Interactive worksheets as a resource for teaching building performance and energy systems simulation

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Abstract. This paper describes the development, implementation and evaluation of Jupyter Notebooks as a digital tool to promote (i) self-directed learning of theory concepts and (ii) active engagement with practical assignments in a graduate-level course on building performance and energy systems simulation. Jupyter Notebooks are gaining popularity as an educational tool for their ability to accommodate digital documents that weave together executable code, equations, data visualizations, and narrative text, without the need for dedicated software environments or advanced programming skills. Specifically, Jupyter Notebooks allow the user - in this case both the lecturer and the student - to bring together data, code, and prose, to tell an interactive, computational story. In our case, the Jupyter Notebooks are used as a teaching resource to foster individualized place and time-independent learning as part of a regular on-campus course, with particular emphasis on homologation of students with heterogeneous backgrounds and for proactive engagement with theoretical subjects.

This paper follows the principles of 'constructive alignment' to highlight various aspects of the use of Jupyter Notebooks in this engineering education context. After a general discussion of the course set-up and key learning objectives, the implementation part of the paper showcases a number of concrete examples of the interactive worksheets on the subjects of thermal comfort assessment, building-integrated renewable energy systems and smart grid interaction. These example assignments illustrate a variety of tasks and functions, including dataset manipulation, scripting assignments, click-and-learn apps and explanatory video clips. An evaluation of the approach is presented on the basis of student questionnaires and informal evidence collected during two years of running the course. The paper finishes by providing a critical reflection of opportunities and caveats and suggested directions for further development.

Keywords. Engineering education, blended learning, Jupyter Notebooks, building performance simulation
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1. Introduction

There is increasing awareness of the opportunities provided by digital and blended teaching methods to enable place-and-time independent learning in conjunction with on-campus teaching. Studies have shown that such approaches can effectively accomplish intended learning outcomes [1] with efficient use of resources, while accommodating diverse learning styles [2]. The COVID-19 pandemic has necessitated an almost unimaginable acceleration in the uptake of novel self-directed learning formats in higher education, and it is expected that the positive elements of this transition will prevail, also in the post-pandemic world [3]. Community-wide sharing of examples and lessons learned, to ultimately develop a repertoire of best-practices, is therefore of great international interest, especially also considering the need for educating the next generation of engineers who is entrusted with the challenge of realizing the transition towards an energy-efficient, circular, digitized and healthy built environment.

This paper contributes to these developments by reporting on the development, implementation and evaluation of interactive worksheets based on Jupyter Notebooks as a resource for promoting place-and-time independent learning in a graduate-level course on building performance and energy systems simulation at Eindhoven University of Technology, the Netherlands.

The course context and challenges that have led to the development of these interactive worksheets are described in Section 2. Section 3 then provides more information about the developed solution direction and its key characteristics. Notes about the actual implementation together with a selection of illustrative examples of the Jupyter Notebooks are presented in Section 4, followed by an evaluation and reflection in Section 5. Finally, the paper concludes by providing a general discussion and future outlook in Section 6.

2. Context and motivation

2.1 course outline

Building Performance and Energy System Simulation is a 5 ECTS core course in the master track Building Physics and Services and in the master programme Sustainable Energy Technology at Eindhoven University of Technology, the Netherlands. The objectives of the course are to:

- Present the underlying theoretical and operational principles of building-integrated sustainable energy systems from component/system-level to district-scale.
- Introduce performance-based analysis as a useful tool for assessing the trade-offs between indoor climate, cost-effectiveness and environmental performance.
- Highlight the opportunities and challenges of state-of-the-art building performance simulation and to provide hands-on training in the use of such software.

Following the principles of constructive alignment [4], the weekly teaching activities (Figure 1) consist of a mix (i) oral lectures, (ii) self-guided learning using a combination of theory assignments based on the enriched skeleton concept mapping approach [5] and interactive videoclips on the FeedbackFruits platform [6], and (iii) hands-on tutorials for simulation-aided design assignments.

It is widely understood that learning to become proficient in building performance simulation entails much more than being able to generate results with a specific software tool [7]. The practical work in the course is therefore designed to demonstrate and reflect on the importance of underlying theoretical concepts in an applied context, and to gain practical hands-on experience in using state-of-the-art building performance simulation software for design of integrated building and energy system concepts. As such, the course set-up is well-aligned with the principles of experiential learning in building performance simulation [8] as it has evolved from the fundamentals of quality assurance as described in [9].

2.2 issues and challenges

Due to continuous shifts in student population and because of the desire to integrate more 21st century skills in the classroom, a number of issues and challenges were identified to further enhance the course:

1. Students in this first-year MSc course come in with very heterogeneous backgrounds from different (international) bachelor programs. The range of topics that is covered is quite broad. Only a small group of students (~25%) possesses all the required background knowledge, whereas for most of the others, something is lacking (e.g. either related to buildings and indoor comfort, or to energy (thermal or electrical) issues). Due to the compact scheduling, the course allows for very limited time for brushing up background knowledge, which increases chances that students get lost. Before the intervention, deficiencies were addressed in an ad-hoc way, by suggesting extra reading and practice material on an individual basis. A more systematic and integrated solution for homologation would likely lead to significant enhancements in the learning experience.

2. Intentionally, most of learning objectives in this course are approached from a rather application-oriented perspective in terms of subjects that are covered. A consequence of this is that there is less time to explain the more basic theoretical concepts (which would anyhow be a repetition for roughly half of the students). It is also believed that broadcasting this information in extended oral lectures is not the most efficient way of learning, for the material at hand. Instead, it would be desirable if

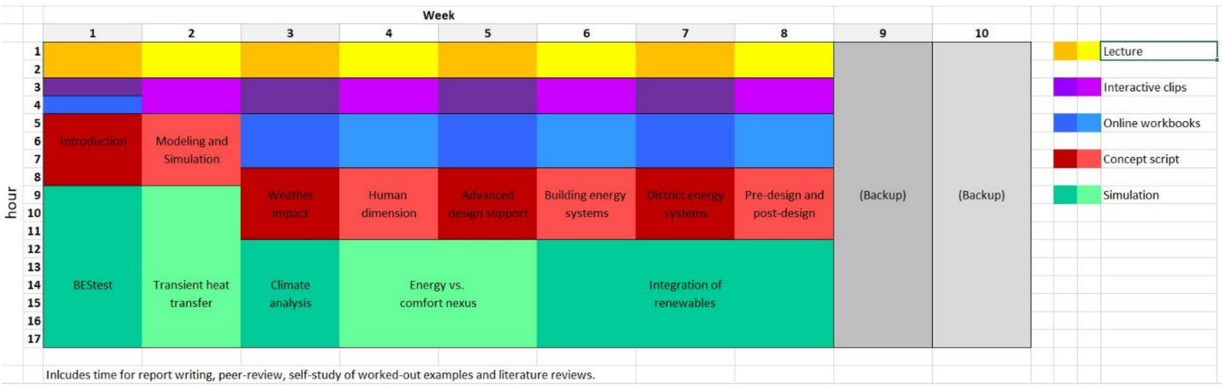

Fig. 1 – Outline of various teaching activities in the course Building Performance and Energy Systems Simulation at Eindhoven University of Technology, the Netherlands

students had access to a curated set of interactive explanatory and practice material (video, text, animations, small scripting exercises and app-like click-and-learn case studies for formative feedback), so they can revisit the theory if and when needed.

3. The course works with a series of weekly assignments. Before the intervention, the students would perform simulations and write separate reports. It would be desired to evolve these traditional written reports into a more interactive solution in which simple programming, visualizations, plots and explanatory text are all integrated in online worksheets. The intention is that students can submit these worked-out sheets as their report for the assignment. Integrating it in this interactive and updateable format will also allow the lecturer to embed the latest research findings as case study examples in the course.

2.3 proposed solution

To address the abovementioned challenges, an education innovation project was initiated, with the intention to develop, implement and evaluate Jupyter Notebooks to promote self-directed learning of theory concepts and active engagement with simulation assignments based on interactive worksheets.

3. Jupyter Notebooks

3.1 what are Jupyter Notebooks?

A Jupyter Notebook is a digital document that weaves together executable code, equations, data visualizations, and narrative text [10, 11]. Specifically, Jupyter Notebooks allow the user (in this case both the lecturer and the student) to bring together data, code, and prose, to tell an interactive, computational story in a web-based environment. Jupyter Notebooks are part of the Project Jupyter ecosystem, a large international community that promotes the development of open-source software and services for interactive computing across a large range of programming languages.

Popular applications of Jupyter Notebooks in the research domain include its use as (i) an interactive scripting and data analysis environment for individual researchers and research teams, and (ii) deployment platform for shareable web apps based on plug-ins such as Voilà, Bokeh and Dash. Jupyter Notebooks also form an important part of BESOS, the Building and Energy Simulation, Optimization and Surrogate Modelling framework, developed at the University of Victoria, Canada [12, 13].

3.2 Jupyter Notebooks in engineering education

Jupyter Notebooks have recently also gained popularity as an educational resource [14]. Its use is said to enhance: engagement, participation, increased understanding (e.g. guiding learners at their own pace) and student's performance [15]. Notable examples of Jupyter Notebook based teaching material related to the themes of the CLIMA 2022 conference that have served as inspiration for the present project include:

- CFD Python, a course developed by prof. Barba at Boston University [16].
- Data Science for Construction, Architecture and Engineering, an edX course developed by the BUDS lab at the National University of Singapore [17].

In particular, the following capabilities of Jupyter Notebooks are targeted in the present development:

- Deployment of click-and-learn apps, so students can explore relationships between variables in various complex energy systems on the basis of pre-loaded datasets.
- Empowerment of students without former training in programming to execute simple python scripting tasks. Students will receive simple snippets of code and are encouraged to develop this further.
- Code and real-time visualizations are executable from within a browser. There is no need for time-consuming installation procedures and accompanying troubleshooting efforts.
- Students have the possibility to combine code with text and tables and figures to develop stand-alone interactive reports.

4. Implementation and examples

4.1 overview

The developed Interactive Worksheets and supporting datasets are provided to the students via the Canvas learning management system that provides the online portal for all courses at TU/e. The Notebooks themselves are hosted using the Google Colab service, which allows students to execute their tasks in the internet browser of their choice, without the need for installing any additional software.

At present, eight Jupyter Notebooks have been developed, dedicated to the following topics: (i) Notebook basics, (ii) Weather data analysis, (iii) Thermal comfort, (iv) Occupant behaviour, (v) Multi-criteria decision making, (vi) Solar thermal collectors, (vii) On-site energy matching, and (viii) Energy signatures.

Each Notebook makes use of different combinations of text, video clips, data tables, figures, equations, interactive scripting widgets and executable code.

While working their way through the Notebooks, students are requested to complete a series of tasks and assignments. Dedicated answer sheets in pdf format have been developed in which students can note their solutions. These answer sheets are then uploaded for feedback and/or assessment. The time required to complete the tasks in each workbook range from approximately 15 minutes to 1.5 hour.

The developed Jupyter Notebooks are available for download via [18]. In the following sub-sections, a selection of Notebook snippets is presented to highlight specific features and thereby illustrate their potential added value in an education context.

4.2 example A: multimodal information

A typical example that makes use of the multiple modalities of information exchange offered by Jupyter Notebooks, is presented in Figure 2. On the topic of energy signatures, this worksheet fragment contains a combination of explanatory text, equations, hyperlinks, python code and figures. Here, the figures are based on a dataset with actual measurements from many buildings, leading to the possibility for each student to work with an individualized set of buildings.

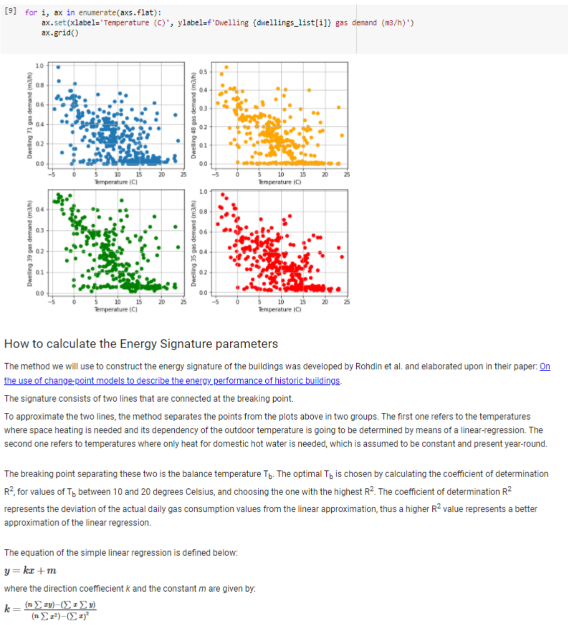

Fig. 2 – Typical Jupyter Notebook fragment, showing different types of information exchange

In addition to the type of information presented in Figure 2, the developed Jupyter Notebooks also take advantage of the possibility to embed video clips. For example, Figure 3 shows a case where a video is used to explain the working principles of solar domestic water systems. Videos from different (external) sources can be integrated. In this example, the embedded YouTube functionality has been used, but it is also possible to include self-recorded clips.

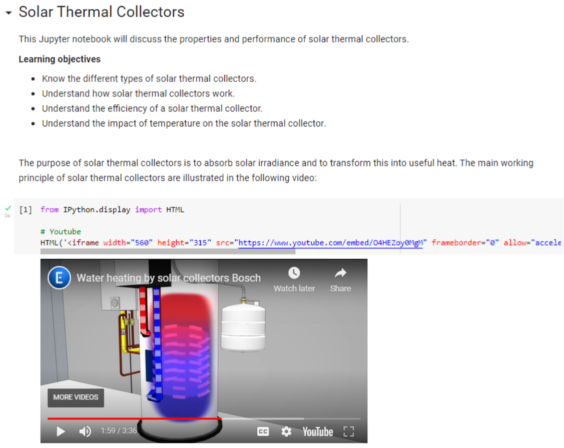

Fig. 3 – Integration of YouTube videos in the Notebook

4.3 example B: interactive widget

Figure 4 shows an example of an interactive widget that was developed to allow students to explore the multi-variate relationships in a thermal energy system. Specifically, in this case, the combined influence of temperature difference and irradiance conditions on the efficiency of various types of solar thermal collectors (flat-plate vs. vacuum) are visualized. By simply adjusting the slider to vary solar irradiance, the lines in the figure update automatically, aiding in the understanding of the complex relationships between variables. In a previous part of the Notebook, the students are presented with the theory and conventional equations for understanding the performance of solar thermal collector. Students can also inspect and adjust the code that is needed to build the widget, for example to observe what happens when different heat loss correction factors are assumed.

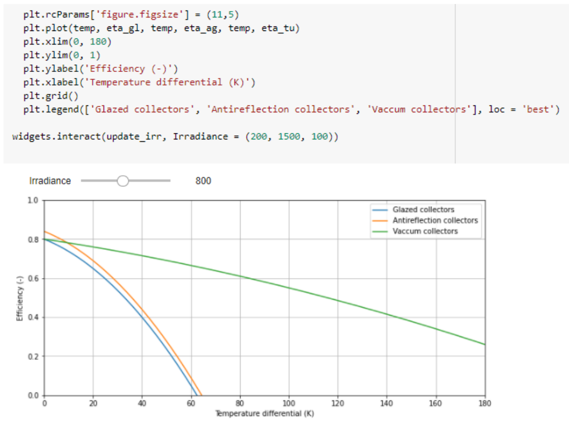

Fig. 4 – Example of an interactive widget

Another example of interactivity, this time related to the subject of variability in occupant behaviour and its influence on load coincidence factors, is presented in Figure 5. In this case, an interactive data visualization is shown, allowing the user to intuitively make the connection between input parameters and resulting output. Figure 5 also showcases an example of how the short assignments are an integral part of the Jupyter Notebooks.

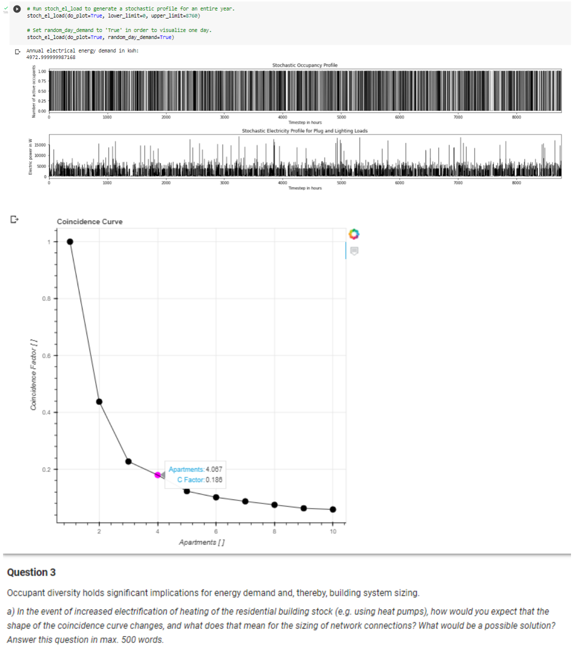

Fig. 5 – Interactive data visualization

4.4 example C: assisted data analysis

The Notebook snippet in Figure 6 is developed to give students a hands-on understanding of energy matching indices On-site Energy Matching (OEM) and On-site Energy Fraction (OEF). These relatively abstract concepts are made more tangible by letting students interact with a pre-loaded dataset that contains monitoring data from 20 houses. Preparatory tasks such as pre-processing, data cleaning etc. are all taken care of by the Jupyter Notebook, so students can immediately start exploring the data itself. In this case, an interactive date selection widget is added to further speed up the learning curve. The question the students are asked to answer in this Notebook is to quantify the effectiveness of rooftop PV by calculating energy matching indices in different seasons.

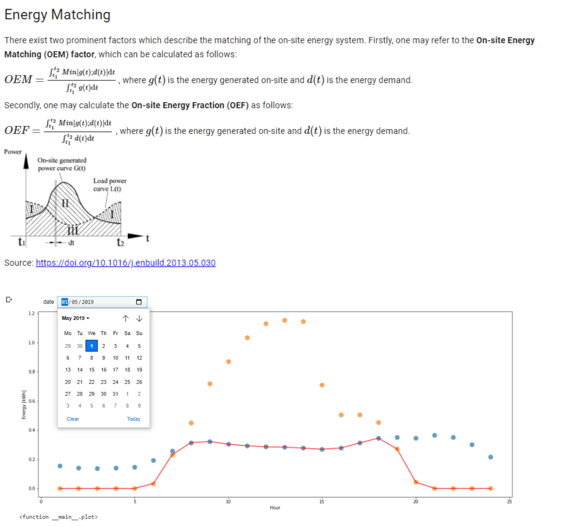

Fig. 5 – Exploring data with the help of a Notebook

5. Reflection

5.1 teacher's perspective

From a teacher's perspective, the experience with the integration of Jupyter Notebooks has been largely positive. No major obstacles were encountered in the practical workflow – all students with different personal laptops and operating systems were able to complete the tasks. It gives peace of mind to know that students have access to a curated set of explanatory documents, and relieves the task of recommending such sources to individual students on a case-by-case basis. One cannot ignore the time it takes to collect and process the material into engaging interactive worksheets, but it was found that teaching assistants are perfectly able to contribute to this effort. Moreover, it is believed that the developed workbooks remain relevant for years to come, which brings opportunities for gradually extending the library of Notebooks over time with new content. Ideally, such a development becomes part of a crowd-sourced open-access database for sharing within the global community.

One of the key benefits of the selected teaching approach is that it provides unprecedented opportunities to introduce bits and pieces of the latest academic research in the classroom. For example, one of the presented Notebooks makes use of functions in the `pythermalcomfort` library [19] to let students experience the differences and similarities between Fanger-based and adaptive thermal comfort models, while another Notebook takes advantage of `richardsonpy` [20] in an assignment were students use stochastic occupancy and electric load profiles based on the Richardson model [21]. Coincident with the transition towards Open Science, it is expected that many more of such developments can be integrated in the near future.

A drawback of the extra assignments is the increase in workload for checking and/or grading of submitted assignments. Until now, this formative and summative assessment was done manually. It would be worth to explore if peer review or automated assessment approaches could take over part of these tasks.

5.2 students' perspective

Questionnaire-based student feedback administered through the Evasys system after the end of the course, indicates that students were moderately satisfied with the interactive worksheets as a learning method. Figure 6 shows responses to the question "the Jupyter Notebook assignments help me to better understand the theoretical concepts covered in this course" for the academic years 20/21 and 21/22, respectively. These results show a fairly wide distribution with an overall positive impression.

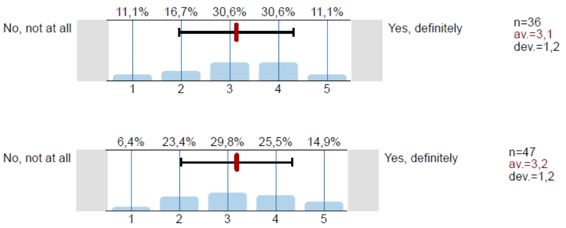

Fig. 6 – Distribution of student responses to the question "the Jupyter Notebook assignments help me to better understand the theoretical concepts covered in this course" for the academic years 20/21 (top) and 21/22 (bottom).

Remarkable results to the follow-up question "the use of Jupyter Notebooks makes the learning process more enjoyable" were found, with shifts towards both extremes indicating stronger feelings of (dis)liking. Answers to the open feedback section of the questionnaire helped in interpreting this observation, particularly relating to a perceived lack of clarity in terms of structure and to what extent the assignments counted toward the final grade.

Additional feedback obtained through informal sessions with student representatives halfway during the course, generally agreed with the findings from the questionnaire. What these sessions revealed, though, is that students without prior experience in the use of scripting languages (e.g. python or Matlab), found it difficult to get going with the assignments, especially in case the Notebook returned generic error messages without concrete indications that novice users could use for troubleshooting. Even though efforts were made to make the entry requirements regarding scripting/programming knowledge as low as possible, this finding highlights the need to be very thoughtful about expected prior knowledge and the possible usefulness of Frequently Asked Question overviews and peer support methods.

6. Concluding remarks

This paper has described the development of Jupyter Notebooks to support self-propelled learning in a graduate course on Building Performance and Energy Systems Simulation. A series of examples was given to illustrate the unique features of Jupyter Notebooks and its potential to deliver an engaging learning experience. Although the evaluation from both teacher's and students' perspective shows positive signs, it is still early to make conclusive statements about the success of this implementation.

Plans for further development in the near future include the development of additional Notebooks to cover more topics in the domain of building performance and energy system simulation. By having these Notebooks available in the public domain, it would be great if this could become the starting point of a joint international effort to make a library of Notebooks available for different types of learners. Within the context of a single course, the challenge will be in finding a right balance between giving students access to more material without creating an overshoot in the workload.

Another direction for further development is a more seamless integration between the task description and the way the responses are collected. At present, these two parts are disconnected, but it would be interesting to explore options for having students submit Notebook files instead of pdfs. The intention is that students would spend less time on writing reports and thus more time on the main learning objectives of this course. In addition, it is also anticipated that this use of the worksheets will reduce that amount of time that is needed to grade the assignments and hence it will increase opportunities for giving timely feedback. In this context, it is expected that much inspiration can be taken from efforts towards the development of "executable research papers", which are also largely driven by the Project Jupyter movement [22].

7. Acknowledgement

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9. Data statement

The datasets generated during and/or analysed during the current study are available in the Gitlab repository of the Building Performance group at Eindhoven University of Technology, https://gitlab.tue.nl/bp-tue/clima2022_jupyter.