The Increasing Importance of Advanced Building Simulations in a New Building Design Paradigm

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Abstract

This paper presents and discusses the increasing importance of advanced building simulations in the design of high performance buildings. A changing building design industry increasingly requires simulations to achieve high energy efficiency and sustainability, while safeguarding occupant comfort, for the built environment. The paper introduces two main numerical design tools, energy simulations (ES) and computational fluid dynamics (CFD). Much of the building industry and even many academic architecture programs have not yet embraced advanced simulations as indispensable tools of the design process and building operation, as well as an important educational focus for the next generation of architects. The paper discusses how a successful implementation of the new design paradigms based on advanced simulation tools in academia and the building industry are hampered by technology and human barriers. The paper proposes several measures to successful overcome these barriers. Several important of application of advanced simulation are discussed such as building energy consumption; natural ventilation, dispersion of pollutants in and around buildings and occupant comfort performance.

Keywords: Paradigm shift in sustainable building design, whole building simulations, computational fluid dynamics (CFD), Leadership in Energy and Environmental Design (LEED), energy efficiency, energy codes, resource responsible building design, natural ventilation

Introduction and the urgent need for a new building design paradigm

Today's building designer face many challenges to work out optimum designs for their customers. The overall trend favors energy efficient and resource responsible yet cost effective buildings, which also have to offer occupants with creative and livable spaces and high comfort. The conventional building design work has been focusing on a sequential work flow where the buildings size, shape and configuration follow the immediate needs of the customers. Typically, under the conventional building design paradigm, energy efficiency and responsible resource on consumption measures have not been the primary decision criteria in the early stages of the building design process. Under the prevailing building design paradigm energy efficiency and other sustainability aspects have been mainly addressed in the building outfitting stage where mechanical and electrical equipment is selected to serve a finished building design. Therefore decisions about selecting energy efficient and sustainability measures are finalized when the basic building shape and orientation has been decided upon. This process can significantly and negatively affect the building's performance.

With the advent of integrated design practices and the increasing usage of passive building measures to achieve a sustainable and high-performance building performance, the prevailing paradigm needs to shift towards giving energy and resource consumption considerations a much more dominant role right at the start of the design phase. The shape and orientation of the building are becoming key design aspects that promote energy savings. Besides other sustainable measures an optimized shape and orientation of the building can reduce unwanted heat gain or loss and increase the ability of the nature to perform functions that typically mechanical or electrical systems have to do, such as daylighting and natural ventilation. By using natural driving forces for ventilation and heat control the designer can use exciting opportunities to integrate beauty and function in a sustainable way. However, using passive design in complicated building geometries can represent challenges for the building designer when conventional design practice and prescriptive code measures cannot provide sufficient guidance. These challenges can be overcome by taking advantage of powerful design simulation design tools that take the guess work out of the process and provide the designer with quantitative feedback right at the beginning of the design.

Description of the design dilemma

Designing a building with the appropriate shape, form and atmosphere so that occupants can have a rich experience of the built environment is a daunting task by itself. It requires creativity, communication skills and also financial acumen of the architect to integrate a wide range of project needs and make sure that the building "works" for the intended function. The challenge to the architect increases significantly when too many energy efficiency and sustainable aspects need to be addressed right at the start of the design process. This might be one of the main reasons why using passive rather than active building systems to ensure adequate comfort is used to a limited extent, although energy savings and achieving sustainable goals are much more likely to be achieved with passive measures. An important example of potent passive measures is natural ventilation of buildings which can save a significant amount of electric energy and load. In natural ventilation the wind regime adjacent to the building creates pressure differentials between the windward and leeward side of the building to drive air through the building and achieve sufficient ventilation. Design for effective naturally ventilated buildings requires relying on relatively small driving forces of wind driven and/or stack ventilation. A slightly wrong design can mean that the natural ventilation of the building is not sufficient, necessitating the costly additions of mechanical supplemental ventilation capacity.

Typically buildings are mechanically ventilated and conditioned, where HVAC systems can consume the lion share of the energy. Mechanical ventilation systems can be configured to produce any required magnitude of driving forces that moves air through and out of the building; it is only a question of sizing the system correctly, which very often means over sizing it and incurring significant energy penalties.

Many designers are faced with the dilemma of wanting to design highly resource efficient buildings using passive energy building measures but they might shy away since passive building measures need significant fine tuning of the exterior shape and air intakes as well as internal air pathway configurations. Therefore, in order to arrive at effective external and internal building configuration, the designer of innovative buildings using natural ventilation had to rely on costly and time consuming physical experiments, most often with scale models, to verify the effectiveness of the design. Such experimental means include environmental test chambers and wind tunnels, which produce reliable predictions of the real prototype. Yet the limitations and costs of using experiments discourage many designers to use them, apart maybe from large and prestigious building projects where the final design alternative requires experimental proof of its performance.

New advanced building simulation programs are disruptive technologies that are increasingly changing the way buildings are designed. These software technologies provide the building designer with ample opportunity to test out different building alternatives early in the design process. Using these powerful software tools allows the designer to get quantitative performance indicators of building alternatives in regard to fulfilling sustainable objectives and at the same time offering favorable life cycle costs. The designer is not limited to rely on previous experience or on guessing or prescriptive design guideline. Using the advanced simulation tools the designer can play out her/his creativity to design unique and out-of-the-box buildings while at the same time ensuring that passive building measures are performing well.

Goal of the new paradigm of a technology supported design process

Architecture has always been an art as well as a science. Among other roles the successful building designer has intuitive skills to create uniqueness in the design. The design "lives" and often the criteria of success of the design are based on subjective response of the occupants. When it comes to designing energy efficient buildings, however, the building also has to show superior energy performance. Energy consumption can be measured and therefore the building design has to satisfy certain numeric energy consumption benchmarks that are dictated by applicable energy codes. The use of advanced simulation tools is therefore contributing to what can be perceived as a "clash" of values in architectural design. The immediate conclusion would suggest that either the creative design process or the quantifiable energy performance must lead the way in the design process. But innovative simulation tools can help to bridge this gap by making it easier for the creative designer to obtain quality quantitative feedback early on in the design process.

Take two examples, which represent opposite sides of building design approaches. On one side we have the architecture acumen with the currently popular glass dominated façade. These buildings are regarded as symbols of openness and weightlessness of the design. There are many examples of breathtaking appearance of glass facades, but for most cases such buildings are not energy efficient at all, except maybe outstanding examples that have successfully incorporated passive design measures. The reason is that glass is not a good insulator and allows significant solar gain. On the opposite side of building design approach is the Passive

House standard, where energy performance is the driving force behind building form, envelope design and equipment choice. Passive House buildings typically have smaller windows, a highly insulated envelope and energy recovery equipment. Passive Houses have superior energy performance but these buildings can lack openness and transparency of large window facades.

Designing a building from the architectural and energy engineering standpoint will most likely result in two opposing designs approaches when following conventional design processes. Yet both architecture beauty and energy efficiency and sustainability do not need to be mutually exclusive. The goal of future oriented integrated designs of beautiful yet energy efficient must be to integrate a quantitative assessment of the objective energy performance, expressed in how many kWh are used per year, with the creative process that produces attractive and uplifting buildings. This bridging of design paradigms requires good understand of energy performance, specifically using passive design measures, as well as a deep appreciation of the creative nature of the building design. Truly sustainable and energy efficient buildings must rely on the seamless integration of these two aspects of the design. Using advanced building simulation tools puts the design team in the position to experiment with the building external and internal configuration and optimize the performance through expedient quantitative feedbacks of the main building performance parameters.

The enabler technologies (ES and CFD)

There are two main simulation tools at the disposal of the building designer. These are energy simulation (ES) and computational fluid dynamics (CFD). Both design tools support the designer to identify of the most energy efficient design building alternative. ES is mainly concerned with the prediction of the building energy consumption over a certain time period, typically on an annual basis. An ES system integrates the 3D-geometry of the building, the adjacent climatic conditions and the numerous sinks as well as sources of electric and heat energy in the building to provide precise predictions of energy consumption. The ES system keeps track of many, sometime thousands of building subsystems, as all the small parts of the building contribute to the overall energy performance of the building over seasonal and diurnal changes. While ES provides information over longer time periods intervals when assessing energy performance CFD provides a snapshot in time when certain multiple physical phenomena interact in establishing the building performance. State-of-the-art CFD systems can accurately predict complex air movement and thermal process in and around the buildings. And these air movement and thermal processes have significance in regard to not only energy performance of the building but also in regard to occupant comfort.

While ES has come a long way in establishing itself in the building industry, CFD is a relative newcomer in. CFD is increasingly used to model air movement around buildings and through internal spaces. Using CFD software has considerable advantages over wind tunnel studies in regard to time and costs for the building analysis. CFD products have been developed to such a high sophistication that the result of simulations rival and in some cases surpass the accuracy of wind tunnel studies. The advantage of CFD is that the flow field, or better the computational domain, is described at any point, whereas wind tunnel measurements can only be carried out for a few selected points around or in the building. Modern CFD products have successfully improved their coding and made the user interface much easier to use. This promises that CFD will see a wider use in building design in the future.

A relatively new application is the so-called coupled ES and CFD analysis. ES usually has to use approximations and averages of important numeric calculation parameters, which can result in inaccuracies in the true heat transfer and energy processes in the building. CFD has the limitations of being a snap shot of certain properties of the building performance. The coupled analysis of ES and CFD provides the ES with very much improved numerical assumptions and therefore significantly more precise energy predictions. Coupled ES and CFD systems are only at the beginning of their development and powerful integrated ES and CFD systems will be coming on the market in the next couple of years.

Main barriers to wider use of ES and CFD and how those barriers can be overcome

The benefits of wide spread use of ES and CFD in the building industry are well understood. What hampers the ready implementation and wider use of these powerful numeric building design tools are technology as well as behavioral barrier. Some of them are described below.

- First of all the building designer need to be convinced that esthetics and good energy performance of the building are two issues that do not collide but which should supplement each other. Building truly sustainable and energy efficient buildings can best be achieved through integrated design teams. Advanced software design tools support design team to integrate function and form of the building with superior energy performance.
- The building industry need to embrace passive building measure that can achieve high energy performance by using naturally occurring processes that replace energy and resource intensive active building systems. Active building systems have their indispensable place, but they need to be designed to produce the most effective energy performance. CFD can support design teams to achieve effective naturally ventilated building as well as optimizing active building systems.
- Early CFD, as well as ES systems, were bedeviled by very complex graphic user interfaces (GUI). Operating such systems was more the realm of highly specialized, and therefore rare and costly, experts than that of a typical design practitioner. Modern CFD systems have dramatically improved their GUIs and made the previously daunting tasks of creating complex 3D-geometries, computational meshes and visualizations of the millions of data set from the analysis much more user friendly. This facilitates the introduction of CFD and ES in the building industry and enables the designer to use these powerful numerical tools to create value in the design process.
- The high costs of CFD and ES programs used to be a barrier for the wider use of these numerical design tools. In addition the lack of trained design professionals has been a detriment to the acceptance of ES and CFD. CFD was traditionally used in the

aerospace and automobile industries to analyze better aerodynamic forms for products. CFD then spread to other industries and has come to age by getting more attention in the building industry. Costs have come down dramatically over the past years and therefore lower costs, combined with a larger pool of trained building professionals, have lowered the entry barriers.

- One challenge remains with a more accessible application of CFD, and to an extent also ES. The operator of both ES and CFD needs to have a sound understanding of the physical phenomena that are being analyzed. The success of ES and CFD can be hampered by designers too readily accepting results of simulation as the reality, while lacking skills to correctly interpret results and placing them in perspective with the recommended measures to improve the building energy and ventilation performance. Good educational offerings will help both practitioners and students of building design to acquire the necessary skills in building physics, numerical analysis and software operation. While the operation of CFD and ES systems become easier there remains the danger that input and results of simulations will be taken at face value, lacking the due scrutiny of the experienced practitioner. As the old saying in simulation correctly states “garbage in - garbage out”.

ES+ CFD case studies

Ostensibly, energy simulation (ES) and computations fluid dynamics (CFD) have become or are on the verge of becoming significant and established design tools in architecture. The CFD simulation industries are growing rapidly and have shown a 13% growth rate in recent years (Keith Hanna 2011). Main reason for ES market expanding in the past years has been the need to improve energy building performance. Both governmental agencies, such as the US Department of Energy and Environmental Protection Agency (EPA) as well as private organizations are increasingly allocating funds, technology, and educational opportunity to expand the user base of building simulations. Therefore architects, engineer, developers, and owner now have the technology means to access information and enhance collaboration for future energy reduction in buildings. The still evolving complexity and improvement of both ES and CFD codes and means of visualization of simulation results will provide a higher level of abstraction, and also allow the user formulate the system closer to actual system behaves (Michael Wetter 2011). The following shows several examples of how ES and CFD application in building design provide significant benefit to the design process, such as energy and environment code compliance, wind load to building structure, natural ventilation, pedestrian comfort, air pollution dispersion in and around, and thermal comfort.

Energy and environment code compliance

Buildings represent approximately 40% of the total energy demands in the US (DoE Energy Information Agency (EIA), 2009). Advanced simulation tools will help to improve the energy performance of building, by identifying opportunities to save energy through reliable quantitative assessment of design alternatives. The collaboration of government and private parties provides important supplementary data to support ES and CFD analysis in building design through warehousing of climate and other environment data.

Several US agencies also provide a range of free environmental simulation tools in whole building energy performance, lighting analysis, environmental validation and testing application for public users. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is recognized to provide important energy, ventilation and occupant comfort standards, such as ASHRAE 90.1 appendix G, ASHRAE 55, and ASHRAE 62. These standards have been embraced by many cities as their energy codes for building energy baseline performance, thermal comfort, and indoor. The most recent versions of the universally recognized energy standards, such as International Energy Conservation Code (IECC) 2009and 2012 require building energy, lighting, and ventilation simulation for building design that are outside conventional design standards. Therefore if the architect wants to build innovative designs that are not covered by generic prescriptive energy saving measures he/she will have to provide proof through whole building simulations that the building is consistent with the applicable energy codes. Furthermore, the US Green Building Council (USGBC) requires simulations to qualify for most of the available energy related LEED certification points. We consider two code related issues as important in the assessment of the role of building simulations:

- Energy code compliance derived by ES and CFD simulations will benefit the future building industry by infusing state of the art technologies in the early stages of the design. In order to minimize construction cost and erroneous investment in mechanical and electrical building equipment the simulations will identify the most economic and energy efficient building design alternative. The building simulation also provides multiple design scenarios for life cycle cost, energy performance, and other sustainability aspects. Many environment and energy code such as ASHRAE and BREE have been embedding in building construction material library, which allow users to derive efficient design scheme faster and closer to targeted energy benchmarking.
- It can be safely assumed based on current trends in energy codes that future code compliance will require stringent scientific evidences to prove satisfactory energy performance of the building design.

Wind load / wind engineering

Wind loading represents design challenges and significant risk of structural damage if the wind derived forces are not appropriately assessed in the design, especially for high-rise building. Wind pressure characteristics resulting from upwind air movement characteristics can exert significant structural loading that directly affects the building geometry and structure. Wind velocity and derived pressures on the building envelope are not linearly distributed in the vertical dimension; correctly predicting wind loading requires considering the effect of the atmosphere boundary layers (ABL). The ABL is significantly affected by building density and is dependent on different terrain and roughness (Figure 1. Many CFD programs offer settings to account for the non-linear distribution of vertical wind velocities for building located in open field, suburban, or urban density will cause the gradient wind velocity (P. Mendis, 2007). More advanced CFD programs can actually model the complex unstable and dynamic wind derived pressures on the building façade.

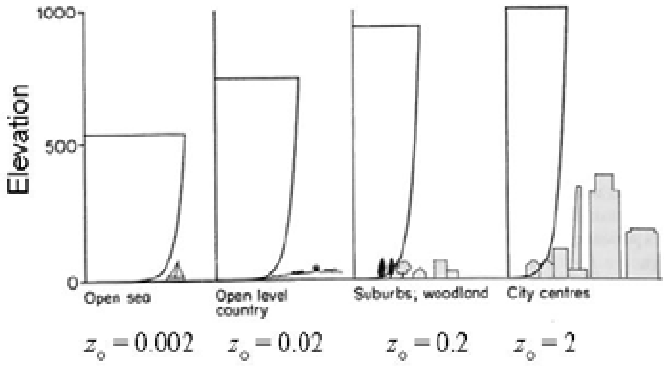

Figure 1 Mean wind profiles for different terrains: (P. Mendis 2007)

Some state-of-the-art CFD simulation programs offer very sophisticated numeric analysis to quantify the distribution and magnitude of pressure (Pa) on building façade as well as wind velocity based on context and building geometry. Figure 2 depicts an example of CFD simulation that demonstrates and visualizes wind velocity and wind pressure distribution on building surface, and also provides a tool of measurement at node point, line, and grid on building façade.

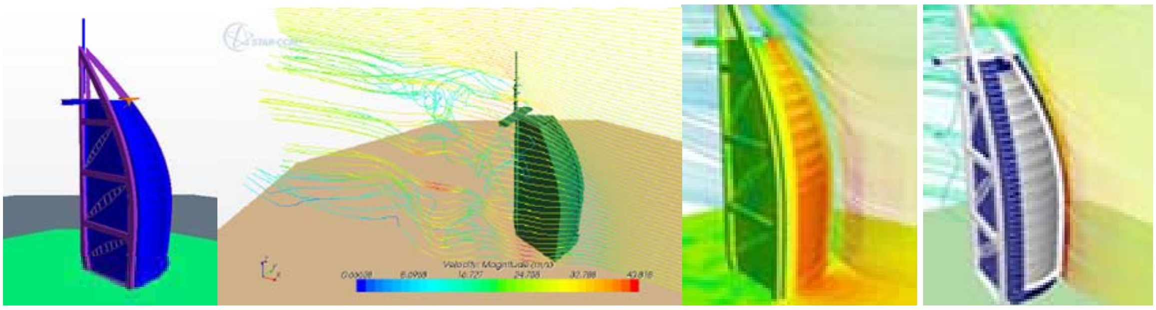

Figure 2 Velocity and pressure distribution create wind loading on building structure: (STAR-CCM+ for Building Services Analysis 2011)

Natural ventilation

Passive design strategies using appropriate natural ventilation designs schemes promise to provide the occupant comfort by using significantly less energy. Using natural ventilation in buildings can significantly reduce energy by avoiding energy intensive building conditioning using HVAC technologies. The CFD technology allied to wind patterns around and inside buildings provides a high quality and high precision as well as intuitive visualization of velocity and pressure. The significant importance of external CFD simulation (Figure 3) defines the characteristic of wind driven force and pattern around the buildings, including commuted building blocks or adjacent buildings. As an example, using STAR-CCM+ as the CFD building analysis tool helps visualizing and understanding what is the site constrain of wind movement through adjacent building. For internal CFD analysis the wind driven force on the upwind façade and the pressure drop between upwind and downwind external building façade represents the driving force that contributes to the conditioning of spaces. Figure 4 demonstrates the CFD software able to calibrate airflow and movement patterns from external to internal conditions in the case of cross ventilation.

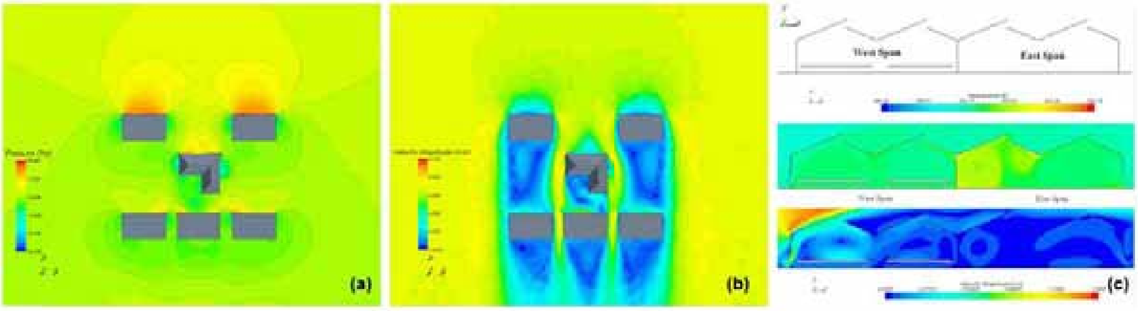

Figure 3 Example of external wind pressure (a) and velocity (b): (Sanphawat Jatupatwarangkul, 2013) and Natural ventilation study (c) of STAR-CCM+ CFD simulation:(SunitaKruger2006)

Pedestrian comfort and air pollution dispersion

Satisfying pedestrian comfort is an increasingly important design criterion for buildings that affect the wind regime in neighborhoods. CFD software can simulate to ascertain that pedestrians in the areas affected by the new building feel comfortable when they are walking or standing close to new buildings. Particularly in the urban dense neighborhoods, all stacked and packed buildings are considerably affected by wind patterns that possibly cause improper wind comfort. Figure 4(a) demonstrates a CFD investigation that simulates wind speeds for pedestrians. Another aspect of environmental condition in Figure 4 (b) demonstrates the CFD prediction of smoke and dust due to collapsing World Trade Center building 9/11 which affected air pollution in the entire Manhattan district.

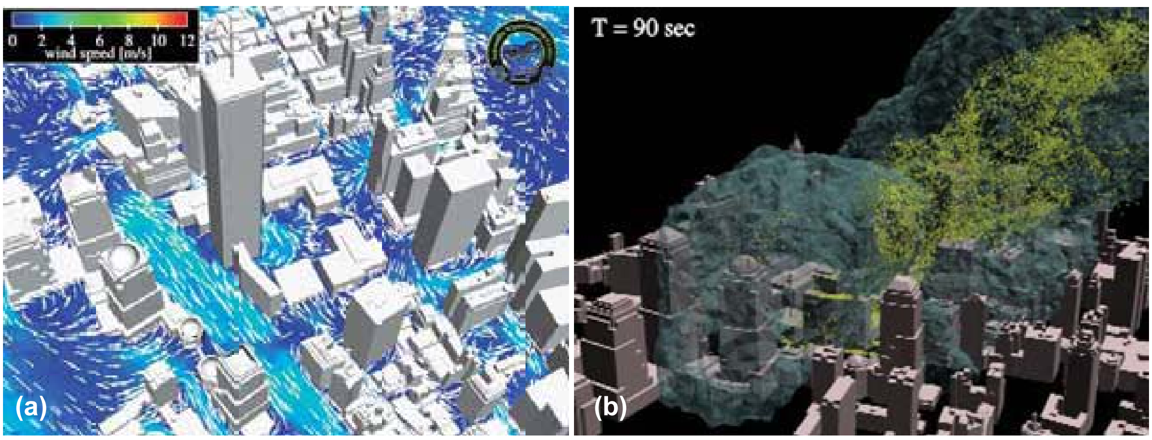

Figure 4 Example of wind pattern between buildings of Manhattan (a) and at 9/11 building collapse smoke (b):(Alan Huber 2006)

Occupancy comfort / thermal comfort

The ultimate goal of architectural design is to provide a quality space on the built environment. This means that the designer is able to provide high comfort level to occupants. Thermal comfort is the significant criterion to measure the occupants' comfort. Because of the fact that occupant comfort is measured using probability tools in determining the percentage of unsatisfied occupants, it is paramount that simulations assist the designer to select the appropriate design alternative by determining the most probable future building performance. For example, the new versions of occupant comfort standards are deviating from conventional definition of comfort that use one representative comfort conditions for an entire space, regardless of the actual distribution of thermal and ventilation quantities in the space. The new evolving comfort standards are trying to reverse the one-dimensional focus on satisfying comfort level in the entire space by also considering physiological and psychological experiences of occupants (ASHARE 55 2010). The new understanding of occupant comfort includes the personal comfort experience of the occupant. This new understanding of comfort supports the viability of naturally ventilated buildings and the selection of HVAC solutions that are significantly more energy efficient as conventional buildings.

The ability of CFD simulations to visualize and quantify the thermal comfort performance at distinct locations of the internal space will guide architects and engineers to improve the energy performance of building design scenarios. Examples of thermal comfort calculation in Figure 5 (a) shows the Predicted Mean Vote (PMV)which addresses the personal seven points thermal sensation scale values from cool to warm. The same simulation result in Figure 5 (b) demonstrates amount Predicted Percentage of Dissatisfied (PPD) which directly quantifies expected comfort levels. Figure 5 (c) demonstrates the surface irradiation and the flow pattern in the main lecture hall at the Hermann-Rietschel-Institute of the Technical University of Berlin which was also calculated using Solar Loads Model during a lecture.

Figure 5 Example of PMV value and velocity slice place (a) and PPD result (b) of thermal comfort simulation result: (Autodesk Simulation CFD 2013) and Example of surface irradiation (c) of main lecture room: (STAR-CCM+ Building services 2013)

Conclusion

Architects, engineers, and builder professions are facing a new paradigm of integrating performance based building design and the resulting need for whole building simulation. Code compliances will include mandatory quantitative predictions of energy performance and occupant comfort based on simulation. The key success of sustainable design is integrating systems and techniques into building design to create a synergy of environment, building, systems and users (Gordon Gill 2008). Whole building energy simulation (ES) and computational fluid dynamics (CFD) simulation are examples of integrating scientific and quantitative design approach strategies that predict how building should performance under any design scenario. The Architecture 2030 Challenge addresses the need for the global architecture, engineering and planning community to commit that building, community, and infrastructure new designs and renovations will reduce 60% of fossil-fuel derived energy consumption.

Building designers must commit to the challenge goal since the fact how much energy will be consumed in buildings affects the local and global energy market as well as the environment and global warming. Building designers and professions alike will require the immediately feedback of powerful simulation tools to derive better building designs right at the start of the design process. While the benefits of using ES and CFD in the building industry are many, so are numerous barriers to the wider introduction of these powerful simulations. The challenge for the building industry will be to satisfactorily navigate the paradigm shift in building design and embrace simulations as integral parts of the design process.

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