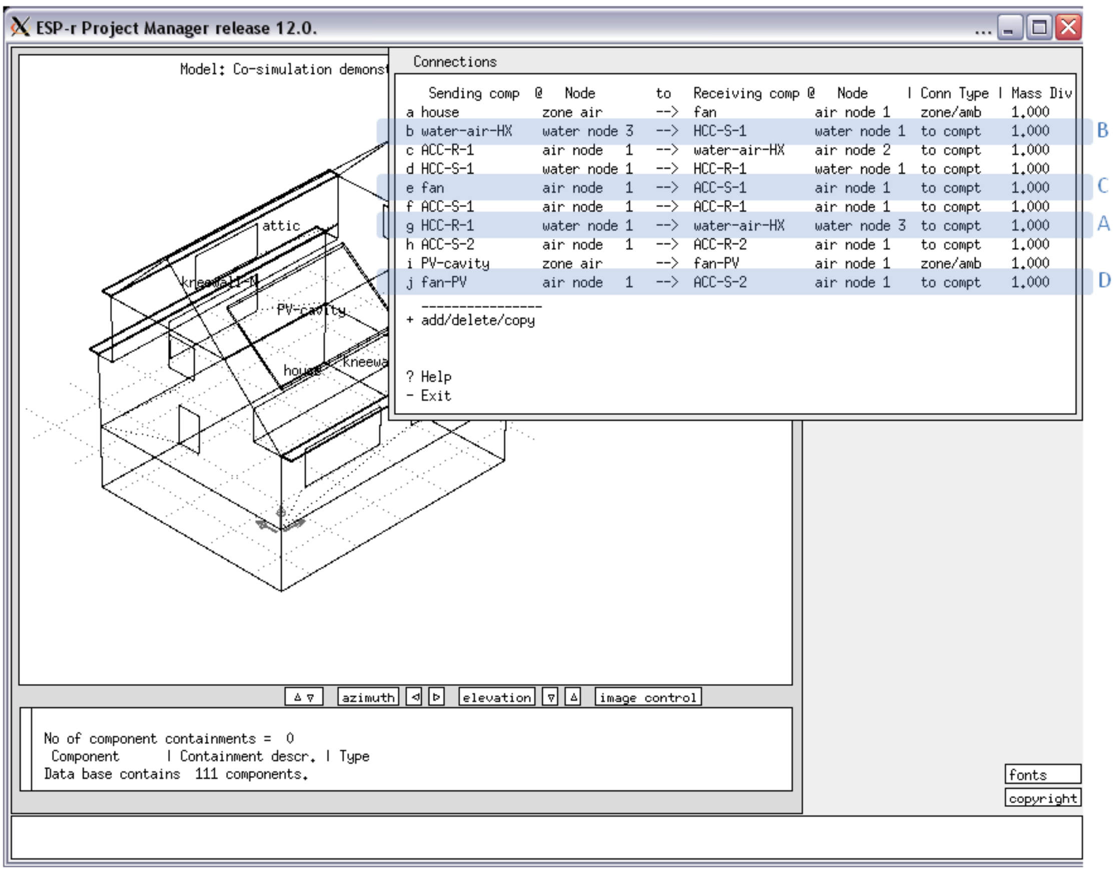

Figure 5: ESP-r plant network connections including couplings to TRNSYS

coupling component has been labelled *HCC-R-1* (any label can be provided by the user) and the heat exchanger has been labelled *water-air-HX* (see connection A in the figure). Once the energy is transferred to the air in ESP-r's water-air heat exchanger, the cooled water stream is returned from ESP-r to TRNSYS (see connection B in Figure 5).

The PV/t system is handled in a similar manner. Recall that ESP-r is sending two streams of air to TRNSYS (see Figure 3): return air from the building's convective heating system and warm air from the PV/t heat recovery system. These streams originate from thermal zones in ESP-r and are communicated to TRNSYS through two instances of ESP-r's new *air coupling component* (see connections C and D in Figure 5). These streams are received in TRNSYS by Type 130 where they are directed to the cold and hot sides of the air-air heat exchanger (see the red loop in Figure 4), respectively. A user-defined equation (labelled *Bypass* in Figure 4) receives the temperatures of these air streams and the temperature of the house from ESP-r and takes a control decision for the bypass valve to determine whether or not the PV/t system can and should supply heating at the current time-step. Once the heat exchange between the air streams has taken place, TRNSYS returns the two streams to ESP-r via Type 130 and the Harmonizer, where they supply two more instances of ESP-r's *air coupling component*.

EXECUTING A CO-SIMULATION AND APPRAISING RESULTS

Once prepared in the manner outlined above, the ESP-r and TRNSYS models are ready for co-simulation. A TRNSYS *deck* file is created from the Studio and the location of this file is identified in a *Harmonizer input file* that is created with a text editor. This likewise specifies the location of the ESP-r *configuration* file. A co-simulation is then commissioned by launching the Harmonizer program from a command line (see bottom left of Figure 2) and by specifying the Harmonizer input file. As mentioned, the Harmonizer manages the interactions between ESP-r and TRNSYS to enable them to collaboratively model the building and its energy systems. At each time-step of the simulation, data are passed back and forth between ESP-r and TRNSYS via the Harmonizer multiple times until system-wide convergence is achieved. (The computational burden of this has been found to be modest (Beausoleil-Morrison et al., 2013)).

ESP-r and TRNSYS each create results files from the simulation. Each program's internal reporting tools are aware of the data that are passed through the fluid couplings, but otherwise are ignorant of variables calculated by the other. For example, referring to Figures 4 and 5, ESP-r is cognizant of the flow rate and temperature of water that is passed from *pump-SH* into its *HCC-R-1* coupling component, but has no knowledge of the operational state of the solar collector and tank that are treated by TRNSYS. Similarly, Type 130 can be linked to a TRNSYS printer to create a results file that includes the flow rates and temperatures of the one water and the two air streams received from ESP-r, but TRNSYS has no knowledge of the electrical energy drawn by the fans or the heat losses from the water-air heat exchanger to the containing zone. Consequently, an appraisal of the co-simulation requires an analysis of results files emanating from both simulation tools. This is achieved by synchronizing the ESP-r and TRNSYS results files using their time stamps to develop a coherent view of overall system performance.

Figure 6 provides an example of the results that can be attained. By combining data from the ESP-r and TRNSYS results files, it plots for a two-day period the passive solar gains through windows, the thermal contribution of the PV/t loop, and the thermal input from the solar thermal loop.

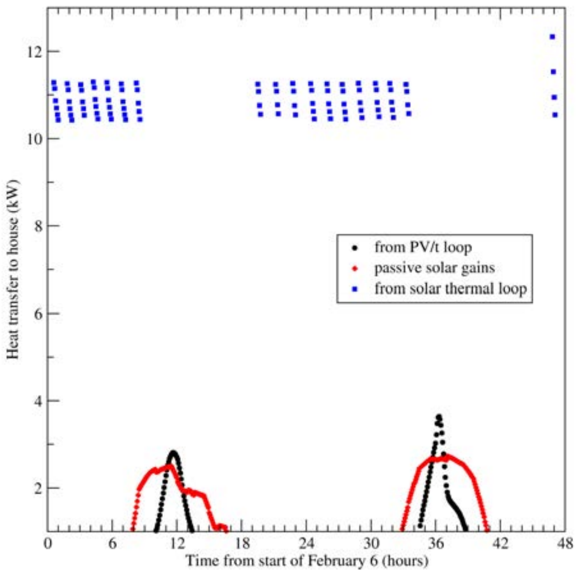

Figure 6: Solar thermal, PV/t, and passive solar input to house over two days in February

APPRAISING PERFORMANCE THROUGH CO-SIMULATION

For the case study introduced in the previous section the house's net space-heating load amounts to 33.1 GJ over the course of the heating season (October 1 through April 30). This is the net load imposed upon the active energy systems after accounting for 7.9 GJ of passive solar gains and 14.1 GJ of internal gains (some of which come from the tank's skin losses).

The PV/t system contributes 1.6 GJ of thermal energy and the solar thermal system contributes another 4.6 GJ, resulting in almost 19% of the space-heating load being met by the active solar systems. Furthermore, the solar thermal system meets 92% of the DHW load. 1.6 GJ of electrical energy are required to operate the systems' fans and pumps, which amounts to 31% of the production from the PV/t system. The solar-generated electricity responds to 13.5% of the total demands generated by the non-HVAC loads, auxiliary heaters, and pumps and fans.

Possible measures aimed at improving this performance include the following (labels are used to identify each):

- Adding additional insulation to the tank. (+ *tank insulation*)
- Altering the control on the space heating hydronic loop to delay activating *heater-SH* for a period of time to preferentially supply the load from the solar-charged tank. (*delay heater-SH*)
- Adding insulation to the house's above-grade walls. (+ *wall insulation*)
- Rather than conditioning the house to a constant temperature throughout the heating season, reducing the setpoint temperature of the space heating loop at night. (*night setback*)
- Increasing the flow rate of air through the PV/t cavity to increase the heat transfer rate in the air-air heat exchanger. (+ *PV/t air flow*)
- In addition to delaying the activation of *heater-SH* (refer to measure *delay heater-SH*), reconfiguring the space heating hydronic loop so that the tank and *heater-SH* are arranged in parallel. (*parallel SH-loop*)
- Increasing the airtightness of the house's envelope. (+ *airtight*)
- Adding a triple glaze to the windows and applying an on/off shading control to avoid overheating rather than controlling the slat angle of the blinds. (*triple-glazed*)

Some of these measures alter the building envelope while others affect the energy systems. However, due to the strong interdependencies between these domains, a realistic appraisal of the impact of each measure requires an integrated simulation. This need can be demonstrated by considering the + *PV/t air flow* measure. Referring to Figure 7, it can be seen that the enhanced thermal gain from the PV/t system causes the house's air temperature to rise to $24^{o}C$ on a cold winter day. This is the setpoint temperature that triggers the deployment of the external blinds. The impact of this can be seen in the figure, which shows the sudden reduction in passive solar gains shortly after 12h. Essentially, some of the additional thermal gains from the PV/t system are offset by a reduction in passive solar gains, an effect that would go undetected if the treatment of the energy systems were segregated from the simulation of the building physics. This effect was repeated on many days. When these results are integrated over the heating season, it is found that almost one quarter of the gains achieved by increasing the air flow rate through the PV/t cavity are offset by a reduction in passive solar gains as a result of blind actuation.

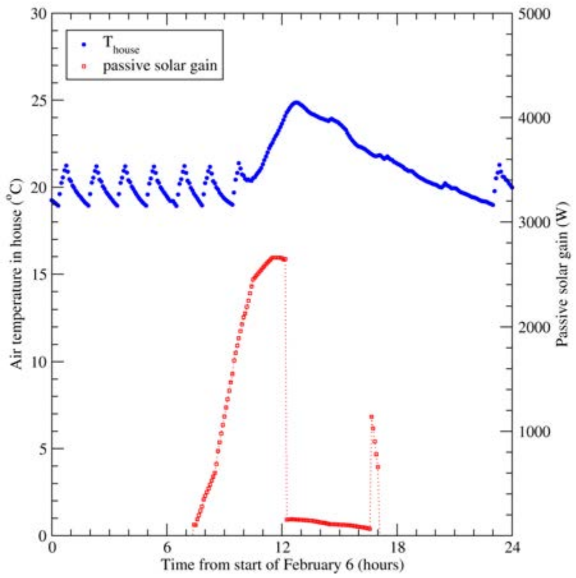

Figure 7: Performance of measure + PV/t air flow *on a single winter day*

These heating-season-integrated results from the + *PV/t air flow* co-simulation as well as those from the other measures are given in Figure 8. Each measure is identified by its label. This figure also shows the performance when a number of the effective individual measures are combined (label *combined*). With this, the 35% of the space-heating load and 92% of the DHW load are met by the active solar systems, while the solar-generated electricity responds to almost 22% of the total demands generated by the non-HVAC loads, auxiliary heaters, and pumps and fans.

CONCLUSIONS

This paper has demonstrated the application of the ESP-r / TRNSYS co-simulator. It briefly described the co-simulation approaches employed and then focused on how co-simulations are configured from the user's perspective. By focusing on a case study, it demonstrated how the new TRNSYS type and the new ESP-r coupling components are configured to enable the two BPS tools to collaboratively simulate the behaviour of a building with an integrated energy system. It then described how results are attained, and illustrated how these can be used to develop an appraisal of overall performance.

The design of the co-simulator exploits the strengths of both simulation tools to enable the modelling of innovative building and energy system configurations more accurately than either simulation program could achieve on its own. ESP-r treats the building domain, and potentially a portion of the mechanical and electrical energy systems; and TRNSYS resolves most or a portion of the mechanical and electrical energy systems. Importantly, the design enables the collaboration between ESP-r and TRNSYS in modelling HVAC systems through the exchange of data within the time-step, an approach that is referred to as *strong* or *onion* coupling in the literature. This is an important contri-

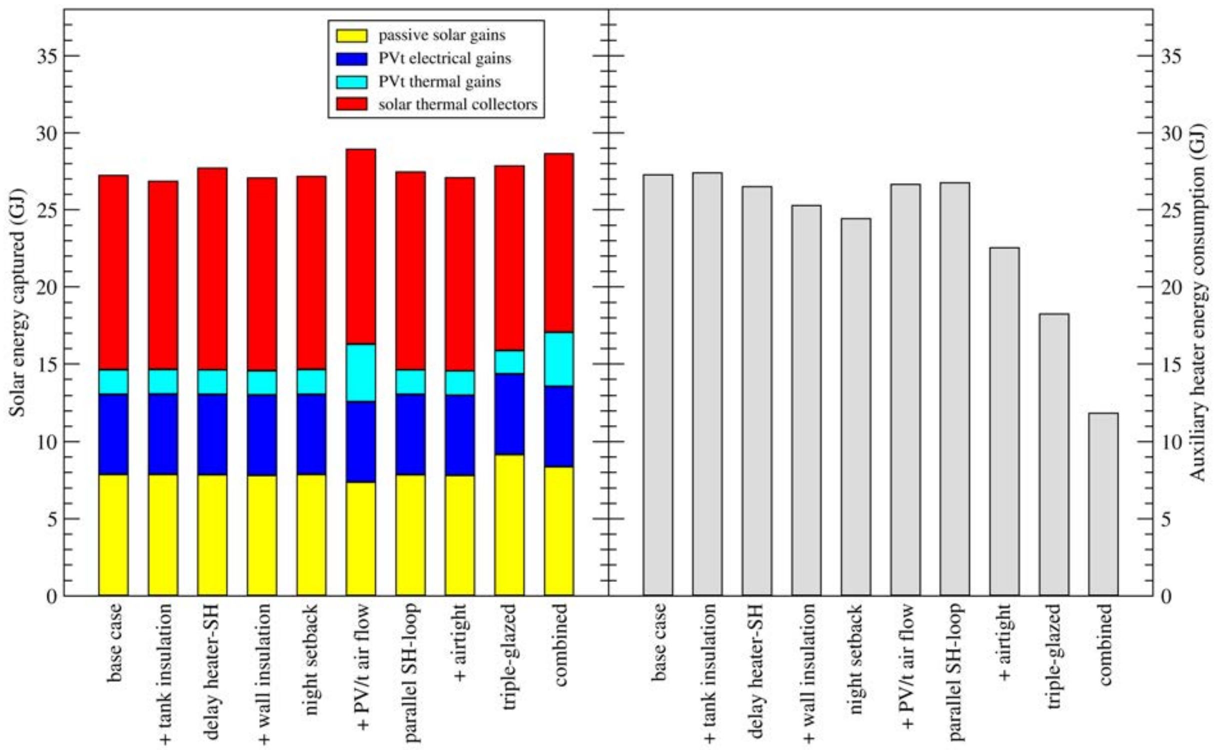

Figure 8: Impact of individual measures on solar energy gains and auxiliary heating consumption integrated over heating season

bution because co-simulation methods that rely on a *loose* or *ping-pong* coupling approach could not adequately resolve tightly integrated architectural and energy systems, such as were treated in this paper.

The co-simulation is managed by a new middleware program called the Harmonizer. The ESP-r / TRNSYS co-simulator is not a prototype or proof-of-concept. Rather, the co-simulation capabilities are supported in the release versions of ESP-r and TRNSYS, while the Harmonizer is freely available under an OpenSource license.

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