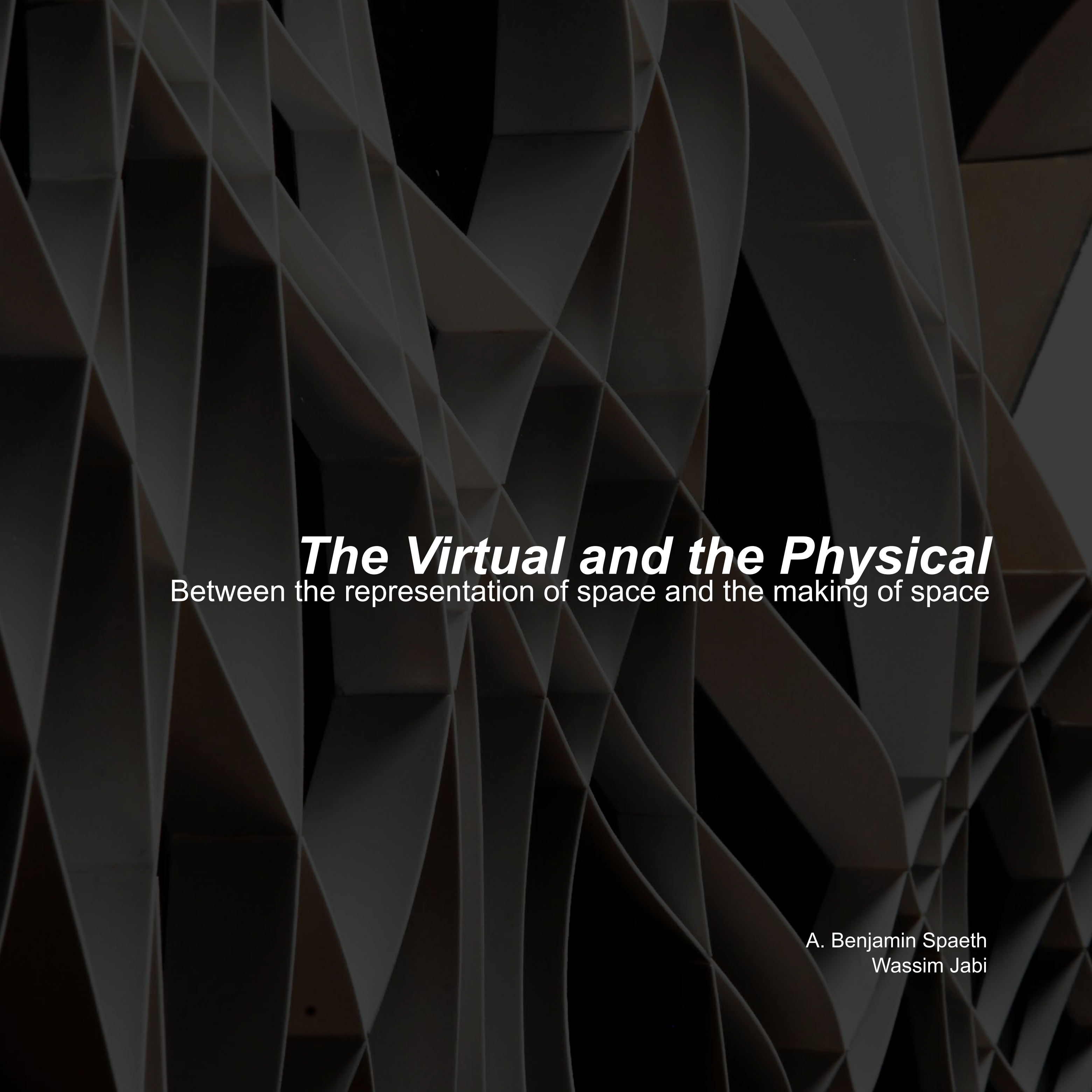

The Virtual and the Physical

Between the representation of space and the making of space

A. Benjamin Spaeth
Wassim Jabi

eCAADe RIS 2017

The Virtual and the Physical

Between the representation of space and the making of space

A. Benjamin Spaeth, Wassim Jabi

Welsh School of Architecture, Cardiff University, Wales, United Kingdom

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Proceedings of the 5th eCAADe Regional International Symposium

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Cardiff, Wales, United Kingdom

Edited by

Benjamin Spaeth
Wassim Jabi

The Virtual and the Physical

Between the representation of space and the making of space

The realm of computation in architecture extends from the virtual representation of space through to its physical making. Beyond the visualisation of space we are concerned with the different models of space to explore and uncover its relevant properties. At the symposium we explored the dimensions of space beyond its physical existence and tried to understand the implications of computation in architecture on social, political and environmental discourse.

At the other end of the spectrum computation in architecture seeks to optimise, automate and integrate effective methods and concepts into architectural production. Through biomimicry/biophilia and material computation, we explore alternative approaches to spatial construction. We are interested in the gravitational field between the aforementioned extreme ends of computation in architecture. At the symposium we intend to uncover how computation in design and fabrication influences our understanding of space and, reciprocally, how the computational representation of space impacts the production of architecture. We aim to reach to the extremes of the spectrum of architectural space to critically speculate about its creation in theory and practice.

We called for academic papers, practical work or design propositions that engage with the transition from the virtual to the physical, or vice versa and that explore the realm between the representation of space and the making of space. We are interested in how we represent architectural space and its manifold diversity of social interactions, economic determination, environmental impacts, functional requirements and spatial quality to make it available and impactful on computational design processes.

Some questions include: How does architectural space manifest itself in built shape and solid form? How do we represent non-geometrical parameters to find their role in the design process? How do we account for spatial quality to be sustained during computational design procedures? Where do we integrate potential social interaction and functional interconnection in the various design systems? What are the driving forces of architectural design computing?

Apparently these questions exist in academia but they are increasingly infiltrating architectural practice. The question of what and how and who is influencing and controlling the design process is increasingly pressurising the practicing architect. Is the academic promise of computationally-driven design really viable in practice? Is robotic fabrication an alternative way for mass customising building elements in a cost-effective way? How is virtual reality supportive in the daily design routine of architectural practices? What are some of the viable procedures to transform the virtual representation of space into the physical space of a building? What material properties impact the fabrication process and become manifest in the design system?

Evidently the advances in integrating computation into architectural design and production has a vast influence on how we educate future architects at our universities. We are interested in how education has changed. We want to discuss how methods of learning and teaching have changed, what content has been added to curricula and what impact this might have had – and will have - on the understanding of pedagogy, architecture and computation.

A. Benjamin Spaeth
Wassim Jabi

Acknowledgments

We, the organisers of the 5th eCAADe Regional International Symposium (RIS2017), are grateful to the many helping hands who made it possible for us to bring people for different parts of the world together at the Welsh School of Architecture (WSA) in Cardiff to share and discuss their latest research in computational architecture and design.

We want to thank Joachim Kieferle, President of the eCAADe, for trusting the organisation of the RIS2017 to us at the WSA. The intellectual and practical support by Jose Manuel Pinto Duarte, Bob Martens, Henri Achten and Nele de Meyere was greatly appreciated.

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Among the many people at WSA who supported the RIS2017, we want to mention Alicia Nahmad Vazquez for her indefatigable engagement: initialising, organising and coordinating the “Frictional Assemblies” workshop.

Last but not least we want to thank the eCAADe for providing basic funding for the symposium. Without the financial support this symposium would not have been possible.

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Contents

3 **Spatial Representation**

5 **Graphical Representation of Sonic Urban Morphologies**
Merate A. Barakat

15 **FEEL YOUR DESIGN**
Maria da Piedade Ferreira, Andreas Kretzer, José Pinto Duarte, Didier Stricker, Benjamin Schenkenberger, Markus Weber, Takumi Toyama

23 **Open Virtual Reality**
Valentin Dolhan, Huda S. Salman

33 **Computational Thinking**

35 **Qualitative Representation and Spatial Reasoning in a Rule-Based Computational Design Model**
Amer Al-Jokhadar, Wassim Jabi

45 **Computation in Architecture**
Werner Lonsing

55 **Digitizing the Unexplored**
Sema Alacam, Orkan Zeynel Guzelci

63 **Building Performance Computation**

65 **Architectural space quality, from virtual to physical**
Aida Siala, Najla Allani, Gilles Halin, Mohamed Bouattour

73 **Architects' use of tools for low energy building design**
Gabriela Zapata-Lancaster

83 **Investigating Spatial Configurations of Skycourts as Buffer Zones in High-Rise Office Buildings**
Saba Alnusairat, Shan Shan Hou, Phil Jones

93 **Computational Fabrication**

95 **A robotically-driven additive construction planning process using an ecological material**
Odysseas Kontovourkis, Philippos Michael

105 **Before and After NURBS**
Serenay Elmas, Erenalp Saltik

115 **Visual Thinking Through Model Making**
Andrew N.J. McDonagh, Huda S. Salman

125 **Modular Mycelia**
Sean Campbell, David Correa, Dylan Wood, Achim Menges

Investigating Spatial Configurations of Skycourts as Buffer Zones in High-Rise Office Buildings

Coupling building energy simulation (BES) and computational fluid dynamic (CFD)

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Skycourts are attracting widespread interest in the contemporary construction of high-rise commercial buildings. Due to their remarkable function as public realms and transitional nodes, those spaces could introduce alternatives to the vernacular courtyards/atriums in high-rise buildings. This paper outlines the methodology that was adopted to examine the performance of basic spatial configurations of skycourt in high-rise office buildings in a temperate climate. Significantly, these areas accomplished as buffer zones that are non-ventilated and unheated while accommodating combined ventilation strategy. The study is processed via coupled simulation between a building energy simulation (BES) and a computational fluid dynamic (CFD). The developed coupling approach aims to improve the prediction for skycourt performance that is essential for the assessment of thermal comfort conditions and energy consumption. Results to nominate the optimum spatial configuration of skycourt along the vertical section of the high-rise office buildings are discussed briefly. However, the focus is on the methodology.

Keywords: *Skycourt, Spatial Configuration, Coupling Simulation, Thermal Comfort, Energy Efficiency*

INTRODUCTION

The skycourt, by its various configurations, is recognised as communal areas in high-rise commercial buildings, established from the concept of the courtyards in low-rise buildings. They function as public social void spaces which can provide leisure; wellbeing for workers, obvious connections and social interaction as hubs. They could perform such as areas for circulation and transition. Moreover, they could perform as buffer zones between the indoor and the outdoor thus could mediate the climate conditions, provide thermal and acoustic protection to the interior and reduce heat loss. Furthermore, skycourt can offer a contemporary alternative to the vernacular courtyard or atrium in high-rise buildings due to its potential to allow natural light and ventilation to enter deeper into the interior of the high-rise building and avoid unwanted solar gain (Goncalves and Umakoshi, 2010; Pomeroy, 2008, 2007; Yeang, 1999).

Therefore, these areas could play a promising role in conserving energy and improving the thermal comfort for buildings (Alnusairat and Elsharkawy, 2015; Pomeroy, 2014). The perspectives of obtaining significant reductions in energy consumption besides enhancing the thermal comfort of users in these areas are considered in this study. The paper is part of research seeks to investigate the energy saving potentials associated with the modification of the skycourt design. This objective could be achieved by demonstrating skycourt as an integrated buffer element in high-rise office buildings and exploring its consequence on reducing demand for heating and cooling, besides potential advantages on occupants' thermal comfort at the skycourt, in temperate climates such as London.

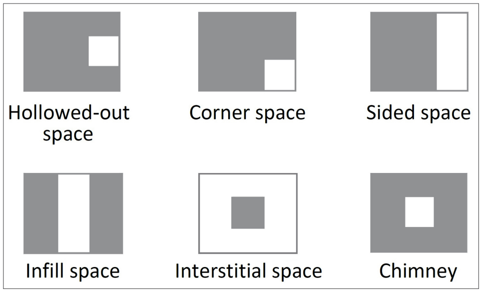


Figure 1
Diagrams for the spatial configuration of skycourt in high-rise office buildings (the white coloured zone represents the skycourt)

Skycourt may be classified on the basis of position in the midst of the high-rise building into sky-entrance, sky-terrace, sky-court and sky-roof. The sky-entrance is the open or void space located at the lower floor(s), whereas the sky-roof is located at the top of the building. The sky court is the open or void space between floors, and finally, the sky-terrace is the space located at the corner(s) of the building. These spaces are two or more floors height linked directly with the surrounding indoor and outdoor areas by open walls or indirectly through enclosed walls.

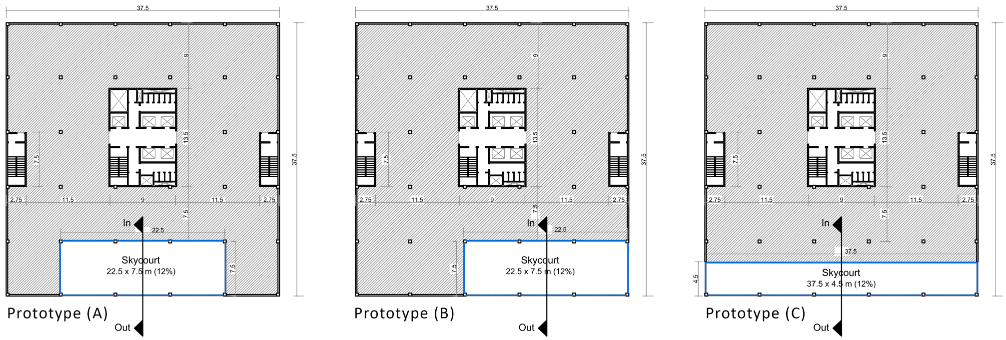
However, the space configuration or form geometry of skycourt can be divided into several prototypes: hollowed-out space, corner space, sided space, infill space, interstitial space and chimney space (Pomeroy, 2014). See figure 1. This paper focuses on the first three configurations because these spaces are widely constructed in the study context. Also, these configurations reveal useful models to test the research's hypothesis that skycourt could function as a buffer zone that is non-ventilated and unheated space intermediate between the inside -the office zones that combined controlled air temperature- and the outside- the external environment-. These glazed void areas could be connected with the outdoor by one edge, two edges and three edges. See figure 2. The hollowed-out prototype (A) represents the one edge connection. The corner prototype (B) displays the two edges connection and finally the three edges connection illustrated by the sided prototype (C).

COUPLING STRATEGY: BUILDING ENERGY SIMULATION (BES) AND COMPUTATIONAL FLUID DYNAMIC (CFD)

A large and growing body of literature has argued that simulation plays an important role as an intermediate point of knowledge for developing design solutions in construction. It is a useful technique for developing and testing theory, in addition, it could be used as a design tool for generating design alternatives, predicting performance and defining the optimum solution that improves performance. This technique could be conducted for analysing the effect of space(s), the system(s) or device(s) at several scales to inform more details (Groat and Wang, 2013).

However, methods for modelling the ambient conditions concerned for investigating thermal comfort, air containment and energy efficiency could be divided into two groups: physical models and numerical models. These differ in the base of modelling techniques and level of details for the input data. The physical (reduced scale) models could represent or reproduce the characteristics of the full-scale physical context or system, such as materials and products that are readily manipulated by exper-

Figure 2
The spatial configurations of skycourt (the white shaded zone) floor plans considered in the study: (A) hollowed-out, (B) corner, and (C) sided prototypes



imenters and difficult to be obtained in full scale. On the other hand, numerical (mathematical) models are recommended when dealing with questions of scale and complexity. These use numerical approximation to predict the thermal, airflow performance inside and outside the buildings, and energy consumption, in various constructions such as atrium and glazed buildings due to cost-effective and efficiency (Wang and Wong, 2008). In this model, mathematical problems are formulated so that they can be solved with fundamental arithmetic equations of heat transfer and fluid dynamics (Prajongsan and Sharples, 2012). However, the most powerful modelling is the computer simulation, which offers a useful tactical tool that could produce a large body of accurate information in short periods for determining the thermal and energy performance (Ali and Armstrong, 2008; Groat and Wang, 2013). Computer programs could replicate the real-world contexts or events (''virtual world'') for the purpose of studying dynamic interaction (''synthetic elements'') that resulted of manipulated factors within the setting (Groat and Wang 2013). Therefore, numerical simulation model technique was selected to investigate the thermal, air performance inside the skycourt, and encounter the most affordable spatial configuration of skycourts in high-rise office buildings.

Recently, the new direction of building thermal and energy simulation has been established is in which, two models could be interrelated. This method is known as the "coupling models" that is widely used in ventilation studies. Simulation methods in the construction are classified into two major modules: the building energy simulation and the airflow method. In recent years, many literature has recognised the Computational Fluid Dynamics (CFD) as the most accurate and detailed model among the airflow models (Zhai and Yan, 2003). Barbason and Reiter (2014) concluded from reviewing several simulation studies that computational fluid dynamics simulation has been accepted as an appropriate simulation to investigate all kinds of aero-thermal phenomena in buildings. For example, it can predict the full distribution of air velocity, air temperature and air quality. In addition, it can inform the performance of both the natural and mechanical ventilation, the contaminant dispersion, the internal and external airflow, and the heat islands. Moreover, CFD is sophisticated for the current architectural style, which characterised by glazed facades and atrium configurations (Barbason and Reiter, 2014). On the other hand, fully CFD simulation requires long calculation times. Further, airflow models require thermal and flow boundary conditions that can be obtained from the BES (Zhai and Yan, 2003). CFD stands on numerical techniques to solve the equations for the fluid flow, the mass of containment species, the thermal comfort and indoor air quality analysis. It can solve the equations by dividing the spatial continuum into cells among grid, which requires iterations to achieve a converged solution (Zhai et al., 2002). In contrast, the Building Energy Simulation (BES) stands on the principles of energy (heat) balance equations that considers the internal heat transfer between the space air and surface. These include energy balance equations for a space air, for a surface (e.g. wall and window) and for the radiative heat flux (Zhai et al. 2002). Therefore, BES could provide thermal, energy analysis for the whole building and the HVAC systems. The output of this simulation includes mean (average) air temperature, heating, cooling, ventilation, solar gain, fabric and incidental loads. BES could be obtained on an hourly basis for the whole year. Unfortunately, this type of simulation assumes air as well-mixed. Therefore, it is unable to provide detailed predictions of the spaces' indoor air properties such as the distributions of air velocity and temperature, the relative humidity and the contaminant concentrations (Zhai et al. 2002; Zhai and Yan 2003). Therefore, it is argued that integrating BES and CFD together can produce complementary information for the energy consumption and the indoor thermal comfort for buildings. Furthermore, it is agreed that the coupled simulation can predict more accurate, detailed and quick results compared to the separate simulation (Barbason and Reiter, 2014; John and Yan, 2005; Wang and Wong, 2008; Zhai et al., 2002; Zhai and Yan, 2003). The coupling approach stands on providing the interior surface temperatures and the heat extraction rate that are obtained from BES to the CFD model so the airflow simulation could calculate specific air thermal conditions (Zhai et al. 2002). Therefore, the CFD model can receive more exact and real-time internal thermal conditions thus can predict the dynamic indoor thermal conditions. This significance is essential for the assessment of indoor air quality and thermal comfort. Moreover, the BES can obtain more accurate convection heat transfer coefficient from the boundary envelope. This process produces a more precise calculation of energy demand and full thermal behaviours of the building enclosure (John and Yan 2005). In addition, using this mechanism of integration can eliminate few assumptions that handled via each separate application, reduce the computation time of CFD (Wang and Wong, 2009; Zhai and Yan, 2003).

There are two major approaches for coupling thermal and CFD simulation to reduce computing time-cost: the static coupling and the dynamic coupling. However, Zhai et al. (2002) distinguished a third key strategy for coupling simulation. That is the bin coupling. The static coupling process includes one-step or two-step data exchange between BES and CFD programs. The process can be performed manually with a few coupling iterations and does not require hard modifications of individual ES and CFD programs. While, the dynamic coupling process requires continuous coupling between the BES and the CFD at each time step. This method may occur in one-time step, quasi-dynamic or full-dynamic. The one-time-step focuses on the coupling at one specific time step of interest. At that point step, the iteration between ES and CFD is carried out to reach a converged solution. However, coupling might happen without iteration at each time step in a period such as in the quasi-dynamic. That is the CFD simulation obtains the boundary conditions from the previous BES calculation at the specific time step, then returns the thermal information of indoor air to BES of the next time step. The full dynamic coupling involves iteration between BES and CFD to reach a converged solution at each coupling time step before moving on to the next step. In the bin coupling process, the BES receives info that is pre-calculated by the CFD and saved it in the bins to be used for subsequent energy computation (Zhai et al. 2002).

Generally, the approaches of exchanging data between the BES and the CFD modules may be classified depending on the type of data transfer into three methods. In the first method, the indoor surface temperatures transfer from BES to CFD, then convective heat coefficient and indoor air temperature from CFD to BES. The second approach considers transferring indoor surface temperature from BES to CFD and then convective heat flux from CFD to BES. The third method includes transferring interior convective heat flux from BES to CFD and then returns convective heat coefficient and indoor air temperature gradients from CFD to BES. Method one is considered the most appropriate one due to its stability. However, method two is the most expensive one since it requires explicit in BES and implicit in CFD. Whereas, method three is not recommended since it is unable to control air temperature (John and Yan, 2005; Zhai and Yan, 2003).

The next section describes the coupling simulation approach that is adopted in the study.

INTEGRATING HTB2 AND WIN AIR FOR THE SKYCOURT ANALYSIS

HTB2 and WinAir are used in this study. The HTB2 software version 10 is used to inform the thermal performance and energy efficiency while WinAir Version 4 is adopted as a CFD simulation to inform the ventilation performance inside the skycourt. The input data required for the HTB2 comprises information of both the regional climate data and the building, including info regarding the building size, construction materials, small power, building services (heating, lighting, ventilation and occupancy) during the occupation and avocation periods and the diary of application. The output data includes thermal conditions represented by air temperature, air humidity, mean radiant temperature, element surface temperature, and mean surface temperature. Furthermore, energy performance embodied by space gains and losses from heating, cooling, incidental, solar, ventilation and fabric loads. The output information could be in the form of power (W) or energy (kWh). This information could be based on the hourly, daily, monthly or yearly database. On the other hand, the WinAir software requires knowledge of the building size, inflow and outflow rate in case of fixed flow rates (mechanical ventilation), pressure boundaries in case of varying flow rates (openings -natural ventilation), internal heat gain and heat loss and pollutant conditions in the event of source of contaminants. See figure 3. The climatic data considers specific time at the specific date. The study investigates the performance of skycourt in summer, winter and transitional seasons emplacing the hottest hour, the coldest hour and mid-temperature hour. The output data comprises graduating information of air temperature, air velocity and air concentration showing the airflow pattern.

The paper aims to predict the indoor air temperature, and the air velocity at the occupancy level of the skycourt under the assumption that these zones are buffer areas do not consume energy for heating neither cooling. However, constant air supply that exhausts from the adjacent offices' zones is assumed to modify the internal environment of the skycourt. Similar conditions are conducted for the three spatial configurations to perform the fair comparison. External coupling is adopted in this study to ensure accurate prediction of the indoor environment for the skycourt, and to eliminate time cost. Therefore, two models should be built separately in the HTB2 and the WinAir. A schematic model was developed in the energy simulation to predict the thermal conditions inside the skycourt space and the energy consumption for heating, cooling and ventilation, considering that the skycourt space consists of three zones; lower, middle and upper zone. Furthermore, a grid model was built in the WinAir to investigate in details the airflow phenomena - air temperature and velocity. Data exchange for boundary conditions is needed to bridge the two programs. The static coupling strategy is chosen to couple the two simulations. The thermal conditions for the CFD (WinAir) simulations are obtained from previously calculated values from the energy modelling software HTB2. These include the surfaces' heat transfer, the inlet -air supply, the outlet -air exhaust and the internal heat gains involved inside the skycourt. Then, the resulted temperature from the CFD simulation was compared with the average skycourt temperature from the BES to find the predicted temperature difference. The temperature difference was small (approximately 1° C). That little difference is usually accepted for venti-

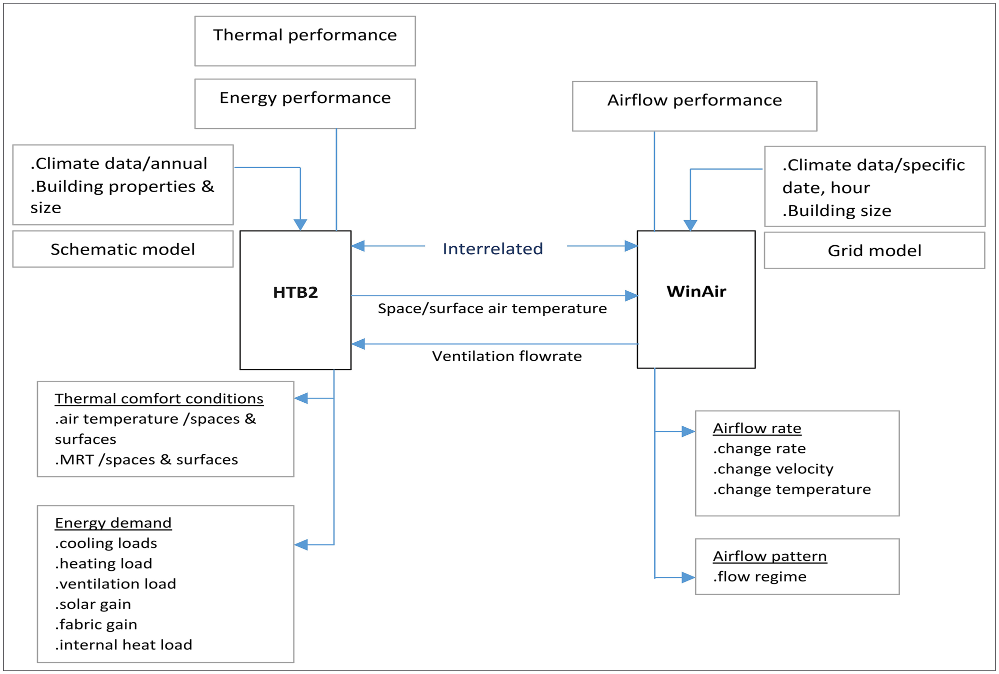


Figure 3
Diagram shows the HTB2 and WinAir coupling models

lation cases to continue the simulation for the next time step (Wang and Wong 2008). Therefore, one-step data exchange was adopted in the study.

RESULTS AND COMPARATIVE ANALYSIS

Results from the energy simulation for the annual energy demand for heating and cooling the buildings are represented in Figure 4. The difference of energy demand for heating and cooling in the building between the selected prototypes is small. Detailed monthly heating, cooling, solar, fabric, ventilation and power loads for the skycourts are shown in Figure 5.

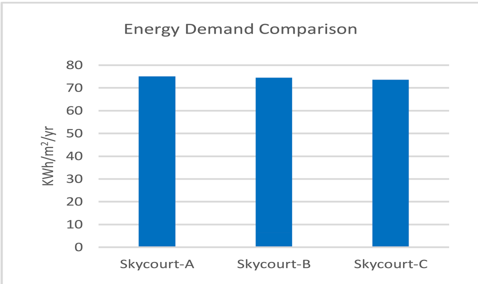


Figure 4
Results from BES of annual energy demand for heating and cooling for the buildings

Figure 6 provides an overview of the thermal conditions including air temperature, mean radiant temperature and the external air temperature, further, it presents the heating, cooling, ventilation, incidental, solar and fabric loads at the lower zone of the skycourt in the hottest week in summer for the three prototypes (A), (B) and (C).

Figure 5
Results from BES of monthly heating, cooling, solar, fabric, ventilation and power loads for skycourts

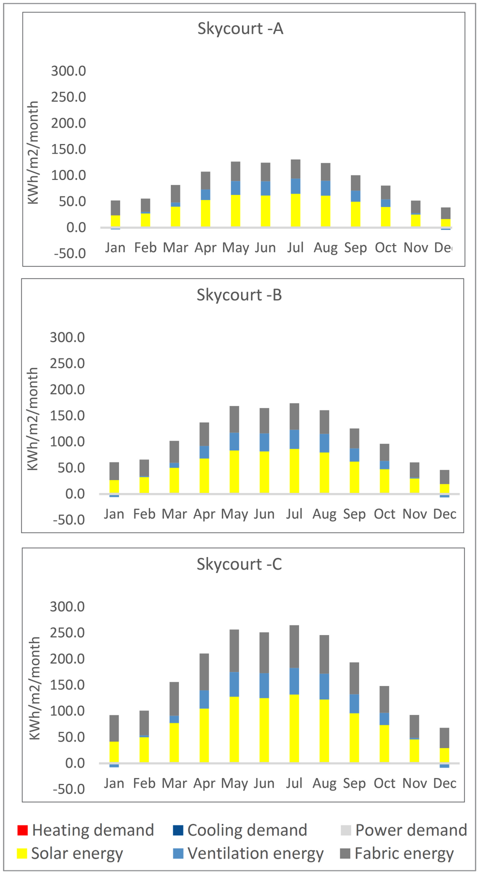


Figure 7 illustrates the specific gradient thermal conditions -air temperature and air velocity obtained from the CFD simulation for one case simulation at 14.00, 28 June.

The results from the BES and CFD simulation are highlighted in Table 1. It is apparent from this table that CFD simulation can provide accurate information at the occupancy level of the skycourt related to the comparison criteria, while the BES provides an average temperature for the whole skycourt space. The table shows that there is a small temperature difference (nearly 1 ° C) between the two models. This provides strong evidence of the efficiency of integrating both the HTB2 and the WinAir programmes. Overall, the results indicate that skycourt prototype A is the best among the three prototypes in terms of thermal comfort- air temperature and air velocity and energy consumption reduction for the building.

CONCLUSIONS

The paper has described a method to explore the thermal performance and the energy consumption of several spatial configurations of skycourt in high-rise office buildings in a temperate climate. The coupling simulation system of integrating BES and CFD is recommended for studies that examine the thermal performance of spaces in details at specific zones within the whole space. Significantly, studies that use simulation as a design tool. It can be seen from the simulation results that the method shows efficiency to study the thermal conditions at the skycourt space. Therefore, this approach could be applied to investigate spaces that are humongous and tall such as skycourt, atriums, courtyards and plazas. However, to further improve the accuracy of the results, segmentation of the skycourt space in the BES model into more than one space to obtain more specific results to feed to the CFD model is recommended.

It is anticipated that the coupling of HTB2 and WinAir programmes produce minimum temperature difference (nearly 1 ° C). This result acknowledges the corresponding and compatibility between the two programmes. Therefore, the technique described in this paper to couple HTB2 and WinAir programmes could be applied to predicting the indoor environment of other spaces.

The comparison between the three spatial configurations of skycourt (A, B and C) regarding thermal comfort -air temperature and air velocity- and energy loads shows that prototype A is the recommended configuration.

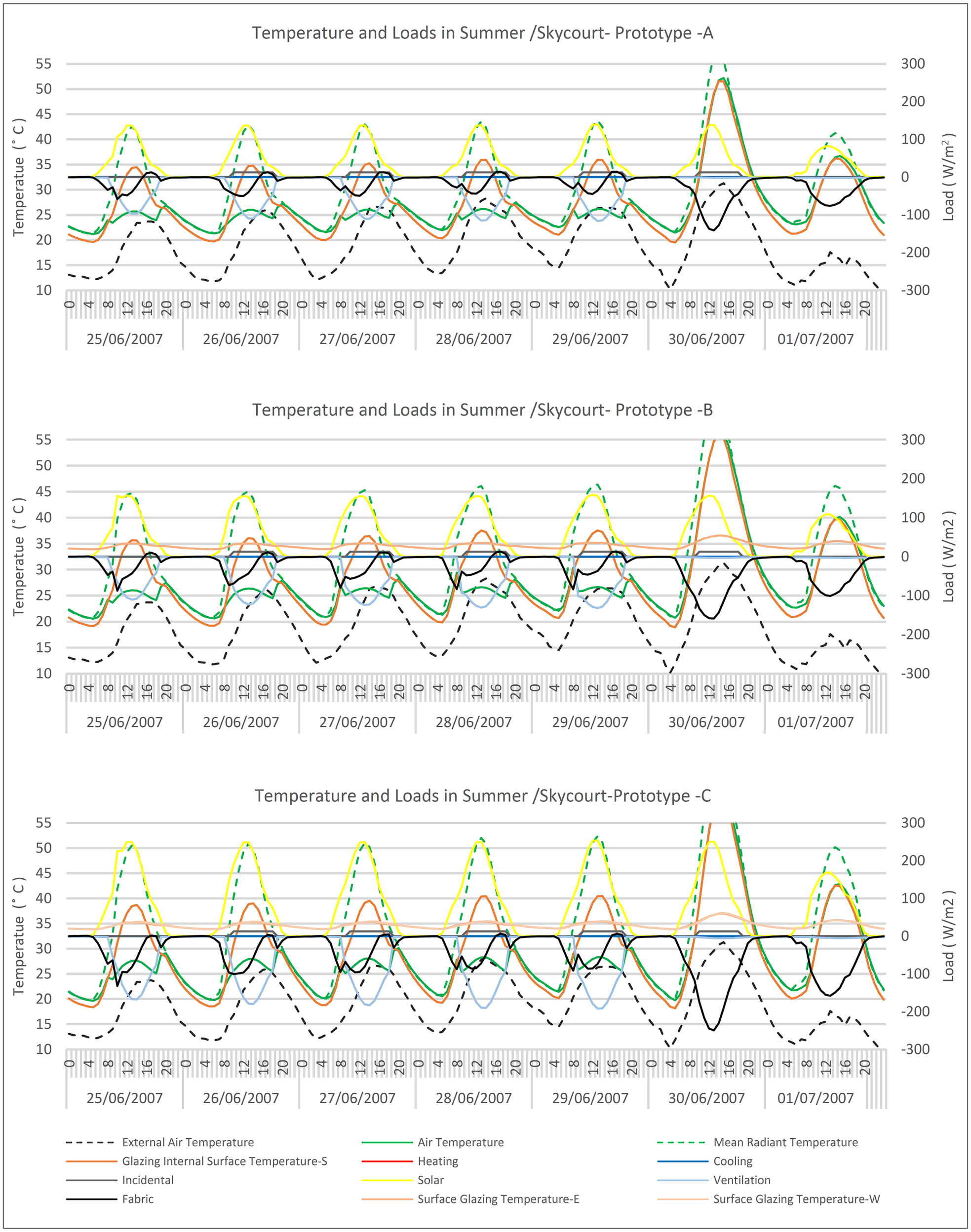


Figure 6
Results from the BES of thermal conditions and loads in skycourt -A, B and C models at summer

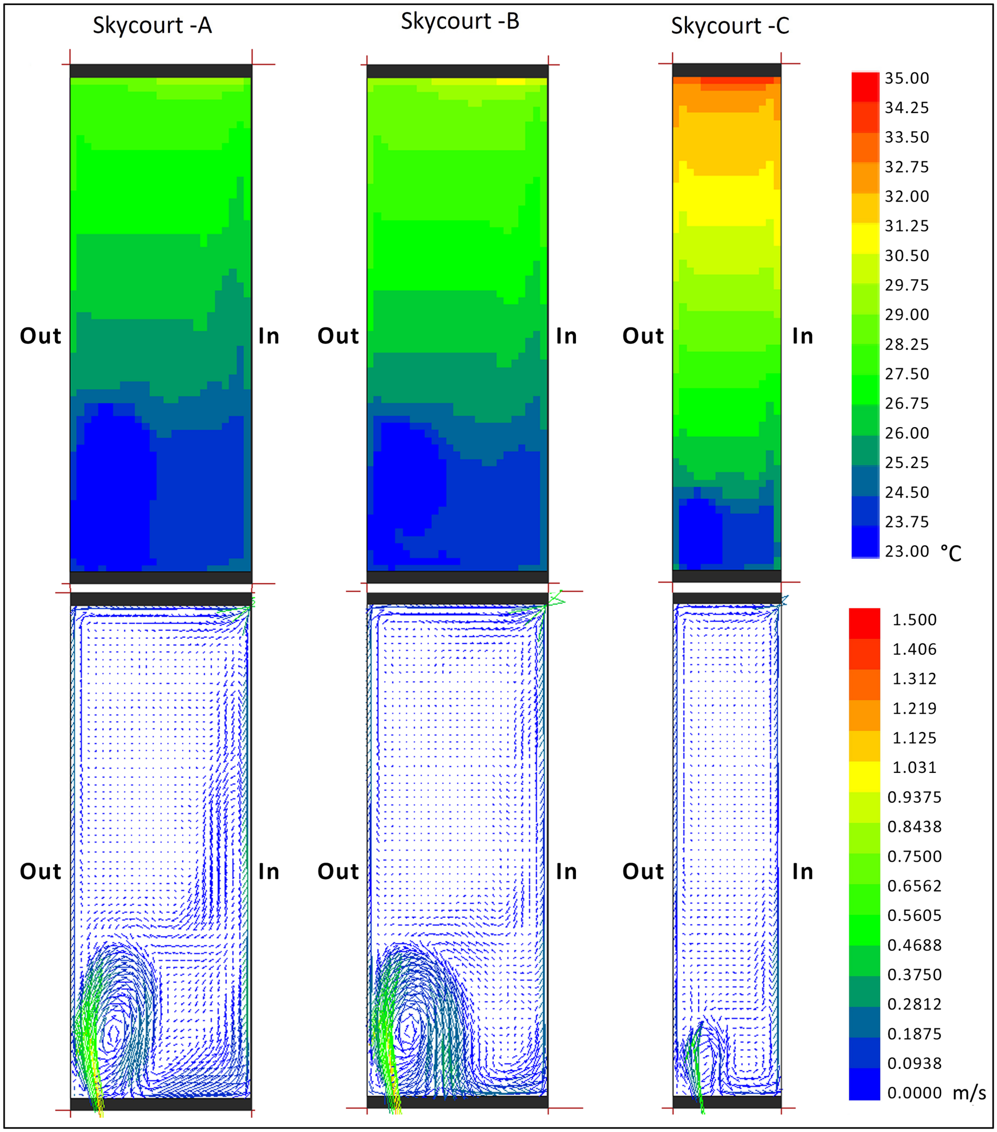


Figure 7
Results from CFD of the thermal conditions -air temperature gradient (° C) and air velocity (m/s) in skycourt -A, B and C models at 14.00, 28 June, summer, External air temperature is 28.3° C, RH is 42%. Location of cross sections is shown in figure 2

Skycourt	Simulation	Air temperature (° C)	Airspeed (m/s)	Air temperature (° C) at occupancy level*	Airspeed (m/s) at occupancy level
Simulation at hot day at summer/ 28 June –14.00, external air temperature: 28.3° C, RH: 42%					
A	BES	27.8	-	-	-
	CFD	23.0-30.2	0.114	23.0-26.0	0.20
B	BES	28.4	-	-	-
	CFD	23.0-31.5	0.114	23.0-27.0	0.22
C	BES	31.0	-	-	-
	CFD	23.0-35.0	0.066	23.0-27.7	0.15
Simulation at cold day at winter/ 7 December –09.00am, external air temperature: -5.1° C, RH: 95%					
A	BES	14.7	-	-	-
	CFD	13.4-19.0	0.323	14.0-19.0	0.34
B	BES	14.1	-	-	-
	CFD	11.6-18.9	0.336	12.5-19.0	0.35
C	BES	12.8	-	-	-
	CFD	11.1-18.8	0.436	11.0-18.8	0.51
Simulation at typical day at spring/ 19 April –09.00am, external air temperature: 13.2° C, RH: 91%					
A	BES	20.5	-	-	-
	CFD	20.0-21.6	0.198	20.0-20.7	0.17
B	BES	20.7	-	-	-
	CFD	20.0-22.2	0.191	20.0-20.9	0.18
C	BES	21.0	-	-	-
	CFD	20.0-22.5	0.094	20.0-21.0	0.13

Table 1
Summary of coupling results from BES and CFD

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REFERENCES

Ali, Mir M. and Armstrong School, Paul J. 2008 'Overview of Sustainable Design Factors in High-Rise Buildings Mir', *Proceedings of CTBUH 8th World Congress*, Dubai

Alnusairat, Saba and Elsharkawy, Heba 2015 'Passive design approach for high-rise buildings: from courtyards to skycourts', *Proceedings of ZEMCH 2015 International Conference*, Lecce , Italy, pp. 739-748

Barbason, Mathieu and Reiter, Sigrid 2014, 'Coupling building energy simulation and computational fluid dynamics: Application to a two-storey house in a temperate climate', *Building and Environment*, 75, pp. 30-39

Goncalves, Joana Carla Soares and Umakoshi, Erica Mitie 2010, *The Environmental Performance of Tall Buildings*, Earthscan

Groat, Linda and Wang, David 2013, *Architectural Research Methods*, John Wiley & Sons

Pomeroy, Jason 2007, 'The sky court - A viable alternative civic space for the 21st century?', *CTBUH Journal*, Fall 2007, pp. 14-19

Pomeroy, Jason 2014, *The Skycourt and Skygarden: Greening the urban habitat*, Routledge

Pomeroy„ Jason 2008 'Sky Courts as Transitional Space: Using Space Syntax as a Predictive Theory', *Proceedings of CTBUH 8th World Congress*, Dubai

Prajongsan, Pimolsiri and Sharples, Steve 2012, 'Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts', *Building and Environment*, 50, pp. 104-113

Wang, Liping and Wong, Nyuk Hien 2008, 'Coupled simulations for naturally ventilated residential buildings', *Automation in Construction*, 17, pp. 386-398

Yeang, Ken 1999, *The Green Skyscraper: The Basis for Designing Sustainable Intensive Buildings*, Prestel

Zhai, Zhiqiang 2003, 'Solution characters of iterative coupling between energy simulation and CFD progrms', *Building and Environment*, 35, pp. 493-505

Zhai, Zhiqiang John and Chen, Qingyan Yan 2005, 'Performance of coupled building energy and CFD simulations', *Energy and Buildings*, 37, pp. 333-344

Zhai, Zhiqiang, Chena, Qingyan, Haves, Philip and Klems, Joseph H. 2002, 'On approaches to couple energy simulation and computational ?uid dynamics programs Zhiqiang', *Building and Environment*, 37, pp. 857-864