nature portfolio

Peer Review File

A hypergraph model shows the carbon reduction potential of effective space use in housing

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

The article presents a new method called hypergraph framework for designing and evaluating architectural floor plans, with a focus on optimizing space use and environmental performance. The method uses a graph-based representation of floor plans to generate automatic designs. The framework integrates cultural and architectural norms and minimizes excess space to enhance sustainability. The traditional architectural design workflow is criticized for relying heavily on manual labor, which limits the ability to optimize building performance and space utilization. In contrast, the hypergraph method automates the design process, enables extensive design explorations, and performs several floor plan iterations. The implications for rapid plan test that were developed with the hypergraph method are quite impressive.

Comments on the manuscript

1. Although the method is novel, the authors did not consider other realistic condition in building industry. The optimization algorithm should have some constraints related to MEP layout, vertical load distribution, and construction cost on the optimized floor plans. Unlike other product (or system), the building industry has many other constraints. Otherwise, it can't be realized. Another issue should be addressed for its liability, in doing these designs the future users would still need to be reviewed by engineer and architects right? So, I wonder by using these if issues could slip through the cracks.

2. In the simulation setup, one important consideration is occupant behavior. If the program of the space is changed, the occupant behavior in such space should be changed accordingly. It is recommended to take into account occupant behavior as one of the simulation inputs for resulting in reliable results. In addition, the metric of SDA alone is not enough to prove its energy saving potential. Other generic metrics on building energy consumption should be calculated. Last, the baseline comparison of the optimized floor plan is rather unclear.

3. The English of the manuscript should be improved. Especially, the authors need to check the rule for using ',' for English writing. Generally, this is well written but some severe errors on grammar issues hinder to follow the manuscript.

Reviewer #1 (Remarks on code availability):

The author's explanation is understandable on a README file. The code is easy to follow.

Reviewer #2 (Remarks to the Author):

This paper presents a comprehensive study on the impact of spatial efficiency on building energy performance through the innovative use of a hypergraph model. By comparing buildings in Zurich, New York, and Singapore, it demonstrates that optimizing spatial configuration can significantly outperform traditional envelope upgrades in reducing carbon emissions. Despite its potential, the approach faces challenges related to its complexity, design diversity considerations, and the quality of input data. Overall, the paper provides a valuable perspective that can help drive building design towards a more efficient and environmentally friendly direction.

Strengthens:
+ The introduction of the hypergraph model for encoding building floorplan organization and facilitating automatic geometry creation is a novel approach that addresses the overlooked aspect of spatial configuration in building energy efficiency.
+ The study highlights the potential of automatically generated floorplans to increase daylight

access by up to 24%, which is significant for improving the quality of residential spaces.
+ The paper is well-written and organized, making it easy to understand.

Weaknesses:
- The complexity of the hypergraph model might pose a barrier to widespread adoption.
- The quality of the automatically generated designs heavily depends on the quality of the underlying floorplans in the reference database, which could vary significantly.
- While models are capable of generating effective floorplans, they may lack consideration for architectural design diversity and creativity.

Reviewer #2 (Remarks on code availability):

The work utilizes hypergraphs to accomplish automated analysis and generation of floorplans. By following the guidelines provided in the README, I successfully set up the environment and installed the requisite software. With the aid of the provided sample scripts and environmental simulation tools, I was able to automate the creation and assessment of floorplans, encompassing space, energy use and daylight analysis. This process allowed me to effectively replicate the work and experience the practical application of hypergraphs in the automation of architectural design.

Reviewer #3 (Remarks to the Author):

This well-structured manuscript presents a method producing an abstract representation of the internal configuration of dwellings. This abstraction's capability to support building design to produce plausible variant that can be evaluated by simulation tools, and to minimize the area for a given program. The authors propose this as an attempt to improve building performance by occupancy rather than floor area.

While I consider the proposed adjustment of optimization targets from per area to per occupant well justified, I recommend to expand a critical reflection of the underlying assumptions and inevitable limitations of the research. For example, the spatial subdivision of a residential unit is directly related to occupancy in the manuscript. The authors are certainly aware that this "occupancy" is actually the maximum a unit can accomodate, but can hardly be enforced by design methods. Here the limitation of the approach is quite similar to that of the current practice of EUI - subdividing a dwelling into more & smaller rooms helps little if the number of inhabitants of the dwelling does not increase accordingly. This shall not diminuish the value of the method, but I hope for a clear problem statement that may link this method to research in fostering not only the optimized desgin of buildings, but also their use. Other questions that may araise are whether the approach may penalize multi-functional and shared rooms, and on possible implications on design targets such as flexible use of rooms, and re-organisation of dwellings (that may have in common with most optimization). So the general recommendation is to clearly state limitations that may then be translated to future research.

On a methodological level, it was not entirely clear to me to what extent the design of windows responds to the layouts. This is of particular interest when optimizing for daylight availability.

In-detail comments:

Lines 9: should this read "minimum"?

Lines 33-38: This paragraph contains statements on current design practice that sound plausible, but lack backing by references. There may also be other, systematic means to partition dwellings, e.g. by relying on known typologies and building up on prior project experience.

Lines 81-89: Is it possible that the text refers to a less refined version of Figure 1?

Line 122,123: Please check this sentence.

Lines 373ff: Windows significantly impact energy demand and daylight supply. According to Table 1, the simulations assume a constant WWR of 0.6. Was this WWR also imposed on the reference layouts, or are generated layouts with WWR 0.6 compared to as-built layouts with other WWRs?

Response to reviewer #1:

Reviewer #1 (Remarks to the Author):

The article presents a new method called hypergraph framework for designing and evaluating architectural floor plans, with a focus on optimizing space use and environmental performance. The method uses a graph-based representation of floor plans to generate automatic designs. The framework integrates cultural and architectural norms and minimizes excess space to enhance sustainability. The traditional architectural design workflow is criticized for relying heavily on manual labor, which limits the ability to optimize building performance and space utilization. In contrast, the hypergraph method automates the design process, enables extensive design explorations, and performs several floor plan iterations. The implications for rapid plan test that were developed with the hypergraph method are quite impressive.

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1. Although the method is novel, the authors did not consider other realistic condition in building industry. The optimization algorithm should have some constraints related to MEP layout, vertical load distribution, and construction cost on the optimized floor plans. Unlike other product (or system), the building industry has many other constraints. Otherwise, it can't be realized. Another issue should be addressed for its liability, in doing these designs the future users would still need to be reviewed by engineer and architects right? So, I wonder by using these if issues could slip through the cracks.

Response #1.1:

In response to this comment, we have updated our discussion to clarify the focus and scope of the research presented in the manuscript.

The hypergraph specifically targets spatial generation of residential building layouts. Currently, the scope of the research excludes the generation of MEP layouts, as well as structural layouts of a building. The hypergraph can generate a volumetric 3D model with rooms which in the scope of this research is used to create a building energy model. This volumetric 3D model of an apartment could in the future be combined with existing tools that autogenerate HVAC systems based on such volumetric zones and a building energy model of a building, such as BuildVac by Ali Irani (Irani 2023). In the scope of the current research the method only works in two dimensions and excludes structural systems. Further research should address and extend the method for three-dimensional design generation, which would be necessary to create structural column grids or analyze lateral loading systems through a building.

Irani, A., & Reinhart, C. (2023). buildvac (Version 1.0.0) [Computersoftware]. https://doi.org/10.5281/zenodo.10711824 [LINK]. https://github.com/MITSustainableDesignLab/buildvac

Hypergraph generated design proposals should be validated by a human designer. We see the tool appropriate for augmenting current digital design processes, where the visual representation can be double checked by an architect and an engineer. For fully automated procedures we see opportunities in building analytics, automatically evaluating different urban conditions, survey of building stock or figuring out how offices could be converted into residential buildings. There, the focus would not be on a single floor plan, but instead at average performance or quantitative analysis of different options: e.g. what is the average number of bedrooms in a building. For such quantitative analyses a perfect floor plans would be less important, since averages would be derived from fitting thousands of different designs.

2. In the simulation setup, one important consideration is occupant behavior. If the program of the space is changed, the occupant behavior in such space should be changed accordingly. It is recommended to take into account occupant behavior as one of the simulation inputs for resulting in reliable results. In addition, the metric of SDA alone is not enough to prove its energy saving potential. Other generic metrics on building energy consumption should be calculated. Last, the baseline comparison of the optimized floor plan is rather unclear.

Response #1.2:

In response to this comment, we expanded and clarified the description of our method in the manuscript.

We agree that occupant behavior is an important factor in creating accurate building energy models. As discussed in the methods section and in more detail in Table 1, we utilize the EnergyPlus within the software ClimateStudio to create building energy models from which the annual energy use of an apartments is calculated. As outlined in Table 1 we utilize the industry standard templates for the different climates within ClimateStudio; ASHRAE 90.1 – Climate Zone 4, ASHRAE 90.1 – Climate Zone 1 and SIA 2024 that include standard occupancy for buildings. We did not customize the industry standard templates for building occupancy, as this would make the results hard to reproduce. Further studies should address the impact of varying occupant behavior on energy use.

To clarify, sDA is not used as a way to measure energy savings in our study. SDA is a metric that shows what percentage of a space receives an average of 300 lux of daylight. Although daylight and solar radiation are heavily linked with the energy use of a building it can not be used as a proxy. Instead, Energy Plus, the engine that creates the building energy models in our study, uses simplified raytracing algorithms to calculate heat gains from solar energy and includes them in the reported EUI.

To clarify the reported comparison of the different floor plans in Figure 3. For all surveyed apartments from Zurich, Singapore and New York we create different carbon saving scenarios, taking the different emission factors of electric grids of the specific cities into account (as described in Table 1): (1) the annual carbon emissions savings from upgrading the building envelope of the apartment, (2) the annual carbon emissions savings from not having any excess area in the apartment (see Methods, Excess area and emission delta.). As described in Equation 6 we then compute the emission delta that shows if the excess area or the building envelope are more important for lowering carbon emissions.

3. The English of the manuscript should be improved. Especially, the authors need to check the rule for using ‘,’ for English writing. Generally, this is well written but some severe errors on grammar issues hinder to follow the manuscript.

Response #1.3:

In response to this comment, we have carefully edited and proofread the manuscript.

Reviewer #1 (Remarks on code availability):
The author's explanation is understandable on a README file. The code is easy to follow.

<u>Response to reviewer #2:</u>

Reviewer #2 (Remarks to the Author):

This paper presents a comprehensive study on the impact of spatial efficiency on building energy performance through the innovative use of a hypergraph model. By comparing buildings in Zurich, New York, and Singapore, it demonstrates that optimizing spatial configuration can significantly outperform traditional envelope upgrades in reducing carbon emissions. Despite its potential, the approach faces challenges related to its complexity, design diversity considerations, and the quality of input data. Overall, the paper provides a valuable perspective that can help drive building design towards a more efficient and environmentally friendly direction.

Strengthens:
+ The introduction of the hypergraph model for encoding building floorplan organization and facilitating automatic geometry creation is a novel approach that addresses the overlooked aspect of spatial configuration in building energy efficiency.
+ The study highlights the potential of automatically generated floorplans to increase daylight access by up to 24%, which is significant for improving the quality of residential spaces.
+ The paper is well-written and organized, making it easy to understand.

Weaknesses:
- The complexity of the hypergraph model might pose a barrier to widespread adoption.
- The quality of the automatically generated designs heavily depends on the quality of the underlying floorplans in the reference database, which could vary significantly.
- While models are capable of generating effective floorplans, they may lack consideration for architectural design diversity and creativity.

Response #2.1:

In response to the comment, we have revised the discussion section of the manuscript.

We agree that while designers should be comfortable in manipulating architectural layouts, while manipulating the graph itself could be quite complex. Because of this, we rely on an automated procedure to create the hypergraphs (as shown with the sample code and in Figure 1). A designer would therefore not be required to interact with the hypergraph itself, but could use the method entirely via its programmatic layout representation by creating layouts and then transferring or applying those to new boundary conditions or by using an existing dataset of hypergraphs.

As stated in the discussion, we agree that good quality floor plans depend on the underlying dataset. However, we see both opportunities for quality control and creative design opportunities that would come through using the hypergraph method. As shown in the manuscript, hypergraph generated floor plans can be evaluated easily for spatial use, energy or daylight performance. This allows designers to discard infeasible floor plans or create additional quality control metrics that can be applied automatically. Furthermore, through the source attribution of the hypergraph, a floor plan's original design can be tracked. Here one could imagine validated, quality-controlled design databases.

The computational speed of the method allows for iterating through many different designs, which in turn increases the chance for finding and identifying good design alternatives. The bijective workflow, where every hypergraph creates a spatial counterpart, allows for manually overriding certain aspects of a design and new types of creative workflows. For instance, in a hybrid workflow: (1) A graph output is translated into geometry using a programmatic layout and a boundary, (2) the programmatic layout suggestion is then manipulated by a user, (3) the resulting programmatic layout is used to generate a new hypergraph. Furthermore, new types of graph-based machine learning approaches could be deployed to generate new hypergraphs artificially based on user preferences.

Reviewer #2 (Remarks on code availability):

The work utilizes hypergraphs to accomplish automated analysis and generation of floorplans. By following the guidelines provided in the README, I successfully set up the environment and installed the requisite software. With the aid of the provided sample scripts and environmental simulation tools, I was able to automate the creation and assessment of floorplans, encompassing space, energy use and daylight analysis. This process allowed me to effectively replicate the work and experience the practical application of hypergraphs in the automation of architectural design.

Response to reviewer #3:

Reviewer #3 (Remarks to the Author):

This well-structured manuscript presents a method producing an abstract representation of the internal configuration of dwellings. This abstraction's capability to support building design to produce plausible variant that can be evaluated by simulation tools, and to minimize the area for a given program. The authors propose this as an attempt to improve building performance by occupancy rather than floor area.

While I consider the proposed adjustment of optimization targets from per area to per occupant well justified, I recommend to expand a critical reflection of the underlying assumptions and inevitable limitations of the research. For example, the spatial subdivision of a residential unit is directly related to occupancy in the manuscript. The authors are certainly aware that this "occupancy" is actually the maximum a unit can accomodate, but can hardly be enforced by design methods. Here the limitation of the approach is quite similar to that of the current practice of EUI - subdividing a dwelling into more & smaller rooms helps little if the number of inhabitants of the dwelling does not increase accordingly. This shall not diminuish the value of the method, but I hope for a clear problem statement that may link this method to research in fostering not only the optimized desgin of buildings, but also their use. Other questions that may araise are whether the approach may penalize multi-functional and shared rooms, and on possible implications on design targets such as flexible use of rooms, and re-organisation of dwellings (that may have in common with most optimization). So the general recommendation is to clearly state limitations that may then be translated to future research.

Response #3.1:

In response to this comment, we expanded the discussion section of the manuscript to include more information about the research question, limitations of the approach, and research outlook. We see opportunities in applications in a design context as well as for building analytics at urban scales. On a building level, we highlight different opportunities for design in Figure 4c, showcasing how hypergraph-generated floor plans could be used to give design feedback, prompting designers to create smaller or larger apartments, as well as changing the layout to improve daylight access. Architecturally, being able to predict interior layouts of buildings will allow for the more performative designing of whole buildings, and through which the relationship of building form and interior layout on performance can be explored.

On a methodological level, it was not entirely clear to me to what extent the design of windows responds to the layouts. This is of particular interest when optimizing for daylight availability.

Response #3.2:

Currently, the windows do not respond to the layouts. The window to wall ratio, and through that the window size, are kept at a constant that is a typical standard value used in industry. Changes in daylight availability are only stemming from different internal configurations and subdivision of the rooms to make the floor plans comparable. Since a focus of the paper is on the floor plan subdivision, the scope of the research excludes an exploration of different window configurations. Further research should address if there is a correlation between floor plan configurations and window layouts.

In-detail comments:

Lines 9: should this read "minimum"?

Response #3.3:
We clarified the wording of the abstract in response.

Lines 33-38: This paragraph contains statements on current design practice that sound plausible, but lack backing by references. There may also be other, systematic means to partition dwellings, e.g. by relying on known typologies and building up on prior project experience.

Response #3.4:
In response to the comment, we have revised this section in the manuscript. We want to highlight the potential of coupling quantitative analysis with design processes.

Lines 81-89: Is it possible that the text refers to a less refined version of Figure 1?
Line 122,123: Please check this sentence.

Response #3.5:

We have addressed this in the updated manuscript.

Lines 373ff: Windows significantly impact energy demand and daylight supply. According to Table 1, the simulations assume a constant WWR of 0.6. Was this WWR also imposed on the reference layouts, or are generated layouts with WWR 0.6 compared to as-built layouts with other WWRs?

Response #3.6:
That is correct. In the scope of this research, we assumed the WWR as a constant at 0.6 for both all the reference apartments, as well as all artificially generated layouts. We hope to further study the impact of both prevalent local WWR in different cities or apartment typologies, as well as the impact of different WWR on apartment energy use in future research.

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

The revision by the author does not sufficiently address the concerns that I originally reported. The MEP and structural component are important but the authors stated this as a future study. Also, the validation challenge is also just mentioned by “should be validated by human designer”. Regarding occupant behavior modeling, the authors mentioned occupancy profile from the existing library but the main point is how they deal with such variation in their AI generated floor plan. I believe this revision has not addressed any of my concern but mentioned it as a future study or limitation. Therefore, I again not recommend this manuscript for the nature communication.

Reviewer #1 (Remarks on code availability):

Code availability is confirmed.

Reviewer #3 (Remarks to the Author):

Dear authors, thank you for revising the manuscript and addressing the comments and questions.

In response 3.1, you highlight the expanded discussion. I agree that the discussion covers the strenghts and technical limitations of the proposed method. However, the introduction raises very fundamental questions about efficieny and presents the juxtaposition of area-based energy use intensity with evaluating based on actual use. The discussion takes up this line of thought proposing space sufficiency. Since you bring up this question and example, I still miss a (possibly very brief) statement of the conditions under which the proposed method actually leads to more efficient space use. The detached single-family home, that you give as an example in the introduction, could be optimized by your method in terms of tailoring the individual rooms - but if inhabitated by just two persons, would still not get any closer to efficient space use or even space sufficiency. So under which conditions can your method actually achieve this? I could imagine that in the case of buildings that are subject to some policy ensuring that e.g. the number of occupant matches the number of rooms, and this would link your research to e.g. more policy-focused research on how to match househould- and dwelling size.

Thank you for clarifying that windows size and location were not in the scope of the research (response 3.2). I propose to briefly mention this in the manuscript, too. In particular the formulation "floor plans are automatically converted into a simple 3D model, with walls and windows", and figure 2e) showing one unit boundary with two differen window configurations, could otherwise be misinterpreted by the reader.

Finally, one comment that was not brought up in the first review round. Would it help the reader to both grasp the concept of the hyper-graph and its potential if you would first introduce that in a more general manner here? E.g. the concept of graphs sharing nodes, that you implement here by combining zone boundaries and access, but that could also represent other information?

RESPONSE Revision 2:

To the editor and the reviewers,

We sincerely apologize that our previous response came across as dismissive. We deeply value the input provided by the reviewers, and aim to revise the paper accordingly. Regarding the scope of the research, it was not our intention to propose a method that would fully automate all aspects of architectural production, including integrating the full scope of engineering work. We see the work presented in the manuscript contributing through the creation of a new framework for representing and generating architectural geometry for spatial layouts. This resolution of representation allows the creation of both daylight and energy models that, together with the spatial design opportunities of the hypergraph can give new insights into building performance of residential buildings. We agree with the reviewers that, in the last version of the paper, the question of the research scope and how floor plan changes affect actual energy use was unclear, and we have worked to clarify this in the revision of the paper.

Response to reviewer #1:

Reviewer #1 (Remarks to the Author):

The revision by the author does not sufficiently address the concerns that I originally reported. The MEP and structural component are important but the authors stated this as a future study. Also, the validation challenge is also just mentioned by "should be validated by human designer". Regarding occupant behavior modeling, the authors mentioned occupancy profile from the existing library but the main point is how they deal with such variation in their AI generated floor plan. I believe this revision has not addressed any of my concern but mentioned it as a future study or limitation. Therefore, I again not recommend this manuscript for the nature communication.

Reviewer #1 (Remarks on code availability):

Code availability is confirmed.

Response #1.1 Integration with structure and MEP

We agree that the complexities around fully automating the design of a building go way beyond automating spatial layouts and must ways to integrate building systems and structure. We see the digital representation and automated generation of spatial layouts enabled by the hypergraph framework as a first and necessary step in this direction, on which future research that specifically addresses MEP, or structural systems can build on. In response to this comment, we outlined ways of how the hypergraph can already support the design of MEP and structural systems (Line 495, Methods section "Integration of the hypergraph method with automated design workflows") and how future extensions of the hypergraph could integrate such constraints. Furthermore, we added Supplemental Figure 14 to show how the hypergraph workflow could fit into future larger automation workflows that can more fully integrate structural or MEP constraints. We agree with the reviewer that the conceptual possibility of extending the approach is necessary to make it viable for integration into future automation workflows.

Response #1.2 Validation of floor plans

We see the visual inspection of results as a strength of the method, especially when applied to architectural design. As shown in the supplementary code and sample files, the hypergraph method allows for quick iterations and designers to input and modify floor plans to fit their specific needs. As discussed in the methods section "Apartment validity heuristic" we propose two automated ways to evaluate a floor plan: The "perimeter difference score" (Equation 1, Supplemental Figure 3 & 4) and the automated furniture placement (Supplemental Figure 7).

Response #1.3 Occupancy

In response to this comment, as well as the comment of Reviewer #3, we created an additional energy simulation of an apartment to test the influence of occupancies on the energy use (Methods, Line 454). While typical energy modeling does not consider differentiated zoning and occupancy modeling, our approach could allow for such granularity. While the zone-based approach is necessary to capture complex features such as natural ventilation, we don't see it influencing our findings with the load-based approach for evaluating energy use. To illustrate this, we created an additional series of simulations where the load profiles of the different rooms are differentiated by occupancy: Living spaces are used during the day and the bed rooms during the night time. The temperature set points in the rooms are only active when the room is occupied (for example heating and cooling is only enabled in the living room when it is occupied). The results are outlined in Supplemental Figure 15 and Supplemental Figure 16 show only a modest impact of the differentiated zoning. Because of the comparably small impact and the lack of standardized schedules for this kind of simulation, we opted for not differentiating zones for the main simulations in the manuscript.

<u>Response to reviewer #3:</u>

Reviewer #3 (Remarks to the Author):

Dear authors, thank you for revising the manuscript and addressing the comments and questions.

In response 3.1, you highlight the expanded discussion. I agree that the discussion covers the strenghts and technical limitations of the proposed method. However, the introduction raises very fundamental questions about efficieny and presents the juxtaposition of area-based energy use intensity with evaluating based on actual use. The discussion takes up this line of thought proposing space sufficiency. Since you bring up this question and example, I still miss a (possibly very brief) statement of the conditions under which the proposed method actually leads to more efficient space use. The detached single-family home, that you give as an example in the introduction, could be optimized by your method in terms of tailoring the individual rooms - but if inhabitated by just two persons, would still not get any closer to efficient space use or even space sufficiency. So under which conditions can your method actually achieve this? I could imagine that in the case of buildings that are subject to some policy ensuring that e.g. the number of occupant matches the number of rooms, and this would link your research to e.g. more policy-focused research on how to match househould- and dwelling size.

Response #3.1:

We agree that in some cases, the assessment from an occupancy would lead to interesting insights. The method can extend to evaluate a floor plan based on minimal furniture blocks per occupant inside a dwelling. That way, the single-family home would be assessed with the furniture blocks equivalent to a one-bedroom apartment, if only occupied by two people. As a response to the comment, we updated the discussion section (Discussion, Line: 248) and added 1.8. Supplementary note on occupancy and Supplementary Figure 13. To illustrate this further we created a supplemental sample file in the github repository*, that allows users to change the number of occupants and show the impact on excess area and emissions.

*(https://github.com/ramonweber/hypergraph/blob/main/samples/Hypergraph%20Reference%20Script%203%20Occupancy.3dm & https://github.com/ramonweber/hypergraph/blob/main/samples/Weber2024%20Hypergraph%20Reference%20Script%203%20Occupancy.gh)

Furthermore, in response to this and the comment from reviewer #1 we tested differentiated zoning of occupancy (Response #1.3 Occupancy) on the energy use in the BEM.

Thank you for clarifying that windows size and location were not in the scope of the research (response 3.2). I propose to briefly mention this in the manuscript, too. In particular the formulation "floor plans are automatically converted into a simple 3D model, with walls and windows", and figure 2e) showing one unit boundary with two differen window configurations, could otherwise be misinterpreted by the reader.

Response #3.2:

In response to the comment, we updated the wording in the manuscript (Line 125).

Finally, one comment that was not brought up in the first review round. Would it help the reader to both grasp the concept of the hyper-graph and its potential if you would first introduce that in a more general manner here? E.g. the concept of graphs sharing nodes, that you implement here by combining zone boundaries and access, but that could also represent other information?

Response #3.3:

The expendability is important to highlight and links to comments from reviewer #1 about the research outlook. In response to the comment, we updated the manuscript (Line 80 and 496).

REVIEWERS' COMMENTS

Reviewer #1 (Remarks to the Author):

Thanks for revisiting my original comments. The improvement is sufficient to recommend the paper to the journal. Good work!

Reviewer #3 (Remarks to the Author):

Dear authors, the revised manuscript addresses all the concerns I raised in my review.