Environmental thermal impact assessment of regenerated urban form: A case study in Sheffield

Mohammad Fahmy[1,*], Abigail Hathway[2], Laurence Pattacini [3], Amr Elwan [1, 4]

[1] *Military Technical Collage, Department of Architecture, Cairo, Egypt*
[2] *University of Sheffield, Department of Civil Engineering, Sheffield, UK*
[3] *University of Sheffield, Department of Landscape, Sheffield, UK*
[4] *University of Sheffield, School of Architecture, Sheffield, UK*
** Corresponding author. Tel: + (202)2 40 29 382, Fax: + (202)2 26 21 908, E-mail: md.fahmy@live.com*

Abstract: Urban comfort is becoming increasingly important due to climate change, increasing population and urbanization. Greater use of mechanical cooling is not reasonable due to consuming more energy, discharging anthropogenic heat and CO_2 emissions which all can be minimized by passive strategies. As part of the EPSRC funded project Urban River Corridors and Sustainable Living Agendas, URSULA, two radically different urban regenerations for a site in Sheffield were passively designed and had to be microclimatically assessed upon their thermal impacts. Passive design strategy for the first is wind tunneling and solar shelter effects owed to compact form that provides river bank access by perpendicular streets. The second, park option, offers space for the river to flood into a green channel which provides evaporative cooling. Simulations using ENVI-met BETA4 applied four receptors to record different meteorology and the pedestrian comfort in terms of Predicted Mean Vote, PMV. The increased green coverage showed horizontal shifting of about 0.2 with 2h of urban time lag in PMV records from 14.00-16.00LST in some places. Results give advantage for the park option design but needs more emphasize on indoor performance.

Keywords: *Thermal impact assessment, urban thermal mass, urban time lag, urban regeneration*

1. Introduction

Temperature increases due to climate change are further exasperated within urban areas due to hard urban surfaces, reduced porosity, and deep canyons preventing radiation release and ventilation [1-4]. Careful design of urban form and the use of green infrastructure can mitigate this effect [5]; many studies showed the benefits of vegetation such as trees [6-9] and Parks [10-13]. However there are often many other, sometimes competing, drivers which affect the design of our urban forms. Urban forms are the fabric of a site along with its network and vegetation. From these standing points, a statistical study in Sheffield presented the distances to the nearest green node which is followed by the biometeorological green structure study, GreenSect, to confine UHI effects [14] by the application of park cooling island effect, PCI [15]. In this study, microclimate effects of two radically different urban form designs for one site in Sheffield took place as part of URSULA project. Site is located near the centre of Sheffield, in the temperate UK climate. Although the city is having high levels of vegetation it showed an UHI of 2C on a spring day [16]; with the potential for greater, and more frequent heat waves. Site is approximately 1.2 hectares (c.300mx400m) adjacent to the river Don. The riverside location offers recreational benefits, but also presents a high risk of flooding and the rationales for two urban form designs for this site have been developed in relation with these two issues. The first design alternative has been developed to facilitate and enhance access to the river, through the use of streets running perpendicular to the bank. On the river front the buildings have been stepped back from the river to create new urban squares looking onto the river, and also to reduce the risk of high wind speeds [17]. The streets are designed to a similar scale to the surrounding existing infrastructure and the open spaces have an urban character with hard landscape treatment and urban trees. In the second design the main objective is to make space for water as an adaptation method for present day climate change symptoms. As the risk of flooding was the initial driver, a channel for flood water has been created through the middle of the site. In order to avoid obstruction when it floods, the channel is treated as a meadow planted with only grass and reeds. This long continuous open space is expected to provide cooling effect according to the principle that park land provides cooling up to approximately 300m from the park [7, 18- 20]. The two radically different proposals are designed also differently from passive strategies' point of view. Passive urban form design is believed to affect indoor energy consumption and thermal performance so that energy supplies can be minimized [3, 4, 7, 9]. As the main objective of passive design is to minimize indoor heat gain/loss so that energy is saved, first design case, C1 provide cooling/heating by compact form tunneling and thermal mass effects. The second design case, C2 provide evaporative cooling in summer by the more vegetated area. With respect to URSULA concerns about heat waves and floods in summer, the study was then to find which of both alternatives have the better thermal impact in comparison to their existing urban form.

2. Methodology

Methodology is composed of two steps; first, urban climate conditions of each case is simulated to have meteorological plots at same certain points in each case. Second, average outdoor meteorology for each case is calculated to ensure results from receptors as well as validating the averaging methodology and tool.

2.1. Method

Numerical simulations using ENVI-met were applied for its easy and few data entries as well as the understanding of urban climate it gives [21]. ENVI-met simulates the surface-plant-air interactions with a resolution of 0.5 to 10 m in space and 10 sec in time from microclimate to local climate scale using the fundamentals of thermodynamics and heat transfer as a CFD package [22, 23]. The model formatted on a number of on sub-models to model and analyze surface-plant-soil-air relations, its 3.1 version is validated for radiation and RH and still have limitations [9, 21]. The software is relevant to this study as it assesses the outdoor thermal performance in terms of different meteorological outputs along with pedestrian comfort levels using the modified Predicted Mean Vote, PMV following the work of Jendritzky [24-26]. ENVI-met gives results in terms of thematic maps extracted from results by the Leonardo tool or numerically in terms of meteorological records corresponding to each grid in the simulated urban form [22]. In order to ensure results of the receptors along with having a complete idea about whole outdoor spaces performance rather than only single receptor points, PolygonPlus has been used. PolygonPlus is a visual basic tool used after ENVI-met to generate reference averaged neighborhood meteorology rather than records at single non-representative points [13]. Moreover, comparisons of different urban designs upon their urban spaces meteorological averages can take place against receptors' outputs to validate PolygonPlus.

2.2. Parameterization

Table 1 shows the simulation input data for the 27th of July which is the extreme summer day for Sheffield, UK (Lat; 53.38, Long; -1.46), fig. 1 [28]. Two methods of recording outdoor meteorological data were used, snapshot receptors of ENVI-met and the averaging tool PolygonPlus. Four snapshot receptors were located at the boundaries and the middle of the site to record air temperature T_a, Relative Humidity RH, wind Velocity V, and PMV at 1.5m above ground level, fig. 1/b, c, d. The hypothesis assumes that pedestrian PMV of both cases will be different as the fabric, network and vegetation elements of the built environment are varying. Output were then compared with the whole site averaged records calculated by PolygonPlus tool developed by Fahmy [29] to represent a whole local scale urban spaces' climate condition rather than single points, fig. 2. Due to no modeling measurements for trees foliage, urban trees, U1, U2 and U3, used in simulations were modeled after Fahmy [9] by the application of the value LAI=1, table 1.

Table 1: Inputs used in simulations based on [22, 30, 31].

Parameter	Value
Outdoor T_a	295.45 K
RH	60%
V	3.4 m/s at 10m height
Indoor T_a	293.15 K
Ground temperature	288.15 K from 0-0.5m and 286.35 K from 0.5-2m
Ground humidity	40% from 0-0.5m and 50% from 0.5-2m
U value Walls	1.0 for all buildings walls
U value Roofs	2.0 for all buildings roofs
Albedo Walls	0.475 for all buildings walls
Albedo Roofs	0.45 for all buildings roofs
Albedo Pavement	0.67
Albedo Asphalt	0.20
Human walking speed	1.1 m/s
Pedestrian Clo.	0.50
U1; Alunas cordota	10m total height – 1.8m height to canopy – 3 height of max diameter
U2; Alunas cordota	7m total height – 1.8m height to canopy – 3 height of max diameter
U3; London plane	20m total height – 2m height to canopy – 10 height of max diameter

Fig.1/a: Google maps capture for the site area and the existing fabric.

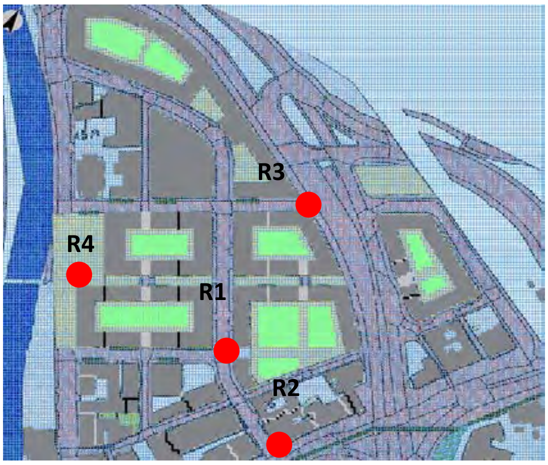

Fig.1/b: ENVI-met Graphical user interface; Modeling the urban form alternative 1 for the case area, R is abbreviation for the receptor placed at points 1-4.

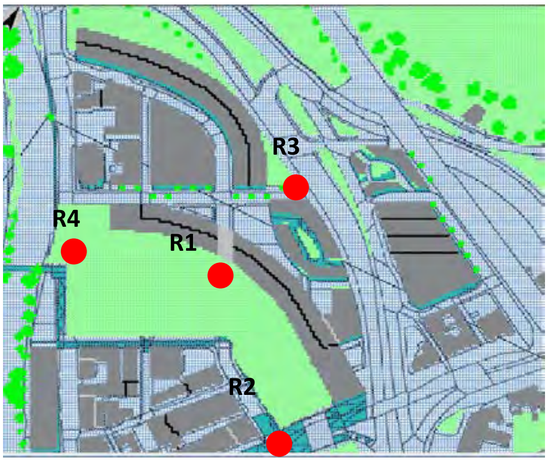

Fig.1/c: ENVI-met Graphical user interface; Modeling the urban form alternative 2 for the case area.

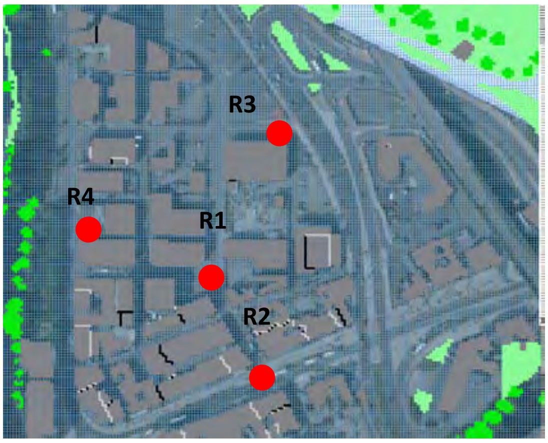

Fig.1/d: ENVI-met Graphical user interface; Modeling the urban form base case.

3. Simulation course

3.1. Results

Fig. 3 illustrates the comparison for T_a, RH, V and PMV extracted from the receptors plotted along with the averaged reference local climate condition calculated by PolygonPlus for 12h except the base case which simulation encountered a numerical flow error at the last simulated hour. However, it didn't affect the comparisons and the concluded remarks as there was 11 common hours from 8-18LST. Good agreement appeared between records from the individual receptors and the averaged values for T_a and RH, whereas considerable difference found between the receptors and the average value for V and PMV, demonstrating a microclimate manipulation on the local scale. All T_a and RH records show the same trend in all cases with reductions in C2 T_a due to the more vegetated area used in comparison to both C1 and BC. The opposite trend in RH occurred attributed also to the different vegetated area used. The sudden drop in PMV record of some cases like C1 at the receptor point R2 indicates the effect of shading. Wind speeds are much higher in C2 than both C1 and BC owed to open fabric used that removed the blockage effect might occur by the fabric in C1. And in combination with the reduced T_a in C2, and resulted more acceptable PMV records at receptors microclimate regardless the reduced PMV of the averaged local records of C2 than PMV at C2R3 as the averaged records is a reference for the whole neighborhood rather than for a single point. The effect of urban thermal mass firstly found by Fahmy [13] has been also found in this study despite the different climatic region. Regardless the close PMV trend of both alternatives' averaged values; increasing green coverage in the park option showed a minor urban thermal mass effect represented by a difference in PMV of 0.1-0.3 at peak time almost with no urban time lag. Receptor, R, no.1 and no.2 showed similar PMV horizontal shifting on the curve of about 0.2 with 2h of urban time lag from 14.00LST to 16.00LST. R3 showed vertical shifting indicating reductions due to the more vegetation in C2. R4 also showed vertical shifting but with increased PMV value at peak time due to the less trees in comparison to C1.

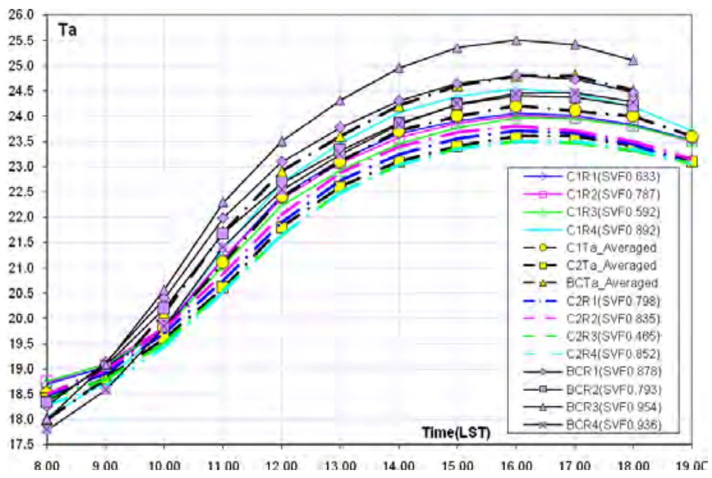

Fig.3/a: Comparison of averaged T_a and the receptors outputs for different cases.

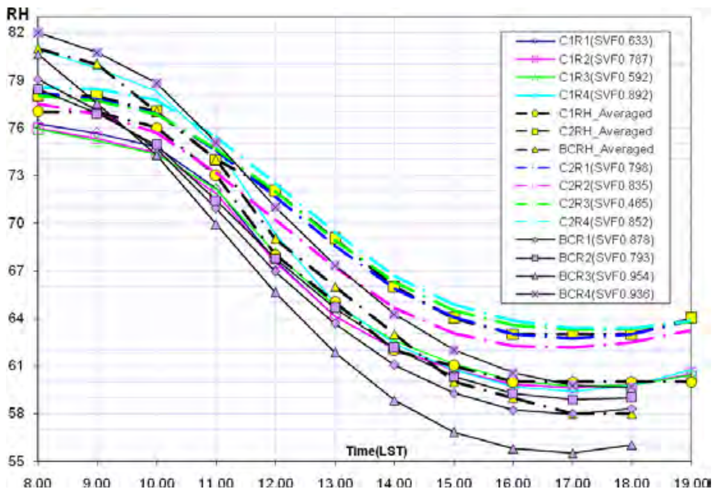

Fig.3/b: Comparison of averaged RH and the receptors outputs for different cases.

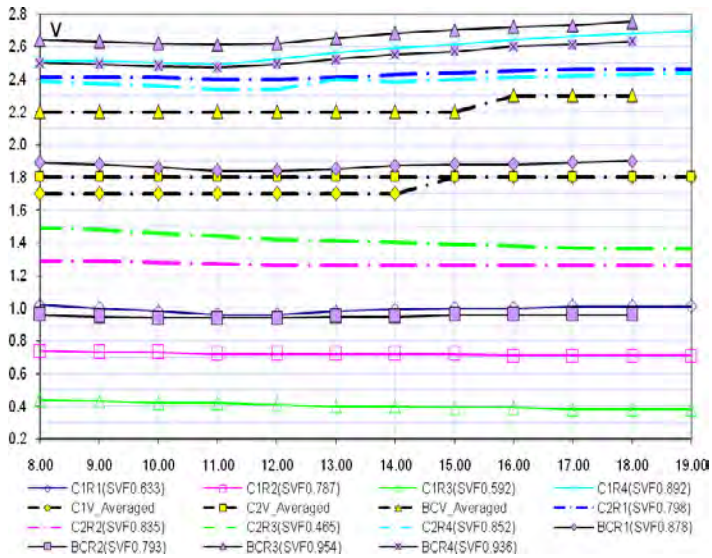

Fig.3/c: Comparison of averaged V and the receptors outputs for different cases.

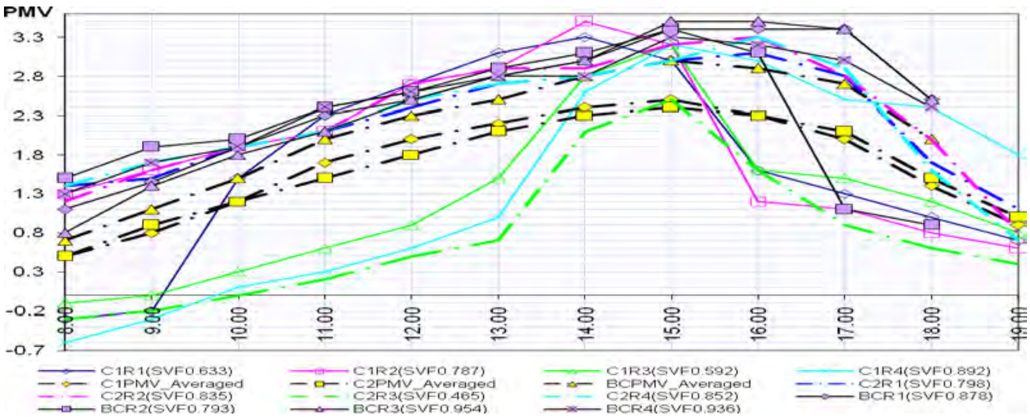

Fig.3/d: Comparison of averaged PMV and the receptors outputs for different cases.

3.2. Discussion and conclusion

This study aimed to assess the thermal performance of two radically different urban regeneration alternatives with their existing case in Sheffield in order to give on of the alternatives an advantage for execution. Methodology composed of two steps; first, urban climate conditions of each case is simulated to have meteorological plots at same certain points in each case. Second, average outdoor meteorology for each case is calculated to ensure results from receptors as well as validating the averaging tool, PolygonPlus. All averages' records occurred between the maxima and minima of receptors outputs of each case which validates PolygonPlus. The more vegetated alternative revealed reductions in the whole neighborhood pedestrian comfort records. This is owed to the open form that allowed more wind speed averages as well as more park cooling effect. On the other hand, an urban thermal mass effect has been noticed. It can be said that the whole C2 urban green structure turned the neighborhood form into *urban thermal mass* that shifted PMV curves from C1 as shown in fig.3 and agrees with Fahmy [13], p-138, regardless the different climate classification of Sheffield's case in this study. After all, outdoor climate assessment suggests that the second urban form design is probably more sustainable with reference to urban spaces simulated in the two alternatives in comparison to the existing site urban form, but further indoor analysis is required to study the impact of each urban form on the energy demand and the green house gases emissions; i.e. coupling whole neighborhood buildings' indoor thermal performances with their outdoors.

4. Acknowledgement

This paper is based on work undertaken within the URSULA project, funded by the UK Engineering and Physical Sciences Research Council (Grant number: EP/F007388/1) and the authors are very grateful for this support. The views presented in the paper are those of the authors and cannot be taken as indicative in any way of the position of the project sponsors or of colleagues and partners. Any remaining errors are similarly those of the authors alone.

References

[1] Grimmond, C.S.B. and T.R. Oke, Heat storage in urban areas: Local-scale observations and evaluation of a simple model. Journal of Applied Meteorology, 1999. **38**(7): p. 922-940.

[2] PRB, World Population Highlights; Key findings from PRB's 2007 world population data sheet Population Bulletin; a publication of the Population Reference Bureau, 2007. **62**(3).

[3] Rosenfeld, A.H., H. Akbari, S. Bretz, B.L. Fishman, D.M. Kurn, D. Sailor, and H. Taha, Mitigation of urban heat islands: materials, utility programs, updates. Energy and Buildings, 1995. **22**(3): p. 255-265.

[4] Stone, B. and M.O. Rodgers, Urban Form and Thermal Efficiency: How the Design of Cities Influences the Urban Heat Island Effect. Journal of the American Planning Association, 2001. **67**(2): p. 186 - 198.

[5] Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S. , Adapting Cities for Climate Change: The Role of the Green Infrastructure. 2007. **33**(1): p. 115-133.

[6] Giridharan, R., S.S.Y. Lau, S. Ganesan, and B. Givoni, Lowering the outdoor temperature in high-rise high-density residential developments of coastal Hong Kong: The vegetation influence. Building and Environment, 2008. **43**(10): p. 1583-1595.

[7] Shashua-Bar, L. and M.E. Hoffman, Vegetation as a climatic component in the design of an urban street: An empirical model for predicting the cooling effect of urban green areas with trees. Energy and Buildings, 2000. **31**(3): p. 221-235.

[8] Yang, F., S.S.Y. Lau, and F. Qian, Summertime heat island intensities in three high-rise housing quarters in inner-city Shanghai China: Building layout, density and greenery. Building and Environment, 2010. **45**(1): p. 115-134.

[9] Fahmy, M., S. Sharples, and M. Yahiya, LAI based trees selection for mid latitude urban developments: A microclimatic study in Cairo, Egypt. Building and Environment, 2010. **45**(2): p. 345-357.

[10] Dimoudi, A. and M. Nikolopoulou, Vegetation in the Urban Environments: Microclimatic Analysis and Benefits. Energy and Buildings, 2003. **35**(1): p. 69-76.

[11] Jensen, M.B., B. Persson, S. Guldager, U. Reeh, and K. Nilsson, Green structure and sustainability -- developing a tool for local planning. Landscape and urban planning, 2000. **52**(2-3): p. 117-133.

[12] Lam, K.C., S. Leung, W.C. Hui, and P.K. Chan, Environmental Quality of Urban parks and open spaces in Hong Kong. Environmental Monitoring and Assessment 2005. **111**(1-3): p. 55-73.

[13] Fahmy, M., Interactive urban form design of local climate scale in hot semi-arid zone, in School of Architecture. 2010, University of Sheffield: Sheffield.

[14] Fahmy, M. and S. Sharples, Extensive review for urban climatology: Definitions, aspects and scales, in 7th International Conference on Civil and Architecture Engineering, ICCAE-7. 2008a: Military Technical Collage, Cairo May 27-29.

[15] Saaroni, H. and B. Ziv, The impact of a small lake on heat stress in a Mediterranean urban park: the case of Tel Aviv. International journal of Biometeorology, 2003. **47**(3): p. 156-165.

[16] Lee, S.E. and S. Sharples. Analysis of the Urban Heat Island of Sheffield - the Impact of a Changing Climate. in Proceedings of PLEA2008 - 25th Conference on Passive and Low Energy Architecture. 2008. Dublin: PLEA.

[17] Kofoed N U and G. M., Considerations of Wind in Urban Spaces. In: Designing Open Spaces in the Urban Environment: a bioclimatic approach. Ed. Nikolopoulou M. Available online at http://aplha.gr/ruros/. 2004 Greece.

[18] Yokohari, M., R.D. Brown, Y. Kato, and H. Moriyama, Effects of paddy fields on summertime air and surface temperatures in urban fringe areas of Tokyo, Japan. Landscape and Urban Planning, 1997. **38**(1-2): p. 1-11.

[19] Jauregui, E., Influence of a large urban park on temperature and convective precipitation in a tropical city. Energy and Buildings, 1990. **15**(3-4): p. 457-463.

[20] Oke, T.R., J.M. Crowther, K.G. McNaughton, J.L. Monteith, and B. Gardiner, The Micrometeorology of the Urban Forest [and Discussion]. Philosophical Transactions of the Royal Society of London. B, Biological Sciences, 1989. **324**(1223): p. 335-349.

[21] Ali-Toudert, F., Dependence of Out Door Thermal Comfort on the Street Design in Hot and Dry Climate. 2005, Institute of Meteorology: PhD. Thesis, Freiburg, Germany.

[22] Bruse, M., ENVI-met V3.1BETA4, a microscale urban climate model, [Online], Available: www.envi-met.com. Accessed 11/6/2010. 2010.

[23] Bruse, M., ENVI-met bulletin board [Online], Available: http://envi-met.de/phpbb/index.php. Accessed 17/3/2009. 2009.

[24] Jendritzky, G., W. Sönning, H.J. Swantes, d. Beiträge, and f. Akad, Ein objektives Bewertungsverfahren zur Beschreibung des thermischen Milieus in der Stadt- und Landschaftsplanung (Klima-Michel-Modell). Raumforschung und Landesplanung, 1979. **28**.

[25] Jendritzky, G. and W. Nübler, A model analysing the urban thermal environment in physiologically significant terms. Meteorology and Atmospheric Physics, 1981. **29**(4): p. 313-326.

[26] Jendritzky, G., A. Maarouf, D. Fiala, and H. Staiger, An Update on the Development of a Universal Thermal Climate Index. 15th Conf. Biomet. Aerobiol. and 16th ICB02, Kansas City 27 Oct - 1 Nov, 2002.

[27] Bruse, M., ENVI-met V3.1BETA4, a microscale urban climate model, [Online], Available: www.envi-met.com. Accessed 11/6/2010. 2010.

[28] AutoDesk. ECOTECT2010, [Online], Available at: http://www.autodesk.co.uk/adsk/servlet/mform?validate=no&siteID=452932&id=14205163. Accessed 19/4/2010.

[29] Fahmy, M., Interactive urban form design of local climate scale in hot semi-arid zone, in Architecture. 2010, University of Sheffeild: Sheffeild. p. 254.

[30] Akbari, H., P. Berdahl, R. Levinson, S. Wiel, W. Miller, and A. Desjarlais, Cool Color Roofing Materials. 2006, University of California: California.

[31] Oke, T.R., Boundary layer climates. 1987, London: Methuen.

[32] Fahmy, M., A. Trabolsi, and S. Sharples, Dual stage simulations to study microclimate thermal effect on comfort levels in a multi family residential building., in 11th International Building Performance Simulation Association Conference 2009: University of Strathclyde in Glasgow, 27-30 July.