HIVE Parametric Tool

A simplified energy simulation tool for educating architecture students

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This paper presents HIVE, a new open source design toolbox, which focuses on teaching concepts of Energy and Climate Systems integration in buildings. .The aim is to empower architecture students to integrate aspects of energy efficiency during the architectural design process. The tool employs a simplified input format designed for ease of use and provides almost instantaneous, direct feedback to support students of all experience levels in the early, conceptual building design stages, where numerous iterations need to be conducted efficiently within a short period of time.The project aims to create a robust toolbox that will become an innovative reference in architecture and engineering - lectures, design studios, and project-based learning - through its capacity to quickly, and effectively, translate building energy systems concepts into graphic formats central to building design teaching and practice. The fast feedback that the users receive to their design parameters changes will enable an effective and quick build-up of tacit knowledge about building energy systems, complementary to the explicit, theoretical knowledge that is usually taught in courses, thus creating a more complete learning experience.

Keywords: *Building Simulation, Low-energy architecture, Integrated curriculum, PV Assessment, Simplified GUI, Architecture Education*

INTRODUCTION

In current architectural education, there is a rising awareness that a key component to reducing global greenhouse gas emissions is a deeper understanding of how climate and building systems for heating, cooling, and ventilation can be better integrated into building design. However, regrettably, it is visible in many architectural design courses and studios in universities worldwide, that climate systems, energy performance, and sustainability in building design are mostly afterthoughts. Although this topic is taught in theory-based lectures and exercises, there is a lack of transfer knowledge transfer into architectural and engineering design studios and practice. One of the reasons is the heavy theory behind such topics, another is the lack of time architecture students dedicate to learn and apply their learning in design projects, which in turn results in lack of knowledge and experience of the students. This highlights the need for a simple and fast method to understand, use, and visualize the physical effects of active and passive systems in buildings.

ENERGY SIMULATION TOOLS

Although Building Performance Simulation (BPS) tools offer an important part of the solution to the above highlighted problem, they often prove to be challenging in the early design stages, since evaluating energy and climate systems performance in buildings requires an understanding of the buildings' energy demand, as well as data on the systems supplying the necessary electricity, heat, water and air. Additionally, another challenge of using current BPS tools in early conceptual work is the often large computational time based on large amounts of data [1, 2]. Moreover, many BPS tools have a steep learning curve, producing outputs that are challenging to interpret, and require knowledge of topics beyond the scope of what is taught in many architectural programs; thermodynamics for example. Not least, integrated approaches to assessing Energy and Climate Systems performance in building analyses are rare, since BPS tools are typically specialized and rather isolated, focusing for example only on Technical Building Systems, Structural Analysis, Life Cycle Assessment (LCA) or Economic Assessment. This specialization-focused approach and the lack of integration make it challenging for architecture and engineering students to include BPS tools in their early design decisions, where it would benefit them most.

Energy simulation engines, such as EnergyPlus [3] or TRNSYS [4], have assisted designers in the development of energy efficient buildings. These have been further amended with user friendly interfaces, such as DesignBuilder [5] or Sefaira [6], both are standalone software running on EnergyPlus, or TRNlizard [7], Ladybug (LB) and Honeybee (HB) [8], plugins for the Grasshopper parametric environment [9]. These interfaces allow architects and engineers to use simulation tools during the development of their projects in order to assess the energy performance of a proposed building design. However, for architecture students, BPS tools are less tangible, as they differ to a high extent from the typical tools used in the architectural domain. While interfaces such as DesignBuilding, TRNLizard, LadyBug and HoneyBee are easy to manipulate, significant time is invested in conducting a single correct simulation, leaving insufficient time to evaluate and interpret the results. Sefaira solves this issue by limiting the number of inputs, however it is not available as a free version, and the calculations behind the model are less transparent. This means that the user will have to trust the software output and reflect less on their validity. DesignBuilder is an easy interface to work with, however, the immense number of inputs and their effects on the outputs result require significant time investment in trying to make the simulation run correctly, leaving minimum time to analyse and understand the outcome of the simulations. The creators of LB and HB simplified their components, created appealing and clear visualization techniques, and designed the tool to allow for a high level of flexibility and modularity in connecting different components. However, with 149 components in LB and 220 components in HB, which are continuously de-bugged and updated, requiring the user to spend much time to study the various components and remain up to date with the latest releases. Moreover, the flexibility of being able to adjust the code is not necessarily an advantage, as many architecture students do not have programming experience. Finally, to run thermal simulations, the user will need to connect both Ladybug and Honeybee Plugins, which results in an even higher level of complexity in the simulation model setting.

There is a clear need to develop a building performance simulation toolbox targeted at students, with the aim of creating an intuitive and practice-based learning experience. This approach will aid students in elevating the overall quality of their building design proposals, enrich their learning experience, and prepare them for the challenges of professional practice. There is also a lack of parametric tools based on simplified calculation models, with an intuitive interface that would help architecture students to learn about performance assessment methods of the built environment and allow them to easily integrate energy performance simulations as part of their design process.

The rest of the paper is organised as follows. The next chapter introduces the HIVE toolkit detailing the developments in the interface, the back-end models that drive the tool, details of a case study at a course at the ETH Zurich, and finally the last chapter concludes the paper.

THE HIVE TOOLBOX

This paper presents HIVE [10], a new open source toolkit for simple building simulations. It offers a fast, intuitive, Rhino/Grasshopper-integrated parametric simulation framework, ideal for teaching energy and systems integration concepts in architecture. The fundamental purpose of HIVE is to support students in developing a deeper understanding of how various configurations of technical building systems, i.e. heating, cooling and ventilation systems, impact both the performance and visual expression of building designs. A key feature of the tool is the "learning by doing" process flow which enables beginners to conduct simple energetic evaluations, and visualize the results with minimal knowledge of building energy modelling.

A core aspect of the HIVE toolkit is that it facilitates the tacit acquisition of energy and climate systems concepts and their transfer into application for architecture and engineering students. Additionally, it prepares students to utilize more complex design and simulation tools, if they desire. Except the design studios, the knowledge transfer in architecture and engineering courses is mostly explicit, meaning that students have to acquire large quantities of theoretical knowledge and connect it to their prior knowledge base. Most of the times, the insufficient exercises and their lack of direct connection to realistic scenarios only result in a "pseudo-knowledge" that gets forgotten after the end-semester exams, instead of becoming part of the student's permanent professional repertoire [11].

The core principle of HIVE is to support - novice, intermediate, and advanced - student learning on topics of energy and climate systems integration in buildings (Figure 1), while simultaneously advancing pedagogical approaches in the fields of architecture and engineering not only at ETH Zurich, but also at teaching institutions worldwide. Therefore, the tool features three main levels of complexity, the first with most of the inputs set to default values from standards and common values, while requiring the user (i.e. students) will be required only to connect the minimum number of inputs to run a successful simulation. The type of inputs students need to provide depends on the lesson taught in class. The below example shows one case, where an architecture student with little knowledge on the topic of building physics is conducting a thermal simulation of an office unit. In the first level of complexity, the student is only required to connect the geometrical components of the analysed case study (i.e. external walls, windows, shading elements, thermal bridge linear thermal transmittance, and thermal capacitance per floor area). In this case, the lesson taught to students corresponds to the physical inputs (i.e. thermal bridges and thermal capacitance). The students then run a series of simulations while varying these values to assess their impact on the heating and cooling demand.

Front-End Overview

The current HIVE toolbox allows users to conduct dynamic thermal simulations for a single thermal zone, calculate solar gains and shading impact on the façade, as well as electricity generation from renewable solar energy sources (Figure 2).

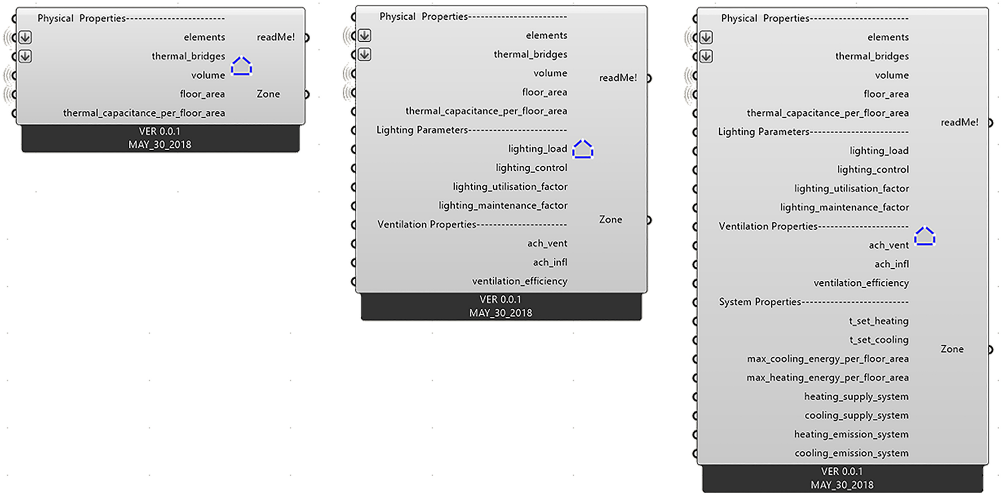


Figure 1
Example showing the three levels of complexity integrated in HIVE toolbox.

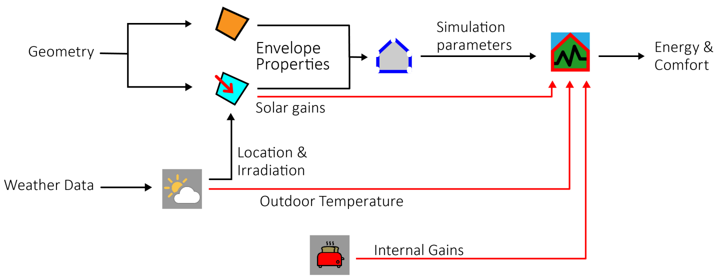


Figure 2
Current HIVE components workflow

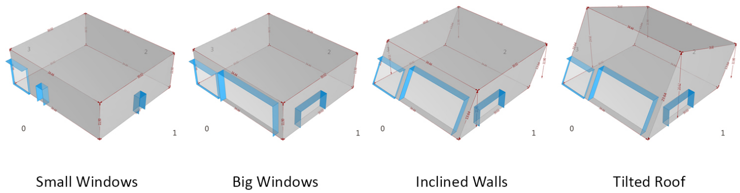
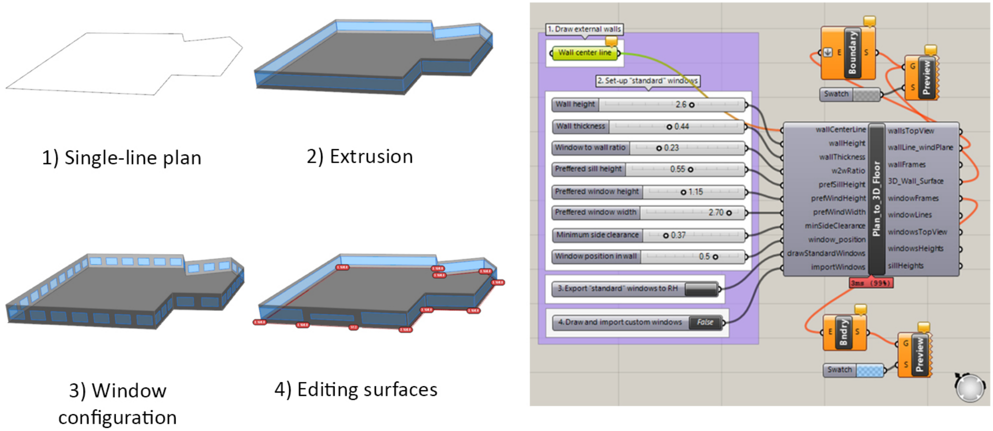


Figure 3
Screenshots from the 3D Parametric Voxel component

Figure 4
Process of Building generation from a 2D plane.



The following components list illustrate in what is included:

- **Simplified real-time geometry parametrization:**
- A 3-D parametric unit, where students can easily add and manipulate building components (e.g. windows, shading systems) and extract their geometrical properties to simulate. This component helps students with no experience in using these parametric tools to be able to conduct simple and quick analyses, and get familiar with building energy simulations (Figure 3).
- A plan (2D) to building (3D) real-time geometry editor: Uses the same process students use in computer aided architectural design (CAAD) to draw buildings/spaces. The building model is parametrized through both 2-D drawings and numerical inputs (Figure 4).
- **Building demand simulation (two methods):**
- Heating and Cooling Degree Days (HDD & CDD) demand model: Simplified assessment of the annual/monthly heating and cooling demands using HDD and CDD.
- Resistance-Capacitance model (R-C): A simplified, dynamic building energy simulation module based on ISO 13790 standard, which offers fast and accurate dynamic/hourly demand results for early stage design projects. Details on the calculation model are found in the following section.

- **Building heating, cooling and electrical final energy estimation:**
- The building energy demand output of the R-C model will be used to calculate more precisely the actual final energy requirements of the building based on the energy generation and emission systems.
- **Building Integrated Photovoltaic (BIPV), Solar Thermal (ST), and Hybrid Photovoltaic and Thermal (PVT) simulation:**
- This simulation module should offer fast estimates of the PV and/or solar thermal potential for a building, taking into account the different factors that affect PV efficiency (shading, system losses etc.).
- Simplified structural analysis: The module should offer an easy way to design the required structure for supporting PV/ST/PVT

modules and estimate their dimensions. This information could be used further for life cycle assessments.

- **Data input and output visualization options:**
- Includes educational material on the systems used in the analysis and their impact on design guidelines.
- The inputs chosen (i.e. Photovoltaic module type), their general characteristics and physical properties are visualized in an intuitive, simple and didactic manner.
- The output of the geometry and the performance assessments of the building are presented to the user through clear and meaningful visuals, and serve as feedback for improving the design. These include 3D visualizations and renderings, energy demand and production graphs, visualization of optimal PV/ST/PVT distribution etc. (Figure 5)

Back-End Mathematical Models

The development of a fast, intuitive, user-friendly front-end interface required the customisation, simplification, and acceleration of existing mathematical models. The following subsections will detail key models that were developed.

Radiation Model. Solar radiation modelling on a building surface is dependent on three key factors: The sun position relative to the building surface, context geometry and the radiation intensity. The sun position is calculated through a variation of the Astronomical Almanac's Algorithm for Solar Position calculation [12]. Because building radiation analysis does not require millisecond accuracies of the solar position we can use simplifications in the calculation of the declination angle [13] and the hour angle [14]. This results in a faster approximation of the solar angle, which is sufficiently accurate for the hourly simulations that are conducted. Radiation and illuminance intensities are then extracted directly from an

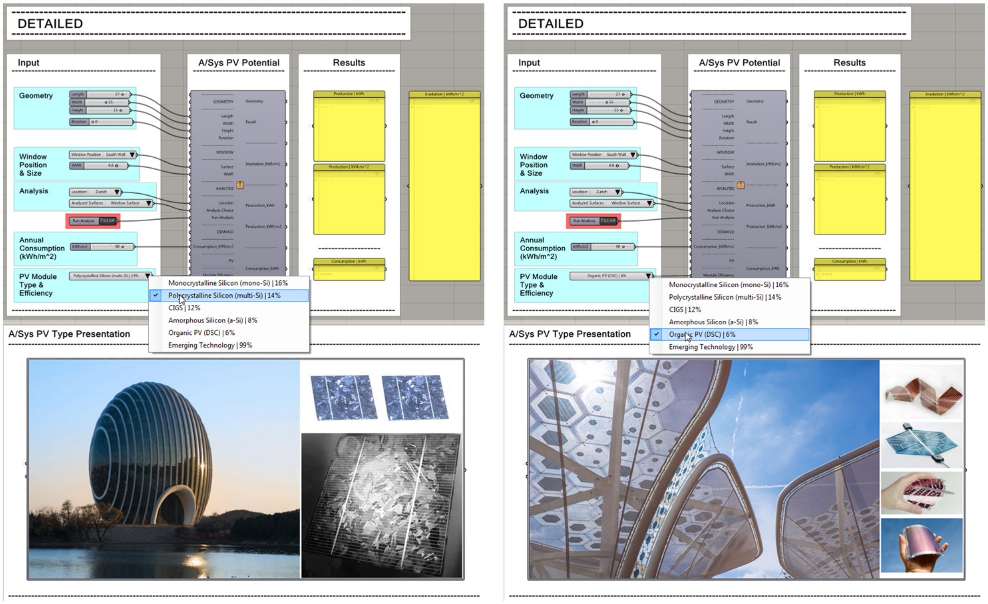


Figure 5
Example of how course material is incorporated in one of the tool templates.

energy plus weather file.

Shading analysis is conducted based on the Clipper library that can subtract the shaded area of the shading system from the window surface [14, 15]. The angle of the building surface and shading surfaces are extracted directly from the physical geometry in the Rhino environment. Through the knowledge of the global solar radiation, building surface angle, and the solar angle, the radiation normal to any building surface can be calculated.

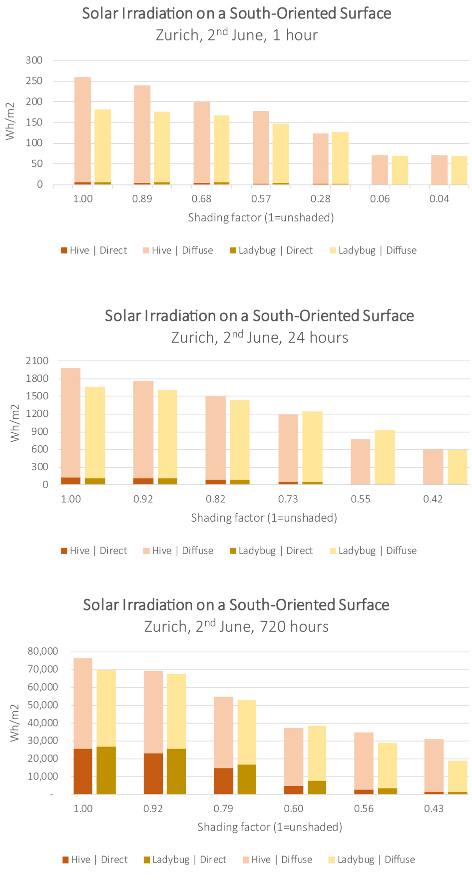


Figure 6
Comparing the incident Solar irradiation on a South-facing window between Ladybug and Hive, for different levels of shading and across different time periods

Radiation model comparison with Ladybug

The direct and diffuse components were analysed separately and compared to simulations from Ladybug. Different values for window tilt, orientation as well as different shading geometries were tested (Figure 6, Figure 7). The model used in HIVE tends to overestimate the diffuse component relative to Ladybug, the difference is highest for unshaded windows. At an hourly level, the difference between the two results was up to 45%. The gap decreased to below 10% for all but the last shading ratio.

In terms of speed, for the same window it would take Ladybug between eight to twelve minutes to simulate solar irradiation for a month (744 hours), while the same calculation takes around 300ms in HIVE. To conduct a fair speed test, the analysis grid in Ladybug would need to be set to a size that produces results that are similar in accuracy to those produced by HIVE. Although such a test has not yet been conducted, HIVE's ability to calculate annual hourly simulations in under 2 seconds makes it very useful for rapid energy simulation studies.

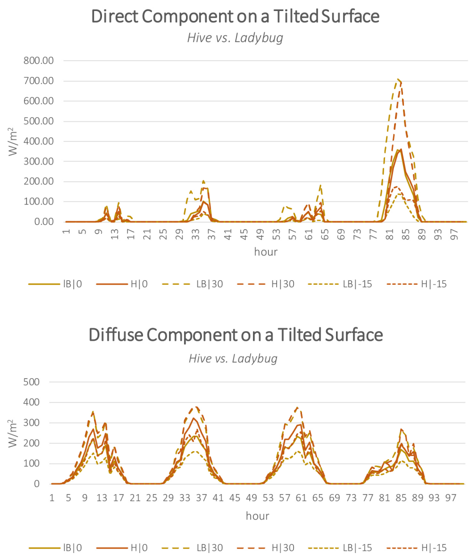


Figure 7
Testing the effect of window tilt for a South-facing window. The angles tested were 0 (vertical), 30 (facing the sky) and -15 (facing the ground). Hive and Ladybug result.

Lighting model. The luminance passing through the windows in the radiation model is averaged across the entire floor area as a single zone using the total flux method [16]. Artificial lighting control is based on the desired internal luminosity defined by the user. The user also selects the lighting technology used from a drop down menu, which determines the overall lighting demand of the building.

R-C Model for building energy demand assessment. The building energy demand is calculated using a physics based resistance capacitance (R-C) model, which simulates the thermodynamic behaviour of the building. It is based on an electrical analogy corresponding to the equivalent thermal physics. The model consists of one internal capacitance and five resistors and is based on the ISO 13790 standard [17]. A full description and source code of the model can be found here [18, 19].

The energy calculations consist of a set of differential equations, which solve a physics-based thermodynamic system analogous to an electrical circuit (resistor-capacitance model). The single-zone, first-order model, shown in Figure 8, consists of one internal capacitance and five resistors and is based on the ISO 13790 standard.

The values of the five resistors and capacitance are automatically generated through based on the user's definition of the building weight (light, medium and heavy), and the u-value of each opaque and glazed surface. Weather data necessary for the simulation is extracted from an EnergyPlus weather file (epw).

The model solves for indoor temperature, and thermal demand. Thermal energy demand can be converted into electricity demand through an average coefficient of performance, which is specified by the user.

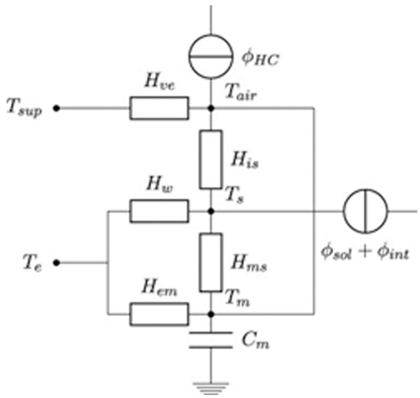


Figure 8
5R1C Model of the a single zone space

Photovoltaic design and calculation. A drop down menu allows the user to select a photovoltaic (PV) type, which is also accompanied by an image of the panel and a reference project, which uses the selected type of PV technology. The energy harvesting potential is determined using the radiation data previously described, which is multiplied with the efficiency of the selected PV technology, the loss factors and its area.

A panelling component will allow the user to study which combination of panel size, rotation and offsets can yield the best possible PV harvesting configuration. This can be further coupled with an optimization component (such as Galapagos), enabling the user to find the optimum PV panelling and apply that directly in the design or use it as a benchmark for manually configured PV designs.

Results Visualisation. Hourly results of the heating, cooling, and lighting demand of the building are visualised and compared against the PV production potential. This feedback enables the user to attain a good first impression of the initial building performance. The simple and fast algorithms enable the user to modify building variables and visualise the outputs in real time.

CASE STUDIES

For proof of concept, an early demonstration version of HIVE was tested and evaluated in 2017 in two architectural courses at the ETH Zurich, addressed to both masters and bachelor students. The first course, in the format of a design studio, analysed a residential multi-family house in Zurich, with the aim of covering most or all of the annual energy demand using photovoltaic electricity. The second course, directed in the format of lecture series with the theme of climate responsive design, focused on passive and active solar design for a single thermal zone unit in multi-story residential and office buildings.

The new tool prototype was compared with previous years where Ladybug and Honeybee tools were used, in terms of the time students spent learning the tool, the time staff had to invest for tool tutorials and feedback on how to use it, number of bugs and the time needed to fix them, and quality of the students' output and their level of understanding of the tool outputs/results.

At the end of the semester, the teaching staff reported that time spent to teach the tool and give feedback reduced by approximately 50% relative to the time they dedicated in previous years. This is due to the fact that the students had less problems using the interface, thus less questions regarding the operation of the tool, as well as less bugs. Moreover, an anonymous survey for a class sample of 12 students was conducted, together with a set of random feedback discussion sessions showed that the students' tended to spend most of their time questioning the simulations outcome, the relation between the change in the inputs and resulting output, and their reflection on the related theoretical course material improved significantly.

OUTLOOK

In terms of tool functionality extension the under-development modules feature the following:

- **Geothermal boreholes sizing and placement:**
- This component will simulate the interaction between the building's energy systems and an energy source (ground / groundwater), and help dimension the boreholes and borehole fields, and estimate their long-term behaviour.
- **Life Cycle Assessment (LCA):**
- A module, which offers insight on the embodied energy of building components and systems. First, it will be based on Swiss databases, but the future goal is to make it easily adaptable to other contexts as well. Also, this component should feature different LCA concepts, such as embodied land use and return on carbon metrics.
- **Simplified economic assessment:**
- The economic assessment module should compile a rough cost estimate of the building components and energy use as well as the possible cost reductions due to renewable energy generation.
- **Systems:**
- Based on the demand data calculated by the RC-model, this component will size the systems and simulate their dynamic behaviour.
- Included systems: ventilation (both natural and mechanical), heating and cooling generation and emission systems.

CONCLUSION

In this paper, we present HIVE, an educational and early stage design tool for the prediction of building energy performance. The tool was developed as an aid for teaching architecture students, and combines simplified radiation models, physics-based building energy models, and simple photovoltaic calculations. The tool works in the Grasshopper environment and uses a task-oriented approach to conducting building simulations. This means students spend less time in the model compilation phase and more time on analysing the output and reducing the CO2 emissions footprint in successive design iterations. The paper includes two case studies of using the tools in both bachelor and architecture courses.

The tool is however not limited to teaching and can be used by building planners to attain a quick energetic evaluation in the early design stage. This means that energy performance of a building can already be a design parameter in the early conceptual design phase.

One important limitation is the multiple simplifications made. It is therefore important that the tool is only used for introductory educational programs and early stage design. For final design evaluations, more advanced tools such as EnergyPlus or TRNSYS should be implemented.

Ultimately, this paper introduces and shows how complex thermodynamic models can be simplified in a "learning by doing" interface for students and building planners to conduct preliminary studies of building energy performance.

The final goal of the HIVE project is to become the leading toolkit for architecture and building engineering students, educators, and practitioners from around the world who would like to integrate energy and climate systems analyses into the early-stage decision-making process of their building design projects. The HIVE project will provide a much-needed tool to support the next generation of architects and engineers in planning and realizing zero-emission, plus-energy buildings, neighbourhoods and cities to adapt to the impacts of climate change and support the transition of our energy systems.

The fast feedback approach promoted by HIVE is not only viable in teaching, but also in practice, as it can also positively affect the design process in the early stages, when the possibility of influencing decisions is the greatest. Such a platform would also accelerate the decision making process, offer the stakeholder a much stronger decision base in the early project phases and create a stronger link between designers and stakeholders, thus transforming the regular project update meetings in collaborative design sessions.

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