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Simulating natural ventilation in large sports buildings. Prediction of temperature and airflow patterns in the early design stages.

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ABSTRACT

In large sport's buildings, a big part of energy can be saved by providing natural instead of mechanical ventilation. However, additional challenges arise while controlling airflow and temperatures in different zones. These measures highly depend on the shape, construction and ventilation openings, which are mostly decided in the early design stages. Computational optimization can support these early stages of design, but needs to be performed in efficient ways. In this respect, the project proposes rapid assessment of temperature and airflow patterns using customized Grasshopper components, which would be able to evaluate a given model using CONTAM and EnergyPlus software as simulation engine. The proposed method integrates these simulations within an environment, which is familiar to architects and is largely used for parameterization of design in its early stages. A case study (Jiangmen Sports Center, Jiangmen, China) is used to test the developed process for a large indoor sports hall.

Author Keywords

Natural ventilation; early design stage; large volumes; sports buildings; rapid assessment; CONTAM; EnergyPlus, Passive cooling, Building Envelope, Building performance and simulation, Thermal comfort.

ACM Classification Keywords

I.6.4 SIMULATION AND MODELING (Model Validation and Analysis).

1 INTRODUCTION

Based on the emerging climatic changes, reducing energy consumption of buildings has become an important issue within the last decades. Large sport buildings such as indoor stadiums, swimming pools, arenas etc. are hefty consumers of energy used for ensuring high comfort levels for both athletes and spectators. While a big part of energy can be saved by providing natural instead of mechanical ventilation, in case of large volume buildings additional challenges arise when it comes to controlling airflow and temperatures in different zones. These measures highly depend on the shape, construction and ventilation openings of such large envelopes, which are mostly decided in the early design stages. Therefore, availability of rapid simulation of temperature and airflow patterns may lead to informed decisions, which tackle important issues related to both indoor comfort and energy performance.

Detailed assessment of natural ventilation, such as Computational Fluid Dynamics (CFD) analysis, can give detailed information on the airflow and temperature patterns in large indoor spaces, but require long computational time to achieve convergence; while faster calculation methods such as Airflow Network (in software like CONTAM) often lack thermal analysis. On the other hand, energy simulation software mostly assumes constant ventilation rates, which do not reflect known dependencies on indoor-outdoor conditions and ventilation system operation [1]. However, output for both air temperature and airflow rates are necessary for determining the passive control of indoor comfort and the related energy saving potential. Especially, in the early stages, this optimization needs to be performed in a fast way.

This project proposes rapid assessment of temperature and airflow patterns using a series of customized Grasshopper components, which would be able to evaluate a given model using CONTAM and EnergyPlus software. The building model to be analyzed is divided into smaller zones in order to retrieve detailed temperature and airflow results. The proposed method integrates these simulations within an environment, which is familiar to architects and is largely used for parameterization of design in its early stages.

The swimming pool of the Jiangmen Sports Center, in Jiangmen (China) is used as case study to test the proposed method for a large swimming pool. The outcomes of rapid simulations are validated using alternative software commonly used for assessing natural ventilation within buildings.

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2 PROPOSED METHOD

The proposed method has been developed by an interdisciplinary team at TUDelft, composed by staff members from the Chairs of Design Informatics and Climate Design at the Faculty of Architecture and the Built Environment. The need for a fast assessment of the indoor thermal environment in the early stage of design led to the development of a method for coupling thermal analysis and airflow calculations. The goal is to retrieve results of the indoor microclimate in large volumes, when passive conditions and natural ventilation need to be simulated.

Standard energy simulations based on thermal analysis only investigate the indoor temperature assuming well-mixed air temperature for an entire volume (thermal zone) [2]. When designing large volumes, this assumption cannot be reliable, especially if the goal is to optimize the indoor comfort in specific parts of the volume (i.e. where spectators and athletes are). Therefore, ways to predict the indoor microclimate of large volumes were investigated, with a focus on the subdivision of a large space in sub(thermal)-zones.

A thermal zone is defined as an indoor space with similar thermal requirement, where transient calculations for the heat balance of both internal and enclosing surface temperatures are calculated and solved for each time step [3]. These calculations of the heating and cooling loads are affected by the rate at which air is infiltrated into the zones. This rate is normally set as parameter dependent on the building program. On the other hand, ventilation rate in naturally ventilated building is highly dependent on the relationship indoor-outdoor thermal environment.

The method proposed in this paper tries to quickly balance the airflow and temperature calculations. It is based on the well-known “onion” approach for convergence between thermal and airflow analysis [4]. In the onion approach, for each time step, the thermal analysis results are used for the airflow calculations. This process is iterated for every time step until convergence is found. However, differently from the typical onion approach, the proposed method iterates for the whole analysis period. During the first step, the thermal analysis runs for the whole analysis period (e.g. hourly month simulation), and the results (air temperatures for every zone) are used to calculate the airflow rates. In the second step, the new air temperatures are calculated based on the first airflow simulation. This process is iterated until the new iteration has small difference from the previous one. The major difference between the two approaches is that the computational time needed to achieve convergence in the proposed approach is shorter compared to the onion approach used in other simulation software, such as EnergyPlus [5].

Commercial software embed this approach. For example, the Design Builder software (DB) calculates airflow rates by setting an airflow network simulation and coupling the flow results with thermal results. The limitation is that the results are not related to specific locations within the indoor environment. In order to simulate the internal temperature distribution, it is possible to run a CFD analysis of the design, based on the airflow rates and the other boundary conditions calculated by other software[6].

2.1 Choice of software

The overall purpose of creating a rapid assessment tool for evaluating design in its early stages requires tools to be easy to use and integral to a platform, which is familiar and comprehensible for architects and allows evaluations of various design options without rebuilding the models in a different software. Moreover, the proposed framework needs to be easily adjustable for specific cases. Therefore, Grasshopper plugin (GH) for Rhino has been chosen as an intermediary between parametric modelling and simulation software.

CONTAM 3.1 has been chosen as a software for calculating airflow rates to assess the adequacy of natural ventilation based on income airflows, exfiltration, and zone-to-zone displacements in building systems driven by wind pressures on the exterior of the building, and buoyancy effects induced by air temperature difference [7]. The software is able to determine the ventilation rates over time and distribution of ventilation air within building zones. The software was also chosen due to the straightforward control possibility while launching a simulation through command-line interpreter. It is free of charge and available for Windows and Linux platforms.

The part of thermal simulation has been commended to EnergyPlus (E+) due to its high level of calculations, with the possibility of performing transient heat balance simulations, multi-zone modelling and hourly time steps [8]. Moreover, its input and output data structures are specifically designed to facilitate third party modules and interface development, which makes it easier to integrate into the generic workflow of Grasshopper. The software is free, open-source and cross-platform.

The connection between GH and E+ is done through the Honeybee Plugin for Environmental Analysis (GPL) started by Mostapha Sadeghipour Roudsari, which also connects GH to Radiance, Daysim and OpenStudio for building energy and daylighting simulation [9].

2.2 System framework

The overall scheme of computational system framework can be seen in Figure 2. It is explained in details hereafter.

The process starts with the definition of a simplified model of the design, which is then used to construct zones for thermal and airflow analysis. Outputs of both analysis are then coupled until convergence (balanced airflow rates and temperatures) is reached. Finally, the results can be used for the assessment of thermal comfort performance.

Simplified model
The overall iterative computational process for optimizing comfort levels based on temperature and airflow predictions is performed on a 3D model of the building. Such model is highly simplified as compared to the complexity of the building, even in early design. Simplification is needed in order to ensure reasonably short computation time. In particular, the computation time is pertained to the number of faces in the simplified geometry – the lower amount of faces, the shorter computation time. Curved surfaces need to be approximated as much as possible to keep the balance between running time and oversimplifying geometrical features, which have impact on performance values. The relationship between the number of faces and overall computation time can be seen in table 1.

Thermal analysis
In order to perform thermal analysis, building volume needs to be separated into thermal zones based on zones of interest (e.g. spectator zone vs. playground), physical barriers (e.g. walls and floors) and educate guess on different thermal conditions. The partitioning is performed manually.

The thermal zones besides the simplified geometry hold provided or intended material properties, including glazed surfaces. Thermal analysis is performed by E+, providing an average temperature (to be considered to be in the middle of the zone) in each of the zones for the desired period on hourly basis (or other step size defined by user).

Airflow analysis
Airflow analysis is based on an airflow network simulation, i.e. the model is restricted to a single forced air system. Similar to thermal analysis, an analyzed building is represented by a network of zones connected by airflow paths. Zones are discrete volumes of air within which mass is conserved with uniform temperature and pressure values. Air moves between zones along airflow paths with pressure-dependent resistance to airflow [10].

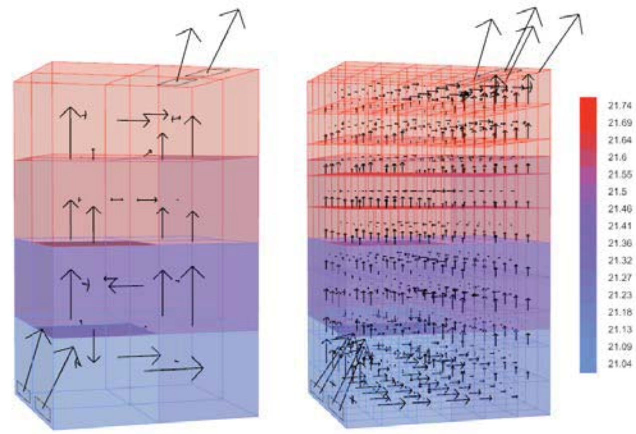

Figure 1. Left: Thermal zones colored according to temperature values, arrows showing airflow directions and relative amount of air in between neighboring thermal zones. Right: Airflow zones colored according to temperature values, arrows showing airflow directions and relative amount of air in between neighboring airflow zones.

Modelling of airflow zones are based on a different simplification method than thermal zones, however, influenced by the latter as well. The general differences between the two are conditioned by the different size and shape. Airflow zones are modelled as equal size voxels composing the whole building volume. Each voxel inherits its thermal properties (temperature) from the thermal zone it belongs to and is aware of its neighboring voxels and possessed openings (airflow paths). Openings are modelled either as fixed size physical openings towards outside, provided by the user, or virtual openings between neighboring voxels which have the size of an entire voxel face.

Voxel size is decided by the user bearing in mind the balance between desired resolution of the results and computation time, since smaller voxel size yields longer computational time. Smaller voxel size means more accurate geometry definition and therefore more accurate

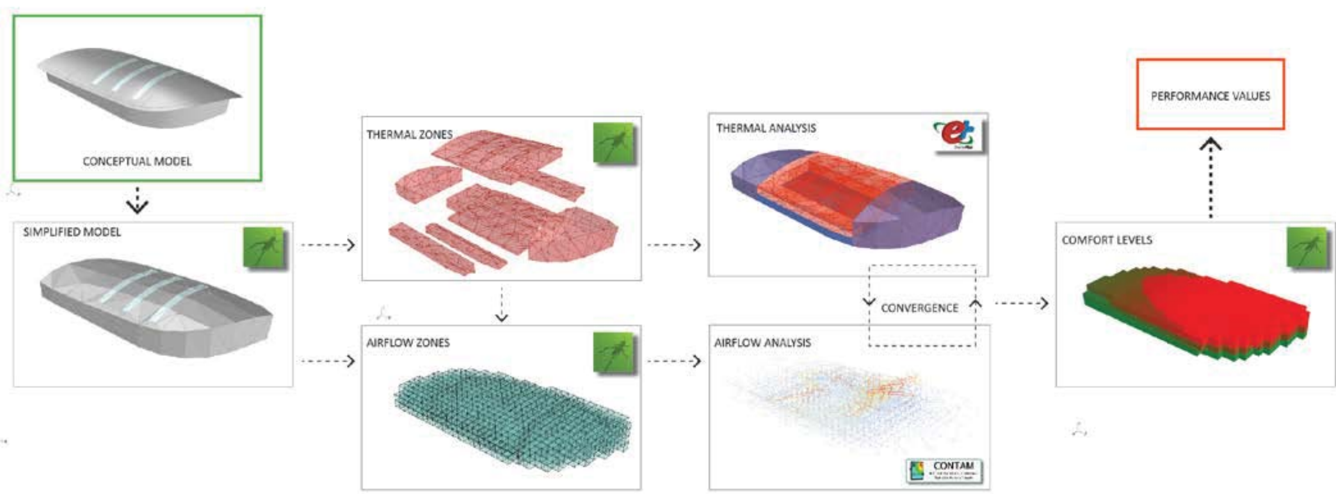

Figure 2. Computational system framework for the rapid assessment of comfort levels based on temperature and airflow predictions, using CONTAM and E+ simulation software integrated with Grasshopper plugin for Rhino.

results. When complex shape buildings are simulated, the voxel grid definition is important in approximating at best the shape of the building envelope, and therefore getting more accurate results, in terms of airflow.

The relationship between the number of voxels and overall computation time can be seen in Table 2. The voxel grid is generated automatically using a customized Grasshopper component. The airflow simulation is performed by CONTAM software and provides the air exchange rate between all neighboring voxels and the outside environment in kg/s (then translated in m3/s). Air change rates are calculated as the total flow of outdoor air into the building divided by the floor area. As the process is still under development, the effect of wind façade pressures on ventilation performance now is not taken into account (but possible future implementation).

Coupling of thermal and airflow analysis

As mentioned previously, common thermal analysis assumes constant ventilation rates, which do not reflect an actual situation for ventilation, while airflow analysis is based on provided temperatures. Since indoor temperatures are influenced by the air exchange within the building and outdoor-indoor environments and the air exchange is determined by the air density, (i.e. temperature differences in different zones), both systems need to be coupled and analyzed simultaneously. In order to achieve this, the values are looped in between both until convergence is achieved.

The loop starts with thermal analysis assuming constant ventilation and air mixing between the thermal zones. The simulated temperatures are then provided for the airflow analysis. Whereas airflow simulation provides air exchange rates between the thermal zones. Since airflow zones are of different geometry than thermal zones, the obtained values are aggregated to express air exchange rates between them and ventilation values for the zones, which possess openings towards outside. Figure 1 shows the difference between thermal and airflow zones of a simple rectangular volume. The transmission of values between the airflow and thermal simulations is performed until convergence of desired tolerance is reached. Alternatively, a fixed number of cycles can be chosen dependent on the desired accuracy of the results.

In order to loop them, the thermal and airflow simulations have to be consistent with each-others. Specifically, though zone areas and the number of zones may be different between the thermal and airflow models, the total building area is consistent between the two. Moreover, both thermal and airflow simulations share the same weather data for the specific location, which contain outdoor temperature, outdoor humidity, and wind direction and speed. The weather data is obtained from the E+ weather file online database [11].

Performance values

The method allows obtaining values relevant to assess thermal comfort.

Specifically, the output from the natural airflow analysis can give an overall estimate of the airflow behavior inside a large space, predicting the capability of the design to deliver a sufficient amount of air changes (ach) in relation to the specific micro-zone requirements within the indoor space. For example, for a sport building, the requirements for air changes per hour related to indoor air quality differ between the spectator area and the area where the athletes perform.

Moreover, the thermal analysis of the macro-zone is done by considering the ventilation rate within the zone, and therefore the performance of passive cooling of a design can be assessed. The useful outputs of this analysis are operative temperatures (°C) and relative humidity (%). Operative temperatures, together with air speed (m/s), for each macro-zone can be used to predict the thermal comfort level. This further assessment can be done by using a thermal comfort model, in which these parameters play a role in defining comfort. Since the focus of this research is the way of delivering a computational process for indoor microclimate simulation, the final assessment of estimating thermal comfort levels is not tested on the case study.

2.3 Computation time

As mentioned, the method aims at rapid assessments of temperature and airflow patterns for early design. Computation time is highly dependent on the accepted level of simplification and required accuracy. Since the tool supports the identification of the preferred design direction and the ranking of chosen designs according to their performance values, rather than deliver detailed assessment. Therefore, high accuracy is generally a less important factor than short computation time.

No. of faces	**100**	**200**	**300**
Time (s)	26	47	82
No. of voxels	**1636**	**845**	**455**

Table 2. The relationship between the number of voxels and the computation time for a single airflow simulation. Numbers are based on the case study described in section 4.

Voxel size(m)	4	5	6
Time(s)	798	216	86

Table 1. The relationship between the number of faces and the computation time for a single thermal analysis. Numbers are based on the case study described in section 4, where four thermal zones are calculated.

The tables show dependencies between the level of simplification and computational time required for one simulation. The tests were run with an Intel® Core(TM) i5-330M CPU @ 2.80 GHz, 8 GB RAM, 64-bit OS.

The overall computation time for the performance assessment is also dependent on the number of cycles required for the convergence between the results simulated by CONTAM and E+.

3 VALIDATION

In order to test the reliability of the proposed computational method, a test on a simple design case was performed and compared to the results from the same case modelled in the DB software, known as a reliable tool for design performance assessment [12].

Specifically, the comparison was made on two levels. One is the overall airflow rates and temperature of the design case along the whole simulation period (averaging the zones temperature and total results from the developed process). The other is on detailed level, for one snapshot of the simulated period. The results are compared against the CFD module within the DB software, looking at the temperature and airflow distribution within the indoor space. In this way it is possible to tell to what extent the results coming from the proposed method can be used for design evaluation.

The design case used for validation is a "box-like" space, with a 6x6m floor, and height of 10m. The bottom part of this construction is completely glazed in all façade orientations. Two ventilation openings are modelled, one at the bottom part of the west façade, the other one at the roof. The constructions of the design case were set the same as in the DB model. The design case was divided into 6 horizontal sub-zones for thermal analysis and 200 sub-zones for airflow network analysis. The simulation period was set for the whole month of May, with no closing hours for the ventilation openings. The number of coupling iterations was set as 10. The outdoor condition was set on Guangzhou (China). In order to account for hourly temperatures, the thermal analysis derives this data from the E+ weather data file (EPW).

3.1 Temperature results

In Figure 3, the results of the proposed method and the ones from DB are compared hour-by-hour. As it can be observed, the difference between the temperature results from DB and the average temperature of the sub-zones defined in the proposed method, is generally small (max 2°C). Moreover, it is clear that the general trend of the indoor temperature under natural ventilation conditions has convincing results. In Figure 4 the temperature distribution within the design case is compared to a CFD analysis done in DB. The boundary conditions (average indoor temperature, surface temperatures, airflow rate) were set as the ones retrieved from the E+ model. The comparison shows similarities in terms of temperature gradient. Temperature distribution of the upper part has slightly higher magnitude in the developed approach. The results, especially at the zone close to the inlet opening shows a good match with the CFD analysis.

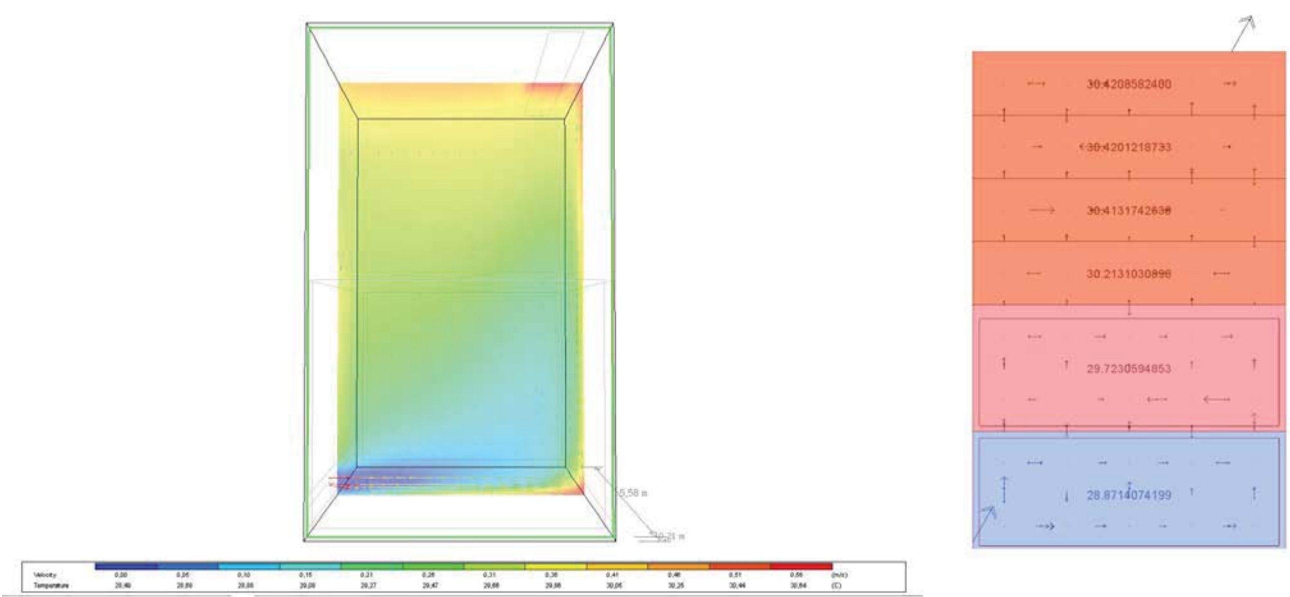

Figure 3. Left: CFD analysis done in the DB software. Right: Zone temperatures and airflow distribution with the developed approach.

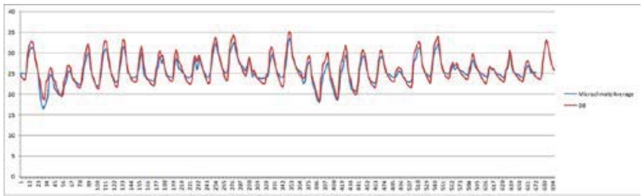

Figure 4. Average indoor temperature fluctuation for the simulated period (May). Red: DB results. Blue: Proposed process results.

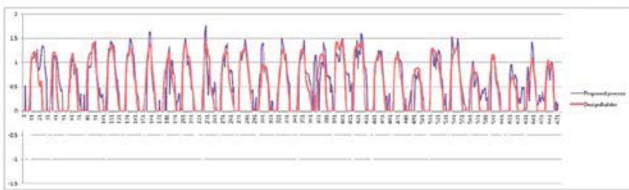

Figure 5. Total air flow rate within the indoor environment for the simulated period (May). Red: DB results. Blue: Proposed process results.

3.2 Airflow results

In terms of airflow simulation, the following graph shows the comparison of the total air mass entering and leaving the space (ach).

As for the temperature fluctuations, also the airflow rates can be comparable with the ones retrieved from DB. The overall behavior of the two methods generally has similar results, with small distances in some cases (max 0.4 ach).

However, at the detailed level, the flow pattern appears to have relatively greater distance from the CFD analysis, apart from the flow pattern at the ground level.

The main conclusion that can be derived from this comparison is that the proposed model is able up to a certain extent to predict the thermal behavior of the microclimate inside a large space, while not able to completely predict the airflow pattern (apart from a general trend). The reason behind this is that CONTAM does not take into account complex turbulence problems, which can however be accurately simulated by CFD.

More testing is needed to entirely assess the extent at which this approach can lead to reliable results to be used in early stage of design.

4 CASE STUDY

The method is being tested also on a real project (currently under detailed development) located in Guangzhou (China). This case study has been developed together with team from the State Key Lab of Subtropical Building Science, South China University of Technology and from Sun Yimin Studio. The case study is a building of the Jiangmen Sports Center, a large swimming pool that will be used for sport events of national level.

The idea of this test is to retrieve results from the analysis that can be used to improve the early design concept for natural ventilation and thermal comfort goals.

In this case, the relationship between building shape and ventilation opening size is investigated and the results analyzed.

4.1 Design concept

Indoor thermal comfort in sport buildings is a complex subject, depending on the level at which the building is used and on the related requirements that need to be satisfied. For high-level sport events, the most used strategy to deliver indoor air quality and thermal comfort is the use of mechanical systems for cooling, heating and ventilation. The main reason for this is the generally strict normative in terms of sport events and human comfort. However, the strategy adopted in this case study, is to improve the design in terms of passive climate control, in case of low level events (e.g. times during the year when the building is only used for small competitions and training). Passive cooling and passive ventilation would be an efficient way of delivering comfort for this type of occupancy level.

The main goal is to investigate the indoor microclimate in which both spectators and athletes would be standing, according to the specific (passive) design. The building, located in a hot and humid climate, is naturally ventilated during the day (from 8:00 to 20:00). Ventilation occurs thanks to the operable windows located on the sides and the operable skylights. All openings can be completely open for ventilation.

For this investigation, the number and size of operable skylights are the parameters that were set in order to investigate two different design proposals.

The main air displacement principle used in order to deliver natural ventilation is the stack effect, induced by the shape of the large roof.

In order to retrieve a faster feedback of the design efficiency, the simulated period was set as 31 days (month of May).

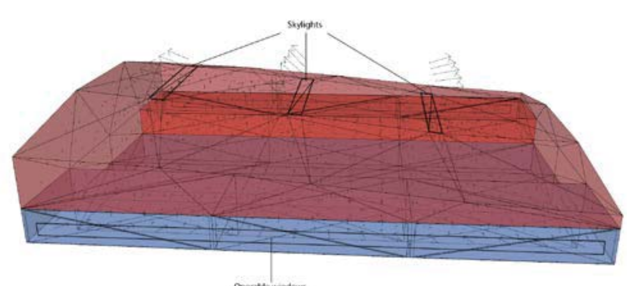

Figure 6 Ventilation openings on the side facades and roof.

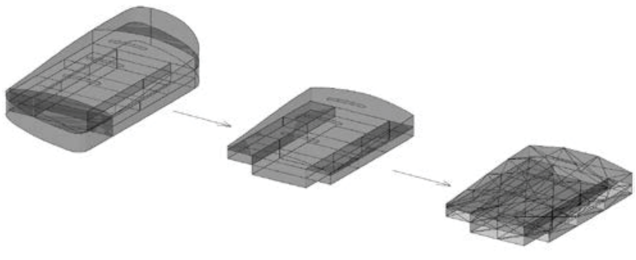

Figure 7 Thermal sub-zones division and meshing.

4.2 Model simplification

The building model (built in Rhino/GH) is simplified in order to have faster results for thermal analysis. The double curved geometry of the roof and the curved facades were meshed in a medium mesh size.

The building is divided in sub-zones for thermal analysis. Since the focus of this design exploration is the zones where spectators and athletes share the same space, and since the neighboring zones are not consistently affecting the energy balance of the main zones, the rest of the building was cut-out of the simulation (Figure 7). The surfaces shared with the excluded zones were set as adiabatic. The total number of mesh faces of the simulated zones is 245.

4.3 Results

The results of the investigation done on the case study are reviewed separately for the two simulated design options. In the investigated case study, the number of iterations used to achieve convergence was 6, as it was observed that no major changes (airflow rate and temperature values) would occur for the specific case after the 6^{th} iteration.

Design case 1

The first design configuration has 4 operable skylights and operable openings with height of 1.5m on both side facades. This first thermal and natural airflow analysis show an uneven distribution and potential differences in comfort levels within the large indoor volume.

As it can be observed in Figure 8, the zone close to the south façade (right side in figure) shows the highest temperature among all the zones. Generally, the sub-zones show high temperatures, especially considering the south zone and related thermal comfort level for the spectators.

The reason for this is the number of skylights and their dimensions, which allow for a large amount of solar radiation, causing local overheating. The buoyancy driven natural ventilation, entering the side facades and leaving at the top roof, is not sufficient at lowering the air temperatures in every zone, as it might be expected.

Design case 2

In this design option, the building shape and constructions are kept stable, while the number of skylights is decreased to 3 and their dimensions reduced by half. The total openable area of the roof is therefore also reduced by half, while the total ventilation openings at the sides are left unchanged.

As expected, the thermal distribution appears to be generally similar to the first case, with the south zone having higher temperatures than the others.

The airflow result (shown in Figure 9 with vector magnitude) shows a reduction of total mass flow rate. This is due to the decrease in gains, resulting in a lower pressure difference between the indoor and outdoor environments.

In this case, it might be expected that the overall air temperature would be increased because of a reduction of natural airflow rate (since the outdoor air temperature is at 28°C). However, the overall temperature levels are lower than the previous case (ca.1.5°C). This is mainly due to the reduction of the total skylights area, drastically reducing direct solar radiation.

5 DISCUSSION AND FUTURE WORK

The process has shown very promising results. Future research is required in order to completely verify the level at which the developed process can be used in early stage of design optimization and investigation.

A challenge to overcome is the limitations of the E+ software in calculating solar distribution with a high number of thermal zones. Beam solar radiation is transmitted as diffuse radiation only to the first zone, neighboring the zone with glazing on its external surfaces. Thermal analysis of the sub-zones is highly affected by the

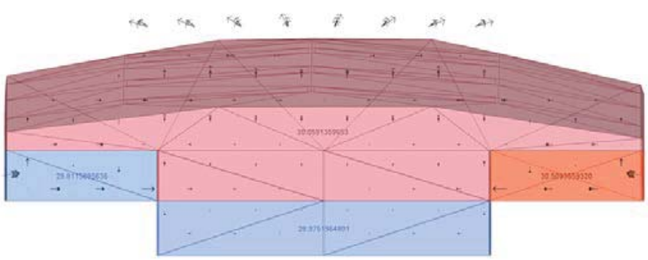

Figure 8 West elevation, thermal and airflow patterns for design case 1.

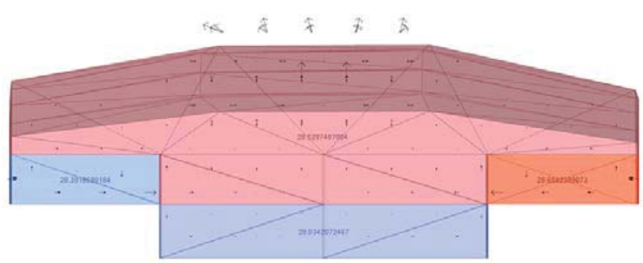

Figure 9 West elevation, thermal and airflow patterns for design case 1.

way solar radiation is distributed in the indoor environment. A possibility for this is to test ways of approximating thermal stratification in natural ventilated buildings. This solution would result in a higher level of detail for microclimate investigation and possibly in more convincing results, especially in terms of natural airflow pattern within a large indoor space.

As for the time being neglected, another possible implementation within the CONTAM software is the effect of façade wind pressure, which would lead to more accurate ventilation performance results.

Finally, more investigation needs to be done in order to better assess the way levels of simplification affect the model accuracy, in terms of thermal sub-zoning.

6 CONCLUSIONS

In the paper, a method has been presented for fast assessment of the indoor thermal environment in the early design stage, by coupling thermal analysis and airflow calculations. A validation of the method has been presented for a simple case. Moreover, the application of the method in a complex case study has been also presented. For both cases, the results have been discussed and future work has been addressed.

The research is currently under development and the results shown in this paper are only partially assessing such a developed computational method. However, it is possible to state that the results gathered so far show an interesting match in terms of overall thermal and total airflow behaviors, compared to a reliable commercial simulation software.

The case study shows that this type of simulation in early design stages can lead to higher future performance of buildings in terms of indoor microclimate. This is especially true when the design needs to satisfy different thermal conditions within the same space, such as in case of sport buildings.

Interesting to notice is the way this process can steer the design decisions in early stages towards unexpected solutions. This is shown in the application on the case study, where correlations between even simple design parameters leads to partially unexpected results that might not be directly foreseen by the designer.

Since the procedure is highly automated by a set of GH components, the developed approach can be reused for many different cases.

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