

CARDIFF SCHOOL OF ENGINEERING



# Developing a BIM-based methodology to support renewable energy assessment of buildings

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THIS THESIS IS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR  
THE DEGREE OF  
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*“Karmanye Vadhikaraste, Ma phaleshou kada chana, Ma Karma Phala Hetur Bhurmatey Sangostva Akarmani” - Sanskrit verse from the Hindu scripture Bhagawad Gita*

The literal translation of this verse is *“You have the right to perform your actions, but you are not entitled to the fruits of the actions. Do not let the fruit be the purpose of your actions, and therefore you won’t be attached to not doing your duty.”*

This verse has taught me to perform my duties without worrying about the outcome. I’ve always interpreted this as ‘Don’t chase success, if you work with diligence then success will follow you’.

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*“Guru Brahma, Guru Vishnu, Guru Devo Maheshwara, Guru Sakshat Parabrahma, Tsmat Shri Guruve Namaha”*

The translation of this Sanskrit verse is - *“A teacher like Lord Brahma generates the knowledge within us, like Lord Vishnu he directs the ideas/knowledge in our mind on the right path, and like Lord Shiva he destroys the wrong concepts attached to our knowledge, while enlightening us on the desired path. Thus the teacher is like our ultimate God and we should pray and give respect to our teacher.”*

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## SUMMARY

Realising the benefits of implementing Building Information Modelling (BIM) tools and processes on projects worldwide, the architecture, engineering and construction (AEC) industry is rapidly moving towards BIM adoption. This calls for higher levels of interoperability amongst existing design and analysis tools used by various project team members. An approach to achieving higher levels of BIM maturity and interoperability is to adopt open, non-proprietary data exchange standards such as the Industry Foundation Classes (IFC). Efforts are currently underway to establish IFC-compliance in analysis tools.

Establishing interoperability between architectural BIM models and energy analysis tools has been a challenging effort. With the industry chasing renewable energy targets for existing and new building stock, it becomes imperative to incorporate analysis tools for renewable energy systems (RES) in this effort. A plethora of tools are used by the project team to assess the performance of various RES in existing buildings or in post-design stages of new buildings. A holistic RES simulation tool is required that can assess various RES and their impact on the building's energy consumption, carbon emissions and operational costs. Developing this tool's interoperability with architectural BIM models would lead to higher adoption.

The aim of this thesis is to develop a methodology to support renewable energy simulation by using architectural BIM models based on open data exchange standards thereby enhancing their interoperability. The research process involved a literature review of the existing RES analysis methods and approaches of developing IFC-compliant analysis tools. A methodology was developed that involved a standardised conceptual framework that can be used to establish compliance in RES analysis tools with open-data exchange schemas. The conceptual framework was implemented in a solar PV simulation model by means of a prototype. The prototype was validated against existing PV analysis tools and presented to industry experts to gain their feedback. It was concluded that the tool supported RES assessment of buildings in early design stages and could be widely adopted as a BIM tool by the AEC industry.

## LIST OF PUBLICATIONS

The following conference papers are published by the author:

- Gupta, A., Hopfe, C. J. and Rezgui, Y. 2011. A low-energy retrofit study of an off-gas Welsh village using renewable energy simulation combined with the UK Standard Assessment Procedure. In: 12th Conference of International Building Performance Simulation Association. Sydney, Australia.
- Gupta, A., Hopfe, C. J. and Rezgui, Y. 2011. Building integrated vegetation as an energy conservation measure applied to non-domestic building typology in the UK. In: 12th Conference of International Building Performance Simulation Association. Sydney, Australia.
- Gupta, A., Hopfe, C. J. and Rezgui, Y. 2012. BIM and Solar PV modelling In: ECPPM 2012-eWork and eBusiness in Architecture, Engineering and Construction. London. Taylor & Francis Group.
- Gupta, A., Cemesova, A., Hopfe, C.J., Rezgui, Y., Sweet, T. 2013. Development of a solar PV simulation tool compatible with the Industry Foundation Classes. In: 13th Conference of International Building Performance Simulation Association. Chambery.

The author is currently involved in publishing the following journal publications:

- Gupta, A., Cemesova, A., Hopfe, C.J., Rezgui, Y., Sweet, T. 2013. A conceptual framework to support solar PV simulation using an open-BIM data exchange standard. *Submitted to Automation in Construction journal.*
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## LIST OF ABBREVIATIONS AND SYMBOLS

The following abbreviations and symbols have been used in this thesis

AEC	Architecture, Engineering and Construction
AIM	Architectural Information model
API	Application Programming Interface
ASHP	Air Source Heat Pump
BCU	Birmingham City University
BIM	Building Information Modelling
BPS	Building Performance Simulation
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BrIM	Bridge Information Model
BSI	British Standards Institution
BSIM	Building Services Information Model
CAD	Computer Aided Design
CEN	European Committee for Standardisation
CHP	Combined Heat and Power
CIBSE	Chartered Institute of Building Services Engineers
CIC	Construction Industry Council
CIS/2	CIMsteel Integration standard
COBie	Construction Operations Building Information Exchange
CPIC	Construction Project Information Committee
CSH	Code for Sustainable Homes
CSV	Comma Separated Value
EDP	Early Design Phase
eeBIM	energy extended BIM
EPBD	European Performance of Buildings Directive
ER	Exchange Requirements
ESBO	Early Stage Building Optimization
FIM	Facilities Information Model
FiT	Feed-in-Tariff
FM	Facilities Management
gbXML	Green Building XML
GHG	Green House Gas
GIS	Geographic Information System
GSA	General Services Administration
GSHP	Ground Source Heat Pumps
GUI	Graphical User Interface
H&SF	Health and Safety file
HUT-600	Helsinki University of Technology Auditorium Hall 600

iBIM	Integrated BIM
ICT	Information and Communications Technology
IDA ICE	IDA Indoor Climate and Energy
IDE	Integrated Development Environment
IDM	Information Delivery Manual
IDR	Input Data Requirements
IES-VE	Integrated Environmental Solutions- Virtual Environment
IFC	Industry Foundation Classes
IFC2x3-TC1	IFC2x Edition 3 Technical Corrigendum 1
IFD	International Framework of Dictionaries
IPD	Integrated Project Delivery
LBNL	Lawrence Berkley National Laboratory
LCBP	Low Carbon Buildings Program
LZC	Low and Zero Carbon
MEP	Mechanical Electrical Plumbing
MOB	Medical Office Building
MVD	Model View Definition
NASA	National Aeronautics and Space Administration
NASA SSE	NASA Surface meteorology and Solar Energy website
NBIMS	National BIM standard
NBS	National Building Specifications
NHBC	National House Building Council
NIBS	National Institute of Building Sciences
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
O&MM	Operations and Maintenance Manual
ODF	Output Data File
PM4D	Product Model and Fourth Dimension
PV	Photovoltaic
RES	Renewable Energy Systems
RHI	Renewable Heat Incentive
RHPP	Renewable Heat Premium Payment
RIBA	Royal Institute of British Architects
ROI	Return on Investment
SAP	Standard Assessment Procedure
SBEM	Simplified Building Energy Model
SIM	Structural Information Model
SPF	STEP based Physical File
SQL	Structured Query Language
TMY	Typical Meteorological Year
TRY	Test Reference Year

WBEA	Whole Building Energy Analysis
XML	eXtensible Mark-up Language
$E_p$	Energy generated by PV array
$f$	Modulating factor
$G_o$	Extraterrestrial horizontal radiation
$G_{sc}$	Solar constant (1367 W/m <sup>2</sup> )
$H$	Global horizontal radiation
$H_b$	Beam radiation
$H_d$	Diffused solar radiation
$H_T$	Tilted radiation
$K_T$	Clearness Index
$n$	Day Number
NOCT	Nominal Operating Cell temperature
$P$	Module peak power
$R_b$	Ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface
$S_M$	Optimum tile angle
$t$	Solar time
$T_a$	Ambient Temperature
$T_C$	PV cell temperature
$T_r$	Reference Temperature (25 °C)
$\beta$	Slope
$\beta_p$	temperature co-efficient of module efficiency
$\gamma$	Azimuth
$\delta$	Solar Declination
$\eta_p$	Module efficiency at cell temperature
$\eta_r$	PV module efficiency at reference temperature
$\theta$	Incidence Angle
$\theta_z$	Incidence Angle at Zenith
$\rho_g$	Ground Albedo
$\psi$	Latitude
$\omega$	Solar Hour angle
$\omega_s$	Sunset hour angle



## CHAPTER 1. INTRODUCTION

The UK Government Construction Strategy report announced the government's intention to require collaborative 3D Building Information Modelling (BIM), with all project and asset information, documentation and data being electronic, on its projects by 2016 (UK Cabinet Office 2011). Additionally, the government has set up an ambitious environmental policy that all new homes and new schools to be zero carbon by 2016, all public sector buildings reach zero carbon by 2018 and potentially all new buildings by 2019 (DCLG 2006; King and Clare 2008). The integration of onsite renewable energy systems (RES) is encouraged to deliver zero carbon homes in the UK (Spencer 2007). In order to achieve these targets, it is integral to assess the performance of renewable energy technologies throughout the building design process. This would ensure that the building's orientation, design, location, and structure are optimised at an early design stage to enhance the performance of RES.

BIM authoring tools have limited capabilities of predicting the performance of RES against the building's energy consumption (Dubois and Horvat 2010). There are various tools for RES modelling used by energy modellers separately from the BIM model to assess the renewable energy generation potential of their projects (Markvart and Castaner 2005). These tools involve a scientific basis in their simulation algorithms and the level of building information detail required as input data. The current practice predominantly involves collecting this building information from a variety of sources and manually transforming this information into the specific input required by energy simulation (Gupta et al. 2011). However, there have been recent efforts to enhance interoperability between architectural BIM and energy simulation and currently is an active research area (TUD 2011; buildingSMART Finland 2012b; LBNL 2013).

However, certain input data can be extracted from the BIM model, reducing the need for the energy modeller to repeat the often erroneous data re-entry process particularly involving building geometry. This data re-entry process can be eliminated by developing interoperability between BIM model and existing RES simulation models by using a data-exchange standard. RES simulation tools also require non-geometric data such as climate and technical specifications of RES components to meet their simulation requirements. These inputs are provided externally to the BIM model.

Hence, an integrated design approach can be developed by using information contained within the BIM model and external data repositories for climate and technical data of RES components that aids in energy analysis of various RES, thereby helping the client in making an informed decision of integrating RES within the building design.

## 1.1 Problem Description

### 1.1.1 Renewable Energy Systems integration in buildings

European policies to mitigate climate change have set ambitious goals for energy and carbon reduction in the built environment (European Commission 2008). In particular, the EU renewable energy directive has set targets for all member states, such that the EU will reach a 20% share of energy from renewable sources by 2020 and a 10% share of renewable energy specifically in the transport sector (European Parliament 2009a). The directive also sets out targets for each member state for example; the UK is directed to achieve 15% of its energy consumption from renewable sources by 2020 (European Parliament 2009b). Subsequently, the UK Renewable Energy Strategy (UK Government 2009) outlined scenarios of meeting this legally binding target by generating at least 30% of the country's electricity and 12% of heat from renewables. The strategy also outlined the provision of financial support for renewable electricity and heat worth around £30 billion between 2009 and 2020. This led to the introduction of Feed-in-Tariff (FiT) in 2010 and Renewable Heat Incentive (RHI) in 2011, to provide guaranteed payments to individuals, business and communities for renewable heat and small scale electricity.

Buildings, in the UK, account for 35% of the total green house gas (GHG) emissions arising from business, industrial, public and residential sectors (Thistlethwaite et al. 2012). In December 2006, the UK government had set up an ambitious environmental policy that all new homes and new schools to be zero carbon by 2016, all public sector buildings reach zero carbon by 2018 and potentially all new buildings by 2019 (DCLG 2006; King and Clare 2008). The government's commitment to this target was further reaffirmed in the UK Budget 2013 announced by the Chancellor George Osborne (UKGBC 2013). This also conforms with the renewed obligation of EU member states of moving towards new and retrofitted nearly-zero energy buildings by 2020 (2018 in the case of Public buildings) under the recast European Performance of Buildings Directive (EPBD) (European Parliament 2010). Although, the revised definition of 'zero-carbon' is still being investigated (McLeod et al. 2012a), it supported the use of on-site low and zero-carbon technologies for achieving carbon compliance (BIS 2011). The revised definition included the emissions covered by the building regulations (heating, fixed lighting, hot water and building services) and encouraged the uptake of solar PV, solar thermal, heat pumps and biomass heating technologies.

The uptake of RES systems however in reality has not been consistent especially after the financial incentives were announced by the UK government. Over 358,338 PV installations in the UK were reported from April 2010 till December 2012 (Ofgem 2013). However, only 9445 installations were for mostly retrofitted non-domestic properties. In the period August 2011-March 2013, only 1511 biomass boiler installations and 191 heat pump installations were reported in non-domestic properties.

Environmental standards such as Building Research Establishment Environmental Assessment Method (BREEAM) and Code for Sustainable Homes (CSH) have special provisions for the inclusion of low and zero carbon (LZC) technologies. In order to achieve higher levels of the CSH one of the main factors is to consider integrating renewable energy technologies into the overall design concept from the earliest design phases (DCLG 2012). There are various RES simulation tools in the market (Connolly et al. 2010) that are used in an ad-hoc manner to determine renewable energy potential of projects. There is a lack of simple tools that can quantify and illustrate the influence of various solar applications, at the early design stages (Wall et al. 2008). At the design stage, the building shape, massing, material type and orientation can be optimised to gain maximum benefit from the use of LZC technologies. This would further contribute in meeting the government's ambitious targets in renewable energy adoption and zero-carbon buildings.

### 1.1.2 BIM and the building design process

Building Information Modelling (BIM) has gained widespread attention in the architecture, engineering and construction (AEC) industries in the past years (Azhar et al. 2008). Majority of architecture and construction firms have their transitions from Computer Aided Design (CAD) to BIM well underway (NBS 2013). It is the process of generating and managing data and information about a building during its entire life cycle from concept design to decommissioning (Howard and Bjork 2008). Hence, it is imperative to adopt BIM in the building design process.

The adoption of BIM could result in many benefits as seen by BIM-users in the UK (Figure 1.1).

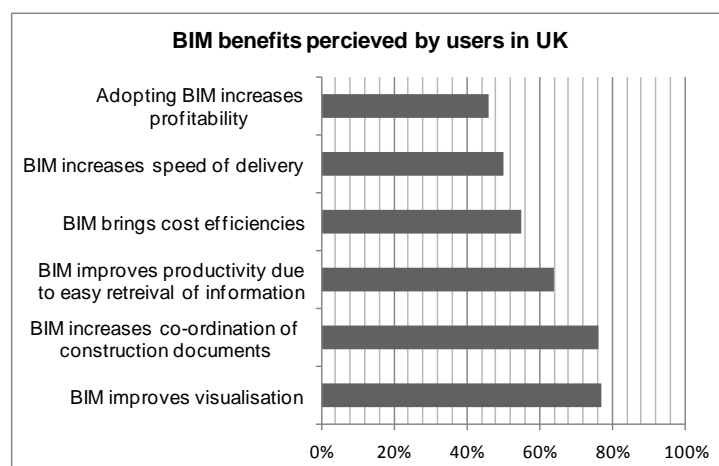


Figure 1.1 BIM benefits perceived by users in the UK (NBS 2013)

While 77% of the BIM users agree that BIM improves visualisation, more importantly it is seen that it increases co-ordination of construction documents (76% agree) and improves productivity due to easy retrieval of information (64%). Hence, half the users agree BIM increases speed of delivery and 55% agree that BIM brings cost-efficiencies (NBS 2013).

Financial savings achieved has been seen worldwide by key BIM-adopting countries. 71% of UK, 82% of French, 67% of German and 63% of North American adopters have perceived a positive return of investment by adopting BIM (McGraw-Hill Construction 2010)(Figure 1.2).

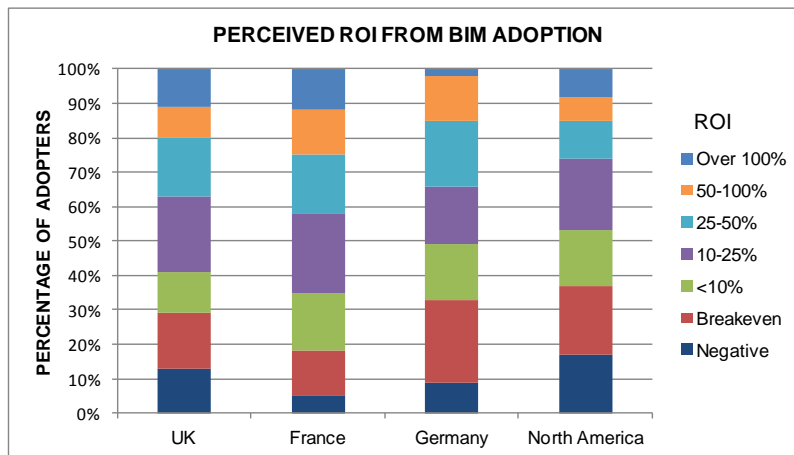


Figure 1.2 Perceived ROI from BIM adoption in different countries (McGraw-Hill Construction 2010)

In the UK, the definition and applications of BIM in the design process is still ambiguous. The UK government has introduced levels of BIM maturity and made it mandatory for all public sector projects to adopt fully collaborative BIM level '2' by 2016 (UK Cabinet Office 2011). In order to reduce the ambiguity, the Royal Institute of British Architects (RIBA) published a BIM overlay to RIBA Plan of work that outlines what is expected from BIM at every stage of the building design and construction process (Sinclair 2012). Sinclair (2012) believes that architects have a central role to play in ensuring that the construction industry responds to the opportunities offered by BIM in both public and private sectors.

Architects first used BIM models for 3D visualisations of their projects. With advances in technology, various tools that were used by architects for daylight analysis, shading studies, energy and carbon emissions analysis, etc. were made interoperable with BIM models. Further development in BIM processes and software encouraged collaboration between all professional domains of a project team with BIM models being created for architectural, structural and MEP digital 3D representations of buildings. Various proprietary tools in the market provide interoperability across all domains developed by the same software vendor (Autodesk 2013; Bentley Systems Inc 2013). The UK construction industry is also following this trend of using proprietary suite of tools developed by a vendor that ensures interoperability across all domains as an approach towards BIM adoption in their projects (Draper et al. 2013).

Considering that proprietary solutions will always diverge, in order to adopt fully-collaborative BIM past Level 2, the main requirement will be software interoperability using open-BIM standards such as the Industry Foundation Classes (IFC) (NBS 2013).



### **1.1.3 BIM and RES assessments**

There are various state-of-the-art system design tools for RES in the market (Connolly et al. 2010). Tools like TRNSYS can model nearly 12 identified renewable energy technologies, previous work suggests that the tool is neither easy to use in conceptual design nor is interoperable with the BIM model (Acquaviva et al. 2012). Standalone simulation tools like RetScreen version 4 (RetScreen International 2005) and HOMER 2 version 2.81 (Khan and Iqbal 2005) are used for preliminary analysis of renewable energy generation potential of their projects (Gupta et al. 2011). Additionally, for detailed system design there are standalone tools specific for analysis of each renewable energy technology. For example, PV\*Sol Pro (Valentin EnergieSoftware 1992), PVsyst (version 5.64) (PVsyst SA 2012), PVWatts (version 1) (NREL 1999), etc. for solar PV simulation; T-Sol Pro (Valentin EnergieSoftware 2011), TRNSYS (version 17) (University of Wisconsin 1975), etc. for solar thermal simulation; Geo-TSol basic (Valentin EnergieSoftware 2013) for design of heat pumps, and various guidance tools available through manufacturers and other organisations for sizing of biomass boilers. However, to the author's knowledge none of these tools are BIM or IFC compliant.

RES simulation is often a subset of building performance simulation (BPS) tools or Whole Building Energy Analysis (WBEA) tools. For example, Integrated Environmental Solutions Virtual Environment (version 5.9) (IES ve) does preliminary energy analysis of solar PV, CHP, solar thermal for domestic hot water and wind turbines (Integrated Environmental Solutions Limited 2011). IESve is interoperable with BIM through the gbXML data exchange standard. Energy simulation tools like RIUSKA (Granlund 2004) and IDA Indoor Climate and Energy (version 4) (Equa 2013) have been proven to be IFC compliant that conduct energy analysis of the building, however, since the tools are more focussed toward heating and cooling energy simulations and indoor comfort analysis, they have limited renewable energy simulation capability (Crawley et al. 2008). An effort has been made to make EnergyPlus 'IFC-compliant' by developing an IFCtoIDF Transformation Utility, that transforms building geometry in an IFC building model into an Input Data File (IDF) to run EnergyPlus simulations (Hitchcock 2000). Energyplus can conduct detailed energy analysis of solar PV, solar thermal, heat pumps wind turbines (US DOE 2013b). However, it lacks a graphical interface, due to which a number of proprietary user interfaces have been developed that range from being simple to complex and can handle various types of CAD or BIM imports (US DOE 2013a).

Past efforts have shown ad-hoc approaches in developing interoperability between RES simulation tools and BIM models. Interoperability between BIM and RES has been established through BPS tools which lack in holistic RES assessment. Existing standalone RES tools that conduct system sizing and financial analysis are not interoperable with BIM. There is a lack of tools in the market that conduct holistic assessment of RES in terms of savings achieved in energy consumption, carbon emissions and financial analysis.

In order to adopt various levels of BIM maturity there is a need for RES tools to be interoperable with the BIM model. As the construction industry worldwide embraces BIM in the building design process and is headed to achieve renewable energy targets, it is integral to develop approaches in making RES tools interoperable with BIM models in order to build zero-carbon buildings of the future.

## **1.2 Motivation for thesis**

The author was involved in a number of renewable energy assessment studies of existing and new buildings during the course of this thesis along with the Building Research Establishment (BRE). These projects have been motivational case studies for the thesis. They provide evidence that firstly, there is a lack of a holistic RES tools in the market due to which ‘mixing and matching’ of software tools is conducted to complete a renewable energy assessment for all available technologies. And secondly, there is a need for interoperability between various software tools used in renewable energy assessments.

### ***1.2.1 A low-energy retrofit study of an off-gas Welsh village***

In UK, residential and commercial heating is supplied through the mains gas network. However, there are a number of villages that are cut-off from the gas network deemed as ‘off-gas’. The author was involved in conducting a renewable energy assessment for a local authority for one of their off-gas villages. The village mainly consisted of pre-1919 solid wall dwellings that are ‘hard-to-treat’<sup>1</sup> in terms of energy efficiency.

The consultancy team had no data for conducting energy simulation available for the village. Geometric data involving the dwellings’ dimensions were obtained through traditional surveying methods. The housing typology was mapped by a visual survey. A house to house survey was conducted to assess the existing energy profile of the house; for example, type of heating system, annual fuel bills, occupancy profile, etc. The data collected lacked the level of complexity required for conducting dynamic energy simulation through BPS tools. Hence, the method chosen to assess the existing energy consumption and impact of energy efficiency and renewable energy measures, was the UK’s Standard Assessment Procedure (SAP 2009) (BRE 2011a). For RES simulation various limitations of SAP have been identified in the past (Gupta et al. 2011; Murphy et al. 2011). Hence, Solar PV assessment was conducted in PV\*Sol (Valentin EnergieSoftware 1992) and Wind turbine assessment in RetScreen (Natural Resources Canada 2011) software. Due to lack of tools and the required input data for detailed simulations, energy calculations were conducted in SAP for the assessment of

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<sup>1</sup> A ‘hard-to-treat’ dwelling, a UK terminology, is defined as one that, for whatever reason, cannot accommodate ‘staple’ or cost-effective fabric energy efficiency measures. Examples include dwellings with solid walls, dwellings off the gas network, dwellings with no loft and high-rise flats.

biomass heating and heat pumps. The financial assessment for all solutions was done using RetScreen spreadsheets.

The house-house survey took around two days, and since many tools were used the task was divided amongst consultants as per their expertise such SAP, EnergyPlus calculations and RetScreen and PV\*Sol calculations. These calculations were conducted simultaneously by three consultants and took around 3 weeks as all input data was not provided and had to be assumed and measured against benchmarks. The report writing took further one-two weeks. In total four tools were used along with spreadsheets for financial calculations and the process proved to be quite cumbersome as all the input data required (surveyed drawings of houses, technical data for RES, etc.) was not readily available.

### ***1.2.2 Renewable heating assessment of a block of flats***

The author was also involved in conducting a renewable heating feasibility assessment of a block of flats currently using electric heating. The building was built in 1995, however, CAD drawings were not available for an accurate energy assessment. Geometric data for simulations were obtained through traditional methods of surveying the building. Visual survey helped in identifying door and window type. Interviews with occupants revealed their occupancy profile, heating schedules, comfort temperatures, DHW consumption, etc. Due to lack of data, the building fabric characteristics (thermal conductivity of building elements) were assumed as defaults in the 1995 building regulations. All data was collected to conduct a dynamic energy simulation in order to determine the heating demand for sizing of the heating system. The simulation was conducted using Designbuilder which uses EnergyPlus (Crawley et al. 2001) as its simulation engine. Two renewable energy technologies, Biomass boilers and Ground Source Heat Pumps (GSHP) were assessed. System sizing for biomass was conducted using various guidance documents provided by British Standards Institution (BSI), European Committee for Standardisation (CEN), Carbon Trust, and Chartered Institute of Building Services Engineers (CIBSE). A preliminary feasibility of heat pumps was conducted using heat pump installers' experience that deemed them unviable due to requirements of occupants for high comfort temperatures and heating to be available 'on-demand'. GeoT\*Sol was identified as a simulation tool for sizing and performance assessment of GSHP. Due to time and financial constraints, the detailed system design of GSHP was not conducted. The financial analysis including system costs and income from renewable heating was done using RetScreen spreadsheets.

This property was around 2300 m<sup>2</sup> and it took two days to survey and make measured drawings of the property. Due to the large scale of the building the calculations in Designbuilder proved to be quite cumbersome since it could not handle large file sizes and took around 8-10 hours to run simulations. Simulations were left overnight to get results in the morning. As a workaround, the building model was divided into three distinct parts and stored as separate files which reduced the file size. Since only renewable heating systems was

considered in this project, Designbuilder and RetScreen were used for all calculations. Due to lack of credible tools in biomass system design, various guidance documents were used, that took up the consultant's time. Around two weeks were spent on building the model in Designbuilder and run calculations and another two weeks for financial calculations and report writing.

### ***1.2.3 Renewable energy solutions for an off-grid farmhouse***

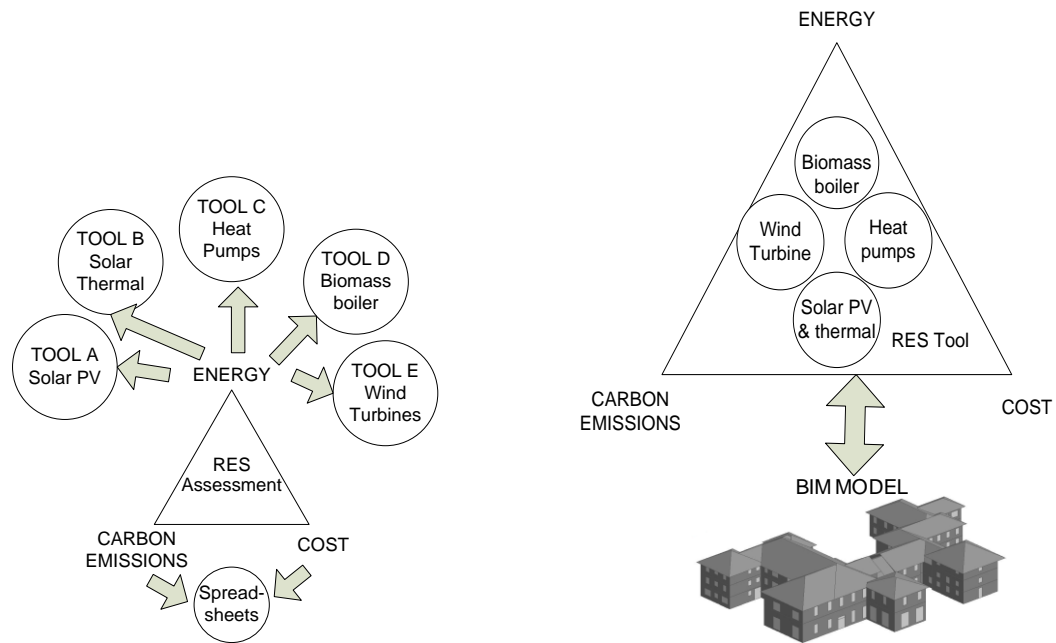
Renewable energy solutions for a new-build farmhouse in a location with no water, power, heating or sewage supply was to be devised by the project team. The farm house constructed in 2013 needed to achieve Code Level '3' of the CSH as a mandatory requirement of new-build dwellings. As it was new-build, detailed information about the dwelling was made available to the consultancy team along with complete set of CAD drawings. A BIM model was not available for the dwelling. However, the CAD drawing was available to be imported in Designbuilder for energy simulations. The 3D model of the house in Designbuilder was easier to build with the imported CAD file. The heating demand and renewable energy options were determined using the same methodology as the above case studies. However, since the house was not connected to the electricity grid, a battery storage system with a diesel generator back up had to be included in this case study. They were sized using installers' past experiences and industry rule of thumb. GSHP were excluded from the assessment as the topography was not suitable for their installation. The solution included solar PV for electricity and biomass boilers (log-boiler) for heating.

The availability of CAD drawings made it easier to assess the project for RES options in Designbuilder. Lack of credible tools was found for off-grid applications due to which guidance was sought from installers' past experiences and industry rule of thumb. The energy model was built and analysed within a week, but finding the various guidance documents, using them for the project, and subsequent analysis of result and report writing took further three-four weeks.

### ***1.2.4 Discussion***

The above case studies show the current approaches of integrating RES within buildings both existing and new-build. There is a lack of RES tools that can be used for a complete assessment of all renewable energy technologies in terms of energy, carbon emissions and financial analysis. The current approach of RES assessment includes using a variety of tools some of have either a statistical, steady-state or dynamic simulation logic (Figure 1.3). These tools also lack in interoperability with respect to importing geometric data of buildings. This approach costs a lot of time and effort from consultants. The key factor in enhancing interoperability of these tools would be by adopting open-BIM data exchange standards that contain data of the complete building life-cycle starting with building geometry. Also, a

holistic RES simulation tool is required that can assess all building integrated renewable energy technologies and their impact on the building's energy consumption, carbon emissions, construction and operational costs (Figure 1.3).



**Figure 1.3 Existing (left) and proposed (right) RES integration methods**

With the proliferation of BIM in architectural design there is an increasing need to create accurate as-built BIM data for existing buildings (Woo et al. 2010). The development of as-built BIM models of existing buildings is an active research area (Tang et al. 2010; Diaz-Vilarino et al. 2012). Current environmental standards and legislation have driven the demand of sustainable-retrofit solutions for existing buildings. As and when the creation of as-built BIM models are standardised, there would be a need for interoperability between various energy analysis (including RES) tools and as-built BIM models.

### 1.3 Hypothesis

The hypothesis of this research is that existing open-BIM data exchange standards can be used *in their current state*, by virtue of a *methodology*, that *enhances interoperability* between building architectural BIM models and RES systems analysis, thereby *facilitating decision-making* and encouraging early integration of renewable energy technologies in the building design process.

### 1.4 Aims and Objectives

The aim of this thesis is to develop a methodology to support renewable energy simulation by using BIM models based on open-BIM data exchange standards thereby enhancing their interoperability. This methodology is envisioned to encourage the adoption of renewable

energy technologies in early design process thereby facilitating the development of ‘zero-carbon’ buildings.

The objectives of the thesis supporting the aim are as follows;

1. Conduct a ‘state-of-the-art’ literature review on BIM, existing data exchange standards and renewable energy simulation tools.
2. Identify a problematic area in interoperability between BIM and renewable energy simulation tools.
3. Develop a methodology that can be used to enhance the interoperability between open-BIM and renewable energy simulation tools, thereby making these tools ‘BIM-compliant’
4. Implement this methodology and develop a prototype with a user interface.
5. Test and validate the prototype using a case study.
6. Present the prototype to a target audience in order to gauge the need and usability of the prototype and determine future work.

The main results of this thesis will be a) a methodology that can be implemented to enhance the interoperability between open-BIM and RES simulation models b) a prototype which would be validated against existing tools and c) analysis of the benefits, limitations and future development of the prototype based on expert opinion.

## 1.5 Research Questions and Methods

In support of the aforementioned aims and objectives the thesis endeavours to answer the following research questions;

**Question 1 (RQ1):** *What is the current methodology used by the project team to integrate renewable energy technologies in the early design phases?*

Answering RQ1 involves the following research method:

- Analysis of industry practice in which the author was directly involved using a qualitative method ‘*Action research*’ (Burns 2000) (Chapter 1; section 1.2).

**Question 2 (RQ2):** *What are the benefits of integrating BIM in the design process?*

**Question 3 (RQ3):** *What are the current methods in BIM adoption?*

Answering RQ2 and RQ3 involves the following research method:

- Analysis of the drivers, benefits and barriers in BIM adoption through a literature review (Chapter 2; section 2.2).
- Analysis of BIM adoption approaches worldwide through a literature review and case studies from industry (Chapter 2; section 2.2.3).

**Question 4 (RQ4):** *How are existing RES tools integrated with BIM and the building design process?*

**Question 5 (RQ5):** *What are the main requirements for rapid adoption of RES in buildings?*

Answering RQ4 and RQ5 involves the following research method:

- Analysis of drivers, benefits and barriers in RES integration in buildings through literature review and online survey (Chapter 3; sections 3.1-3.3).
- Analysis of ‘state-of-the-art’ RES and BPS tools used for RES simulation, their interoperability with CAD/BIM model and integration in the building design process through a literature review (Chapter 3; section 3.4).
- Synthesis of a structure of RES simulation model and capturing its input data requirements (Chapter 3; section 3.4.4).

**Question 6 (RQ6):** *How can interoperability with BIM models support RES assessment of buildings?*

Answering RQ6 involves the following research method:

- Analysis of interoperability standards and their implementation through literature review and case study (Chapter 4; section 4.1-4.3)
- Analysis of existing BIM-compliant analysis tools and their development approaches through a literature review (Chapter 4; section 4.4-4.5).

**Question 7 (RQ7):** *How can a methodology based on public (open-BIM) data exchange standards be developed and implemented to make RES tools interoperable with BIM models?*

Answering RQ7 involves the following research method:

- Development of a methodology to enhance interoperability between open-BIM and RES simulation (Chapter 5; section 5.1).
- Implementation of this methodology on a RES simulation tool (Solar PV) by developing a prototype (Chapter 5; section 5.2-5.3).
- Validation of the prototype against existing RES tools to test the simulation model (Chapter 6; section 6.1).
- Analysis of the interoperability achieved between open-BIM and RES through the prototype (Chapter 6; section 6.1-6.2).

**Question 8 (RQ8):** *Does the developed prototype support the design team? What can be improved?*

Answering RQ8 involves the following research method:

- Analysis of the prototype’s applicability in practice by presenting it to a target audience (Chapter 7).
- Quantitative and qualitative analysis of the responses of the target audience (Chapter 7).

Chapter headings, objectives, research questions and associated research methods have been summarised in Table 1.1.



**Table 1.1 Summary of thesis chapters, related aims, objectives, research questions and methods**

Chapter	Title	Objective	Research Questions	Research Methods
1	Introduction	Formulation, problem description, hypothesis, research questions	What is the current methodology used by the project team to integrate renewable energy technologies in the early design phases?	Literature review Industry Practice 'Action research'
2	BIM and its adoption	Analysis of BIM adoption approaches worldwide	What are the benefits of integrating BIM in the design process? What are the current methods in BIM adoption?	Literature Review Case studies
3	Overview of Renewable Energy Systems (RES)	Analysis of 'state-of-the-art' RES and BPS tools used for RES simulation; Drivers, benefits and barriers in RES integration in buildings	How are existing RES tools integrated with BIM and the building design process? What are the main requirements for rapid adoption of RES in buildings?	Literature Review Online survey
4	Interoperability between BIM and RES simulation tools	Analysis of interoperability standards and existing approaches in developing BIM-compliant analysis tools. Expert's opinion on the consequences of integration of BIM tools and RES simulation	How can interoperability with BIM models support RES assessment of buildings?	Literature Review
5	RenewBIM-compliant simulation tool	IFC-RES Development of a methodology to enhance interoperability between open-BIM and RES simulation. Implementation of this methodology on a RES simulation tool	How can a methodology based on public (open-BIM) data exchange standards be implemented to make RES tools interoperable with BIM models?	Prototype development
6	RenewBIM validation and case studies	Validation of the prototype against existing RES tools. Analysis of interoperability achieved between open-BIM and RES through the prototype		Prototype testing through case study; Quantitative analysis
7	Usability testing		<i>Does the developed prototype support the design team? What can be improved?</i>	Online Survey, quantitative and qualitative analysis
8	Conclusion and Future work	Summary of the development of methodology, RenewBIM tool, findings, expert feedback and future work		

## 1.6 Thesis Outline

The research presented in this thesis concerns the field of renewable energy simulation and building information modelling and the importance of their integration in the building design process. These fields underlie all research activities reported focussing on software interoperability to improve the integration of renewables in the building design process.

The outline of the thesis is based on the following issues;

- Discussion of context and starting points for the research, based on a review of concept of BIM worldwide and RES integration with the building design process.
- Analysis of the current situation, BIM and RES adoption approaches in building design projects. Analysis of existing approaches of improving interoperability between BIM and energy/RES analysis tools (AS-IS).
- Innovation, through development of methods or processes on how to obtain improved integration of BIM and RES; thereby enhancing the integration of RES in the building design process (TO-BE).
- Realisation, through the development of a prototype that demonstrates this improved integration (PRODUCT).
- Validation, through testing against existing tools and presenting the prototype to a target audience, recording and analysing their feedback for future development (IMPROVEMENT).

Based on this structure the content of the following chapters is as follows. Chapter two reviews the concept of BIM worldwide with a special focus on the drivers, benefits and barriers in BIM adoption in the UK. Various adoption approaches in UK are analysed through BIM implementation case studies. Chapter three provides an overview of the drivers, benefits and barriers in the adoption of RES in buildings in the UK. It also analyses the extent of integration of RES simulation in the building design process through an online survey. The chapter also contains a literature review of the 'state-of-the-art' tools used for RES simulation, their level of interoperability with CAD/BIM models and their use in the building design process. Chapter four focuses on the standardisation efforts in data exchange that aims to enhance software interoperability and support the efficient design and construction of buildings. It also reviews the current approaches in improving the interoperability between BIM model and energy analysis tools. Chapter five combines the results of the research and development work of chapter two, three and four into a methodology to support renewable energy simulation by using open-BIM data exchange standards in order enhance their interoperability. This is the underlying aim of the thesis. The chapter also shows the development of prototype tool 'RenewBIM', as a 'proof-of-concept' demonstrating the implementation of the methodology. Chapter six contains the testing procedure of 'RenewBIM', validating the tool against existing RES tools in the market using a case study. The chapter also highlights the challenges encountered in the open-BIM standard implementation process. Chapter seven validates the prototype by presenting it to a target

audience and analysing their responses both qualitatively and quantitatively. And finally, Chapter eight completes this thesis by providing a summary of work involving the development of methodology and prototype implementation, conclusion of research, discussion of future work based on expert opinion.

The overall thesis structure is represented by Figure 1.4.

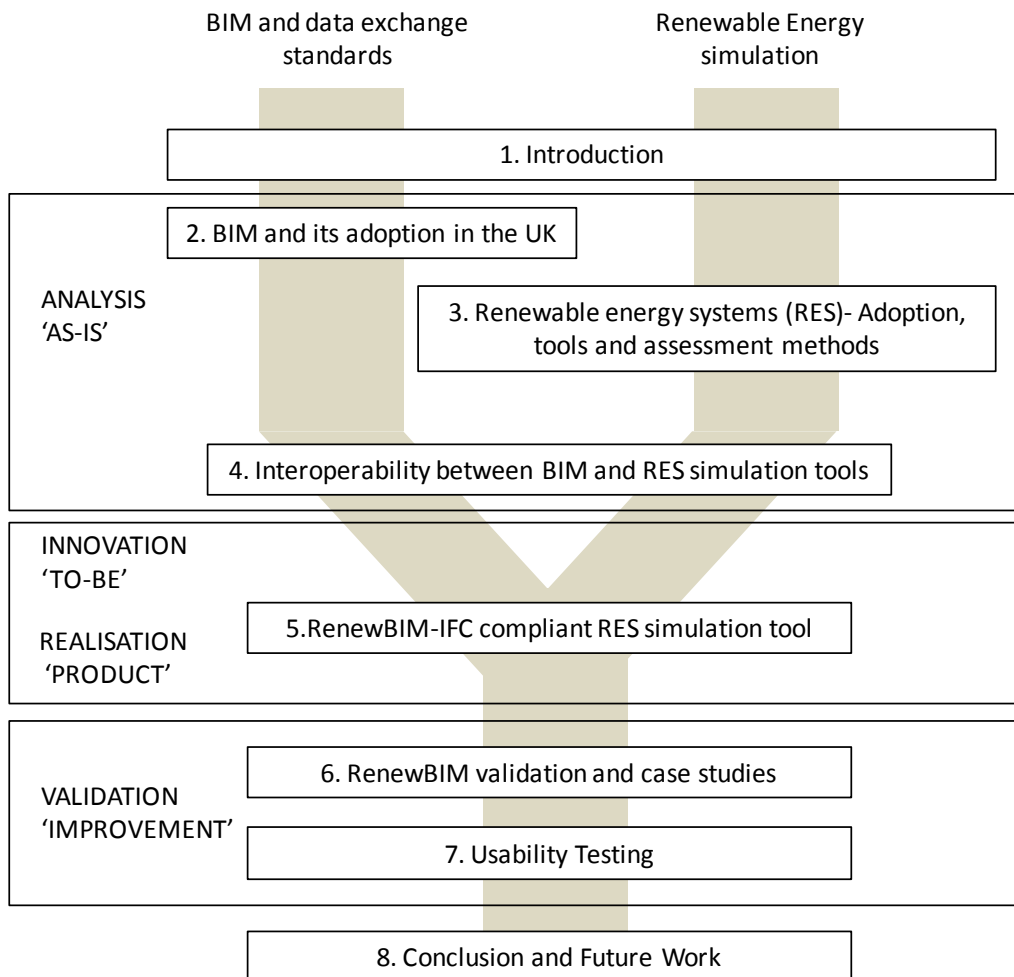


Figure 1.4 Structure of the thesis

## **CHAPTER 2. BIM AND ITS ADOPTION**

Building Information Modelling (BIM) is the process of generating and managing data and information about a building during its entire life cycle from concept design to decommissioning (Howard and Bjork 2008). It is a digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition (NBIMS 2006; Snook 2009). Hence, to gain maximum benefit, BIM should be adopted early on in the building design process.

BIM has gained widespread attention in the architecture, engineering and construction (AEC) industries today (Azhar et al. 2008). Majority of architecture and construction firms have their transitions from CAD to BIM well underway (NBS 2013).

However, in the UK, the definition and application of BIM still remain ambiguous. After the UK government made it mandatory for all public sector projects to adopt BIM by 2016, key institutions in the construction industry published guidance documents on definition and application of BIM in the design process, changes in the associated legal frameworks for projects adopting BIM and the impact of BIM adoption in the house-building sector.

The chapter starts with definition of Building Information Models and various associated authoring tools (section 2.1). It then follows with a review of the drivers, barriers and benefits in BIM adoption focussing on the UK construction industry (section 2.2). The BIM benefits and adoption approaches are then captured through implementation case studies (section 2.3).

### **2.1 Building Information Models**

Building Information Models, henceforth referred to as BIM models, are repositories of project information populated using a BIM authoring tool. BIM authoring tools are based on object-based parametric modelling system where objects or components represented with digital representations that carry computable graphic and data attributes that identify them to software applications; as well as parametric rules that allow them to be manipulated in an intelligent fashion (Eastman et al. 2011). BIM authoring tools are embedded in BIM platforms that can generate data for multiple uses. Different tools and platforms combine within an organisation to form a BIM environment.

BIM models are characterised by components that include data that describe their behaviour as needed for analyses and work processes; for example, quantity takeoff or energy analysis. BIM models contain consistent and non-redundant data such that changes to a component data are represented in all views of a component and the assemblies of which it is a part.

BIM authoring tools currently available in the market are proprietary, owned and developed by software vendors. A state-of-the art review of BIM tools, platforms and environments has been given by Howell and Batcheler (2005) and Eastman et al.(2011).

Table 2.1 summarises the key interoperability features, strengths and weakness of commonly used architectural BIM tools Autodesk’s Revit (Autodesk 2013), Graphisoft’s ArchiCAD (Graphisoft 2013) and Bentley Systems’ Bentley Architecture. In Table 2.1, the applications marked in red are compatible with open-BIM data exchange standards (IFC and gbXML). These would be discussed in detail in Chapter 4.

Autodesk has a stronghold in the UK construction market with Revit and AutoCAD being the most widely used BIM and CAD tools respectively (Figure 2.1)(NBS 2013). It is also referred as the current market leader for BIM in architectural design (Eastman et al. 2011). Revit is a family of integrated products that include Revit Architecture, Revit Structure and Revit MEP. As a propriety solution this ensures interoperability between three domains architecture, structure and MEP through its native format, denoted (rvt).

Revit Application Programming Interface (API) released by Autodesk (latest version Revit API 2014) provides good support for external application development (Howarth 2009). Revit has an easy to use interface. Due to the author’s familiarity in using Revit and its easy availability, it has been chosen as the BIM authoring tool for this thesis. BIM models are created and Revit’s export functionality to open-BIM data exchange formats, such as IFC and gbXML, is analysed.

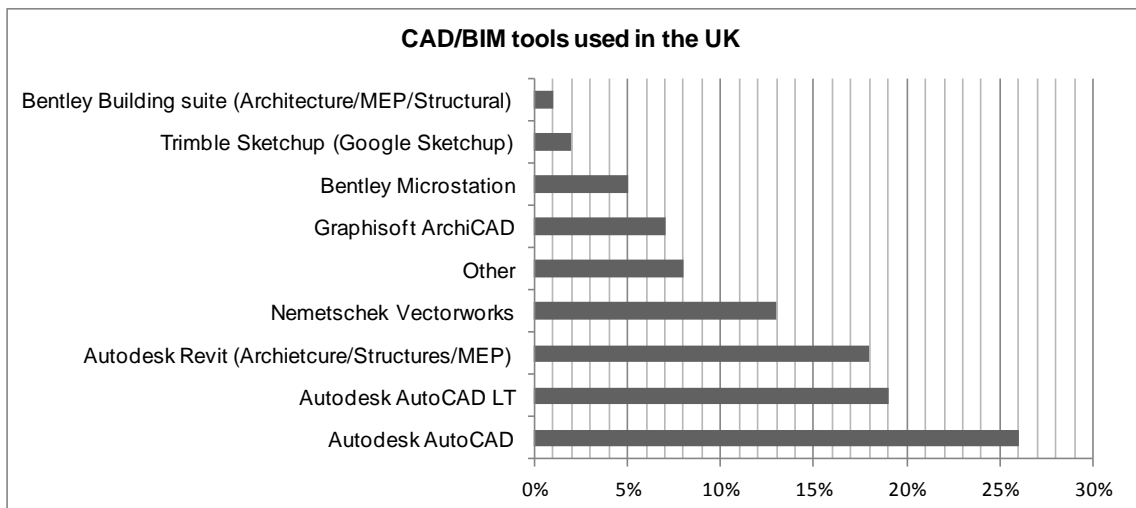


Figure 2.1 CAD/BIM tools used in the UK design and construction industry [Adapted from (NBS 2013)]

Table 2.1 Summary of BIM authoring tools

	Revit	ArchiCAD	Bentley Architecture (runs on Microstation)
Software Vendor	Autodesk	Graphisoft	Bentley Systems
Current version	Revit 2014 (released April 2013)	ArchiCAD 17 (released June 2013)	Bentley Architecture V8i (released November 2008)
Interoperability - Import & Export capabilities	<ul style="list-style-type: none"> <li>• Can import models from Sketchup, AutoDesSys form Z, Mcnell Rhinoceros, Google earth conceptual design tools.</li> <li>• Supported file formats: DWG,DXF, DGN,SAT,DWF/DWFX,ADSK,HTML,FBX,<b>gbXML</b>, <b>IFC</b> and ODBC.</li> <li>• Direct links to associated application through Revit’s Open API or using IFC and DWF. Applications include  <i>Structural Analysis:</i> Revit Structure, ROBOT, <b>RISA</b>, BIM ME SARL, ETABS Link, SismiCAD, Graitec’s Advance &amp; ARCHE, Fastrak Building Designer, StruSoft FEM-Design, SOFTEK S-Frame, STAADPRO, SOFiStiK.  <i>Mechanical:</i> Revit MEP, HyraCAD, MagiCAD, QuantaCAD, TOKMO.  <i>Energy and environmental:</i> <b>Ecotect</b>, <b>EnergyPlus</b>, <b>IES</b>  <i>Visualisation:</i> Mental Ray, 3D Max, Piranasi  <i>Facility management:</i> Autodesk FMDesktop, <b>Archibus</b></li> </ul>	<p>Direct links to associated application through ArchiCAD’s GDL or using IFC.</p> <p>Applications include;  <i>Structural:</i> <b>Tekla</b>, <b>Revit Structure</b>, Scia Engineer, <b>SAP<sup>2</sup> &amp; ETABS</b>, <b>Fem-Design</b>, <b>Axis VM</b>.  <i>Mechanical:</i> <b>Graphisoft MEP Modeler</b>, <b>AutoCAD MEP</b>, <b>Revit MEP</b>.  <i>Energy and environmental:</i> Graphisoft EcoDesigner, <b>ARCHIPHISIK</b>, <b>RIUSKA</b>, <b>Green building Studio</b>, <b>Ecotect</b>, <b>EnergyPlus</b>, <b>IES</b>  <i>Visualisation:</i> Artlantis, Lightwork Design, Maxon Cinema 4D  <i>Facility Management:</i> OneTools, ArchiFM.                      Enables file exchange and design co-ordination through TeamWork/BIM Server repository. Update capability via DELTA server. Enables management of time-stamps and object ID to track object history.</p>	<ul style="list-style-type: none"> <li>• Supported file formats: DWG,DXF, PDF,U3D, 3DS, Rhino 3DM, IGES, Parasolid, ACIS SAT, CGM, STEP AP203/AP214, STL, OBJ, VRML, Google earth KML, Sketchup, Colloada, ESRI SHP. Aso supports IFC, CIS/2 STEP and ADNF. Products are extensible and support user-defines Macros, Microsoft (VBA) .NET, C++, C#, Bentley MDL.</li> <li>• Has a well-developed multi-project server called ‘ProjectWise’. ProjectWise is file-based not object based. Supports object lds and timestamps and their management.</li> <li>• Array of AEC application tools available at Bentley that have limited compatibility against each other, includes; Speedikonm Power Civil, RAM suite,GEOPAK Civil Engineering suite, Building electrical Systems V8i for AutoCAD, Facility Information management, ConstructSim,PowerRebar,ProConcrete, STAAD, Building Mechanical Systems, Tas Simulator, Hevacomp Dynamic Simulation and Mechanical Designer.</li> </ul>

<sup>2</sup> SAP in this context is a Structural Analysis Program developed by Computers and Structures Inc. (Computers and Structures Inc 2013)

	Revit	ArchiCAD	Bentley Architecture
<b>Strength</b>	<ul style="list-style-type: none"> <li>• Strong intuitive design tool, however limitations in ‘free-form’ design</li> <li>• Well-designed, user friendly interface</li> <li>• Broad set of object libraries (SEEK) developed by Autodesk and third parties featuring 13,750 product lines (version 2011) from 850 different companies.</li> <li>• Revit API provides good support for external application development.</li> </ul>	<ul style="list-style-type: none"> <li>• Strong intuitive design tool, Well-designed, user friendly interface</li> <li>• Incorporates a broad range of predefined parametric objects. Supports the creation of custom parametric objects through its Geometric Description Language (GDL).</li> <li>• Rich suite of supporting applications in design, building, systems and facilities management.</li> </ul>	<ul style="list-style-type: none"> <li>• Supports custom parametric objects using the Parametric Cell Studio Model and Generative Components for complex parametric geometry assemblies.</li> <li>• Microstation platform applications are file-based systems, that result in lower loads on memory.</li> <li>• Provides scalable support for large projects with many objects.</li> <li>• Provides multiplatform and server capabilities.</li> </ul>
<b>Weakness</b>	<ul style="list-style-type: none"> <li>• In-memory system that slows down significantly while processing large files (larger than 300MB).</li> <li>• Limitations on parametric rules.</li> <li>• Revit 2011 lacked object-level time stamps which inhibits full object management in BIM environment.</li> <li>• Unlocking object data in BIM and easier access of data in Revit model has been the key focus area for development. The latest version addresses some of these limitations.</li> </ul>	<ul style="list-style-type: none"> <li>• Minor limitations in custom parametric modelling capabilities.</li> <li>• In-memory system that can affect processing of large files. However, this can be effectively managed using its server repositories.</li> </ul>	<ul style="list-style-type: none"> <li>• Large system of modules with lots of functionality but are partially integrated at the data consistency and user interface levels.</li> <li>• Standard set of predefined parametric objects that can only be extended through the MDL API.</li> <li>• Heterogeneous functional modules include different object behaviour, further adding to learning challenges.</li> </ul>

## 2.2 Drivers, barriers and benefits in adoption

BIM provides the basis of new design techniques and construction capabilities and often creates or changes roles in a project team (Eastman et al. 2011). It accommodates many of the functions needed to analyse the building lifecycle. With a focus on the UK, this section discusses the political drivers that pushed the UK's construction industry towards BIM adoption. It also captures the industry responses towards the announced BIM adoption strategy. It is followed by an analysis of the barriers that can be encountered and benefits already seen in projects adopting BIM.

### 2.2.1 Political Drivers for BIM adoption in the UK

A summary of various benefits of adopting BIM worldwide has been captured in Chapter 1. In order to look at the construction and post-occupancy benefits of BIM for use in the UK building and infrastructure markets, a Working Group was invited by the Cabinet Office (BIM Industry Working Group 2011). The BIM Working Group developed a maturity 'Level' index to simplify and aid understanding of BIM. The index (Figure 2.2) was created to make BIM less ambiguous for the client and keep the supply chain transparent in order to understand their offering to a project. The aim of developing the index was to articulate groups of technology, processes and their inherent capabilities.

The 'Level' index was developed by Mark Bew and Mervyn Richards in 2008 that defined the various maturity levels of BIM. It had been devised to ensure clear articulation of levels of competence expected from all disciplines for BIM adoption (BIM Industry Working Group 2011). The levels are defined from 0 to 3 with the main purpose of categorising the types of technical and collaborative working and also to provide a concise description of the techniques and tools associated with it. The maturity index produced recognises that client and their supply organisations are currently at different level of experience with their approaches to BIM and offers a structured 'learning' progression over a period of time.

"BIM Maturity" has also been defined by Succar (2010) as, "the quality, repeatability and degree of excellence within a BIM Capability." BIM Capabilities of organisations are listed in terms of three stages;

- 1) object-based modelling- Deploying an object-based modelling software tool similar to ArchiCAD, Revit, Tekla or Constructor.
- 2) model-based collaboration-The organisation needs to be part of a multidisciplinary 'model-based' collaborative project.
- 3) network-based integration- The organisation needs to be using a network-based solution (like BIM servers). BIM server is a concept that describes server used for sharing building design data.



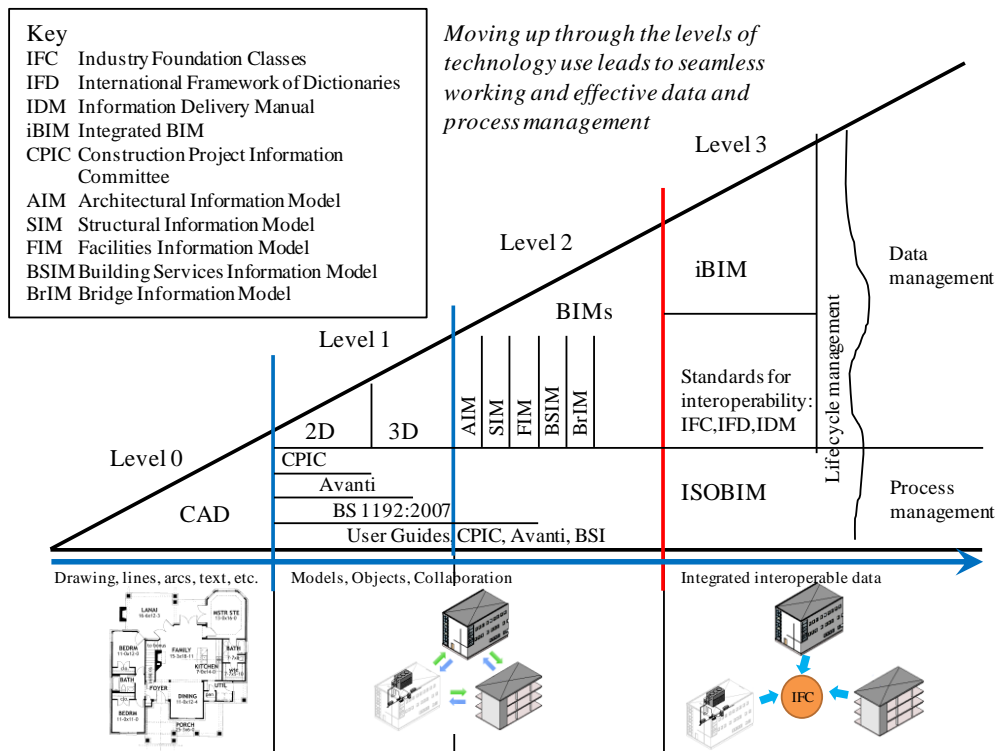


Figure 2.2 BIM maturity ‘Level’ index [Adapted from (BIM Industry Working Group 2011)]

The key recommendation of the BIM Working Group was that all public procurement should be carried out at Level 2 or higher by 2016. This was further reaffirmed by the Cabinet Office (UK Cabinet Office 2011).

“The Government will require fully collaborative BIM level 2 (with all project and asset information, documentation and data being electronic) as a minimum by 2016 (UK Cabinet Office 2011).”

It is expected to achieve a 20% reduction in procurement costs for government buildings compared with traditional practice. The above announcement caused confusion in the construction industry in matters of leadership roles, legal and financial implications of adopting BIM and thereby adopting a different method than the conventional construction practice (Ngo 2012). The announcement was quickly followed by the publication of guidance documents by key institutions that represent UK’s building construction sector; The Royal Institute of British Architects (RIBA) (Sinclair 2012), Construction Industry Council (CIC), and National House Building Council (NHBC). These documents provided guidance to different professions on the process of adopting BIM and its associated consequences on practice.

Amongst architects, there is still confusion in the industry regarding what BIM actually is and how to adopt BIM working methods in architectural practices. Since architects have a central role to play in ensuring that both public and private sectors respond to the opportunities offered by BIM, it was important to align the BIM tasks with the RIBA outline plan of work for a far-reaching adoption of BIM in the UK’s construction industry. In response to the

Government Construction Strategy report (2011), the RIBA provided a BIM overlay to their outline plan of work (Sinclair 2012). The outline plan of work organises the process of managing and designing building projects and administering building contracts into a number of key work stages. The outline plan of work has been recently updated (RIBA 2013a) with its precursor in 2007 (Figure 2.3). An excerpt of the outline plan of work and key BIM activities for each of the stage has been given in Appendix A.

Outline Plan of work 2007			Outline Plan of work 2013	
Preparation	A	Appraisal	0	Strategic Brief
	B	Design Brief	1	Preparation Brief
Design	C	Concept	2	Concept Design
	D	Design development	3	Developed Design
	E	Technical Design	4	Technical Design
Pre-Construction	F	Product Information		
	G	Tender Documentation		
	H	Tender Action		
Construction	J	Mobilisation	5	Construction
	K	Construction to practical completion	6	Handover and Close out
Use	L	Post practical completion	7	In use

Figure 2.3 The RIBA outline Plan of work 2007 and 2013.

Sinclair (2012) highlights the requirements for shifting from level 0 to level 3 as follows:

- Collaborative and integrated working methods and teamwork with closer ties between all designers on a project, including designing trade contractors;
- Knowledge of databases and how these can be integrated with the building model to produce a data-rich model, incorporating specification, cost, time and Facilities Management (FM) information;
- New procurement routes and forms of contracts aligned to the new working methods;
- *Interoperability of software to enable concurrent design activities, for example, allowing environmental modelling to occur concurrent with orientation and façade studies;*
- Standardisation of the frequently used definitions and a rationalisation of the new terms being developed in relation to BIM; and

- Use of BIM data to analyse time (4D), cost (5D) and FM (6D) aspects of a project.

Other responses to the Government Construction Strategy report include the Construction Industry Council's BIM protocol (CIC 2013). Since BIM is envisaged as a methodology which once adopted could radically change construction practices and result in substantial cost savings, the CIC believe that it would change the associated legal frameworks. The protocol is designed to be a contractual document that precedes existing agreements in standard construction practice. It places an obligation on parties to provide defined elements of their services within a model or models at defined stages in a project. It also states the requirement to appoint a member (usually a BIM-co-ordinator) to the role of information management. The protocol is created to streamline the legal framework of construction practice when they adopt the BIM approach thereby encouraging collaborative working methods within project teams and operates within the adoption of common standards.

Domestic clients make up 34% of the architecture firm's client base by number. Nearly half of the architecture profession's income comes from housing (RIBA 2013b). However, the advantages of adopting BIM are being clearly seen in the domain of non-domestic properties. This is partly due to the lack of guidance on the benefits of adopting BIM by the house-building sector. In order for the construction industry to fully embrace BIM across all sectors and professional domains, the National House Building Council (NHBC) developed a guidance (NHBC 2013) that captured the benefits of BIM for the house building sector and suggested ways of how adopting BIM can increase the efficiency of this sector, and improve product quality for residence owners. The survey conducted in this report highlighted that although most house builders were aware of BIM but not using it, more than half of the architects and MEP engineers were already using BIM in practice. The adoption of BIM was focussed in design activities and in producing information for contractor's use. Some advanced practitioners even integrated simulation and calculation software packages with their BIM software to help productivity and reduce errors. BIM was used on a variety of residential projects, from houses to large tower blocks, and the practitioners found BIM particularly useful in solving complex spatial or co-ordination arrangements.

Other key findings of the survey were that BIM practitioners were using some form of document management system usually created in-house and in terms of software platforms they were comfortable using the leading proprietary software products available in the UK, which were also used by other project team members to ensure smooth interoperability and transfer of data.

The use of proprietary BIM software products and creating domain-specific models conforms to the requirements of BIM level 2. This approach in BIM adoption is favoured by the UK construction industry and will be further explained through case studies in the section 2.3.

### **2.2.2 Barriers and benefits for BIM adoption in the UK**

In the route of adopting higher levels of BIM maturity, It is more likely that each party will continue to maintain its own model with a common interface facilitating collaboration and the sharing of information between models.

There are significant challenges in the widespread adoption of BIM in the UK. National Building Specifications (NBS 2013) published a survey to track people's attitudes towards the use of BIM. The survey revealed that in 2012, around 89% users adopting BIM process require a significant adjustment to the current practices in the industry. 39% of the respondents were at that time using BIM and 54% were aware of it, only 6% reported that they were unaware of BIM. It is observed that while the cost is often seen as the barrier to adoption, especially for small organizations, the process/practice change appeared as a major challenge.

Additional barriers to BIM adoption include technical problems (compatibility and reliability of data and data exchange), team fragmentation, lack of training and business process related issues (Howard and Bjork 2008). In the majority of BIM adoption initiatives, there is also uncertainty about the legal, contractual and overall organisational implications of BIM (Ashcraft 2008; Chao-Duivis 2009)

There is a consensus that socio-organisational and technical changes should accompany BIM deployment efforts (Rezgui and Miles 2011). However, there is no consensus as to who owns the BIM model and who is responsible for financing and maintaining it over the facility lifecycle (Eastman et al. 2011).

In the past three years, the industry has become more aware of BIM, in 2010 and 2011, 43% and 21% of the respondents were unaware of BIM respectively (NBS 2013). This indicates an upward trend on the awareness of BIM. Amongst those respondents aware of the BIM maturity levels, the highest level their organisation has reached on a project, only 8% have reached Level 3, and around 47% have reached Level 2, the level the government's construction strategy calls for by 2016.

Even with the existing barriers to BIM adoption, construction companies have successfully implemented BIM in the design and construction of their projects in the UK. For example, the use of BIM models for the construction of a highway helped identify £3m savings in sheet piling requirements and in the Saint Bartholomew (Barts) and the Royal London Hospital project, enabled material quantities to be extracted in 4 hours as compared to 30 man days if conventional construction methods were used (Jeffrey 2012). The adoption of BIM in the detailed design stages of the Aylesbury Crown Court provided benefits ranging from keeping costs in control in real time to keep the client apprised of budget issues, to completely redesigning the scheme after discovering water table issues in the topographic survey (McGraw-Hill Construction 2010). The redesigning of the scheme was completed in a couple of weeks using BIM as all the information was available compared to nearly two months if BIM was not adopted at all. Hence, even in state of relative immaturity and limited scope of implementation, BIM can deliver demonstrable benefits and return on investment.

The benefits of BIM further highlighted in the results of the NBS survey (NBS 2013). 55% of the BIM-users found that BIM brought cost efficiencies, 50% that it increased the speed of delivery and 46% agreed that it increased profitability.

### ***2.2.3 BIM implementation case studies***

Birmingham City University is the one of first public sector clients in the UK to have adopted the BIM process in the construction of Birmingham Institute of Art and Design (BIAD) and a student centre and teaching facility. The current approaches in BIM adoption in the construction industry is highlighted using case studies of Barts and the London Hospital, Birmingham City University and Camino Medical Office Building.

#### *i) Case study 1: Barts and the London Hospital*

The project involved a combination of refurbishment and new build works across two London hospitals covering an area of approximately 270,000 m<sup>2</sup> with a total project value of £1 billion. The 'state-of-the-art' hospitals in central London will have a capacity of 1200 beds and employ 7000 staff (Harty et al. 2010).

The project team chose the BIM approach for the project due to the following reasons;

- The facility management of a hospital project is always a challenge given the high levels of use of medical facilities, complex services and equipment.
- Being located in central London the location of the site posed major constraints for the construction process, for example, site access, delivery of materials, minimising disturbance, routing of various services and foundation works given the busy underground tube network.
- Condition of the contract being awarded stated a 10% savings on the total project cost to be generated by the contractor.

The contractor encouraged the utilisation of BIM technologies. All design works were mandatorily carried out in 3D models rather than 2D schematics using the Autodesk suite of products (AutoCAD). These were then combined into a co-ordinated 3D model using applications like Autodesk Navisworks, with various intelligent attributes added to specific components. The BIM model along with all consistent shared information was stored in a central repository (contractor's intranet) accessed by all members of the project team (Figure 2.4).

Figure 2.5 shows the construction tasks/processes that benefitted with the full or partial adoption of BIM. The main benefits realised by the project team for adopting BIM was that it enabled clash detection amongst various services, integrated models were used to check for safe access for operation and maintenance, development of installation/removal strategies for major plant and medical equipment, link to construction programmes and monitor progress.

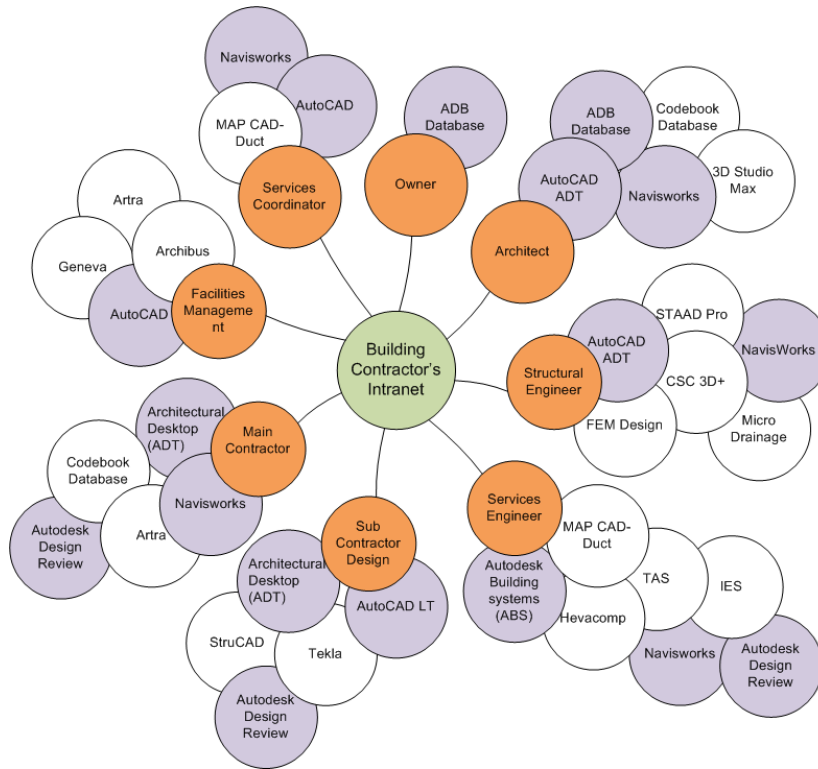


Figure 2.4 BIM tool map used by the project team [Adapted from (Throssell 2010)]

Project tasks	Adoption level
Virtual Briefing and snagging	BIM adopted
Clash prevention	
Safety Reviews	
Data Extraction and material take-off	
Medical equipment installation	
Room progress monitoring	
Room data sheets	BIM partially adopted
Construction Planning (4D)	
Plant Installation	
H&SF/O&MM Linking	
Finishes Check List	
Equipment check list	BIM not adopted
Way Finding	
Snagging	
Site Logistics	

Figure 2.5 BIM adoption level in project tasks

## ii) Case study 2: Birmingham City University

The client, Birmingham City University, were looking to expand its current facilities in two phases (total area 46,500 m<sup>2</sup>), phase one, the Birmingham Institute of Art and Design and phase two a second teaching building. The client mandated the use of BIM in order to deliver benefits both during design and construction and also in the management of the operational life of the building post completion (Jenkins 2013). The project team appointed is shown in Figure 2.6.

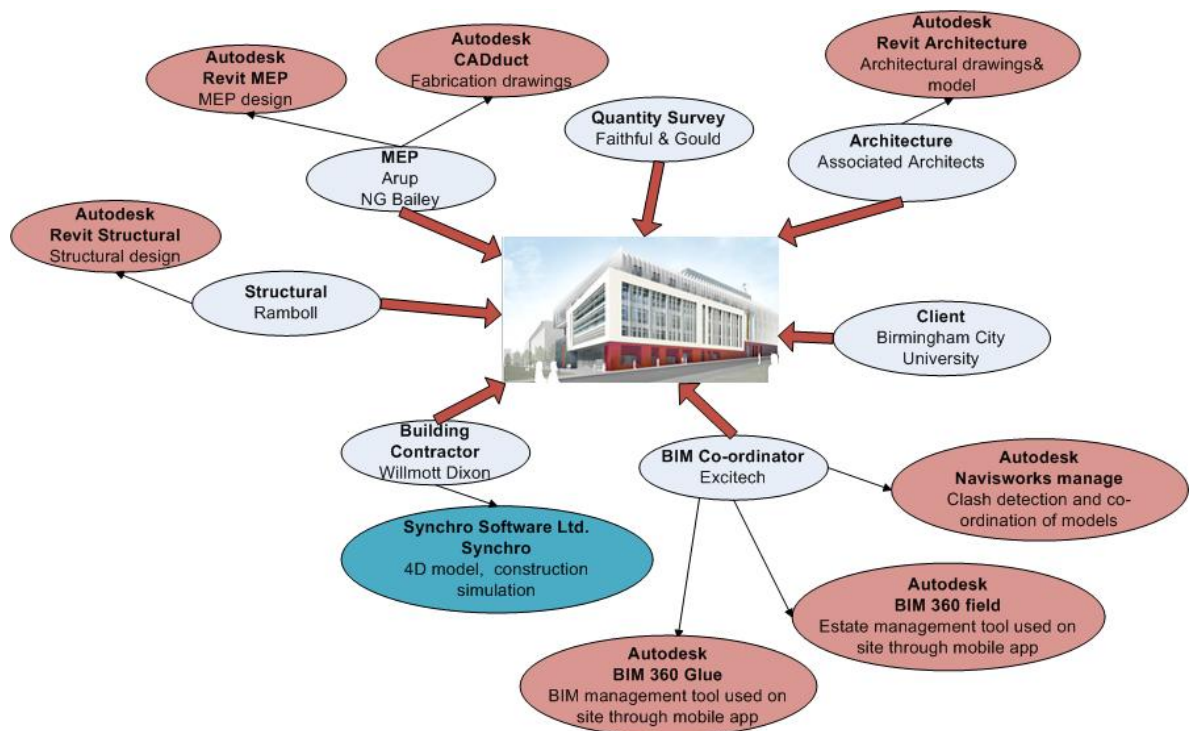


Figure 2.6 Project team and the software applications used for the BCU project.

It is evident that Autodesk suite of products was chosen by the project team to author and manage the BIM model (Figure 2.7). Private sector companies are not constrained with government's route of adoption of open BIM (Draper et al. 2013). The approach and use of BIM in the Birmingham City University (BCU) project by the project team shows their inclination to use vendor-specific proprietary tools developed for all disciplines (Structure, MEP, architecture) by a single vendor that guarantees interoperability and encourages collaboration in the project team (Figure 2.7).

The following benefits were identified by adopting BIM in the design, construction, O&M phases of the project:

- Using BIM measure and CAD measure enabled the surveyors to determine a significant proportion of the cost of the project using 3D model export. 80-90% of the major cost-relevant items were established in less than an hour. This provided a rapid overview of costs.

- 15,000 clashes were reported from the model using clash detection software (Navisworks), a vast majority of which were not design issues. Minimising the clashes virtually helped determine builders work requirements and review costly penetrations through the building fabric.
- The surveyors also identified using 4D (time scheduling) and 5D (cost) aspects of the project using software like Synchro. Cost estimates could be generated very early on in the project.
- Enabled collaborative design through using software like Navisworks for co-ordination of all models. Also helped reducing waste in the design and construction process.

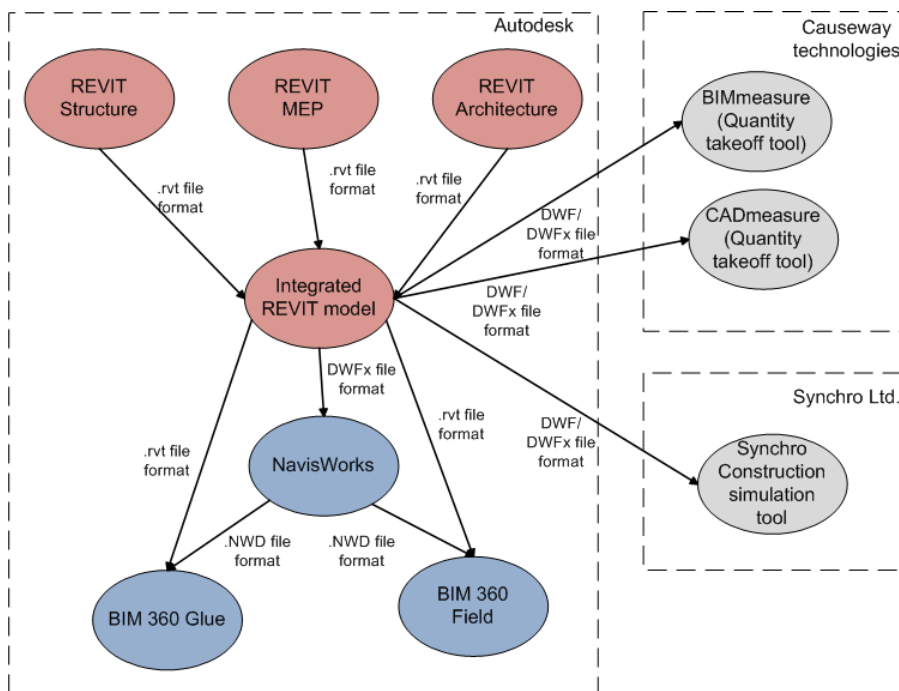


Figure 2.7 Software applications and data exchange formats used by the project team for all disciplines

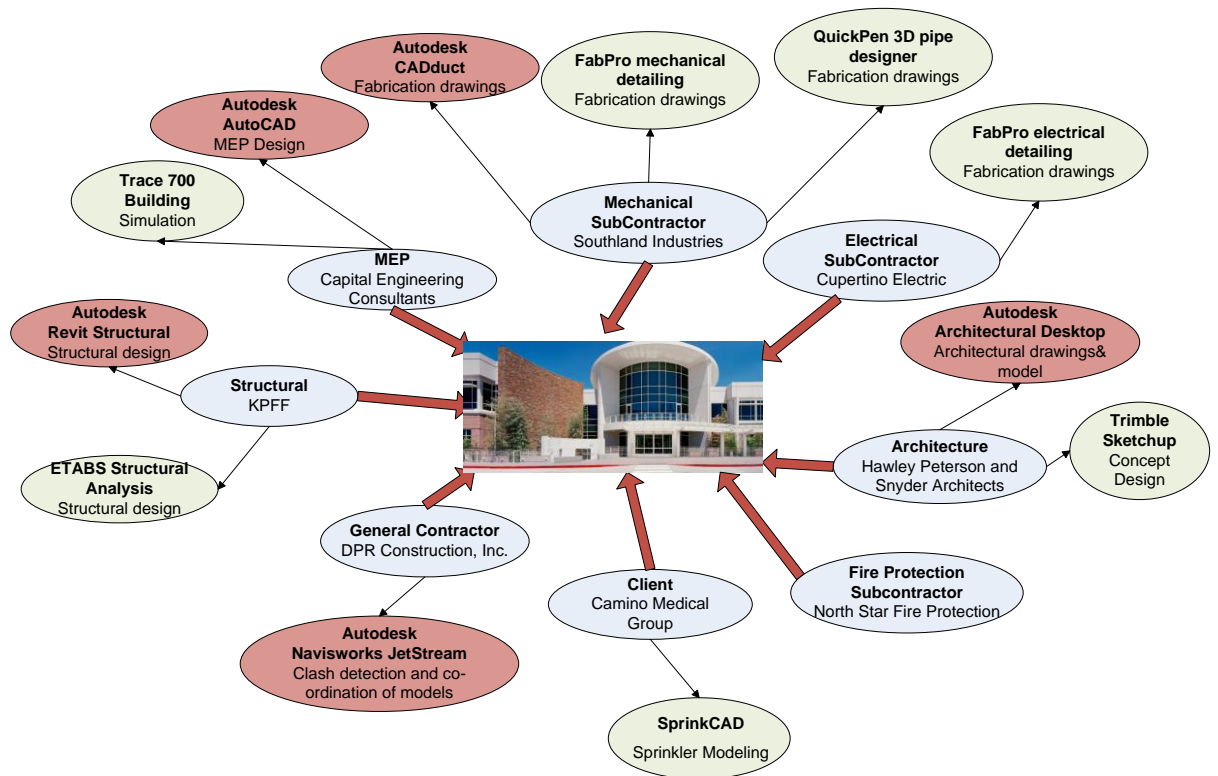
iii) Case study 3: Medical Office Building facility for the Camino Medical Group, California

The construction project of a Medical Office Building (MOB) for the client Camino Medical Group included a 23,250 m<sup>2</sup>, three-level building and a two-level 1,400 space parking garage. The project value was \$96.9 million. The building consists of patient exam rooms, doctor’s offices, surgery and radiology rooms, public spaces, a cafeteria, numerous conference rooms, etc. The project was started in January 2005 and completed in early April 2007.

The benefits and the lessons learnt from implanting BIM tools for MEP co-ordination of this building has been documented by Khanzode et al. (2008) and Eastman et al.(2011).

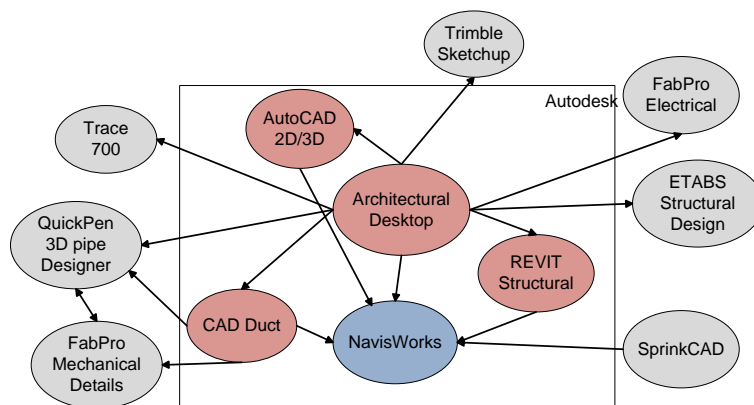


The Camino MOB project team (Figure 2.8) decided early on to use the BIM tools (specifically 3D/4D and automated clash detection tools), for the MEP coordination process (Khanzode et al 2005).



**Figure 2.8** The project team and the various BIM tools used for the design and construction of Camino Medical Office Building

The BIM authoring tools used by project team members were developed on top of the Autodesk platform (DWG compatible). The models that the subcontractors and design team members created using the systems indicated in Figure 2.9 were brought in to NavisWorks JetStream by the general contractor and clashes were identified.



**Figure 2.9** The interoperability between various proprietary CAD/BIM software tools

The following quantitative and qualitative benefits were identified by adopting BIM for the co-ordination of MEP/Fire Protection services;

- When compared to a traditional Design-Bid-Build project, the use of BIM tools for project delivery attributed to a financial saving of \$9 million and time saving of 6 months to the owner.
- The as-built model being used for facility management made it easier to find building information relating to MEP compared to traditional 2D drawings that are submitted to the owner at the end of the project.
- Reduced number of request for information pertaining to field conflicts from 200-300 range to only 2. Zero change orders related to the field conflict led to a substantial cost saving to the owner. Normally, change orders would cost around 1-2% of the cost of the MEP systems to the owner.
- Less time spent by architects during the construction phase of the project for administering the construction due to the reduced number of requests for information.
- 10-15 hours in 8 months spent by contractors to resolve field issues rather than 2-3 hours each day for a comparable project using traditional construction processes.
- The improved workflow due to the use of BIM tools resulted in more off site pre-fabrication, timely deliveries, and efficient field coordination and installation.

From all three case studies, it can be seen that there is a drive in the private sector towards using proprietary vendor specific tools for the creation of building information models. Using vendor-specific proprietary tools guarantees interoperability within various AEC software applications developed by the same vendor. This approach would give one software vendor monopoly in the construction market, and will increase the industry's reliance on using software applications developed by a single vendor. Additionally, this would limit flexibility in the design process and increase the reliance on the vendor to develop software tools for all design activities and AEC applications. It is important to note that certain private sector companies have realised this shortcoming and have adopted non-proprietary openBIM standards on their projects(Koppinen 2012).

## 2.3 Conclusion

When adopted well BIM facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration. BIM is envisaged as a methodology which once adopted could radically change construction practices and result in substantial cost savings. The chapter has captured various benefits of adopting BIM in practice by the UK construction industry which include enhanced cost efficiencies, increased speed of delivery and profitability. BIM implementation case studies discussed in section 2.2.3 further recalled the various benefits experienced through adoption of BIM in the building design and construction process. BIM can deliver demonstrable benefits and return on investment even in state of relative immaturity and limited scope of implementation.

For a wider adoption of BIM in the UK, the government through policy has made it mandatory for all public sector projects to adopt fully collaborative BIM level 2 by 2016. Even though this announcement was met with ambiguity from the construction industry, it has further strengthened the resolve to adopt BIM early on in the design process.

However in the route for BIM adoption, construction industry has adopted proprietary software applications, provided by a single vendor, for various domains, to integrate BIM within their design and construction processes. Using software applications from a single vendor does not only provide them a monopoly in the UK design and construction market but also generates a feeling that perhaps the move to 3D CAD and BIM is driven by the commercial interest of software houses, rather than by a need to improve the construction process (NBS 2013). This is further reaffirmed by the plethora of tools available from leading software vendors reviewed in section 2.1.

BIM should not be viewed as only one of many purpose-built models (Howell and Batcheler 2005) but as a process in which many purpose built models share data (Cemesova et al. 2013). For true collaboration between the members of the project team, the shift from Level 2 to Level 3 seems inevitable. Adopting BIM at 'level 3' maturity will call for advanced interoperability. Level 3 is based on open-standardised formats of data exchange that would permit flexibility in the use of proprietary software. Interoperability of software would enable concurrent design activities, for example, energy analysis occurring concurrently with orientation and façade studies. Interoperability, standardisation efforts in data exchange, and the need to adopt 'Level 3' will be discussed in Chapter 4.

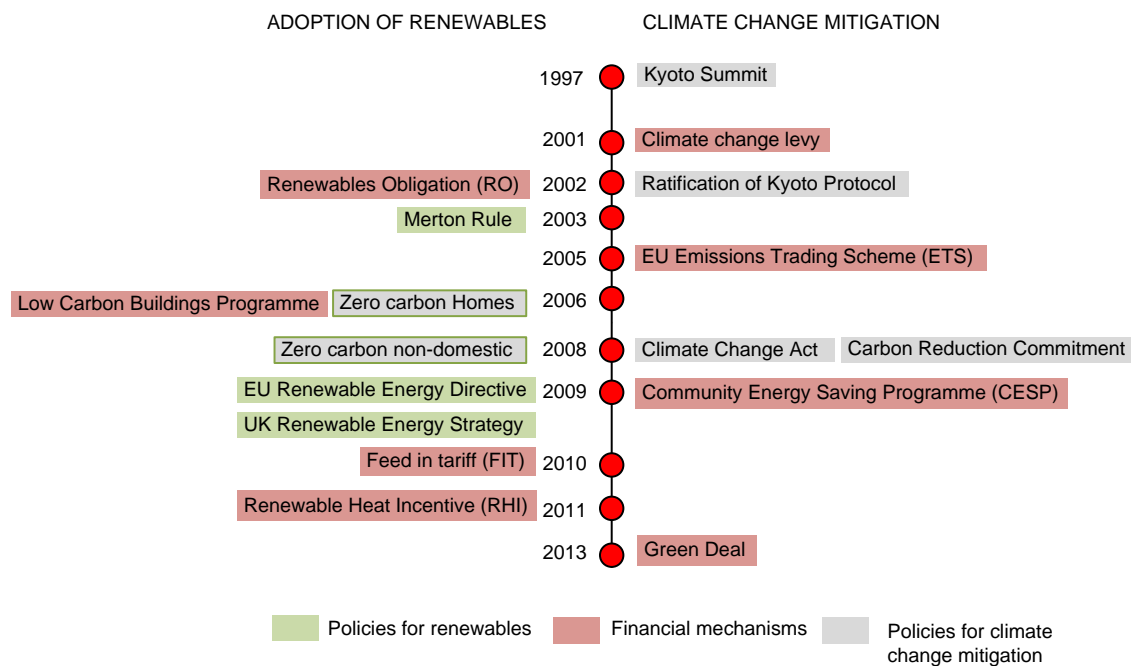
The next chapter provides an overview of RES adoption, their integration in the design process and various analysis tools for RES simulation.

## CHAPTER 3. OVERVIEW OF RES INTEGRATION IN BUILDINGS

This chapter starts with the discussion on the various political and economic drivers developed by the European commission and UK government to combat climate change, and encourage energy and CO<sub>2</sub> reduction, through the adoption of renewable energy technologies in the construction sector (section 3.1). It is followed by a discussion on the contribution of RES in meeting compliance requirements of the building regulations in the UK (section 3.2). A survey was conducted in order to gauge the practitioner's perspective on the use of various RES analysis tools and the integration of RES in the building design process. The survey findings are presented and analysed in section 3.3. Finally, a literature review of the current tools and assessment methods that are used for analysing the performance of various RES in presented in section 3.4, through which the structure of an RES simulation model is developed. The input data requirements for conducting the analysis of various RES is then captured in Tables 3.8-3.11.

### 3.1 Key directives for RES adoption

European policies to mitigate climate change set ambitious goals for energy and carbon reduction in the built environment (European Commission 2008). Figure 3.1 shows the UK's climate change roadmap and introduces key directives and subsequent financial mechanisms that the government has implemented to combat climate change in response to the Kyoto Protocol (UNFCC 1997).



**Figure 3.1 Key directives in climate change mitigation and renewable energy adoption**

A brief description, the current status and impacts of the key directives that led to the adoption of RES are given in (Table 3.1). The government's introduction to various climate

change roadmaps and CO<sub>2</sub> emission reduction strategies paved the way for the adoption of renewable energy sources to meet the energy needs of buildings and transport sectors.

Since this section focuses on key political and financial directives that led to the adoption of RES, a brief description of policies in climate change mitigation that led to the formulation of renewable energy strategies for Europe and the UK is given in Appendix B.

Table 3.1 Key Directives in RES adoption in the UK

Policy/directive	Brief description	Impacts/ Current status
<b>Renewables Obligation (2002)</b>	The RO requires licensed UK electricity suppliers to source a specified proportion of the electricity they provide to customers through renewable electricity generators (provided they generate electricity from eligible renewable sources (DECC 2013c).	Scheme closes to new generators in 2017. Scheme closes altogether in 2037 and all electricity generation accredited by RO will receive 20 years of financial support.
<b>Merton Rule (2003)</b>	Planning Policy developed by the London Borough of Merton, which required new developments (above 1000 sq.m. area) to generate at least 10% of their energy needs from on-site renewable energy technology. (Merton Council 2003)	325 of the 390 councils in England have taken up the Merton Rule while all councils in Scotland and Wales have followed their own version of it.
<b>Low Carbon Buildings Program (LCBP)(2006)</b>	A two phase grant scheme for public and private housing and communities to access funding for renewable energy installations. LCBP was a major government grant funding programme and provided approximately £131 million in grants for around 20,000 projects between 2006 and 2010. (BRE 2010; DECC 2011)	Phase two officially ended in July 2010 for new installations and was replaced by the Renewable Heat Incentive.
<b>Zero Carbon Homes (2006)</b>	The UK Government published the 'Building a Greener Future statement', which announced that all new build homes would be zero carbon from 2016(DCLG 2006). The proposed definition of zero carbon took into account: <ul style="list-style-type: none"> <li>• emissions from space heating, ventilation, hot water and fixed lighting,</li> <li>• expected energy use from appliances</li> <li>• exports and imports from the development (and directly connected energy installations) to and from centralised energy networks.</li> </ul>	Revision of Building Regulations (Part L1 A) in a phased manner (2010- 25% reduction in regulated emissions; 2013 44% reduction in regulated emissions compared to 2006 levels). The introduction of environmental standards such as the Code for Sustainable Homes (2006).
<b>Zero-carbon buildings (non-domestic) (2008)</b>	The 'Zero-carbon policy' was further extended to non-domestic buildings (DCLG 2009). It was announced in Budget 2008 that from 2019 all non-domestic new builds will also be required to have zero net carbon emissions, starting with schools from 2016 and public sector buildings from 2018.	Revision of Building Regulations (Part L2 A) in a phased manner (2010- 25% reduction in regulated emissions; 2013 44% reduction in regulated emissions compared to 2006 levels).

Policy/directive	Brief description	Impacts/ Current status
EU Renewable Energy Directive (2009)	The directive set out ambitious target for all EU member states, such that 20% of the total energy and 10% of the energy in the transport sector should be contributed from renewable by 2020. (European Parliament 2009a)	The directive drew out national renewable energy action plans that stated targets to be met for all member states. For the UK, it is 15% of its energy consumption from renewable sources by 2020.(European Parliament 2009b)
UK Renewable Energy Strategy (2009)	This strategy is UK's national renewable energy action plan. (UK Government 2009)	Targets outlined for heat and electricity sectors as 12% and 30% contribution from renewable sources. Also outlines the provision of financial support worth £30 billion between 2009-2020.
Feed-in-tariff (2010)	Financial scheme administered by Ofgem in which electricity suppliers make tariff payments to building owners on both generation and export of renewable and low carbon electricity. The eligible technologies include solar PV, wind turbine, hydro, anaerobic digestion and microCHP.	The scheme launched in April 2010 to resulted in over 358,338 PV installations in the UK till December, 2012.(Ofgem 2013)
Renewable Heat Incentive (2011)	The world's first long-term financial support programme for renewable heat launched in November 2011 for the non-domestic sector. RHI payments are made to the owner over a 20year period. The eligible technologies include biomass boilers, water or ground source heat pumps, solar thermal and bio methane. Renewable Heat Premium Payment (RHPP) was introduced for domestic installations in which monetary vouchers could be claimed to purchase renewable heat generating technologies.	As of February 2013, 1,013 applications have been accredited and eligible for tariff payment. The total capacity of these installations is 201 MW.(DECC 2013b)

### **3.1.1 UK renewable energy strategy 2009**

The EU renewable energy directive has set ambitious targets for all EU member states, such that the EU will reach a 20% share of energy from renewable sources by 2020 and a 10% share of renewable energy specifically in the transport sector (European Parliament 2009a). The directive also sets out targets for each member state for example; the UK is directed to achieve 15% of its energy consumption from renewable sources by 2020 (European Parliament 2009b).

Subsequently, the UK Renewable Energy strategy (UK Government 2009) outlined scenarios of meeting this legally binding target by generating at least 30% of the country's electricity and 12% of heat by renewables. The strategy also outlined the provision of financial support for renewable electricity and heat worth around £30 billion between 2009 and 2020. This led to the introduction of Feed-in-tariff in 2010 and Renewable Heat Incentive in 2011, to provide guaranteed payments to individuals, business and communities for renewable heat and small scale electricity.

### **3.1.2 The UK's zero-carbon policy for buildings**

Buildings, in the UK, account for 35% of the total green house gas (GHG) emissions arising from business, industrial, public and residential sectors (Thistlethwaite et al. 2012). In December 2006, the UK government had set up an ambitious environmental policy that all new homes and new schools to be zero carbon by 2016, all public sector buildings reach zero carbon by 2018 and potentially all new buildings by 2019 (DCLG 2006; King and Clare 2008; DCLG 2009). The government's commitment to this target was further reaffirmed in the UK Budget 2013 announced by the Chancellor George Osborne (UKGBC 2013). This also conforms with the renewed obligation of EU member states of moving towards new and retrofitted nearly-zero energy buildings by 2020 (2018 in the case of Public buildings) under the recast European Performance of Buildings Directive (European Parliament 2010).

The policy defined a 'zero-carbon' home that would have zero CO<sub>2</sub> emissions from;

- space heating, ventilation, hot water and fixed lighting (referred to as 'regulated emissions' as per the building regulations),
- expected energy use from appliances (referred to as 'unregulated emissions')
- exports and imports from the development (and directly connected energy installations) to and from centralised energy networks.

In order to achieve 'zero-carbon' standard, a hierarchical approach of measures (Figure 3.2) was introduced based on:

- strict **energy efficiency** parameters - building design and appliances
- meeting at least a minimum level of carbon mitigation onsite or near-site- **Carbon-compliance**



- demonstrably additional offsite low and zero carbon energy solutions (**Allowable Solutions**); and, if needed
- contributions to a Community Energy Fund, whose proceeds would be used to fund investment in additional low and zero carbon energy.

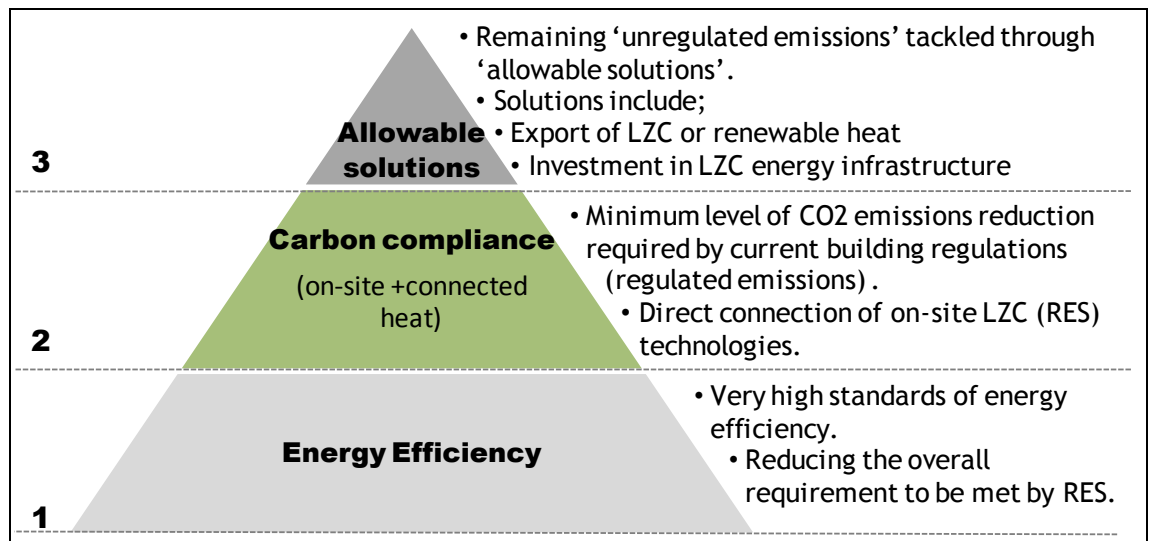


Figure 3.2 Hierarchy of measures for adopting ‘zero-carbon’ standard (Adapted from (DCLG 2008a))

As outlined in Table 3.1, the government intends to revise the building regulations in a phased manner in order to reach the target of zero-carbon homes by 2016 and for all buildings by 2019. The revision in 2010 anticipated all new dwellings built post 2010 would contribute to a 25% reduction in carbon emissions relative to 2006. Similarly, the revision in 2013, will yield 44% reduction in carbon emissions for all new dwellings.

“A wide variety of micro-generation and distributed energy solutions are available that would allow the builders to reach a 44 per cent reduction in regulated emissions, including building-mounted technologies (such as solar hot water and solar photo-voltaic) and larger, free-standing installations (such as combined heat and power).” (DCLG 2008a).

Hence this thesis looks at building integrated solutions for RES and associated tools and methods of their assessment for carbon compliance beyond the minimum standard.

### 3.1.3 Financial mechanisms for the rapid adoption of renewables

The following financial mechanisms were introduced by the UK government to encourage the uptake of renewables; Feed-in-tariff scheme (FiT) for electricity generating renewables and Renewable Heat Incentive (RHI) for heat generating renewables.

The FiT scheme administered through Ofgem, empowers licensed electricity suppliers to make tariff payments on both generation and export of renewable and low carbon electricity. The eligible technologies include solar PV, wind turbine, hydro, anaerobic digestion and microCHP. The scheme launched in April 2010 resulted in over 358,338 PV installations in the

UK till December 2012 (Ofgem 2013). However, only 9445 installations were reported in non-domestic properties; mostly retrofit (Table 3.2).

**Table 3.2 Number of installations under the Feed-in-Tariff scheme**

Number of installations (April 2010- December 2012) under the FiT scheme		
Technology	Domestic	Non-domestic
Solar PV	342377	9445
Wind	3072	866
Hydro	0	108
Micro-CHP	0	2

The Renewable Heat Incentive launched in November 2011 is the world's first long-term financial support programme for renewable heat. In the first phase applications were taken from the non-domestic sector (industry, business and public sector) only, which would guarantee tariff payments for building owners that have installed heat generating renewables on site and are monitoring the generated heat. The Renewable Heat Premium Payment (RHPP) Scheme was launched for domestic customers in which monetary vouchers could be claimed by customers for the installed renewable heat technology. Till March 2013, around 88% of the applications have been for biomass boilers only (Table 3.3) in the non-domestic sector (DECC 2013b).

**Table 3.3 Number of installations under the Renewable Heat Incentive scheme**

Number of installations (August 2011-March 2013) under the RHI scheme		
Technology	Domestic	Non-domestic
Biomass Boiler	N/A	1511
Water or GSHP	N/A	95
Solar thermal	N/A	96

Under the introduction of FIT and RHI schemes, there has been a surge in solar PV and biomass boiler installations (Figure 3.3). The installed capacity of solar PV and biomass boiler installations in non-domestic buildings has been similar; 400 MW and 480 MW respectively. However, there has been a substantial growth in Solar PV installations in the domestic sector with a total of 1110 MW capacity of over 342,377 installations. It is observed that most of the domestic installations have been retrofitted, which means PV panels have been installed on existing buildings (Ofgem 2013) (Table 3.4). The reasons for the reduced uptake of PV installations in new-build sector particularly non-domestic could be economical factors such as high investment costs, different FiT tariff levels, lack of knowledge among decision makers

and architects attributed to general reluctance to 'new' technologies as well as aesthetic considerations (Wall et al. 2008).

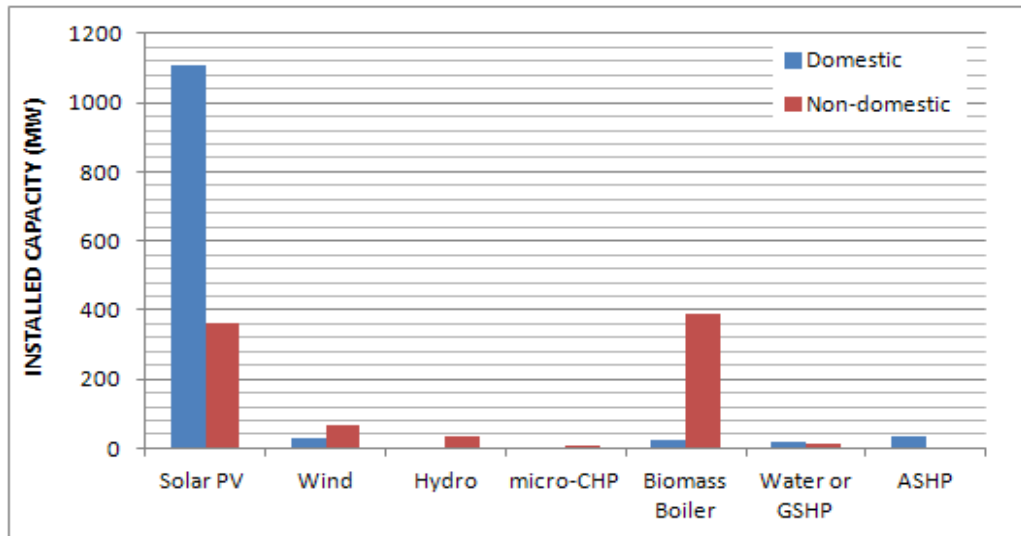


Figure 3.3 Installation of various renewable under the introduction of FIT and RHI schemes

Table 3.4 Number of PV installations on retrofit and new build buildings

Number of PV installations	Domestic	Non-domestic	Community
Retrofit	326836	3967	654
New Build	4582	233	25

Please note: The above data is partial and does not add up to the total number of installations. The remaining installations are categorised by system capacity and year of installation and no data is provided on whether they are 'retrofit' or 'new build' installation.

### 3.2 Contribution of RES in compliance of building regulations and environmental performance standards

The recast of the European Performance of Buildings Directive also led to amendments in the approved document Part L of the building regulations in the UK (HM Government 2013). Part L of the building regulations deals with the conservation of fuel and power and sets standards for energy efficiency and incorporation of LZC technologies for existing and new-build buildings (HM Government 2010). One of the major amendments was the insertion of Regulation 25A -Consideration of high-efficiency alternative systems for new buildings.

Regulation 25A states that

*“(1) Before construction of a new building starts, the person who is to carry out the work must analyse and take into account the technical, environmental and economic feasibility of*

*using high-efficiency alternative systems (such as the following systems) in the construction, if available—*

- (a) decentralised energy supply systems based on energy from renewable sources<sup>3</sup>;*
- (b) cogeneration;*
- (c) district or block heating or cooling, particularly where it is based entirely or partially on energy from renewable sources; and*
- (d) heat pumps.”*

The recognition of the need for carbon reduction from the built environment, along with new EU directives, more stringent building regulations and general environmental concerns, also encouraged the development and application of tools and sustainable building codes, which include the Standard Assessment Procedure (SAP) and Simplified Building Energy Model (SBEM), the Code for Sustainable Homes (CSH) and the Building Research Establishment Environmental Assessment Method (BREEAM) (Table 3.5)

SAP and SBEM are the UK government’s approved methodologies to generate Energy Performance Certificates under the Energy Performance of Buildings Directive (European Parliament 2002), for domestic and non-domestic buildings respectively. BREEAM and CSH are environmental performance rating systems or standards. These environmental standards have special provisions in the ‘Energy’ category for the inclusion of low and zero carbon technologies. Buildings that aim for a higher level of BREEAM or CSH rating would invariably include renewable energy technologies such as solar photovoltaic, biomass boilers and heat pumps. It has also been stated that in order to achieve higher levels of the CSH one of the main factors is to consider integrating renewable energy technologies into the overall design concept from the earliest design phases (DCLG 2012). However, there is a lack of simple tools that can quantify and illustrate (also architecturally) the influence of various solar applications, at the early design stages (Wall et al. 2008).

The next section discusses practitioners’ perspectives on the integration of RES in the building design process.

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<sup>3</sup> ‘renewable energy sources’ include wind, solar, aero thermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases;

Table 3.5 Brief description of SAP, SBEM, BREEAM and CSH

Code/Standard	Description	Provision for renewables
<b>Standard Assessment Procedure (SAP)</b>	<p>SAP 2009 is the UK government's Standard Assessment Procedure to calculate a dwelling's energy efficiency and carbon emissions. It was adopted by government as part of the UK national methodology for calculation of the energy performance of dwellings under the European Directive on the Energy Performance of Buildings (EPBD). It is used to demonstrate compliance with the Building Regulations 2010 - Part L (England and Wales), Section 6 (Scotland) and Part F (Northern Ireland) - and to provide energy ratings for dwellings. Whenever a UK dwelling is constructed, leased or sold, the SAP methodology must be employed to calculate a rating for Energy Efficiency and Environmental Impact.</p> <p><b>SAP is mandatory to be used to generate Energy Performance Certificates (EPCs) for dwellings.</b></p>	<p>SAP allows basic calculations of energy contributed by solar PV, solar thermal, micro-wind turbine, heat pumps and biomass boilers. The algorithms used in renewable energy simulations is given in (BRE 2011a). Comparison have been made between the SAP methodology and detailed simulation for low-energy buildings (Cooper 2008). Comparisons have also been made between SAP and detailed solar energy simulation systems for dwellings (Murphy et al. 2011).</p>
<b>Simplified Building Energy Model (SBEM)</b>	<p>SBEM, similar to SAP, is adopted by the government as part of the UK national Calculation methodology, in support of the Energy Performance of Buildings Directive (EPBD) and the Green Deal. The tool is currently used to determine CO2 emission rates for new buildings in compliance with Part L of the Building Regulations (England and Wales) and equivalent Regulations in Scotland, Northern Ireland, the Republic of Ireland and Jersey.</p> <p><b>SBEM is mandatory to be used to generate Energy Performance Certificates for non-domestic buildings on construction and at the point of sale or rent.</b></p>	<p>SBEM allows basic calculations of energy contributed by solar PV, solar thermal, micro-wind turbine, heat pumps and biomass boilers. The algorithms used in the simulations is given in (BRE 2011b).</p>
<b>Code for Sustainable Homes (CSH)</b>	<p>The Code is the national standard for the sustainable design and construction of new homes. The Code uses a 1 to 6 star rating system to communicate the overall sustainability performance of a new home. The Code sets minimum standards for energy and water use at each level. The Code is currently maintained and developed by BRE Global. The CSH covers nine categories of sustainable design; Energy and CO2 emissions, Water, Materials, Surface Water Run-off, Waste, Pollution, Health and Wellbeing, Management and Ecology.</p>	<p>Additional points in the 'Energy and CO<sub>2</sub>' category for the use of solar PV, solar thermal, micro-wind turbine, Biomass boilers and heat pumps. This category is weighted to make up 21.4% of all the available points under the rating system and also contains minimum standards for each level of the Code, from 1 to 6.</p>
<b>Building Research Establishment Environmental Assessment Method (BREEAM)</b>	<p>BREEAM is a sustainable building assessment system developed by BRE Global, UK and has over 200,000 accredited buildings. The rating scale (%) of BREEAM is Outstanding (&gt;85%), Excellent (70-85%), Very Good (55-69%), Pass (45-54%) and Unclassified (30&gt;). The covered categories are Energy, Management, Health and Wellbeing, Transport, Water, Materials, Waste, Pollution, Land use and Ecology.</p>	<p>Additional points in the 'Energy' category for the use of solar PV, solar thermal, micro-wind turbine, Biomass boilers and heat pumps. The energy category holds 30 credits and is weighted to make up 19% of all available credits (BREEAM 2011).</p>

### 3.3 Practitioners' perspectives through an online survey

An online survey was conducted by the author which was aimed at architects and building service engineers that have a crucial role in decision making around the adoption of RES in the building design. The respondents were four architects and one building services engineer. Specific questions about the type of RES integrated within buildings and associated assessment tools and methods were asked. The results of the survey also gave an insight on the placement of RES assessment in the building design and construction process. The questionnaire for online survey has been given in Appendix C.

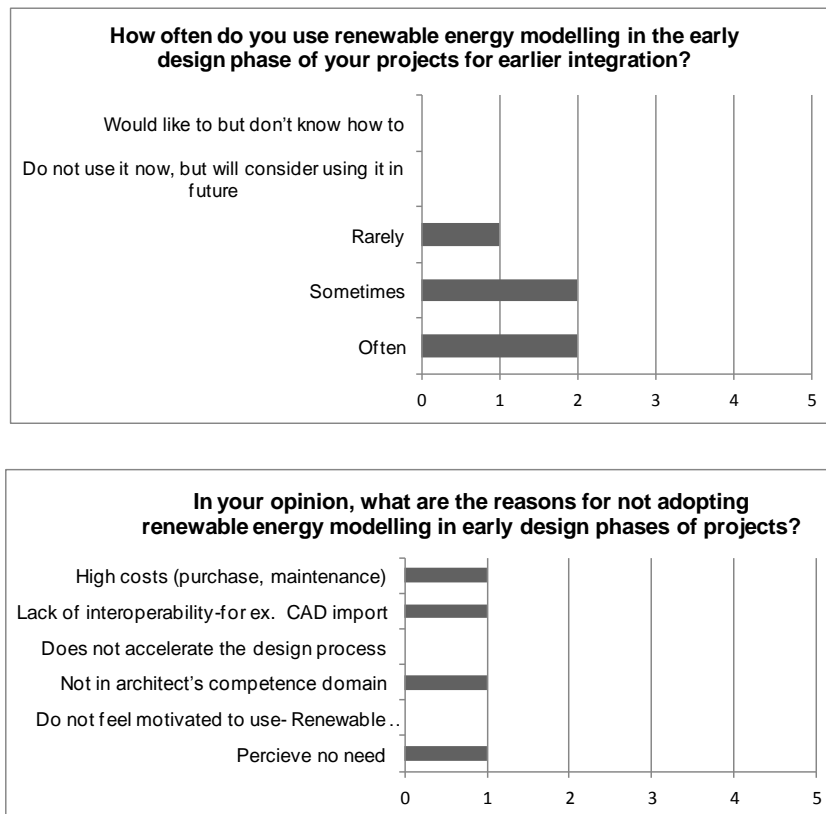


Figure 3.4 Use of RES simulation in the early design phase of projects

The first couple of questions were asked to gauge how often the respondents used RES simulation in the early design phase (EDP) of their projects (Figure 3.4). Two of the respondents often used RES in the EDP of their projects, an equal number agreed that they used RES simulation sometimes, and one respondent used it rarely. Four respondents gave different reasons for not adopting RES simulation in EDP of projects. The reasons included lack of interoperability between RES simulation and CAD, high cost of RES, RES simulation was not in architect's competence domain and that they perceived no need. The fifth respondent provided another reason that sometimes design decisions are subject to planning requirements which sometimes inhibits the use of renewable energy technologies. The respondents perceived no need to adopt RES in their buildings was either due to the carbon compliance being met by improving fabric performance, or the client's brief of not requiring a 'zero-carbon' building by adopting costly RES.

The next question was asked to gauge their opinion of the architect’s knowledge regarding RES simulation tools (Figure 3.5). Even though most of the respondents agreed that they adopt RES in the EDP of their projects, four of them do agree that architects lack the knowledge regarding RES simulation and deem that it is still insufficient. Hence they rely on engineers or consultants when they need to assess the performance of RES on their projects. This is also evident in the findings of Figure 3.8. **This demands an increase in collaboration between engineers and architects to enhance the building design in EDP in order to gain maximum cost and environmental benefits from the adoption of RES.**

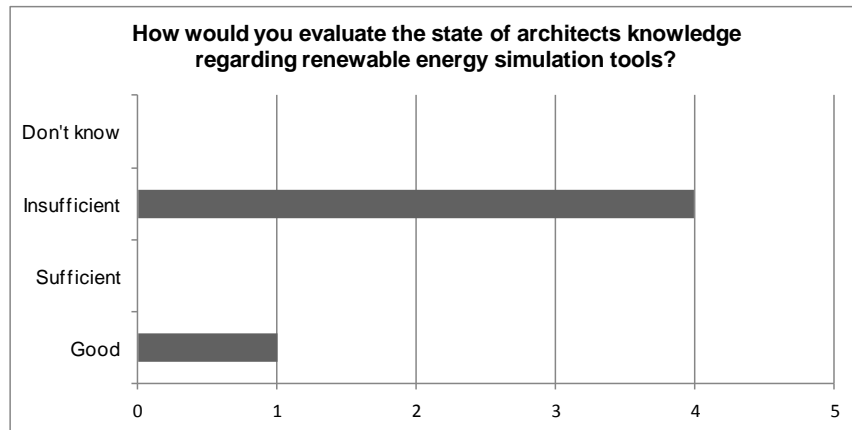


Figure 3.5 Architect’s knowledge in using RES simulation tools

For the next question (Figure 3.6) one out of the five respondents did not provide an answer. Two of the respondents agreed that they included solar PV, often or sometimes in the building design. For solar thermal technology, one of the respondents said that they included it often, two of them said sometimes and one said rarely on their projects. For biomass heating, all four respondents indicated that they used the technology sometimes on their project. Two of the respondents used heat pumps sometimes and two of them used it rarely. For wind turbines, majority of the respondents agreed that they included it rarely in the building design.

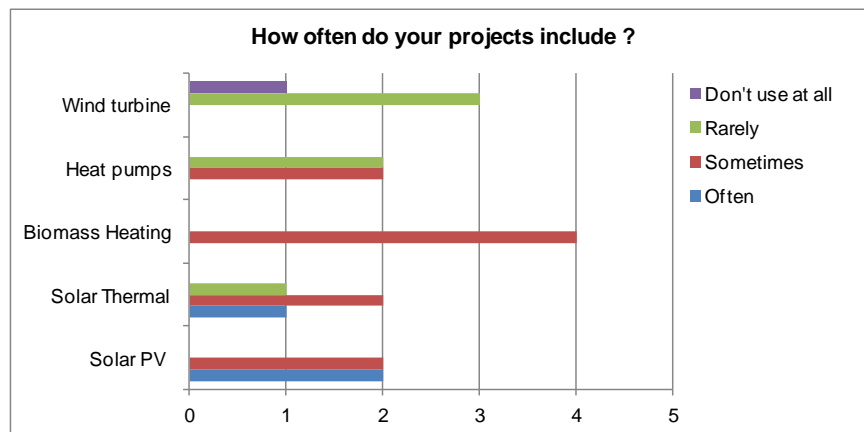


Figure 3.6 Technology specific adoption of RES

The next set of questions was asked to find out the level of RES integration in the building design and construction process. RIBA outline plan of work briefly discussed in section 2.2.1 was taken as reference for the various project stages. Three and five of the respondents agreed that they integrated RES in the conceptual and detailed stages respectively (Figure 3.7). One respondent agreed to have used RES in the pre-construction phase. It is important to note that that building design cannot be optimised at the pre-construction phase to gain maximum benefit from RES integration. The architects/engineers have to settle with the predicted performance of RES at this stage.

The adoption of various RES is also broken down for each RIBA work stage. All the respondents agree to have integrated solar PV technology in either of the design or construction phases of their projects. This proves that after an initial feasibility, solar PV panels are procured and installed in the construction phase. One and two of the respondents agree to have integrated solar thermal in the preparation and design phases respectively. A similar trend is seen in the adoption of biomass heating system in the building design process. Heat pumps and wind turbines seem to be adopted only in the preparation and design stages. This could mean that after an initial feasibility assessment, their adoption would have seemed to be technically or financially unviable for the project team.

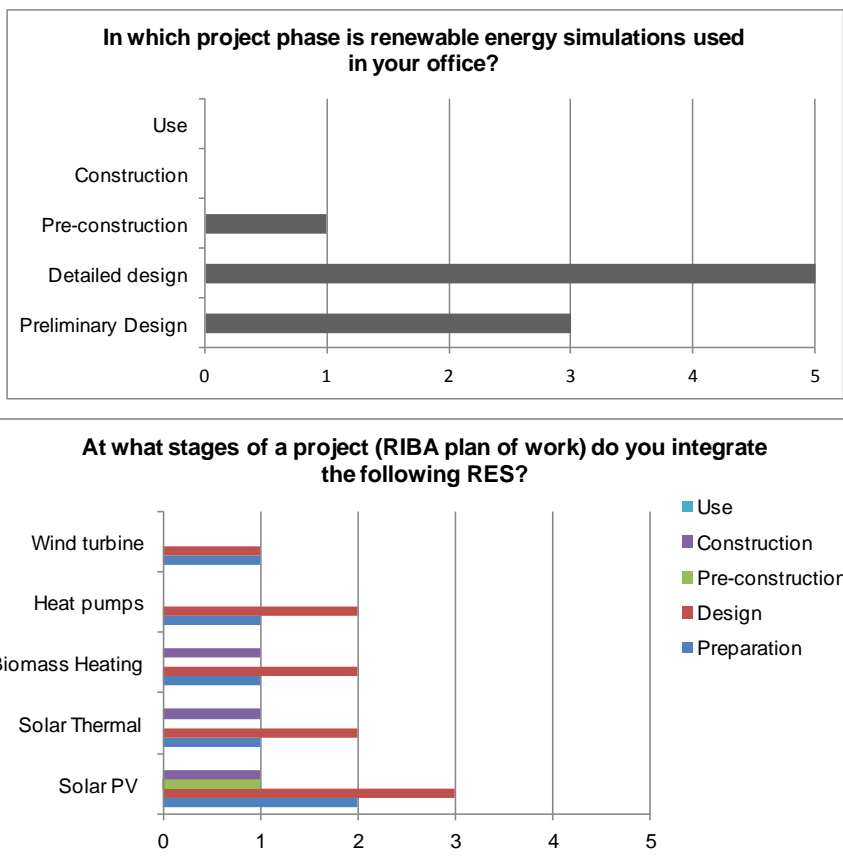


Figure 3.7 RES adoption in RIBA work stages

The final questions were formulated to find out the software tools used by the respondents for RES simulation and the factors that most influence their choice of purchasing or using software. Two of the respondents skipped this question. None of the respondents used HOMER or RetScreen software that assesses a range of RES (Figure 3.8). HOMER is an optimisation



software for power generating RES and RetScreen is a statistical tool used for analysis of range of RES. An in-depth description of these tools would be given in the next section.

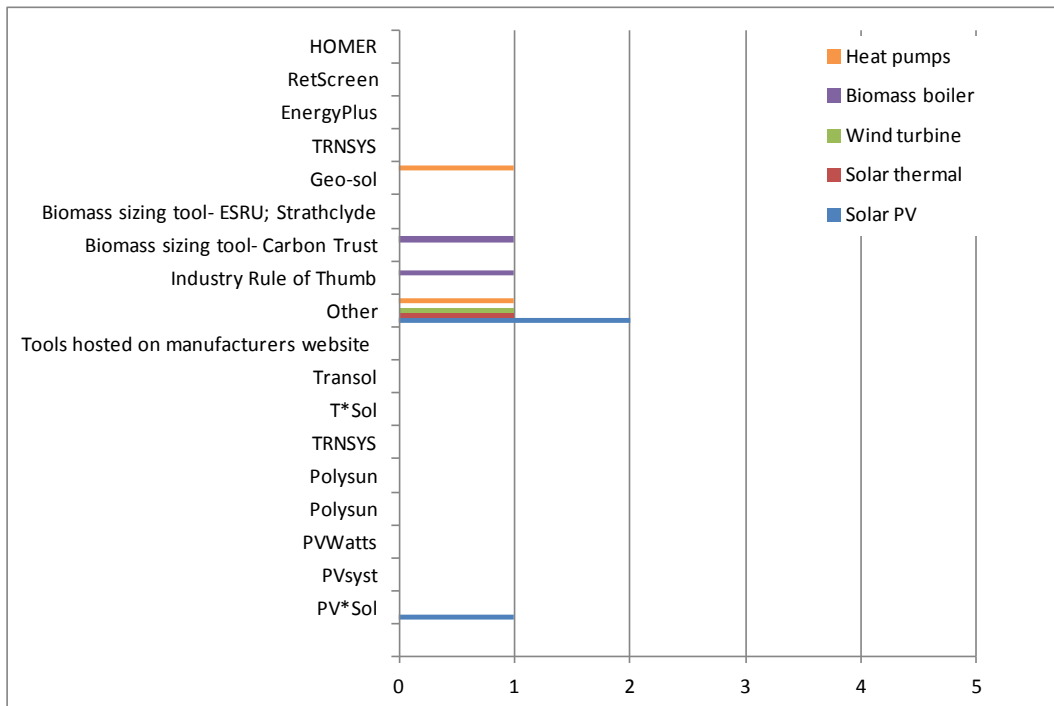


Figure 3.8 Tools used for RES simulation

Most of the tools that were given as options against each technology were not used by the respondents. Only one respondent used PV\*Sol for solar PV analysis. One respondent used GeoSol for analysis of ground source heat pumps. For biomass heating system sizing, one of the respondents used tools hosted on manufacturers’ website and another one used other techniques.

Two of the respondents used software that was not listed in the options given to them in the questionnaire. Other software included their own developed renewable energy toolkits, or using whole building analysis software like Integrated Environmental Solutions (IES-VE). One respondent selected ‘other’ since they used manual calculations. Two respondents that skipped the question relied on energy consultants or engineers for RES simulations hence were not aware of the software they used.

The next section provides a list of popular RES software used most of them specific to each RES. A brief description of software used for solar PV, solar thermal, biomass heating and heat pumps performance simulation is given. Their use in the building design process and capability for interoperability is also discussed.

### 3.4 Tools and assessment methods for various RES

The tools and assessment methods used for RES simulation are of three main types, Firstly, whole building energy analysis (WBEA) tools that contain a feature to assess the performance of RES on the buildings energy consumption and carbon emissions. Examples include, EnergyPlus, TRNSYS and IESve. Secondly, specialised system specific software. For example, PV\*Sol for Solar PV analysis, GeoT\*Sol for ground source heat pump analysis and Transol for Solar thermal systems. Thirdly statistical tools for renewable energy assessments, for example RetScreen and HOMER. A review about the features of the tools, their use in the building design process and level of interoperability will be discussed for tools specific for each technology (Table 3.6). There also have been efforts in creating RES tools to be used by architects in order to conduct RES assessment in the early design phases (Woolf 2003).

**Table 3.6 Outline of simulation tools used for various RES 3**

RES	WBEA tools	Statistical tools	Specialised tools		
Solar PV		HOMER		PV*Sol	PVsyst
Solar Thermal	EnergyPlus		Polysun	TSol	
Heat pumps	TRNSYS IESve	RetScreen		GeoT*sol	
Biomass heating system				Biomass sizing tool- ESRU Strathclyde Carbon Trust	Plan4Heat

#### 3.4.1 RES simulation in whole building energy analysis tools

A ‘state-of-the art’ literature review has already been conducted on whole building energy analysis (WBEA) ,also called building performance simulation (BPS) tools, regarding their usability in early design phases and RES simulation capability (Attia and Herde 2010; Connolly et al. 2010; Attia 2011).

##### i) *EnergyPlus*

###### a) Description and Features

EnergyPlus is an energy analysis and thermal load simulation program. EnergyPlus is a new-generation building energy simulation program based on DOE-2 and BLAST, with numerous added capabilities. The latest version is version 8.0.0 released in April 2013 (US DOE 2013b). Based on the Heat Balance Model, the program performs a comprehensive simulation of the building envelope, fenestration, HVAC systems, and daylighting (Crawley et al. 2001).The applications include energy simulation, thermal design and analysis, heating and cooling loads, solar control, overshadowing, natural and artificial lighting, life cycle assessment, life cycle costing, scheduling (Bahar et al. 2013).

#### b) RES simulation

Since EnergyPlus was developed to perform comprehensive simulation of HVAC systems, boiler sizing and heat pump design and simulation capability was already introduced in its first release. The analysis of solar PV and solar thermal systems was introduced in EnergyPlus versions 1.0.1 and 1.2.0 respectively. These versions (1.0-2.2.0) of EnergyPlus did not include models for balance of system components such as inverters and charge controllers in its solar PV calculation engine(Griffith and Ellis 2004). However, EnergyPlus version 2.2 onwards separate models for inverters, battery storage systems and the wind turbine model were also added(US DOE 2013b).

#### c) Interoperability and use in the building design process

An effort has been made to make EnergyPlus 'IFC-compliant' by developing an IFCtoIDF Transformation Utility, that transforms building geometry in an IFC building model into an Input Data File (IDF) to run EnergyPlus simulations(Hitchcock 2000). EnergyPlus currently has data exchange via IFC, gbXML, and dxf. All CAD programs are linked to EnergyPlus through a plugin or export function (ArchiCAD, Google/Trimble SketchUp, MicroStation, Revit, Vectorworks) and allow active solar system calculation. EnergyPlus and Green Building Studio can operate or allow performing of thermal simulations from Google/Trimble SketchUp (.skp) and Excel (.xls), the non-BIM application (Bahar et al. 2013). Google SketchUp is widely recognized for being used at EDP and is often used in the architect's workflow as a predecessor software to another more complex BIM or non-BIM applications (Dubois and Horvat 2010). Its interoperability with Sketchup deems its use in EDP of projects. More recent developments of Graphical User Interfaces for EnergyPlus like Simergy have been made that enhances the interoperability of EnergyPlus with CAD/BIM tools thereby ensuring better integration of its use in the building design process(LBNL 2013).

#### i) *TRNSYS*

##### a) Description and Features

TRNSYS (Klein et al. 2004) is a transient system simulation program with a modular structure that was designed to solve complex energy system problems by breaking the problem down into a series of components. The latest version is TRNSYS 17.1 (University of Wisconsin 2012). TRNSYS library (TESS version 17) includes many of the components found in thermal and electrical energy systems; solar thermal and photovoltaic systems, low energy building and HVAC systems, renewable energy systems, cogeneration, and hydrogen systems (e.g. fuel cells). It also provides component routines to handle input of weather data or other time-dependent forcing functions and output of simulation results (Crawley et al. 2008). It has been commercially available since 1975 and is primarily used for analysing single project, local community or island-energy systems (Connolly et al. 2010).

#### b) RES simulation

TRNSYS has a mature and well supported facility in the modelling of solar thermal, solar PV, wind power and hydrogen systems (Crawley et al. 2008). TRNSYS has been used extensively to simulate solar energy applications (Ruiz and Martínez 2010; Ayompe et al. 2011; Quesada et al. 2011) . Studies include prototype solar-thermal systems (Hobbi and Siddiqui 2009; Souliotis et al. 2009) and modelling of a hybrid PV-thermal system in Cyprus (Kalogirou 2001).

#### c) Interoperability and use in the building design process

Even, though tools like TRNSYS can model nearly twelve identified renewable energy technologies, previous work suggests that the tool is neither easy to use in conceptual design nor is interoperable with the BIM model (Acquaviva et al. 2012). TRNSYS does offer a 3D plug-in (TRNSYS3D) to create geometry in design tools like Google SketchUp and is capable of importing BIM models from authoring tools like Revit. However, certain limitations in the import of thermal zones and conduct thermal simulation was seen in the work of (Acquaviva et al. 2012). As a tool, it has a steep learning curve and a complex user interface for inputting building data which cannot be used easily by architects in EDP (Attia and Herde 2010).

### ii) *Integrated Environmental Solutions Virtual Environment (IES –VE)*

#### a) Description and Features

Virtual Environment PRO is a bundle of modules that work with the same geometrical model within VE PRO. The modules can perform almost any aspect of building analysis spanning from energy simulation using the heat balance method (ApacheLoads), sophisticated lighting analysis (RadianceIES) to a simplified CFD analysis (MicroFlo). The amount of results that can be obtained from VE is vast; including comfort values, different radiant temperatures and so on. The latest version of IES-VE is VE2013 (Integrated Environmental Solutions Limited 2013a).

#### b) RES simulation

IES-VE PRO allows limited feasibility assessment of user selected renewable and low carbon technologies including DHW systems, wind power generators, photovoltaic arrays, and combined heat & power systems (Attia 2011). It has recently been integrated with Gaia Geothermal GLD software. This allows detailed analysis and design optimisation of geothermal well fields, heat pumps and ground source heat exchanger systems also allowing a complete financial evaluation of the geo-thermal system.

#### c) Interoperability and use in the building design process

VE PRO uses different levels of complexity depending on which module the user chooses. Simple energy and lighting analyses can be performed with little experience with the software early in the design process and it is possible to perform more advanced analysis when needed. Many of the modules in the bundle can exchange results to provide more accurate and detailed analyses (Dubois and Horvat 2010). The tool allows direct connectivity to SketchUp, Revit and ArchiCAD. IES-VE can import building geometry through gbXML and

DXF formats. IES-ve can also import building model and site data through IFC and gbXML from Vectorworks, Revit and ArchiCAD. The analysis results can be exported to Microsoft Excel (Integrated Environmental Solutions Limited 2013b).

From the discussion of the aforementioned three WBEA tools it is evident that either the tools lack in conducting analysis of all RES or, those which are high-end simulation tools, lack in software interoperability.

### **3.4.2 Statistical analysis tools**

#### *i) RETSCREEN*

##### a) Description and Features

RetScreen ‘Clean Energy Project Analysis Software’ is a decision support tool developed with the contributions from government, industry and academia by Natural Resources Canada in 1996. It is currently being used by more than 320,000 people worldwide (Natural Resources Canada 2011). Case studies in literature that have applied the software to assess the feasibility of wind farm development in Saudi Arabia (Rehman 2005), the feasibility of solar water heating in Lebanon (Hourri 2006), the viability of grid-connected solar PV in Bangladesh (Alam Hossain Mondal and Sadrul Islam 2011) , as well as identifying the potential of green house gas reductions in Canada’s residential sector (Kikuchi et al. 2009).

##### b) RES simulation

It is a steady-state tool that evaluates the energy production and savings, costs, emission reductions, financial viability and risk for various types of renewable energy and energy-efficient technologies including technologies of solar PV, solar thermal, CHP, wind turbine and heat pumps.

##### c) Interoperability and use in the building design process

RETScreen may be used by architects and engineers to evaluate their projects. Since it requires a very good description and comprehension of the project, this software is more suitable for detailed design stages. RETScreen uses simplified algorithms to minimise data input requirements and to speed up the calculations, while maintaining an acceptable level of accuracy. It is however, a Microsoft Excel-based application. It does not provide a 3D interface. Simulations are based on numerical inputs in the Excel spreadsheet. While describing the building project all data has to be manually entered by the user. It is not a BIM application as it does not support IFC or gbXML formats.

#### *ii) HOMER*

##### a) Description and Features

The HOMER Micropower Optimization Model is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) in 1992 to assist in the design of micropower systems and to facilitate the comparison of power generation technologies across a wide

range of applications (Lambert et al. 2006). HOMER models a power system's physical behaviour and its life-cycle cost, which is the total cost of installing and operating the system over its life span. HOMER allows the modeller to compare many different design options based on their technical and economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs. The tool has been used in a variety of climatic contexts for example; for economic evaluation of hybrid renewable energy systems for rural electrification in Iran (Asrari et al. 2012), design of PV-wind hybrid power generation system for a remote area in Ethiopia (Bekele and Boneya 2012) , simulate a stand-alone system with hydrogen in Newfoundland, Canada (Khan and Iqbal 2005) and the design of a fuel cell-based renewable energy system for electrifying a rural health care centre in India (Munuswamy et al. 2011).

#### b) RES simulation

HOMER is limited to the analysis of power generating technologies that includes solar PV, CHP (fuelled by biomass) and wind turbines. It can also model hybrid power generation systems that include power generators, fuel cells, hydropower and battery banks for off-grid applications. Its simulation logic is less detailed than specialised tools that use time-series simulations. However, HOMER is more detailed than statistical models such as RETScreen.

#### c) Interoperability and use in the building design process

HOMER is a standalone tool that can be used by architects and engineers. It has an easy to use interface with a simplified data input process. Similar to RetScreen, the data input is done manually by the user. It does not feature any intelligent import or export functionality. The results can be exported to Excel or in XML format. HOMER can import a variety of time-series input data through a text file only. It performs a sensitivity analysis which can help the analyst to do 'what-if' analyses and to investigate the effects of uncertainty or changes in input variables. Hence this tool is more suited to be used before the building design phase begins.

### **3.4.3 Specialised tools and methods**

#### i) SOLAR PV

A state-of-the-art review of specialised tools for building integrated solar PV has been conducted (Bates et al. 1998; Klise and Stein 2009). Additionally, a review of analysis tools used by architects for solar design has also been conducted (Dubois and Horvat 2010; Attia 2011). The tools were reviewed on the following parameters; functions, design stage and users, 3D modelling and BIM functionality, interoperability and solar calculation logic. There also have been attempts for providing simplified PV simulation models to be used in early stages of the building design process (Woolf 2003; Perez et al. 2004; Attia and Herde 2010). This section will discuss three specialised tools for solar PV; PV\*Sol, PVsyst and Polysun in terms of their usability and level of interoperability.

#### a) PV\*Sol

PV\*Sol (latest version 6.0) is a specialised tool for design and optimisation of PV systems (Valentin EnergieSoftware 1992). Tool has a large PV and inverter manufacturer's database and accepts user defined component specifications. It is applicable to any PV surface inclinations and orientations and considers shading effects. The tool allows sizing capability of PV and inverter capacity as it considers partial load performance of inverter unit. It considers different load profiles and utility tariff rates and performs economic analysis by considering the system replacement and the investment residual value.

This dynamic simulation program has been developed for engineers, planners, roofing specialists and electrical engineers or building technicians and can be used at every stage of the design: at the start for pre-sizing and then for the design and optimization of the PV system (Dubois and Horvat 2010). The advanced version, PV\*Sol Expert provides a 3D environment for visualisation of the building with the PV array, and draw surrounding objects for an accurate shading analysis. It is however not a BIM application and does not support the import of 3D geometry from any outside application.

#### b) PVsyst

PVsyst (latest version 6.10) is another specialised tool for design and analysis of stand-alone and grid-connected PV systems (PVsyst SA 2012). The tool simulates the PV system using an inbuilt geographical and meteorological database and 3D CAD facility for visualisation and computation of nearby shading. Similar to PV\*Sol, the tool considers losses including temperature losses, mismatch losses, wiring losses and reflection losses with provision for analysis of measured data capable of modelling of grid-connected system with different inverter(s) configurations and different load profiles. In complex shading situations, PVsyst is more accurate than PV\*Sol (Dubois and Horvat 2010).

PVsyst is used by architects, engineers and researchers at preliminary design and project design stages. At preliminary design, PVsyst is used to pre-size systems. It also evaluates the monthly production and performances and performs a preliminary economic evaluation of the PV system. At project design stage, the software generates detailed simulations computing hourly values and supports the user in the definition of the PV-field and the selection of the right components. It does not possess a 3D CAD modelling feature and it does not require building geometry for its calculations (Bazjanac 2002). It is very simplistic, and like PV\*Sol, it does not have geometry import functionality. PVsyst provides specific graphical or tabular tools, which can be exported to other software. This includes output of solar geometry, various graphs of the components' behavior (PV modules, batteries, pumps), hourly meteorological plots, and calculations of irradiation on tilted planes.

ii) *SOLAR THERMAL*

a) T\*Sol

T\*Sol (latest version 5.5) is a simulation program for solar thermal heating systems including hot water preparation, space and swimming pool heating (Valentin EnergieSoftware 2011). It is possible to simulate different configurations consisting of components from a database. Starting from standard-components (i.e. 1200 different collectors) parameters can be changed according to the individual system. The influence of the system's parameters can be evaluated by easily testing different combinations. An automatic design assistant helps to optimize the design/dimensioning of collector area and storage tank volume. There are functions in order to define consumption profiles and include the influence of partial shading by the horizon and other objects like trees or buildings. The calculations are based on the investigation of energy flows. The energy yield calculations are made based on hourly balances. Besides the standard energy evaluation for solar thermal systems the program also calculates economic efficiency.

T\*Sol has been developed for planners (T\*Sol basic), engineers (T\*Sol professional), building technicians and researchers (T\*Sol Expert). It can be used at any design stage. It can be used for approximate evaluations of a solar thermal system and also for a detailed optimization including all components. However, it does not support the visualisation of architectural design (3D environment) and focuses on the energy balance of the solar thermal system. T\*Sol is not a BIM application (Dubois and Horvat 2010).

iii) *HEAT PUMPS*

a) GeoT\*Sol

GeoT\*Sol is another software recently developed by Valentin Software for the planning and design of heat pumps systems (Valentin EnergieSoftware 2013). It supports the following heat pump configurations; brine/water with ground heat exchangers [Ground-Source Heat Pumps (GSHP)], air/water [Air-Source Heat Pumps (ASHP)]. It allows the simulation of five different system configurations involving heating, domestic hot water and solar thermal support. It is available in the basic version (latest version 1.0). Similar to PV\*Sol and T\*Sol, the software contains a database of heat pump system components that contain all the technical specifications. It is also loaded with variety of system types as templates. It enables a quick calculation of energy usage and cost. GeoT\*SOL basic evaluates the economic efficiency of a system by establishing a ratio of heat price to anticipated service life.

iv) *POLYSUN*

Polysun is a simulation tool that supports the design of solar thermal, heat pump (geothermal only) and photovoltaic systems as well as combined systems (Vela Solaris 2013). It offers a user friendly interface and targets solar energy professionals, who are mainly focusing on standardized systems. Calculations are based on a dynamic simulation model and statistical weather data. With its solar thermal features, Polysun is widely used in retrofit applications



due to its unequalled flexibility in the detailed system representation. In Solar Photovoltaics, Polysun offers an automatic inverter matching as well as an accurate yield prediction. The software contains a comprehensive component database for photovoltaic modules, inverters, solar thermal collectors, heating units, etc. This database contains all system specifications required to run the simulation and regular updates to products are provided on their website. A large number of system templates for solar thermal and PV design are included that increases efficiency.

The interoperability of this software has been enhanced by creating a simulation kernel, a universal software interface, known as 'Polysun Inside' DLL. 'Polysun Inside' DLL is fully integrated in the following applications; LESOSAI (BPS tool), ENERGIEplanner (energy management tool), DDS (CAD/BIM tool) and plan4solar (Solar PV planning tool) (Witzig et al. 2009).

#### v) *BIOMASS HEATING SYSTEMS*

Even though there are financial incentives in the UK that encourage the use of biomass heating systems for renewable heating, the design of the system is yet in the domain of manufacturers and installers and the system design is yet not integrated early in the building design process (Carbon Trust 2009). The basic components of a biomass heating system are a boiler, accumulator tank, fuel store and wet distribution system. Guidance on biomass heating system design is also given in a range of documents published as European Standards and from CIBSE (Table 3.7). Unlike conventional heating systems, the quality of the fuel (logs, chips or pellets) take precedence in the system design. The moisture content of the fuel affects its energy content which impacts the quantity of fuel required to supply the energy demand of a building. The procurement of the fuel, frequency of delivery, and security of fuel supply are also important factors that affect the decision of installing biomass heating systems. Since it is a combustion system that emits volatiles (water vapour, carbon monoxide, carbon dioxide, nitrogen oxide and particulates (smoke)) as a by-product, it has tighter compliance requirements in the UK's building regulations (Part L) (DCLG 2008b).

**Table 3.7 Standards and guidance documents for biomass heating systems**

Standard/guidance document	Institution	Description
BS EN 14961-1:2010 (BSI 2010a)	British Standards Institution	Sets standards for size, chemical and physical properties for pellets and chips.
CIBSE KS10 (CIBSE 2007)	CIBSE	Fuel store sizing
CIBSE Guide B (CIBSE 2005)	CIBSE	Fuel store sizing
Biomass heating A practical guide for potential users (CTG012) (Carbon Trust 2009)	CarbonTrust	Guidance on biomass heating systems, their implementation process, technical specifications
BS EN 303-5:2012 (BSI 2012)	British Standards Institution	Accumulator tank sizing

The author reviewed the following tools for biomass heating system design.

a) Biomass Boiler System Sizing (BBSS) tool -Carbon Trust

The BBSS tool (latest version 6.8) is a pre-feasibility decision support tool jointly developed by the Carbon Trust, with the University of Strathclyde and Campbell Palmer Partnership, freely available from (Carbon Trust 2013b). It is a Microsoft Excel based application. The tool is broken down to a number of modules that run sequentially after the data in one module has been completed. The first module (demand module) requires an estimate of hourly heat demand profile of the building in a day. This can be calculated from any BPS tool or the user can use the embedded heat demand calculator. For existing buildings, heat meter measurements or monthly fuel bills can also be used. The tool can process chip and pellet biomass fuels. The next module requires the fuel specifications and cost from the user. The boiler sizing module requires biomass boiler system parameters available in manufacturer's literature. This contains the technical specifications of the boiler. The type of fuel-feed mechanism will depend of the boiler type. The tool automatically calculates the size of the accumulator tank. It also conducts carbon emission analysis and financial feasibility assessment of the designed heating system.

The user requires a certain level of prior knowledge about heat load calculations in buildings, biomass systems, fuels specifications and fuel storage (Carbon Trust 2013a). Hence, it cannot be used straight away by architects or planners. Being an Excel based application limits its interoperability with other software. Even though the heating demand can be entered using a BPS tool, this has to be entered manually by the user in the spreadsheet. Furthermore, the developers of the tool do not guarantee its accuracy and credibility of this tool hasn't been established in current research. The tool has been designed for the assessment of biomass heating system rated between 50 kW and 3MW, hence excludes domestic applications (except housing estates).

b) Plan4Heat

Plan4Heat (latest version 2.3) has been recently developed by GASCAD 3D technologies GmbH. It is a planning and visualisation tool for biomass heating systems. The basic CAD interface has different modules for creating rooms (room assistant). The user can also add geometric objects with assigned materials such as concrete plinths for the boiler. It contains a library of biomass system components like boiler, accumulator tanks and extractor (a component that transfers fuel from the storage to the boiler) with its associated costs. The user can select these components and the software automatically connects them to complete the system. The user can also modify costs or enter discounts for the products. The tool has provisions to show flexible cables that operate the system. The drawings made in the CAD interface are dimensioned automatically and 3D visualisation of the installation is generated. A total system cost quote is also provided.

Plan4Heat is not a system sizing tool, but is a visualisation tool to help the project team to 'see' what the installation would look like and to estimate the system cost. Hence it cannot

be used in the early design phase as the heating system has to be sized beforehand. It has a CAD and 3D interface but it isn't a BIM application. The integration of this software with BIM and a credible biomass system sizing tool is the need of the day.

#### ***3.4.4 Structure of RES simulation models***

From the above review of existing tools and assessment methods for RES and their integration within buildings, it is evident that either these tools are specialised for a specific RES, or the tools that conduct assessment for all renewable energy technologies are statistical, hence lack detailed simulation logic. Furthermore, these tools lack in interoperability with CAD/BIM tools inhibiting their inclusion in EDP of the building design process.

A simulation model consist of three distinct parts; the input file, a processor or engine and the output or results (Maile et al. 2007; Manke et al. 2013) ( Figure 3.9). In order to enhance the interoperability of RES simulation models it is important to list the input and output data of their simulation logic and investigate the source of the input data. The input data required for outputs such as energy demand, energy supplied from RES, carbon emissions offset by the use of RES and various financial outputs such as payback period, ROI, capital cost and running costs have been analysed for RES such as Solar PV (Table 3.8), Solar Thermal (Table 3.9), Heat pumps (Table 3.10) and biomass heating systems (Table 3.11), by looking at the algorithms used by tools and assessment methods described above. It is important to note that for a range of outputs, a variety of input data is required which can be simplified or detailed according to the simulation logic of the chosen model. For example, a complex dynamic simulation model demands a plethora of input data to be entered by the user, which can be a time-intensive process (Maile et al. 2007).

For renewable energy assessment in buildings, the input data can be broadly classified as building geometry and properties, climate data and technical specifications of RES (Table 3.8-Table 3.11). The source for building geometry and associated properties is the architectural model (conceptual design); climate data is sourced from weather stations or climate data repositories, and technical specifications of RES is sourced from manufacturers' literature. Some RES tools in the market, especially for Solar PV and solar thermal, contain a database of system components with technical specifications. For example, Polysun and PVsyst use PV and inverter databases provided by Photon(Lalwani et al. 2010; Boehne 2013). Polysun uses solar thermal collectors of SPF (Institut für Solartechnik SPF 2013) and heat pump data from NTB (Dubois and Horvat 2010; Institut IES 2013).

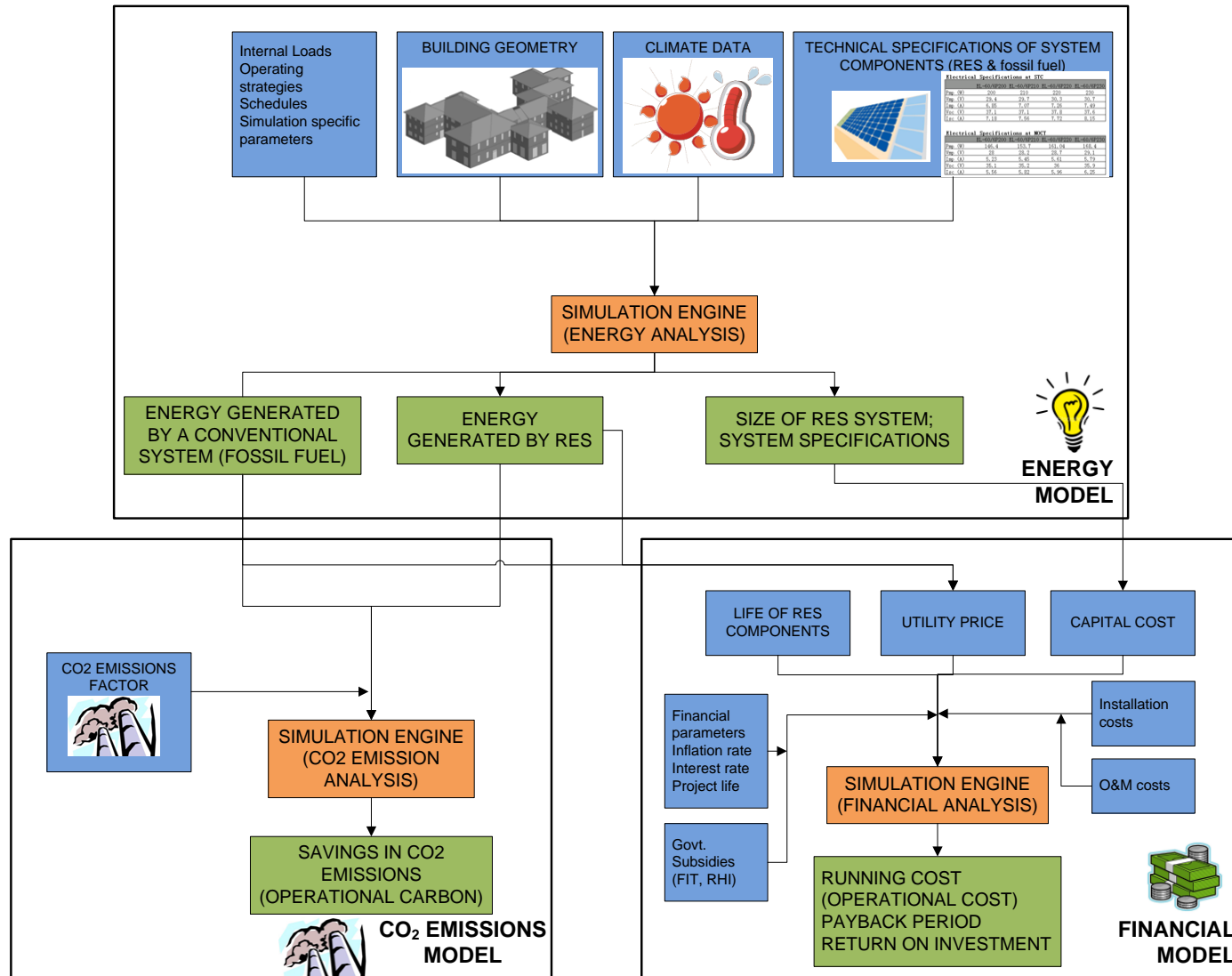


Figure 3.9 Structure of a RES simulation model

Table 3.8 Input data required for Solar PV assessment

Input data	Data source for input (new build)	Process	Output	
Power rating of all appliances	Manufacturers literature	Manual Calculation; Simulation in BPS software	Energy demand; Demand (load) profile	1
Lighting power rating				
Number of appliances				
Hours of consumption				
Lighting schedule				
Surfaces selected for PV	User-defined	Manual Calculation; Simulation in MEP or specialised PV software	Energy supply; Energy supply profile	2
Orientation, slope, area available for PV	As per architectural model			
Location	User-defined; site specific			
Latitude				
Climate Data(hourly , monthly or yearly average values); Insolation; Ambient temperature; Cloudiness	Monitored data; Averaged historic data			
System Characteristics PV specifications;Type, Capacity, Efficiency, Voltage and current at maximum power	Manufacturers literature			
Inverter specifications; Type, power rating, efficiency				
Other Balance of System component specifications (charge controller, battery, etc.)				
Energy demand profile	Output 1	Demand-Supply matching	Magnitude of electrical loads met by PV	3
Energy supply profile	Output 2			
Energy savings through PV	Output 3	Calculation for Payback period, ROI, capital cost, running cost.	Financial viability assessment; Payback period, ROI, capital cost and running cost	4
PV system lifetime (PV array, inverter)	Manufacturers literature			
System cost (PV, inverter, cabling)	Manufacturers quote			
Operation and Maintenance (O&M) cost	Manufacturers/Installers quote			
Government subsidies	Government Policy			
Electricity selling price				
Financial parameters (interest rate, infiltration rate)	Finance market			

Input data	Data source for input (new build)	Process	Output	
Energy demand	<b>Output 1</b>	Manual Calculation	Carbon emission offset of baseline building (operational carbon)	5
Baseline fuel chosen to meet demand	User/context defined			
Carbon emission factor of chosen fuel	Government stipulated carbon emission factors (country specific)			
Magnitude of electrical loads (demand) met by PV	<b>Output 3</b>			

Table 3.9 Input data required for solar hot water heating assessment

Input data	Data source for input (new build)	Process	Output	
Occupancy	User-defined;	Manual Calculation; Simulation in BPS software	DHW (load) profile	1
DHW consumption				
DHW consumption profile				
Incoming mains cold water supply temperature				
Temperature of hot water required				
Surfaces selected for Solar thermal	User-defined	Manual Calculation; Simulation in MEP or specialised Solar thermal software	Energy supply; Energy supply profile	2
Orientation, slope, area available for Solar thermal	As per architectural model			
Location	User-defined; site specific			
Latitude				
Climate Data(hourly , monthly or yearly average values); Insolation; Ambient temperature; Cloudiness	Monitored data; Averaged historic data			
System Characteristics	Manufacturers literature			
Solar thermal specifications; Type, Efficiency, Flow temperatures				
Thermal store specifications; Size of tank; thickness, type of insulation; water temperature				
Auxiliary heating system specifications (fuel type, efficiency)				
Control systems specifications (preventing legionella)				
Input data	Data source for input (new build)	Process	Output	

DHW (load) profile Energy supply profile	Output 1 Output 2	Demand-Supply matching	Magnitude of DHW load met by Solar thermal	3
Energy savings through use of solar thermal	Output 3	Calculation for Payback period, ROI, capital cost, running cost.	Financial viability assessment; Payback period, ROI, capital cost and running cost	4
Solar thermal system lifetime (panels, thermal store,etc.)	Manufacturers literature			
System cost ((panels, thermal store, piping,etc.)	Manufacturers quote			
Operation and Maintenance (O&M) cost	Manufacturers/Installers quote			
Government subsidies	Government Policy			
Financial parameters (interest rate, infiltration rate	Finance market			
DHW demand	Output 1	Manual Calculation	Carbon emission offset of baseline building (operational carbon)	5
Baseline fuel chosen to meet demand	User/context defined			
Carbon emission factor of chosen fuel	Government stipulated carbon emission factors (country specific)			
Magnitude of DHW demand met by Solar Thermal	Output 3			

Table 3.10 Input data required for heat pump assessment

Input data	Data source for input (New Build)	Process	Output	
Building geometry	Architectural model	Simulation in BPS software; Calculation of losses and gains & energy consumption	Heating Load (kW) Energy demand (kWh)	1
Fabric characteristics (Material, thicknesses, U-value of walls, roofs, floors, windows, doors; air infiltration )	Architectural model, User-defined;			
Internal Gains (occupancy+lighting+appliances)				
Ventilation system (type, efficiency, strategy,etc,)				
Climate data (insolation, ambient temperature. Wind speed, etc.) (hourly , monthly or yearly average values)	Monitored data; Averaged historic data			
Setpoint (internal temperature)	User-defined			

Input data	Data source for input (New Build)	Process	Output	
Heating load	Output 1	Simulation in MEP or heat pump software	Heat Pump sizing	2
Heat pump characteristics (COP, seasonal performance, capacity, fuel type etc.)	Output 2, User-defined	Manual Calculation; Simulation	Energy supplied by heat pump; Energy supply profile (Energy consumed by heat pump); Fuel required by heat pump	3
Heat exchanger characteristics (type, land area)	Architectural model			
Climate Data : Ambient air temperature (ASHP); Ground temperature, Soil type (GSHP)	Ground survey, monitored Averaged historic data			
Thermal store specifications; Size of tank; thickness, type of insulation; water temperature	Manufacturers literature			
Auxiliary heating system specifications (fuel type, efficiency)				
Control systems specifications				
Energy demand Energy supply profile	Output 1 Output 3	Demand-Supply matching	Magnitude of heat demand met by HP	4
Energy savings through use of heat pump	Output 4	Calculation for Payback period, ROI, capital cost, running cost.	Financial viability assessment; Payback period, ROI, capital cost and running cost	5
Heat pump system lifetime (heat pump, heat exchanger circulating pumps, etc.)	Manufacturers literature			
System cost (heat pump, heat exchanger circulating pumps, etc.)	Manufacturers			
Heat pump running costs (fuel costs)	Suppliers quote			
Operation and Maintenance (O&M) cost	Installers quote			
Government subsidies	Government Policy			
Financial parameters (interest rate, infiltration rate)	Finance market			
Energy demand	Output 1	Manual Calculation	Carbon emission offset of baseline building (operational carbon)	6
Baseline fuel chosen to meet demand	User/context defined			
Carbon emission factor of chosen fuel	Government stipulated carbon emission factors (country specific)			
Magnitude of energy demand met by heat pump	Output 4			
Fuel consumed by Heat Pump	Output 3			



Table 3.11 Input data required for biomass heating assessment

Input data	Data source for input (New Build)	Process	Output	
<b>Building geometry</b>	Architectural model	Simulation in BPS software; Calculation of losses and gains & energy consumption	Heating Load (kW) Energy demand (kWh)	<b>1</b>
Fabric characteristics (Material, thicknesses, U-value of walls, roofs, floors, windows, doors; air infiltration )	Architectural model, User-defined;			
Internal Gains (occupancy+lighting+appliances)				
Ventilation system (type, efficiency, strategy,etc,)				
Climate data (insolation, ambient temperature. Wind speed, etc.) (hourly , monthly or yearly average values)	Monitored data; Averaged historic data			
Setpoint (internal temperature)	User-defined			
Heating load	<b>Output 1</b>		Biomass boiler sizing	<b>2</b>
Boiler size (capacity)	Output 2		Thermal store size	<b>3</b>
Fuel characteristics (Moisture, ash content, density, calorific value)	Suppliers literature	Manual Calculation; Simulation	Energy supplied by boiler;	<b>4</b>
Boiler characteristics (type, efficiency, fuel feed mechanism, refractor lining)	Manufacturers literature			
Thermal store/buffer vessel characteristics ;thickness, type of insulation; water temperature	Output 2, Manufacturers literature		Energy supplied by thermal store	<b>6</b>
Fuel storage (type-silo, hopper, etc.)	<b>Output 5</b> ; Boiler dependent		Fuel store size and access	<b>7</b>
Flue (type, size, height)	Compliance notes		Height of flue	<b>8</b>
Auxiliary heating system specifications (fuel type, efficiency)	Manufacturers literature		Energy supplied by auxiliary system	<b>9</b>
Control systems specifications				
Energy demand Energy supply boiler Energy supply thermal store	<b>Output 1</b> <b>Output 4</b> <b>Output 6</b>	Demand-Supply matching	Magnitude of heat demand met by biomass boiler & thermal store	<b>10</b>

Input data	Data source for input (NB)	Process	Output	
Energy savings through use of biomass heating	<b>Output 10</b>	Calculation for Payback period, ROI, capital cost, running cost.	Financial viability assessment; Payback period, ROI, capital cost and running cost	11
Biomass heating system lifetime (boiler, thermal store, storage, flue, circulating pumps, etc.)	Manufacturers literature			
System cost (boiler, thermal store, storage, flue, circulating pumps, etc.)	Manufacturers			
Fuel cost (Wood chip, pellet)	Suppliers quote			
Operation and Maintenance (O&M) cost	Installers quote			
Government subsidies	Government Policy			
Financial parameters (interest rate, infiltration rate)	Finance market			
Energy demand	<b>Output 1</b>	Manual Calculation	Carbon emission offset of baseline building (operational carbon)	12
Baseline fuel chosen to meet demand	User/context defined			
Fuel required for biomass heating	<b>Output 5</b>			
Carbon emission factor of chosen fuel	Government stipulated carbon emission factors (country specific)			
Carbon emission factor of biomass fuel				

### 3.5 Conclusion

The UK government has set ambitious targets of achieving zero- carbon buildings by 2019 and replacing 15% of country's current fossil-fuel energy through renewable sources. There have been revisions in the building regulations, establishment of sustainable codes and environmental standards to encourage the uptake of RES in the design of new buildings. However, it has also been stated that in order to achieve higher levels of the Code of Sustainable Homes and BREEAM, one of the main factors is to consider integrating renewable energy technologies into the overall design concept from the earliest design stages. However, simple tools that can quantify and illustrate the influence of various solar applications are lacking in the market, which hinders the integration of renewable energy technologies at the design stage. At the design stage, the building shape, massing, material type and orientation can be optimised to gain maximum benefit from the use of low and zero carbon technologies. This would further contribute in meeting the government's ambitious targets in zero-carbon buildings.

An online survey conducted with architects and building services engineers revealed that although RES simulation was adopted early in the design process, they were using their own developed toolkits or assessment methods. Architect's knowledge in this domain was found insufficient and they relied upon consultants or engineers for RES performance assessments of their projects.

The review of existing tools and methods concluded that there either specialised tools available that conduct assessment of a specific RES, or tools that conduct a holistic RES assessment are statistical and lacking a detailed simulation logic. Furthermore, very few tools are developed to be used in the EDP of the building design process and are far from integration with BIM processes.

Lack of interoperability between RES and BIM models was deemed to be one of the factors for the low adoption of RES in the EDP, in the online survey. The next chapter reviews the standardisation efforts in data exchange and interoperability. It will also review the existing approaches in enhancing the interoperability between BIM and Energy/RES analysis tools. The structure of the RES simulation model, the input data, data sources and processes have been established in this chapter. The next chapter would aid in formulating a methodology for BIM and RES integration, thereby encouraging the integration of RES analysis in the building design process.

## CHAPTER 4. INTEROPERABILITY BETWEEN BIM AND RES SIMULATION

Interoperability is the ability to exchange data between applications, which smoothes workflows and sometimes facilitates their automation (Eastman et al. 2011).

Interoperability eliminates the need to manually copy data already generated in another application. Manual copying of partial project data is an erroneous process, harbours inconsistency and greatly discourages iteration during the design phase, as required for finding best solutions to complex issues such as structural or energy design (Bazjanac 2008). The interoperability between applications can be facilitated by automating every part of the analysis process (structural or energy) that can be automated. This calls for a review of standardisation efforts in data exchange and the existing approaches that have begun to establish interoperability between BIM (openBIM) and RES/energy analysis applications.

This chapter provides an overview of data exchange standards, focussing on the non-proprietary and public standards, gbXML and IFC (section 4.1). It then provides a detailed description of the IFC schema, a review of its worldwide adoption and implementation in industry projects (section 4.2). It is followed by a review on the other BIM standardisation efforts of buildingSMART international that support the adoption of IFCs through Information Delivery Manual (IDM) and Model View Definitions (MVD) (section 4.3). Existing approaches in developing IFC-BIM compliant energy analysis tools are then analysed (section 4.4), thereby providing a basis for the author to develop her own methodology of developing IFC compliant RES simulation tool.

### 4.1 Overview of data exchange standards

The building information data is exchanged in the BIM environment through various formats such as the Industry Foundation Classes (IFC), XML, CIMsteel Integration standard (CIS/2 2007), etc. Generally data exchanges between applications are based on two levels of definition characterised in Figure 4.1.

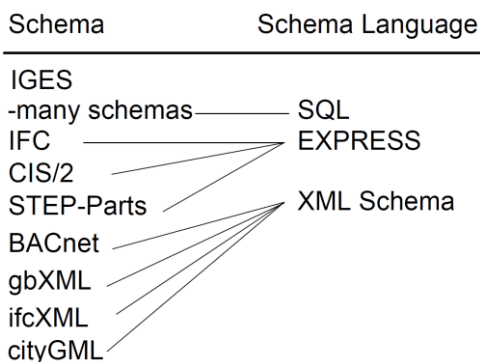


Figure 4.1 Different types of schema and schema languages (Eastman et al. 2011)

The top-level is the model *schema*, defining the meaning of information exchanged. Initially, a file format was defined that did not separate the way information was formatted from its semantic content (for example, IGES and DXF formats).

The separation of the schema from a more general language came into existence in the 1980s; Structured Query Language (SQL) is a prime example, which is a dominant schema definition language for databases. Similarly ISO-STEP developed data modelling language, EXPRESS is the basis for a range of product modelling technologies and schemes, examples include the Industry Foundation Classes (IFC) and CIMSteel integration standard, version 2 (CIS/2).

Apart from EXPRESS, another large set of exchanges are supported by XML (eXtensible Markup Language). Examples are given in Table 4.1.

**Table 4.1 Data exchange formats supported by XML**

Name	Application
BACnet (Building Automation Control networks)	Building mechanical controls
gbXML (Green Building XML)	Schema developed to transfer information needed for preliminary energy analysis of buildings.
ifcXML	IFC schema mapped to XML
CityGML (City Geographic Markup Language)	Format representing buildings within a GIS (Geographic Information system) for urban planning, emergency services, infrastructure planning.

Data exchanges can be of three main types summarised in Table 4.2. The current practice in the construction industry has been ‘mixing and matching’ of software tools to provide functionality beyond what is offered by a single platform. The public sector wishes to avoid the proprietary solution that gives any one software platform a monopoly (Eastman et al. 2011). Hence XML (gbXML) and particularly the IFC have become the international standard for data exchange and integration in the building construction industry since it is public and internationally recognised.

**Table 4.2 Different types of data exchange formats**

Type	Direct Links	Proprietary	Public product data model exchange ormat
<b>Definition</b>	Use the application programming interface (API) of one system to extract data from one application and write that data using the receiving applications API. The exchange can be in the form of a temporary file or a real-time exchange	Interface/file format developed by a company for interfacing with that company’s application. The schema specification can be public or confidential.	Open & publicly managed schema and language
<b>Examples</b>	ArchiCAD GDL Revit OpenAPI Bentley MDL	DXF by Autodesk SAT by Spatial Technology STL for stereo-lithography 3DS for 3D-Studio	XML (gbXML) Text file IFC CIS/2 ISO 151296

#### **4.1.1 The XML schema**

XML provides a robust, non-proprietary, persistent, and verifiable file format for the storage and transmission of text and data both on and off the Web (W3C, 2006). XML allows groups of people or organizations to create their own customized markup language for exchanging information within and between their respective domains of interest. It has a global “language” format, with consistent syntax and can potentially represent any computational building model through translation using appropriate mapping engines.

Key features of XML schema:

- An extension of HTML, the base language of the Web.
- Supports multiple handling of schemas
- Some are embedded within the exchanged data and others rely on external schema
- Can be published, made public or as proprietary
- Especially good in exchanging small amounts of business data between two applications.

vi) *Green Building XML (gbXML):*

Green Building XML (gbXML) is an open schema developed to facilitate the transfer of building information stored in BIM models to a variety of applications that perform energy analysis of building envelopes, zones, and mechanical equipment. Since it is developed on the XML format it inherits all the benefits and features of XML. The schema was developed by Green Building Studio (formerly GeoPraxis) in 1999 with the support of the California Energy Commission Public Interest Energy Research (PIER) Program and Pacific Gas and Electric (Green Building Studio 2002). Several popular CAD software (e.g., Autodesk’s Revit, Architectural Desktop, and Graphisoft’s ArchiCAD) and energy analysis applications (e.g., DOE-2, e-QUEST, HAP) can exchange data using this schema, through the Green Building Studio web service (DOE-2, 2007).

#### **4.1.2 Industry Foundation Classes (IFC)**

The Industry foundation classes are open data model specifications for defining building components’ geometry and other properties in a way that enable CAD users to transfer design data between different software applications (Howard and Bjork 2008; Smith and Tardif 2009).

They provide an authoritative semantic definition of building elements, their properties and inter-relationships. The IFC specification is developed and maintained by buildingSMART International (buildingSMART 2011). It has been included in the ISO standard (ISO/PAS 16739) in the process of becoming an official International Standard ISO/IS 16739. The IFC with its standard set of rules for data storage, data exchange and protocols provides an ideal framework to manage data related to a building throughout its lifecycle.

*The IFC is the only public, non-proprietary and well-developed data model for buildings existing today. It is a defacto standard worldwide and is being formally adopted by different governments and agencies in various part of the world. It is being picked up and used for a growing number of uses, in both public and private sectors (Eastman et al. 2011).*

Notwithstanding the consistent language format, the implementation of the actual data model or schema, with their associated semantics, can still vary significantly across various domains. For example, a gbXML file format cannot be used in the structural design domain. This proves to be a challenge to advancing interoperability in order to achieve an integrated BIM for the construction industry(Eastman et al. 2011). The gbXML exchange format is specific for the energy simulation domain, while IFCs adopt a comprehensive and generic approach to represent an entire building project. In terms of geometry, the generic approach of IFC has the ability to represent any shape of building geometry, while gbXML only accepts rectangular shape, which is enough for energy simulation(B.Dong et al. 2007). IFC uses a “top-down” and relational approach, which yields in a relative complex data representation schema and is able to maintain semantic integrity automatically.

Limitations in the interoperability between BIM modelling tools and energy analysis programs using gbXML has also been stated in the work of Moon et.al.(Moon et al. 2011) The work of Cho et al. (Cho et al. 2010) revealed that Ecotect lacked functions to simulate renewable energy sources although the tool was BIM-integrated through the use of gbXML data exchange format. The CAD model could be directly imported from Constructor to Ecotect through gbXML. However, since Ecotect lacked the capability of modelling geothermal systems, a simulation was also conducted in TRACE 700. TRACE 700 required extensive information such as the room’s area, volume, location, appliance specification, schedule, etc. that couldn’t have been fulfilled by the gbXML data exchange format. Hence, this data had to be input manually by the user. This restricts its use across other disciplines in the project team.

Hence, the IFC data exchange standard has been chosen over gbXML due to its robustness and ability to provide an ideal framework to manage all data related to a building throughout its lifecycle. A detailed description of the IFC, examples of its worldwide adoption and implementation has been discussed in detail in the following section.

## 4.2 The Industry Foundation Classes

The IFCs are currently being adopted in both public and private sectors (GSA 2007; Eastman et al. 2011). The IFC specification is written using the EXPRESS data definition language, defined as ISO10303-11 by the ISO TC184/SC4 committee (Liebich 2009). It is the same data definition language as used in STEP or CIS/2. Since their inception in 1994 there have been many releases to date with IFC Edition 4 (IFC4) being the latest version launched recently (buildingSMART 2013), however its precursor IFC2 x Edition 3 (IFC 2x3) is a stable version that is in practical use today (Liebich 2013). The IFC2x specification was officially accepted as a Publicly Accessible Specification ISO PAS 16793:2005. In the description of the IFCs the term ‘schema’ and ‘model’ is used. For clarity the IFC specification is a schema, and an IFC exchange file (data model) represents an instance of building information ‘model’. The IFC data model analysed in this paper is a population of the IFC2 x Edition 3 (IFC 2x3) specification schema.

The IFC are open data model specifications for defining building components’ geometry and other properties in a way that enable CAD users to transfer design data between different software applications (Howard and Bjork 2008; Smith and Tardif 2009). The specification has defined AEC objects- physical items, the spaces between them and the processes involved. Using IFCs, rich and useful information can be shared between project partners without the loss of accuracy or design intent (BSI 2010b). They provide an authoritative semantic definition of building elements, their properties and inter-relationships. It is a standard set of rules for data storage, data exchange and protocols that provides an ideal framework to manage data related to a building throughout its lifecycle.

The IFC laid the foundation of a standardised data exchange as a mandatory pre-condition for an efficient BIM-based workflow between different project participants also referred to as ‘Integrated BIM’ (iBIM).

### 4.2.1 *Worldwide adoption*

“In the move towards the higher levels of BIM to BIM being fully collaborative, there’s a need to adopt open, sharable, non-vendor specific data formats, typically Industry Foundation Classes” (NBS 2013)

The National BIM survey (NBS 2013) highlighted that 39% of the respondents use IFC in their projects, 31% don’t, and a further 30% don’t know whether they do or not. This suggests that the industry needs more information and education of the Industry Foundation Classes, and roll-out more IFC compliant software that enhances interoperability between different software applications.

Improved interoperability between software applications and improved functionality of BIM software have been voted as the top areas of improvement for BIM by architects and engineers in UK, France and Germany (McGraw-Hill Construction 2010). There have been



publications around experts view on the standardisation and industry deployment of BIM (Howard and Bjork 2008; Rezgui et al. 2012) with an informed and critical view of IFC development (Kiviniemi 2006). Kiviniemi (2006) emphasised that robust modelling software for BIM exists with developments around the IFCs. Business cases based on IFC exchange do exist for design integration and energy and comfort simulation. Although there software applications (Figure 4.2) which have been implemented based on the IFCs, neither the standard nor product modelling were widely used in practice previously (Howard and Bjork 2008).

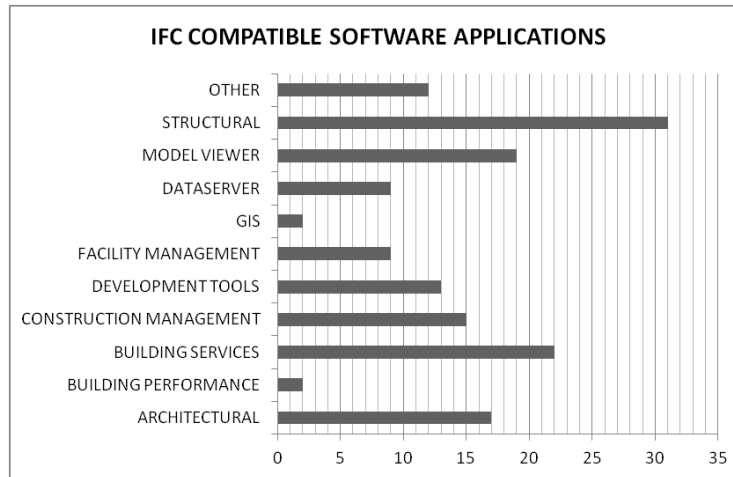


Figure 4.2 IFC compatible software applications

The BuildingSMART website (Espedokken 2013) provides a list of 151 IFC compatible software available in the market for a variety of AEC applications. In the list only two tools IDA ICE developed by Equa Simulation AB (Equa 2013) and RIUSKA (Granlund 2013) developed by Granlund are IFC compatible building performance simulation applications. Lower adoption of IFCs by the building simulation community can be attributed to the strong adoption of other data exchange formats such as gbXML.

Several years ago, the adoption of the IFCs was relatively low (Serror et al. 2008) and there had been a number of barriers that BIM proponents needed to address before industry wide acceptance (Ashcraft 2008). However, some large public sector owners, such as General Services Administration (GSA) in the US and Senate Properties in Finland, have made significant efforts to speed up the adoption of IFC-based integrated BIM by defining specific modelling requirements (buildingSMART Finland 2012a) and publishing BIM guidelines (GSA 2007; Senate Properties 2007). In addition, together with the Norwegian Statstbygg (HITOS) and Danish Enterprise and Construction Authority (Digital Construction project), they made a public statement of intention to support BIM based on open standards such as the IFC (GSA 2008) (Figure 4.3). Another noteworthy project that implemented IFC (IFC 2.0) is the LBNL E-lab building (Bazjanac 2002).

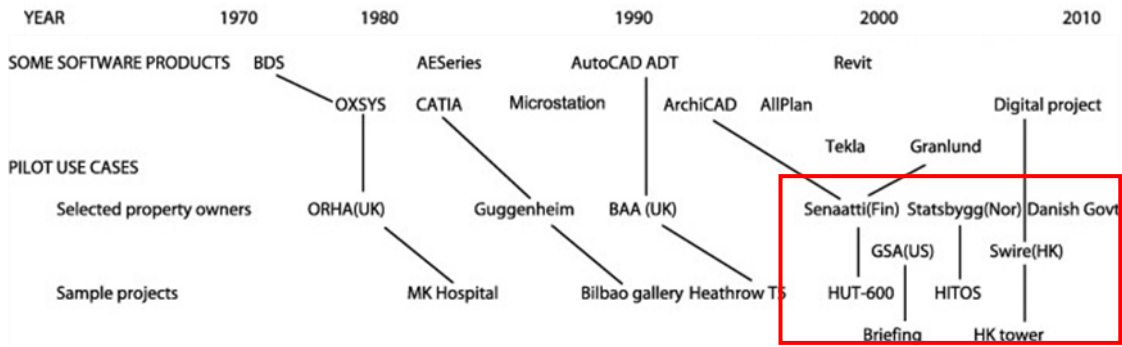


Figure 4.3 Outline of property owners and example projects using IFC-based integrated BIM (Adapted from (Howard and Bjork 2008))

4.2.2 IFC implementation case study

Senate properties have been a global forerunner in deploying IFC-based integrated BIM in real projects. The Helsinki University of Technology Auditorium Hall 600 (HUT-600) was the world’s first IFC-based integrated BIM project (Kiviniemi 2011).

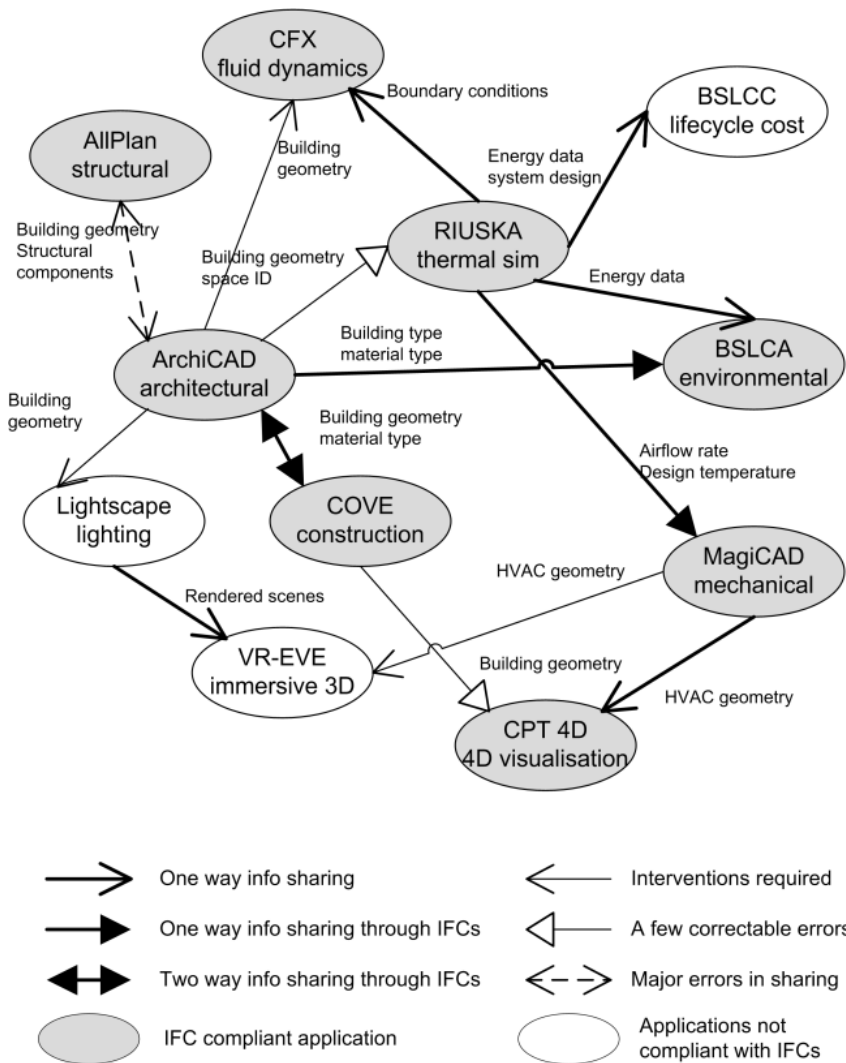


Figure 4.4 Schematic showing data exchange between various project team members in HUT-600 project (Adapted from (Kam et al. 2003))

The design and construction of the Helsinki University of Technology Auditorium Hall 600 (HUT-600) in Finland was done using the Product Model and Fourth Dimension (PM4D) approach (Kam et al. 2003). The approach included constructing and maintaining object-oriented product models with explicit knowledge of building components, spatial definitions, material composition, and other parametric properties by the project team. The Industry Foundation Classes (IFC) interoperability standards were tested and an array of design, visualization, simulation, and analysis tools. The underlying aim of the project team was to test the extent to which the exchange of IFC-based project data could take place among commercially available applications like ArchiCAD (Architectural), MagiCAD (mechanical), RIUSKA (thermal simulation), COVE (construction), etc (Figure 4.4).

Figure 4.4 shows the various data types that were exchanged between various applications. Even though the IFC supported many of the data types, some inputs were required from other software applications and database libraries to execute the analysis in all IFC-compliant applications. Table 4.3 outlines the input data types for RIUSKA supported by IFC version 1.5.1, and those provided by other applications or data repositories.

**Table 4.3 Input data types required for RIUSKA supported by the IFC, other applications or databases**

	Supported by IFC 1.5.1 in HUT-600	Inputs from software applications or data libraries
Import to RIUSKA	Building Geometry Space ID	Site Climatic data (hourly interval) Thermal Design Targets (e.g., indoor air quality) Thermal Loads from Occupants Thermal Loads from Equipment Air-Conditioning System Data (e.g., fan curve, control, efficiency)

The product modelling and information standards community has long touted the advantages of supporting the many software tools used on projects with a common core model. However, to the author’s knowledge till date, the community is still lacking a validated specification for the content of such a core model. The major outcome of this research (Kam et al. 2003) was that such a core model does exist, the contents of which are; building geometry, material types and space identifiers (id). Usually the architect expends significant effort to modify the ‘core’ model to suit the needs of various disciplines hence creating various ‘domain-specific models’ for example, thermal model.

From the experiences of the project team working on the HUT-600 project, a key recommendation in development of interoperability standard was that a distinction be made in the core model and domain specific models (Kam et al. 2003). The research areas of high importance identified were partial model exchanges, support for interdisciplinary revisions, IFC schema extensibility, and the concept of “core model” versus “domain-specific model”. With software and middleware that were compatible with IFC release 1.5.1, the HUT-600

project team benefited from the extensive exchanges of 3D geometries, spatial information, thermal values, and material properties among different software applications and disciplines. The IFC minimized data re-entry, increased accuracy of information exchange, and reduced design time during the schematic design phase.

*i) Other implementation efforts*

The IFC has also been implemented by Singapore's Ministry of National Development for their CORENET (CONstruction and Real Estate NETWORK) project (Building & Construction Authority 2006). The CORENET project established a system for automated checking of building plans submitted online for code compliance through its module e-PlanCheck. It is important to note that the IFC data model alone was not sufficient to implement a code-checking application (Khemlani 2005). A higher level semantics of building components relevant to code checking requirements was required which was provided by an independent platform called FORNAX. Recent developments in automated code compliance checking has been made in the American 'AutoCodes Project' (Fiatech 2012). The Phase 1 of this project has established automated code-checking rule sets to check for the U.S. building regulation compliance in BIM models.

#### **4.2.3 Structure of the IFC data model**

The IFC data model is non-proprietary object based building data model. The IFC model represents not just tangible building components such as walls, doors, beams, ceilings, furniture, etc. but also more abstract concepts such as schedules, activities, spaces, organization, construction costs, etc. in the form of entities (Khemlani 2004). All entities can have a number of properties such as name, geometry, materials, finishes, relationships, and so on.

The IFC 2x3 schema has a total of 653 entity definitions, which means that it represents 623 different kinds of components or concepts (Liebich et al. 2007). These entities are connected through relationships and organised into an object-based inheritance hierarchy.

The IFC data model has a hierarchical object sub-typing structure in which the objects used in exchanges are embedded within a deep sub entity definition tree. All physical objects, process objects, actors, and other basic constructs are abstractly represented. At the most abstract level, IFC divides all entities into rooted and non-rooted entities. Rooted entities derive from *IfcRoot* and have a concept of identity (having a GlobalId), along with attributes for name, description, and owner history. Non-rooted entities do not have identity and instances only exist if referenced from a rooted instance directly or indirectly.

An example of a 'Roof' entity trace down structure is shown in a graphic notation for EXPRESS; an EXPRESS-G diagram (Figure 4.5) , to show how these entities are related to each other. The Roof entity (*IfcRoof*) is defined as a subtype of the Building Element entity (*IfcBuildingElement*), which is a subtype of the Element entity (*IfcElement*), and so on all the way up to the Root entity (*IfcRoot*). Inversely, The Root entity is the supertype of Object Definition entity which in turn is the supertype of Object entity and so on.

The entities have ‘direct’ and ‘indirect’ attributes. ‘Indirect’ attributes are inherited by the supertype. For example, Representation and object placement attributes are inherited by the Roof entity from its supertype Product entity. These attributes provide the basis of defining the geometric description of a building element entity in the IFC schema.

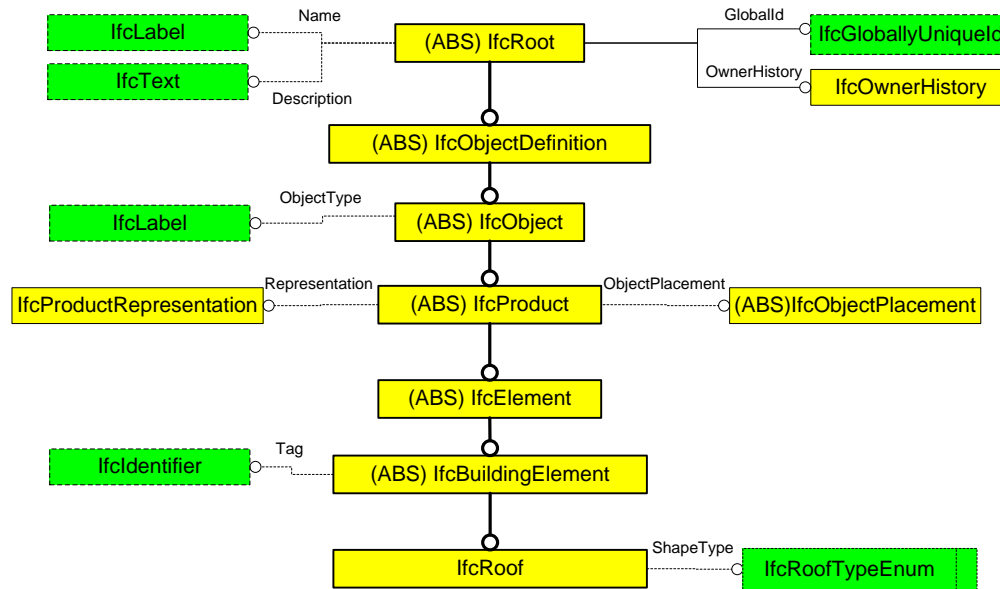


Figure 4.5 An ‘IfcRoof’ entity with its attributes shown using EXPRESS-G

ii) *Property definition in the IFC schema*

One of the key aspects of the IFC model that are specifically designed to enhance its flexibility and extensibility is the Property Set (PSet) that is captured by the property set definition (*IfcPropertySetDefinition*). An example of a property set definition named PSet\_WallCommon is given in Table 4.4. The property set groups properties for assignment to objects (Eastman 1999). These properties behave just like attributes. Each property set has a descriptor, a Unique ID, and a reference to a list of properties (Property Definitions). The list of properties for PSet\_WallCommon is given in Table 4.5. The properties can be statically defined or dynamically extendable. Both, statically and dynamically defined property sets are attached to an object using the relationship class *IfcRelDefinesByProperties* (Liebich et al. 2007). The advantage of using the relationship class to link property sets to objects is that the objects can exist without containing any reference to property sets if none are required. Furthermore, the relationship class allows the property set definition to be assigned to one or many objects. Many objects may share the same property set definition with common values. Hence, each of the object instantiated in an IFC data model receives a predefined PropertySet (PSet), inherited from the *IfcObject* layer.

The property definition comprises of a generic mechanism that allows model users and developers to define, connect and use data-driven, expandable properties with objects. Since there are numerous alphanumeric attribute definitions depending on discipline, life-cycle stage, building regulation and region, there will never be a complete set of internationally standardized attributes. Therefore, IFC defined property sets intent to standardize a basic set

of properties, whereas other property sets can be regionally defined, or agreed upon in projects.

**Table 4.4 Property Set definition- PSet\_WallCommon**

<b>PropertySet Name</b>	<b>Pset_WallCommon</b>
<b>Applicable Entities</b>	IfcWall IfcWallStandardCase
<b>Definition</b>	Definition from IAI: Properties common to the definition of all occurrences of IfcWall and IfcWallStandardCase.

**Table 4.5 List of properties- PSet\_WallCommon**

<b>Name</b>	<b>Definition</b>
<b>Reference</b>	Reference ID for this specified type in this project (e.g. type 'A-1')
<b>AcousticRating</b>	Acoustic rating for this object. It is giving according to the national building code. It indicates the sound transmission resistance of this object by an index ration (instead of providing full sound absorption values).
<b>FireRating</b>	Fire rating given according to the national fire safety classification.
<b>Combustible</b>	Indication whether the object is made from combustible material (TRUE) or not (FALSE).
<b>SurfaceSpreadOfFlame</b>	Indication on how the flames spread around the surface, It is given according to the national building code that governs the fire behaviour for materials.
<b>ThermalTransmittance</b>	Thermal transmittance coefficient (U-Value) of a material. Here the total thermal transmittance coefficient through the wall (including all materials).
<b>IsExternal</b>	Indication whether the element is designed for use in the exterior (TRUE) or not (FALSE). If (TRUE) it is an external element and faces the outside of the building.
<b>ExtendToStructure</b>	Indicates whether the object extend to the structure above (TRUE) or not (FALSE).
<b>LoadBearing</b>	Indicates whether the object is intended to carry loads (TRUE) or not (FALSE).
<b>Compartmentation</b>	Indication whether the object is designed to serve as a fire compartmentation (TRUE) or not (FALSE).

### 4.3 BIM standardisation efforts

As described earlier, since IFC is able to represent a wide range of building design, engineering and product information, the range of possible information to be exchanged is huge. IFC, developed to respond to the different needs of designers, contractors, building support suppliers, government officials, engineers and others, is both rich and redundant (Eastman et al. 2011). It is redundant since it offers different ways to define objects, relations and attributes. Interoperability is no longer limited to data exchange between two BIM applications. It is defined by workflows that support use cases. Apart, from automating a data exchange, interoperability has larger benefits that refine workflows, eliminate steps, and improve processes. Task and workflow information requirements have become recognised as critical for successful exchanges. Detailed functional specification of the content of each exchange must be provided. This functional specification must determine the type of entities, their attributes, level of detail and processes that are needed for passing from one application to another. A standard method for providing this specification or processes for

information exchange is called the Information Delivery Manual (IDM)(buildingSMART 2010b). It has been established that for RES simulations only certain sections of the building geometry would be required. For example the building's outer shell, consisting of roofs and external walls for solar PV, solar thermal applications; spaces or zones, for heat demand calculations for heat pump and biomass heating sizing. These constitute as subsets of the IFC-schema that are required for task (RES simulation) related exchanges. These IFC subsets can then be called Model View Definitions (MVD) for architectural design to RES analysis. However, such an MVD does not exist currently but efforts are underway for MVD in the energy analysis domain (Blis-Project 2010).

There also have been other standardisation efforts in definition and classification of construction information addressed by International Framework of Dictionaries (IFD) and OmniClass respectively. Another standard method that deals with collecting FM and O&M information throughout the building design and construction process is Construction Operations Building Information Exchange (COBie) (Eastman et al. 2011; WBDG 2013).

#### ***4.3.1 Model View Definitions***

Integrated project delivery (IPD) calls for building information modelling data to be exchanged between various actors. A Use-Case defines the information exchanges between any two actors in a project aimed at achieving a specific goal, within a specified phase of a project's lifecycle (Venugopal et al. 2012). The content of the information exchanges for each use case are termed Exchange Requirements (ER). Model View Definition, MVD, defines a subset of the IFC schema that is needed to satisfy one or many Exchange Requirements of the AEC industry. MVD turns the prerequisites and outcomes of the processes for information exchange into a formal statement. Software developers can take the standard and specific Model View Definitions that derive from it and incorporate them into their applications (buildingSMART 2010b; Grobler 2010). The National Institute of Building Sciences (NIBS) and the U.S buildingSMART organisation had taken up the charge of developing model views and published a report on the process of model view development (Hietanen 2006; NBIS 2007).

The major tasks of developing a model view through the National BIM standard (NBIMS) process are outlined in Table 4.6. The model view approach however has certain limitations (Venugopal et al. 2012). For example, the development of an IDM (Task 1,2 &3) is based on industry knowledge and human expertise. Moreover, the translation from IDM to MVD is manual and erroneous. Hence, a more logical framework is required to specify model views and a number of research and industry based initiatives are meeting this requirement currently. An example of such an initiative is the IFC Solutions Factory, a web-based repository of such IFC concepts and research in model view development (Blis-Project 2010). This repository contains exchange requirements, process maps and MVD for various exchange models. In particular, the 'Design' to 'Energy performance analysis' (ref: GSA-003) exchange model consists of an exchange requirement containing energy analysis input data for Solar PV (Table 4.7). This implies a start has been made to include RES in the interoperability

requirement between architectural BIM model (Design BIM model) and energy performance analysis.

**Table 4.6 NBIMS process for MVD development**

Phase	Task no.	Tasks	Actor	Output
PROGRAM	1	Form workgroup Domain experts IT specialist Software company	Industry experts- For ex, in UK, CIBSE, RIBA, BSRIA, etc.	
	2	Identify set of exchanges, provide detailed specification of each exchange	Domain experts	Exchange Requirements
	3	Review of specifications		Process map Information Delivery Manual (IDM) Information Delivery Manual (IDM)
DESIGN	4	Conceptualise ER (from IDM) into reusable information modules called Concepts	IT specialist	Concepts and bindings 'Generic MVD'
	5	Binding the concepts to a schema (IFC 2x3)-Higher level Concept		
CONSTRUCT	6	Implementing the MVD specification Provide import export functionality for each exchange	Software companies	Software implementation
	7	MVD validation & certification Test the functionality against the MVD		
DEPLOY	8	Deployment and field use Provide guidelines for MVD	BIM Users/ Industry	Project test model for real-life testing

**Table 4.7 Exchange requirements (input data) for Solar PV**

Type of information	Information Needed	Data Type	Units
Photovoltaics	The following describe PV electricity generation onsite: Photovoltaics (present? TRUE/FALSE)	Boolean	
	Host Building Element *	Relationship	n/a
	Active Area Fraction (fraction of host element with PVs) *	Real	%
	DC to AC Inverter Conversion Efficiency *	Real	%
	PV Surface Integration (Decoupled, Integrated, Integrated w/ Ventilation)*	Enum	n/a
	PV Cell efficiency*	Real	%

\*(required of 'Photovoltaics' =TRUE ) '



## 4.4 IFC compliant energy/RES analysis tools

A building modelling or analysis tool is deemed to be 'IFC-compliant' if the tool is capable of importing and exporting IFC files. Tools need to go through a two stage certification process in order to be deemed 'IFC-compliant'. In the first stage, a set of IFC files exported by the program in question; in the second stage a pilot project that involves end-users is tested. If both are successful the software program is IFC certified (Maile et al. 2007; buildingSMART 2010a). The IFC model is posted online and provides a framework for software developers to incorporate the IFC import and export capabilities within their program.

In Chapter 2 (section 2.1) various BIM authoring tools were reviewed and it was established that interoperability between them and energy analysis tools was established either through direct links to software vendors own energy analysis applications using the BIM tools API or through open-standards such as gbXML or IFC. The first method led to creation of proprietary tools owned by the same software vendor capable of conducting design and analysis for all AEC domains (structural, MEP and mechanical). Dixit and Wei created an Application Programming Interface (API) for Building Integrated PV simulation in a proprietary Revit software environment owned by Autodesk (Dixit and Wei 2012). These tools can be used in Level 2 BIM of the BIM maturity model (Figure 4.6). The second method is through the development of open-standards that provides more flexibility to the project team in the choice of software but demands higher levels of interoperability. A qualitative study conducted by Howard and Bjork (Howard and Bjork 2008), conferred that using a formal data exchange standard such as the IFCs in the adoption of BIM is the way forward given that proprietary solutions will always diverge. IFC compliant tools are envisaged to be used in Level 3 of the maturity model.

### *4.4.1 Existing IFC-compliant energy/RES analysis tools*

In the review of RES tools in Chapter 3 (section 3.4), it was established that very few RES tools are compatible with IFCs. The only RES tool found to be IFC-compliant was a WBEA tool; EnergyPlus. In specialised RES tools for solar PV simulation, the IFC-BIM based tool DDS-CAD PV is currently the only tool that is IFC-compliant and can conduct solar PV performance assessments by using Polysun, a solar PV simulation software (Data Design System 2013).

The BuildingSMART website (Espedokken 2013) provides a list of 151 IFC compliant software available for a variety of AEC applications. Energy simulation tools like RIUSKA (Granlund 2004) and IDA Indoor Climate and Energy (IDA-ICE) (version 4) (Equa 2013) have been proven to be IFC compliant that are WBEA tools. These two tools are reviewed below for their RES simulation capability.

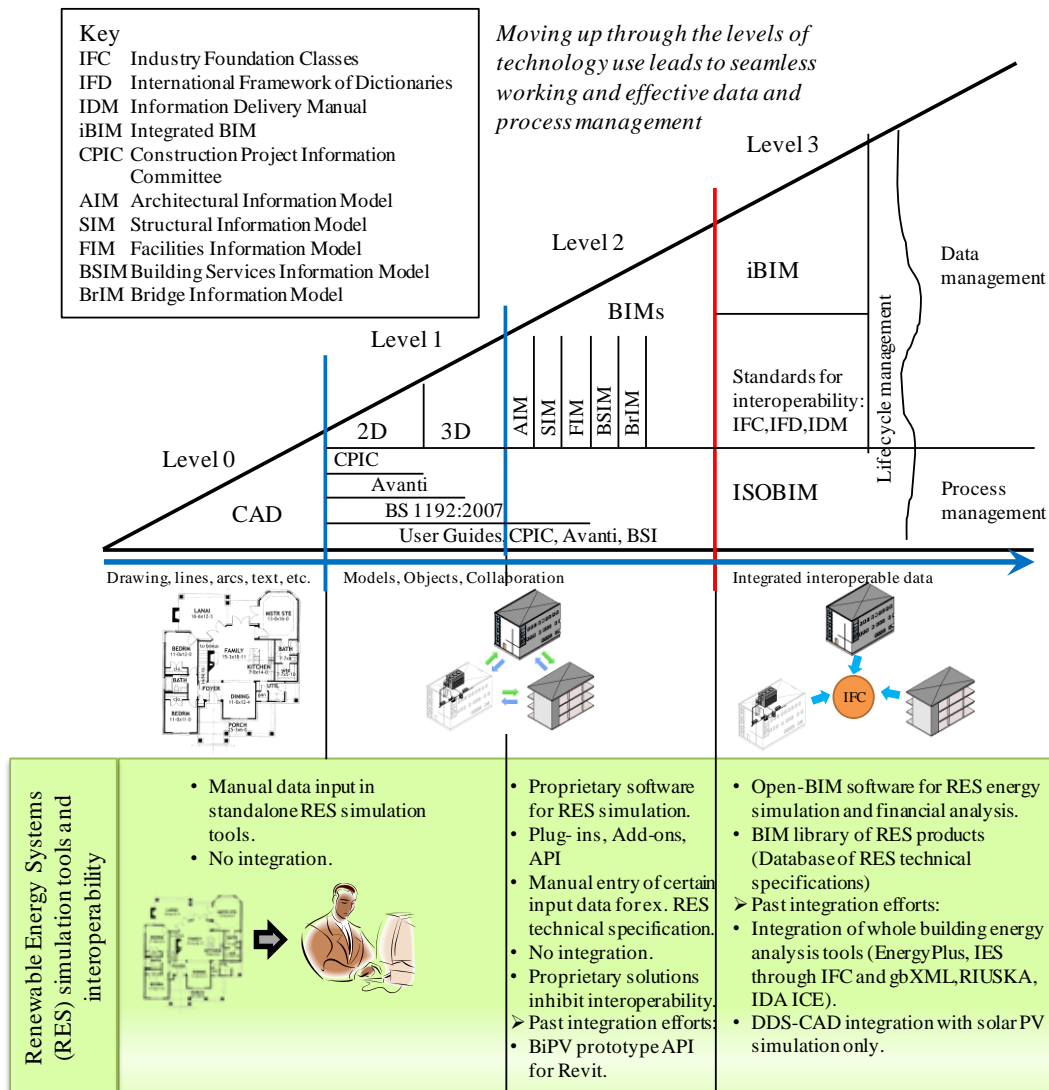


Figure 4.6 Interoperability in RES simulation tools for different levels of the BIM maturity model (Adapted from (BIM Industry Working Group 2011))

i) RIUSKA

RIUSKA is a tool for the dynamic simulation of comfort and energy consumption in building services design and facilities management. It was developed by Olof Granlund Oy started in 1996. RIUSKA (Version 4.4.7) is based on the DOE-2.1E engine and has an IFC interface through the BPro COM server middleware. The BPro COM server (Karola and Lahtela 2000; Karola et al. 2002), also developed by Granlund, automatically simplifies complex geometric information contained in the IFC model for the needs of thermal simulation.

RIUSKA is an HVAC system simulation tool. None of the reviewed literature on RIUSKA (Granlund 2004; Maile et al. 2007; Granlund 2013) gives any indication of its RES simulation capability. Since it is based on DOE-2.1E engine, it has been suggested that DOE-2.1E does not simulate active solar components (solar PV and solar thermal) (Maile et al. 2007). The software is mainly used by design engineers for HVAC design and facility managers during operation and maintenance (USDOE 2011b). Since boilers and heat pump components are intrinsic part of HVAC design, sizing calculations of these can be conducted in this tool.

Many limitations on the IFC import capabilities of RIUSKA have been mentioned in (Maile et al. 2007). The best import results are found to be achieved when RIUSKA is used in conjunction with Granlund's own modelling software SMOG. Problems can occur if CAD models are imported from other CAD applications to RIUSKA. This rather reinforces that effective interoperability is achieved through proprietary software developed by the same software vendor.

*ii) IDA-ICE*

IDA Indoor Climate and Energy (IDA ICE) (version 4.5 released April 2013), developed by Equa Simulation AB, is a whole year detailed and dynamic multi-zone simulation application for the study of indoor climate as well as energy (Equa 2013). The physical models of IDA ICE reflect the latest research and best models available, and results compare well with measured data (Björzell et al. 1999; USDOE 2011a). The IDA ICE user interface is designed to make it easy to build and simulate both simple and advanced cases, and the real-time 3D environment, in combination with comprehensive tables, provides optimal feedback. There is also the Early Stage Building Optimization (ESBO) user interface which makes it possible for users to experiment with variations in both buildings and systems at an early stage with an absolute minimum of user input.

IDA ICE can import all common 2D and 3D CAD files. It supports IFC BIM models generated by tools such as ArchiCAD, Revit, MagiCAD, and many others. Geometry can be imported from SketchUp or other geometry tools.

A full range of component models for renewable energy studies, with boreholes, stratified tanks, heat pumps, solar collectors, CHP, PV, wind turbines, etc. were added in its latest version 4.5 (PRWeb 2013).

## **4.5 Existing approaches in developing IFC-compliant energy/RES analysis tools**

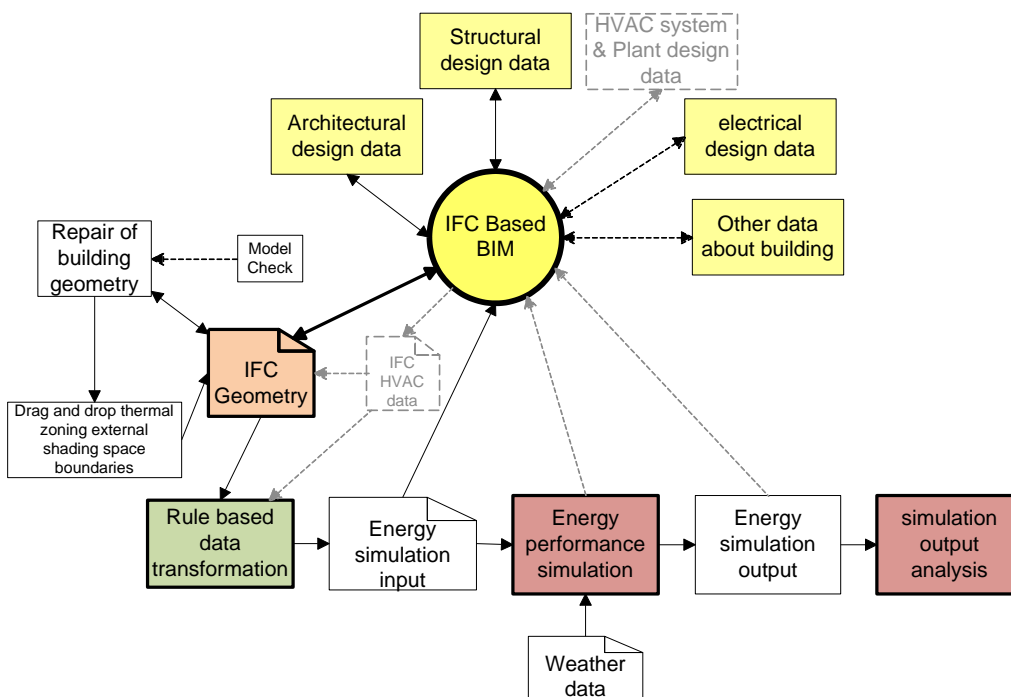
IFC is an extensible data schema, where new extensions are proposed and accepted whenever new business requirements arise. It is typical for a gap-analysis to be performed and new extensions to be proposed during the development of model views. Extensions to the IFC schema are done either by adding new concepts or adding/modifying property sets. The IFC schema was extended to fulfil requirements of the structural analysis domain by adding structural analysis concepts (Weise et al. 2003). In order to enhance the interoperability between IFC based BIM and energy analysis, energy concepts, similar to structural analysis concepts, have been proposed to be added to the IFC schema (Cemesova et al. 2012; Cemesova 2013a). Additionally, property set extensions have been proposed as a method for developing IFC-compliant design information modelling and sharing (Yang 2003). The method involved defining the non-standard and project-specific design information in extensible and

interoperable property sets. There is criticism that some of the extensions are done in an ad-hoc manner (Kiviniemi 2006).

The PM4D approach used in the HUT-600 project confirmed the existence of an IFC-based ‘core’ model linked to domain specific analysis models. One of the conclusions of this research was that the contents core model are; building geometry, material properties and space identifiers, all represented in the IFC schema. The IFC schema primarily used for exchange of building geometric data has been shown in the following methodology developed by Lawrence National Berkeley Laboratory (LBNL) for an IFC-based integration of BPS tools.

LBNL developed an IFC BIM-based methodology to enable the integration of BPS tools into suites of interoperable tools used in building design (Bazjanac 2008)(Figure 4.7). The objective of this methodology is the elimination of inappropriate human intervention that results in subjective and arbitrary decisions which affect BEP simulation. The methodology contains five essential steps outlined below;

1. Populating IFC-based BIM with data;
2. Automated rule-based data transformation;
3. Rigorous model checking;
4. Building energy performance simulation;
5. Analysis of results from simulation.



**Figure 4.7 LBNL methodology to semi-automate BPS and analysis (Greyed areas have not been implemented)(Bazjanac 2008).**

The LBNL methodology assumes that BIM model contains architectural design data (building geometry), HVAC design data, electrical design data and other relevant data (occupancy and operating schedules) to process the required input to run energy simulation. The methodology

was implemented using EnergyPlus as the simulation engine. The geometric data from IFC model was transformed into an EnergyPlus IDF using the IFCtoIDF Transformation Utility. The IDF contained building geometry and other related data but not HVAC data. It was found that HVAC design tools were not IFC compliant, hence HVAC data had to be input manually in the IDF. Selection of appropriate weather data, as well as definition of building location was done automatically using GIS information contained in the IFC model. A path to the local directory, that contained weather files, was included as part of the simulation run control data. Once the IDF was completed with all simulation input data requirements the simulation was executed successfully. The simulation output is then stored as an output data file (ODF), the simulation results are then post-processed and analysed. It is important to note that the LBNL methodology does not favour the automation of the analysis and the post-processing component. Bazjanac (2008) believes that the analysis of simulation results and the subsequent impact on the design decision making require human intervention, involving human expertise and creativity. However, it is important to automatically inform all parties about the results of the analysis and the affected outcome on building design.

Another approach was suggested by Guruz et. al. (2012) wherein an ontological specification called an energy extended BIM (eeBIM) specification was developed. The specification comprised of a multi-model framework with the open BIM IFC schema being the central schema to which all other information sources are connected (Figure 4.8). This aim of developing this specification was to facilitate lifecycle analysis and energy simulations of buildings through the adoption of BIM/ICT tools. The basic premise was to use the existing IFC- BIM models on as-is basis thereby avoiding inflating the IFC model with additional classes and properties. The eeBIM framework was developed using IDM based methodology; wherein the processes, exchanges and related exchange requirements were identified. An IFC-based multi-model concept was chosen as an outcome of an internal investigation conducted by Guruz et. al. (2012) which revealed that;

- IFC can serve as the central integrating model, anchoring any additional non-BIM data
- Multi-models are more flexible and easier extensible to adopt to future needs
- Minimising changes to the IFC (using it on as-is basis) is the approach with the best chances for industry adoption
- Integration with existing software tools appears easier.

The research for developing this specification was done in the frames of the European Framework Project (FP7) HESMOS (TUD 2011).

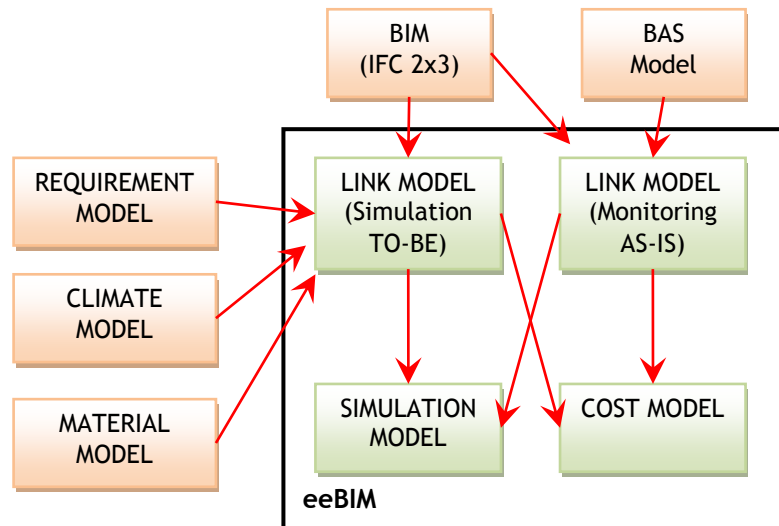


Figure 4.8 Schema level view of the eeBIM modelling framework

## 4.6 Conclusion

The IFC has become the international standard for data exchange and integration in the building construction industry since it is public and internationally recognised. The IFC data exchange standard is robust and has the ability to provide an ideal framework to manage all data related to a building throughout its lifecycle. The IFC provide an ideal data exchange format that can be adopted to move towards higher levels of BIM to fully collaborative BIM.

The IFC has been implement successfully in projects; HITOS (Statstbygg, Norway), Digital Construction project (Danish Enterprise and Construction Authority), HUT-600 (Senate Properties, Finland) and LBNL E-lab building (U.S.A). Public sector owners, such as General Services Administration (GSA) in the US and Senate Properties in Finland, have made significant efforts to speed up the adoption of IFC-based integrated BIM by defining specific modelling requirements (buildingSMART Finland 2012a) and publishing BIM guidelines (GSA 2007; Senate Properties 2007).

BIM-compliance in energy analysis applications is achieved through proprietary solutions; through direct link to software vendors own energy analysis applications using the BIM tools API. These tools can be used in BIM Level 2. RIUSKA and IDA-ICE have been certified as IFC-BIM compliant energy analysis applications and are more suited for Level 3 application. However, these tools are more suited for HVAC design and indoor comfort analysis application and their RES simulation ability is unknown.

There have been various approaches in developing IFC-BIM compliant software applications such the IDM-MVD methodology, IFC-schema extensions by adding additional concepts and property set extensions. However, in various industry implementations (E-lab, HUT-600) it

was found that the IFC model can serve as the core model that can be linked to various analysis models. The content of the core-model was found to be building geometry, space Ids and material properties. The research done in the HESMOS project indentified that using the IFC model 'as-is' and not inflating the schema through various extensions, is the approach for best chances for industry adoption.

Using the IFC model 'as-is' and attaching RES simulation models as the baseline concept, the author proposes a methodology for developing IFC-compliant RES tools in the next chapter.

## **CHAPTER 5. RENEWBIM- IFC-COMPLIANT RES SIMULATION TOOL**

Chapter 3 reviewed existing tools in RES simulation, and concluded with a structure of an RES simulation model (section 3.4.4). The chapter has also outlined the input data requirements for various RES and their energy, carbon emissions and financial simulation models. In the pursuit of proving the underlying hypothesis and from the various IFC implementation projects and methodologies of establishing IFC-compliance in energy analysis tools, it is found that the IFC schema does contain detailed semantic content around the building geometry that can be used as input data for RES simulations. Other input data requirements include information from external data repositories, such as climate data, technical specifications of RES components, and various financial and carbon emission parameters. Currently, various ad-hoc approaches and data sources are used to fulfil these input data requirements.

It is important to note that even though input data requirements for RES analysis have been compiled, the formation of an MVD for renewable energy analysis is not the primary scope of this thesis. The first task in the NBIMS process for MVD development is the formation of a working group consisting of domain experts and software companies. The author instead of following the MVD process establishes a need for a standardised process through which IFC compatibility can be added to RES simulation models by means of a conceptual framework.

This chapter describes this conceptual framework for developing IFC-compliance in RES simulation tools. The energy simulation model is taken as the starting point for developing this framework due to the ability of the IFC schema to partially fulfil the input data requirements (Figure 5.1).

It is envisaged however that the listed input data requirements and the capture of the concepts within the IFC schema that partially fulfil these requirements would pave the way for the development of an MVD, aligned with the development of the MVD for energy performance analysis domain (see Chapter 4, section 4.3.1).

This chapter is divided into three sections. It starts with the description of the conceptual framework for developing IFC-compliant RES simulation models (section 5.1 ). The conceptual framework is then implemented in a solar PV simulation model (section 5.2) and a prototype called 'RenewBIM' is developed in Java as a proof-of-concept (section 5.3).



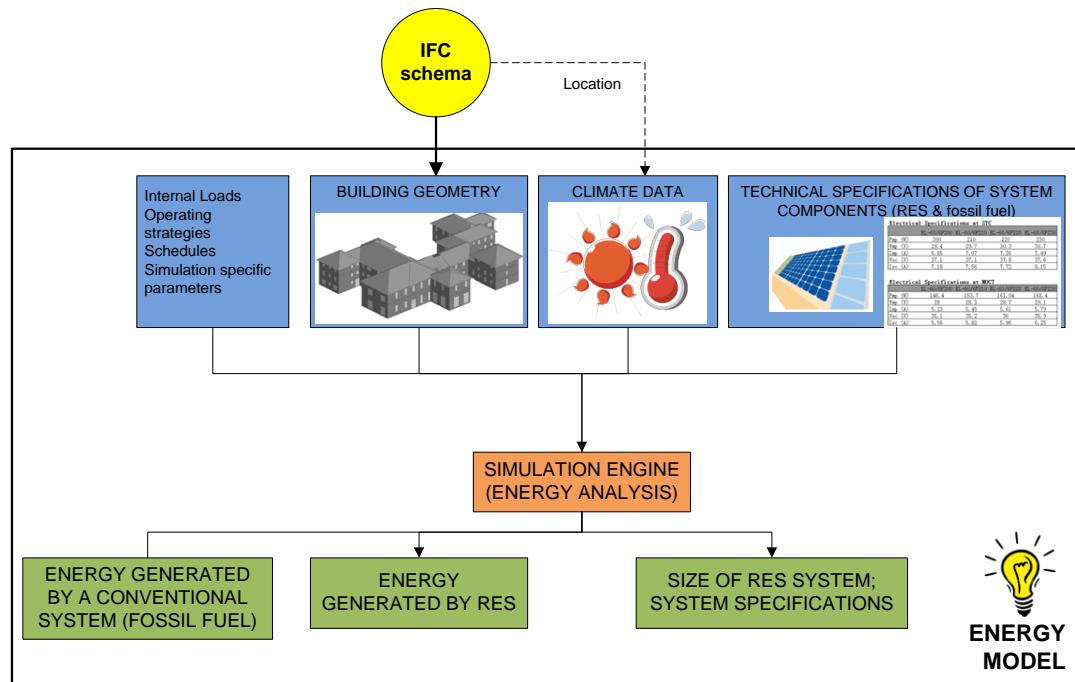


Figure 5.1 IFC schema and input data requirements of energy simulation model

## 5.1 Conceptual framework

An energy simulation model consists of three distinct parts; the input file, a processor or simulation engine and the output or results (Maile et al. 2007; Manke et al. 2013).

The process starts with choosing an energy simulation model. Simulation model for RES such as Solar PV, Solar thermal, Biomass heating system and heat pumps can be provided.

The following are the main tasks involved (Figure 5.2);

1. LIST Input Data Requirements (IDR) of the simulation model- The input data requirements of various renewable energy simulation tools can be categorised under;
  - Location & Weather data- Latitude, Longitude, Global solar radiation, Ambient air temperature, Wind speed.
  - Geometric input data from building model- Slope, orientation and area of host building element for solar PV and solar thermal; zones, external surface area for heat pumps and biomass boilers; dimension and location of openings (window and door)
  - Technical specifications of the technologies- Efficiencies or co-efficient of performance for technologies.
  - Material properties- Building fabric properties (Wall, Floor, roof, door, window) (U-value, material thickness etc.); air infiltration rate
  - HVAC data- Data on type and efficiency of heating and ventilation system, air change rates.

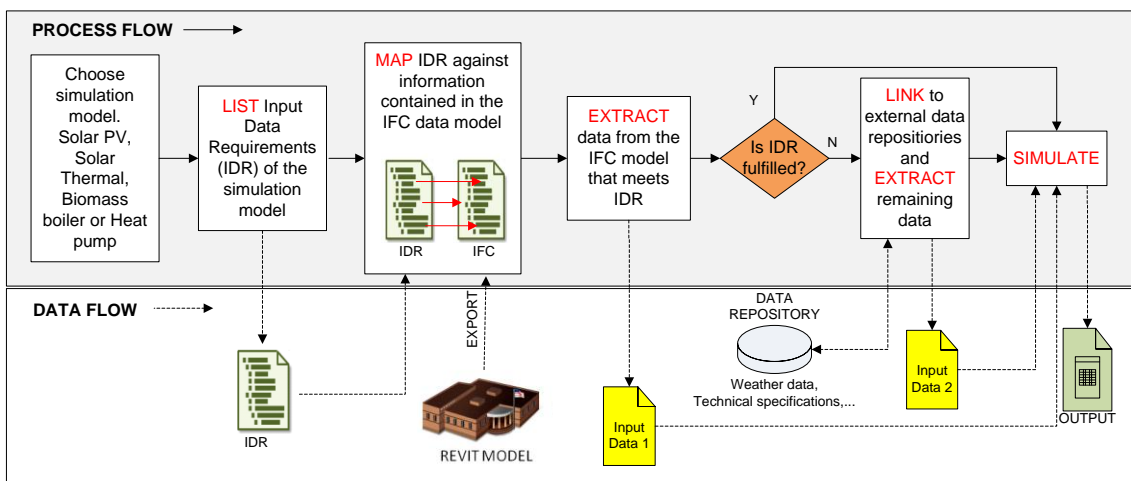
- Electrical loads- Small power consumption, cooking, lighting, pumps and fans.

The input data requirements for analysis of solar PV, solar thermal, biomass heating and heat pumps have been listed in Chapter 3.

2. MAP IDR against information contained in the IFC data model- The IFC data model embeds information of building geometry, location and material properties hence it fulfils partial IDR. All other information may be embedded in external data repositories such as climate databases and RES component technical specification databases.

The following section will describe the mapping of IDR of a solar PV simulation model against the IFC data model.

3. EXTRACT data from the IFC model that fulfils partial IDR- The mapped data from the IFC model which partially fulfils the IDR is then extracted.
4. LINK to external data repositories and EXTRACT remaining data to fulfil complete IDR- Data from external data repositories such as climate data and technical specifications of RES components can be extracted from relevant databases and used in the simulation model.
5. Process IDR in simulation model and SIMULATE to generate OUTPUT. The OUTPUT is stored as a file (Comma Separated Value(.csv) format) that can be used in spreadsheets for further analysis.



**Figure 5.2 A conceptual framework for developing IFC-compliant simulation models**

This conceptual framework provides a standardised process of establishing BIM (IFC)-compliance in RES simulation models. It is standardised to allow linking of any energy simulation model as well as any open-BIM data exchange schema. Though the IFC has been chosen as the data exchange schema, the framework can be adopted for various other open-BIM schemas that are XML based (ex.gbXML) as well by studying their ontology.

## 5.2 Implementation in a solar PV simulation model

The conceptual framework has been applied to a solar PV simulation model. In order to establish interoperability between the IFC data model and solar PV simulation model, firstly the input data requirements of the solar PV simulation model need to be listed and mapped against the information contained in the IFC data model.

### 5.2.1 Input data requirements of a solar PV simulation model

A ‘state-of-the-art’ review of the various models used to assess the performance of photovoltaic (PV) systems has been conducted by Sandia National Laboratories (Klise and Stein 2009) and by Lalwani et.al (2010). PV simulation models are broadly of two categories; statistical models used by hybrid tools such as RetScreen and HOMER and time-series simulation models used by tools such as PV\*Sol, and PVSyst as outlined in Chapter 3. The input data requirements irrespective of the type of PV simulation models used are listed in Table 5.1.

**Table 5.1 Input data requirements of a solar PV simulation model**

Input Parameter		Input Data description
Site Location		Latitude Longitude
User input		Selection of host building element to assess the potential of solar PV.
Geometric data		Slope (Tilt), Orientation (Azimuth) of the host building element.
Weather data		Global solar irradiation Ambient temperature Clearness index
PV module specifications	technical	PV module efficiency Area of PV modules Nominal Operating Cell Temperature Temperature co-efficient of PV module
Inverter specifications	technical	Inverter efficiency

### 5.2.2 Mapping and extracting of Input Data Requirements against IFC data model

From the input data requirements listed in Table 5.1, site location and geometric data of building elements can be extracted from the IFC data model generated by the BIM- authoring tool. All other input data rely on external data repositories such as climate databases and technical specifications of the associated system components (PV module, inverter) found in manufacturer’s literature.

Currently, this process of extracting this input data (especially geometric data) is manually performed by energy consultants by looking at 2D drawings of the building issued by the architect (Bazjanac 2002; Gupta et al. 2011; Cemesova et al. 2013).

If this process was automated, it would save time needed for extracting and re-entering data in specialised simulation tools, and give time to develop design alternatives and optimisation

scenarios by the design team. Using BIM to develop the designs makes it easier to automate this process. The following sub-sections describe how the location data and geometric data required have been extracted from the IFC schema.

i) *Extracting site location data from the IFC schema*

All IFC models provide a common general building spatial structure for the layout and accessing of building elements. It organises all object information into the hierarchy of Project→Site→Building→BuildingStorey→Spaces→Building elements.

The latitude and longitude of the site are required to procure the climate data or to calculate the clearness index and global horizontal radiation, if the climate data for the site is not available. Most BIM-authoring CAD tools allow the user to enter the location of the project which is stored in the IFC schema (*IfcSite* entity) when an IFC file of the project is exported from the BIM environment. The latitude and longitude are optional attributes of *IfcSite*. The structure of *IfcSite* entity is shown in EXPRESS-G in (Figure 5.3). This means that if the user specifies the location of the project in the BIM-authoring tool, the site latitude and longitude is explicitly stored in the *IfcSite* entity and can be extracted and processed as input data for solar PV simulation.

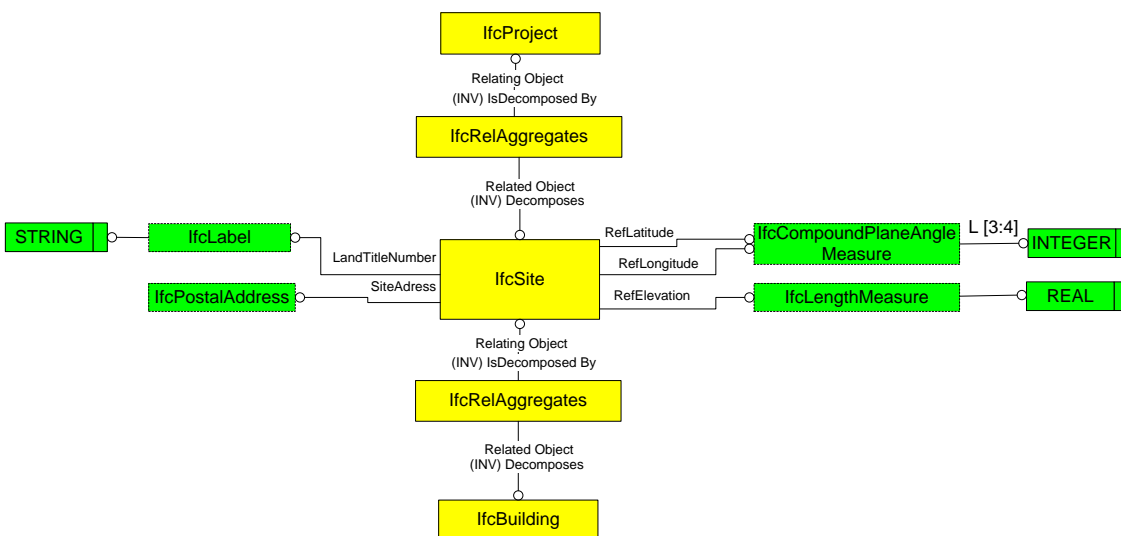


Figure 5.3 The Site object class in the IFC schema

ii) *Extracting geometric data from the IFC schema*

For solar PV and solar thermal energy assessment, only the external shell of the building is required in the IFC. In the IFC Schema, the external shell of the building would be consisting of the following entities that are subtypes of the abstract entity *IfcBuildingElement*; *IfcBuildingElementProxy*, *IfcCurtainWall*, *IfcDoor*, *IfcWall*, *IfcSlab*, *IfcStairFlight*, *IfcWindow*, *IfcRoof*, *IfcBuildingElementComponent*.

Solar PV technologies are commonly applied on the external walls and the roof of the building. Although these technologies have grown for more building integrated applications

such as sun-screens, windows and shading devices (denoted by *IfcBuildingElementProxy*), for simplicity the geometric representation of roofs and the walls only are analysed in this thesis.

As mentioned earlier (Chapter 4, section 4.2.3), property sets are a mechanism by which the user can attach object-specific data to building elements. The ‘orientation’ of the building element is yet not defined as a standard property set. For all roof (*IfcRoof*) that are composed by slabs (*IfcSlab*) instantiated by the relation *IfcRelAggregates*; the pitch angle (referred to as slope) for *IfcSlab* was added as a property definition in IFC 2x3 schema (Liebich et al. 2007). The property definition was added as part of the property set PSet\_SlabCommon. An investigation into the property sets for extracting the slope of the building element has been made by the author in Appendix D. Three test cases with a box (8m x 6m x 3m) with a pitched roof with slope 30°, 45° and 60° were constructed in Revit and the exported as an IFC SPF file. The file was analysed if the property sets of the slab elements contained the slope data. It was concluded that the slope data of a building element contained within property sets may have errors when the IFC file is exported from BIM authoring tools like Revit. Deviation errors of 10 %, 27% and 64% was found for the slopes 30°, 45° and 60° respectively. This error can be attributed to the export functionality in Revit. This however has not been explicitly proven by the investigation. Similar analysis in other BIM-authoring tools like ArchiCAD would have to be conducted to confirm that the errors in ‘Slope’ data are attributed to the export functionality of a particular BIM-authoring tool.

The area of the building elements is stored in quantity sets. Quantity sets are base quantities instantiated by *IfcElementQuantity*. They have the following measured types; count, weight, length, area, volume and time. The quantity sets however, are not automatically generated by Revit. The base quantities are exported when ‘Quantity Add On’ option is selected in the Export Options dialog of Revit. Their use can be satisfactory for solar PV and solar thermal simulation models where the surface area of the host building element does not require a large degree of accuracy. However, in energy analysis applications where the dimensions of the thermal envelope need to be accurately calculated, deriving areas from base quantities should be avoided (Cemesova 2013b). The use of base quantities is generally for “quantity take-off” applications (Liebich 2009).

Hence, assuming that the IFC schema does not contain the slope, orientation and surface area data needed to run solar PV simulation, functionality is added externally that processes geometric data from the IFC data model to deduce the slope, orientation and surface area of the host building element.

a) Placement and Geometric representation of *IfcProduct*

Roofs and walls are instantiated by *IfcBuildingElement* which is a subtype of *IfcProduct* (see Chapter 4, section 4.2.3, Figure 4.5). Hence the attributes that define the geometric representation of a *IfcProduct* are inherited by *IfcBuildingElement* and in turn by *IfcRoof* and *IfcWall*. Therefore, it is important to analyse the geometric representation of *IfcProduct* in order to deduce geometric information about the building elements.

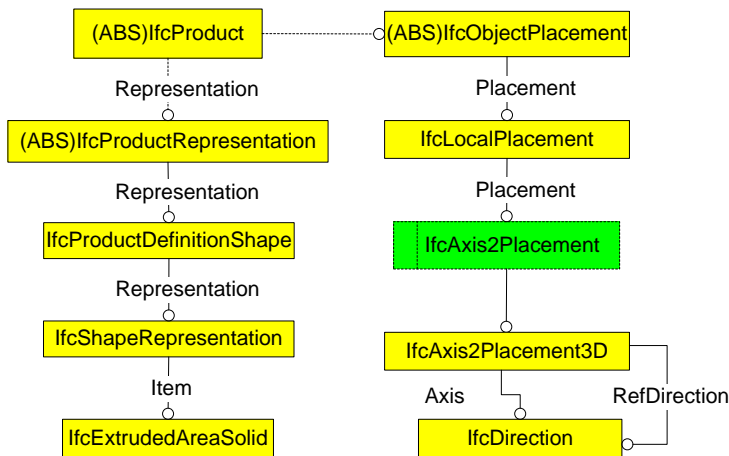


Figure 5.4 EXPRESS-G for geometric representation of a product (*IfcExtrudedAreaSolid*)

Figure 5.4 shows the EXPRESS-G diagram for the geometric representation of a product. The representation attribute (*IfcProductRepresentation*) stores the shape representations of an object. Its location is defined within the context of object placement. It describes the shape of the element through its subtype entity *IfcProductDefinitionShape*. It contains many different types of shape representations through the IFC entity *IfcShapeRepresentation*. The predefined types for solid models are ‘SweptSolid’, ‘Brep’, ‘CSG’, ‘Clipping’ and ‘AdvancedSweptSolid’ (Liebich et al. 2007)( Table 5.2). As a starting point in this thesis, only one type of shape representation extruded solids (*IfcExtrudedAreaSolid*) that come under ‘SweptSolid’ would be dealt with and other geometric representations would be processed in future. The Object Placement (*IfcObjectPlacement*) attribute stores the placement information of an object. It could be absolute (relative to the global coordinate), relative (relative to the object placement of another product), or constrained (relative to the grid axes). The default setting for the placement of an object is relative placement, defined by *IfcLocalPlacement* with a *PlacementRelTo* attribute to specify the referencing spatial context. For example, a roof (*IfcProduct*) is placed relative to a building storey (*IfcBuildingStorey*); a building storey is placed relative to a building (*IfcBuilding*); a building is placed relative to a site (*IfcSite*) and a site is placed relative to a project (*IfcProject*).

Table 5.2 Predefined type of shape representations for solid models

SolidModel predefined types	Description
SweptSolid	swept area solids, by extrusion and revolution
Brep	faceted Brep's with and without voids
CSG	Boolean results of operations between solid models, half spaces and Boolean results
Clipping	Boolean differences between swept area solids, half spaces and Boolean results

b) Roof

All roof occurrences in the IFC schema are instantiated by *IfcRoof*. It acts as a container entity, that aggregates all components of the roof, it represents. The aggregation is handled via the *IfcRelAggregates* relationship, relating an *IfcRoof* with the related roof elements, like slabs (represented by *IfcSlab*), rafters and purlins (represented by *IfcBeam*), or other included roofs, such as dormers (represented by *IfcRoof*). The slab has the following shape representations; *IfcExtrudedAreaSolid* (for all standard slabs), *IfcBooleanClippingResult* (for special slabs with edge cuttings), *IfcFacetedBrep* (for special walls with complex geometry)(Liebich 2009). The local placement of all standard slabs (*IfcExtrudedAreaSolid*) is discussed further in detail.

The local placement of a pitched roof (pitch angle 30°) is shown in (Figure 5.5). This roof is composed of two slabs or aggregates acting as an assembly using the objectified relationship *IfcRelAggregates*. These are placed relative to each other in the building spatial structure. In this example, the project, site, building and building storey have the same local placement denoted by global co-ordinates ( $P_{project}$ ). The north of the project is indicated by the Y direction vector of the global co-ordinates ( $P_{project}$ ).

Also the shape representation of the slab in this example is Extruded Area Solid (*IfcExtrudedAreaSolid*). *IfcExtrudedAreaSolid* is a sub-type of the abstract entity *IfcSweptAreaSolid*.

‘Swept solids’ have the following constraints;

- 1) Solid- instantiated by any one of *IfcExtrudedAreaSolid*, *IfcRevolvedAreaSolid* and *IfcSurfaceCurveSweptAreaSolid*
- 2) Profile- instantiated by any one of *IfcArbitraryClosedProfileDef*, *IfcRectangleProfileDef*, *IfcCircleProfileDef*, *IfcEllipseProfileDef*. The location of the profile like any other shape representation is defined within the context of object placement denoted by the entity *IfcAxis2Placement3D*.
- 3) Extrusion- consisting of extrusion direction and depth attributes.

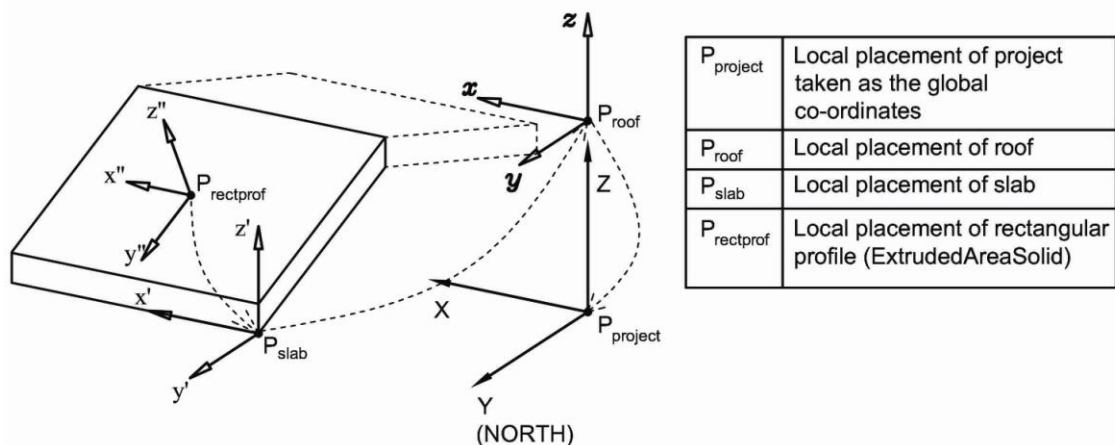


Figure 5.5 Local placement of slab relative to building spatial structure

The *IfcAxis2Placement3D* entity contains three attributes;

- 1) Location- denoted by *IfcCartesianPoint*. This attribute is inherited from *IfcPlacement*.
- 2) Axis and
- 3) *RefDirection*- denoted by *IfcDirection*.

The 'Axis' attribute gives the 'Z' direction vector and the 'RefDirection' gives the 'X' direction vector. Hence, 'Y' direction vector is a cross product of X and Z direction vectors. These direction vectors are an instance of *IfcDirection*.

In the example (Figure 5.5), the object placement of rectangular profile is denoted by Cartesian point ( $P_{\text{rectprof}}$ ), Axis (z" direction vector) and *RefDirection* (x" direction vector); and is placed relative to object placement of slab ( $P_{\text{slab}}$ ). For the deduction of the topological relationship the local placement of an object should be transferred to the placement of the global co-ordinates (Chen et al. 2005; Cemesova 2013b). Transformation matrices have been used to transfer the local placement of an object to the placement of global co-ordinates (world co-ordinate system)(Cemesova 2013b). The global co-ordinates are also represented by the local placement of *IfcProject*. This is essential to derive the orientation of an object in context of the project north indicated by the placement of the global co-ordinates.

In Revit, the project north is denoted in the direction of the Y-axis of the global co-ordinates (Autodesk 2006). When the local placement of the rectangular profile is transferred to the placement of global co-ordinates, the placement is then denoted by a new Cartesian point ( $P_{\text{rectprof}(\text{new})}$ ) and new direction vectors for Axis ( $z_n$ "") and *RefDirection* ( $x_n$ ""). The slope of the slab can then be calculated trigonometrically by analysing the new  $z_n$ "" direction vector. The orientation of slab can be found out by creating certain rules for the  $z_n$ "" direction vector for north, south, east and west orientations. All other orientations are represented by the 'TrueNorth' attribute in the *IfcProject* entity. This attribute describes the orientation of the building at an angle from the north (represented by the Y-axis of the global co-ordinates). These orientations are calculated with an adjustment for the TrueNorth attribute of *IfcProject*. A detailed analysis of the deduction of slope, orientation and surface of roofs (composed of standard slabs) is shown in Appendix E.

Figure 5.6 shows the transformed local placement of the rectangular profile and also indicates that the slab orientation is north by analysing the Z-direction vector. The slope of the slab ( $\beta$ ) can be found out trigonometrically. Similarly, transformed local placements of slab rectangular profiles facing other orientations are shown in Figure 5.7. Additional rules can be developed to find other orientations.



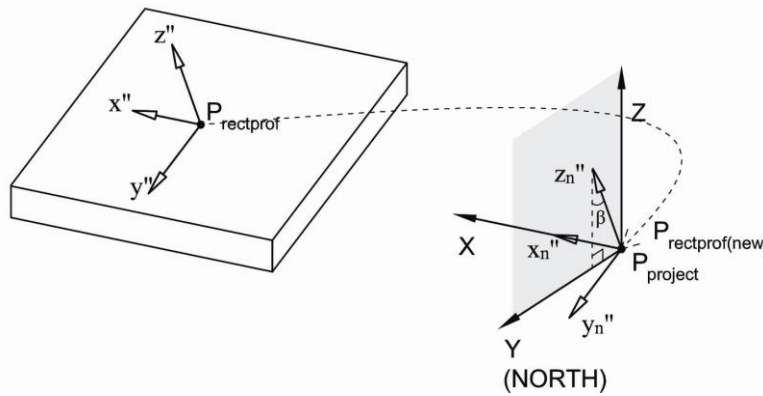


Figure 5.6 Transferring local placement of rectangular profile to global co-ordinates

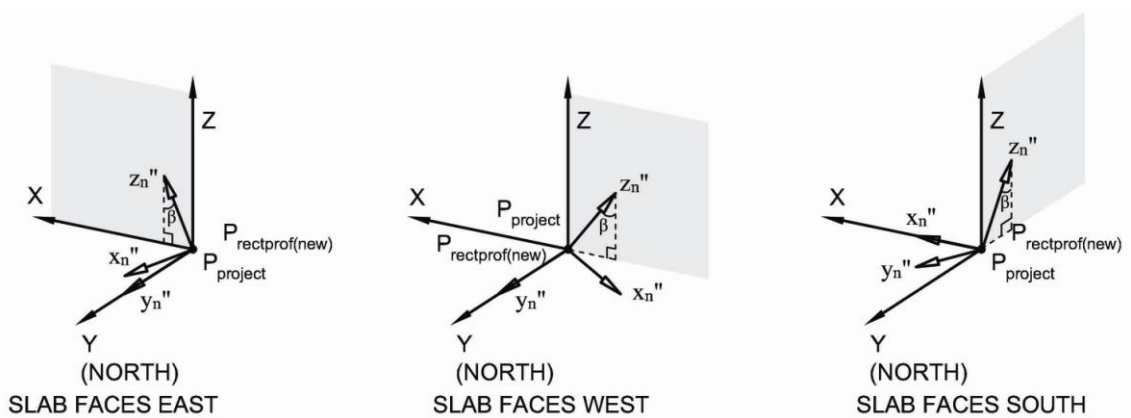


Figure 5.7 Transformed local placements of slab profiles indicating east, west and south orientation

Since the wall is a ‘Swept Solid’ (*IfcExtrudedAreaSolid*) its constraints are profile and extrusion. The ‘profile’ constraint is instantiated by *IfcRectangleProfileDef* which has attributes ‘XDim’ and ‘YDim’ representing the slab length and width respectively. These are multiplied to give the surface area of the slab.

#### c) Wall

The IFC specification provides two entities for wall occurrences (Liebich et al. 2007):

*IfcWallStandardCase* used for all occurrences of walls, that have a non-changing thickness along the wall path and where the thickness parameter can be fully described by a material layer set. These walls are always represented geometrically by ‘SweptSolid’ geometry, if a 3D geometric representation is assigned.

*IfcWall* used for all other occurrences of wall, particularly for walls with changing thickness along the wall path (e.g. polygonal walls), or walls with a non-rectangular cross sections (e.g. L-shaped retaining walls), and walls having an extrusion axis that is unequal to the global Z axis of the project (i.e. non-vertical walls).

*IfcWallStandardCase* is a more useful wall representation since it consists of more parametric description (Table 5.3) and allows more intelligent data to be exchanged (Solihin 2010). Hence, only *IfcWallStandardCase* is analysed further and implemented in the prototype.

**Table 5.3 Rules and parametric data for *IfcWallStandardCase***

<b>Geometric Representation</b>	‘Swept Solids’ and ‘Constructive Solid Geometry (CSG)’ Commonly ‘Swept Solids’ extruded vertically long the positive z-axis of the wall local placement coordinate system and WCS
<b>Rule</b>	Single thickness along the path i.e.: <ul style="list-style-type: none"> <li>• parallel sides for straight walls</li> <li>• co-centric sides for curved walls</li> </ul>
<b>Parametric data</b>	Wall height (from <i>IfcExtrudedAreaSolid</i> ) Wall thickness (from <i>IfcMaterialLayerSetUsage</i> ) Wall offset from axis (from <i>IfcMaterialLayerSetUsage</i> )

Since the geometric representation of *IfcWallStandardCase* is simplified and restricted to ‘Swept Solids’ (and CSG) only, the attributes that would help determine its orientation are object placement and material set usage.

Since only external walls are required, whether the wall is external or internal must be checked for all wall instances in the IFC model. This information is embedded in a property set called ‘Pset\_WallCommon’ (Refer Table 4.5, Chapter 4). The property definition ‘IsExternal’ gives an indication whether the element is designed for use in the exterior (TRUE) or not (FALSE). If (TRUE), *t* is an external element and faces the outside of the building.

The determination of the orientation and surface area for *IfcWallStandardCase* has been described in the work of Cemesova (2013b). Similar algorithms and conventions have been used and implemented in the prototype. The work of Cemesova (2013b), however, only processes orientation for walls that are facing, north, south, east and west and does not account for other orientations. The algorithms are adapted with an adjustment made to the True North attribute in order to account for all orientations (See Appendix F). Since all instances of *IfcWallStandardCase* are ‘Extruded Solids’ extruded vertically in the direction Z-axis of WCS, the slope of all walls are assumed a default value of 90°.

### 5.2.3 External data repositories

#### i) Climate Data

Climate data means the collection of climate elements related to a single unique geographical location (primary location) as a function of time. Normally climate data sets are stored in time steps of one hour over a period of one year. A climate data set can contain more than one measured data or (statistical) calculated data sets.

Typical Meteorological Year (TMY) data sets in the USA, and Test Reference Year (TRY) data in Europe are some of the most commonly used formats of hourly weather data for BPS (McLeod et al. 2012b). The principles behind the generation of these datasets are similar in that a typical weather year is compiled by selecting the mean monthly data from long-term historic data typically spanning a 20-year period. As such these data sets represent typical (historic) conditions and the U.S. National Renewable Energy Laboratory (NREL) states that ‘they are not suited for designing systems and their components to meet the worst-case conditions occurring at a location’ (Marion and Urban 1995). Interpolation software such as Meteonorm 7 (Meteotest 2012) can generate complete data sets for virtually any geographic location in the world. From monthly values (derived from monitoring stations, interpolated or imported) the software uses a stochastic model to calculate hourly values. Meteonorm can export data in 27 different predefined export formats. The evolved data export functionality of Meteonorm is the reason why its climate data sets are adopted by solar PV simulation software and BPS tools (Table 5.4). Meteonorm 7 is licensed proprietary software.

**Table 5.4 Data output formats for Meteonorm software**

Use	Output format
General Use	TMY2, TMY3, TRY
Solar PV simulation	PV*sol, PVsyst, Polysun, PVS, PVScout, Meteo matrix (TISO)
Solar Thermal	T*Sol, Polysun, Solar-Ripp
BPS	TRNSYS, CH Meteo, HELIOS-PC, DOE, Suncode, SIA 380/1, Match, LESOSAI, EnergyPlus(epw), PHPP/WaVE, DYNBIL, WUFI, IDA-ICE, Pleiades/Comfie, SIA 2028, PHLuft

NASA Surface meteorology and Solar Energy (NASA SSE) website provides over 200 satellite-derived meteorology and solar energy parameters. The data is monthly averaged from 22 years of historic data. Like Meteonorm, NASA SSE can also interpolate data from nearby weather stations for any geographical location in the world. Since the weather data is available as daily and monthly averages, it is used by statistical and simplistic time-series simulation models such as RetScreen and HOMER software respectively.

Figure 5.8 shows a graph comparing Meteonorm, NASA SSE, and meteorological (MET) daily solar radiation and ambient temperature data for Cardiff. It is seen that NASA SSE data shows underestimated values for solar radiation, whereas Meteonorm overestimates the solar radiation for 6 months of the year. For the temperature parameter both NASA SSE and Meteonorm data set overestimate the values by an average of 10-13% against monitored data (Table 5.5).

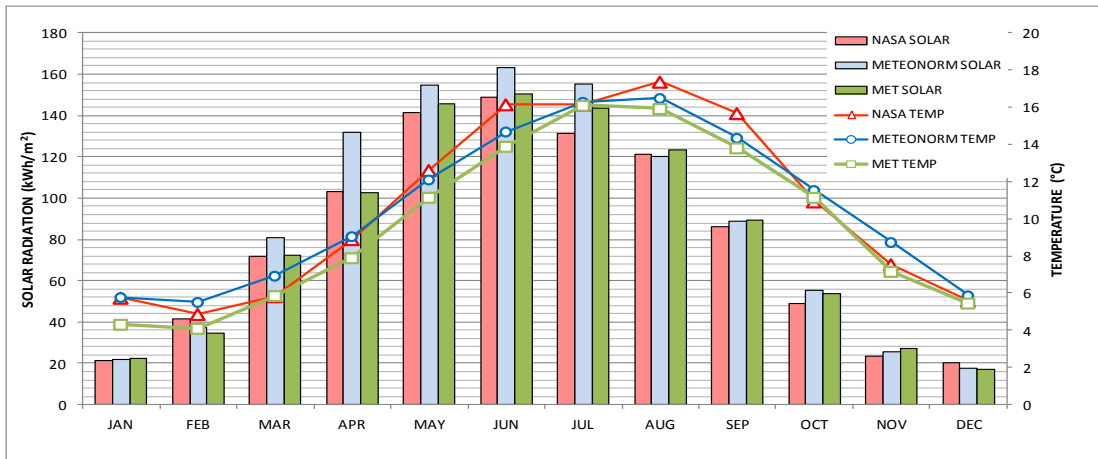


Figure 5.8 Meteonorm, NASA SSE, and MET daily solar radiation and ambient temperature data for Cardiff

NASA SSE dataset is comparable against monitored MET data for solar radiation values. Since the NASE SSE dataset is open-source and freely available, it is selected as the source of climate data to run solar PV simulation in the developed prototype.

Table 5.5 Percentage deviation from MET data for NASA SSE and Meteonorm datasets

	SOLAR RADIATION		TEMPERATURE	
	NASA	METEONORM	NASA	METEONORM
<b>JAN</b>	-3.55	-3.00	33.04	33.86
<b>FEB</b>	19.23	7.38	18.91	34.70
<b>MAR</b>	-0.24	11.83	-0.57	18.27
<b>APR</b>	0.48	28.06	12.73	14.70
<b>MAY</b>	-2.97	6.02	13.13	8.58
<b>JUN</b>	-1.11	8.51	16.26	5.73
<b>JUL</b>	-8.46	8.22	0.17	1.16
<b>AUG</b>	-1.57	-2.50	9.08	3.56
<b>SEP</b>	-3.66	-0.28	13.54	3.94
<b>OCT</b>	-8.89	3.09	-1.97	3.54
<b>NOV</b>	-14.10	-6.15	5.35	22.02
<b>DEC</b>	17.74	1.36	2.55	7.59
<b>AVERAGE</b>	<b>-0.59</b>	<b>5.21</b>	<b>10.19</b>	<b>13.14</b>

a) Structure of the NASA SSE Climate file

Climate files containing daily data for a particular year and location is available to download from the NASA SSE website. The downloaded file is a text file with a file extension *.txt*. The HESMOS project provides a specification of interfaces to material and climate databases as one of its deliverables (Grunewals et al. 2012). A data schema was proposed for describing climate data to be used for energy simulation. The schema structured the climate data into two parts. The first part is called the meta data which refers to the site information, dataset information, data information, and information about data manipulation. And the second part comprises of the climate data elements.

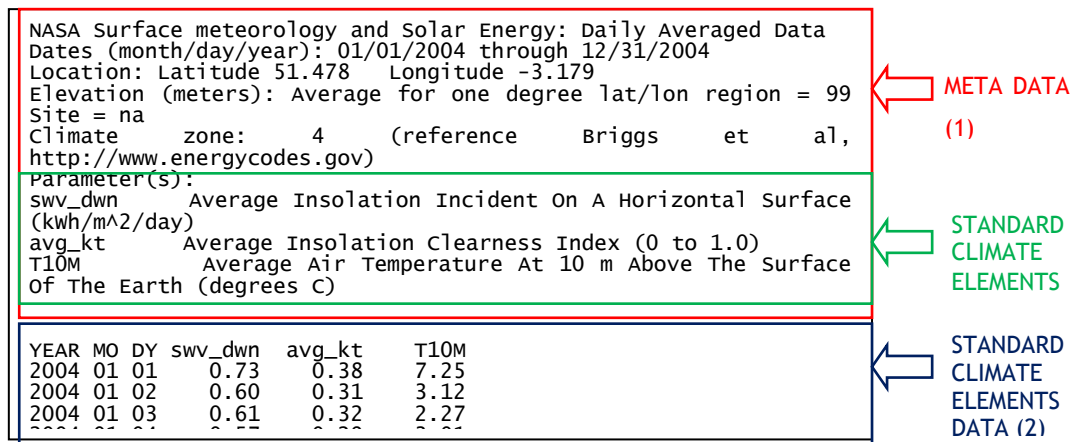


Figure 5.9 Data Structure of the NASA SSE climate data file

Similar parallels can be drawn with the NASA SSE climate data text file (Figure 5.9). The downloaded standard climate elements shown are only 3 of 16 available elements. These three are the only climate data elements required to run solar PV simulations. The information type listed in the meta data and standard element data has been outlined in Table 5.6 and Table 5.7 respectively.

Even though the prototype is only compatible with the NASA SSE text file format, it is envisaged to be extended to incorporate data exchange with various other data formats. Since climate data is available in a plethora of data exchange formats, this calls for standardisation of climate database specification or developing interfaces that can link to various data exchange formats. A start has already been made with the HESMOS project (Grunewals et al. 2012).

Table 5.6 Part1 -Meta data in the NASA SSE climate data file

DESCRIPTION	ADDITIONAL INFORMATION	FORMAT	EXAMPLE VALUE
OWNER	Owner name	Character	NASA Surface meteorology and Solar Energy
TYPE OF DATA	Daily averaged, monthly mean, etc	Character	Daily Averaged Data
LOCATION	Latitude	Float	51.478
	Longitude	Float	-3.179
	Elevation	Float	99
SITE	Geographical location	Character	Cardiff
CLIMATE ZONE	Climate zones as per http://www.energycodes.gov	Integer	4

**Table 5.7 Part 2 -Standard Climate elements data (16 available) in the NASA SSE climate data file (Parameters in Black text are used in the PV simulation model)**

PARAMETER	STANDARD NAME	FORMAT	UNIT
swv_dwn	Average Insolation Incident On A Horizontal Surface	Float	kWh/m <sup>2</sup> /day (daily/monthly) W/m <sup>2</sup> (minute/hourly)
avg_kt	Average Insolation Clearness Index	Float	value from 0 to 1.0
T10M	Average Air Temperature At 10 m above earth's surface	Float	°C
clr_sky	Average Clear Sky Insolation Incident On A Horizontal Surface	Float	kWh/m <sup>2</sup> /day (daily/monthly) W/m <sup>2</sup> (minute/hourly)
clr_dif	Average Clear Sky Diffuse Insolation	Float	kWh/m <sup>2</sup> /day (daily/monthly) W/m <sup>2</sup> (minute/hourly)
clr_dnr	Average Clear Sky Direct Normal Radiation	Float	kWh/m <sup>2</sup> /day (daily/monthly) W/m <sup>2</sup> (minute/hourly)
clr_kt	Average Clear Sky Insolation Clearness Index	Float	value from 0 to 1.0
lww_dwn	Average Downward Longwave Radiative Flux	Float	kWh/m <sup>2</sup> /day (daily/monthly) W/m <sup>2</sup> (minute/hourly)
toa_dwn	Average Top-of-atmosphere Insolation	Float	kWh/m <sup>2</sup> /day (daily/monthly) W/m <sup>2</sup> (minute/hourly)
PS	Average Atmospheric Pressure	Float	kPa
TSKIN	Average Earth Skin Temperature	Float	°C
T10MN	Minimum Air Temperature At 10 m above earth's surface	Float	°C
T10MX	Maximum Air Temperature At 10 m above earth's surface	Float	°C
Q10M	Average Humidity Ratio At 10 m above earth's surface	Float	%
RH10M	Average Relative Humidity	Float	%
DFP10M	Dew/Frost Point Temperature At 10 m	Float	°C

ii) *Technical specifications of PV system components*

Polysun and PVSyst PV simulation software use PV and inverter databases provided by Photon database (see Chapter 3, section 3.5.4). The Photon database is web-based and is copyrighted with the private use of the data allowed free of charge (Boehne 2013). The PV database has over 900 suppliers and technical specifications of over 48,000 PV modules. The inverter database has over 300 suppliers and technical specifications of around 7500 inverters. The databases are available in a Microsoft Access file (file extension.accdb) as a purchased annual license for commercial applications. The specific data required from technical specifications has already been outlined in Chapter 3.

### 5.3 Prototype development- RenewBIM tool

A prototype, called RenewBIM, has been developed in Java for an integrated solar PV simulation tool using the proposed conceptual framework. Eclipse Integrated Development Environment (IDE) was used to develop the Java application. This section explains the architecture of the RenewBIM tool and the specifications of different components.

#### 5.3.1 Architecture of the prototype

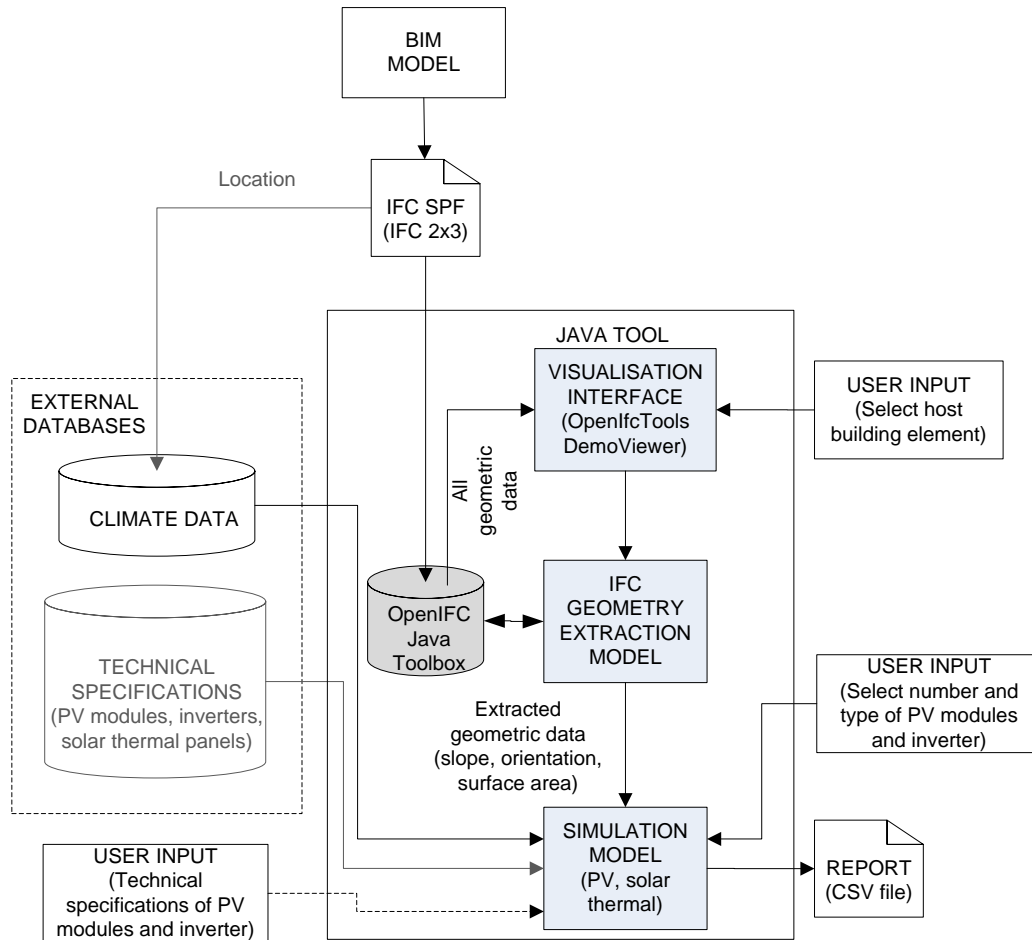


Figure 5.10 Architecture of the prototype

The prototype architecture is shown in Figure 5.10. The architecture shows three basic components; the BIM model (drawn in any BIM authoring tool) and exported in the IFC 2 X3 STEP file (IFC SPF), the RenewBIM tool developed in Java, and the external data repositories consisting of databases for climate data and technical specifications of PV components. The RenewBIM tool itself contains three components; the visualisation interface, the geometry extraction model; and the simulation model. The components of the tool would be discussed in detail in the following sub-sections. The first user input is required for visualisation interface where the user selects the host building element to analyse for PV generation. The second user input is required for the simulation model to run, as the number and type of PV components need to be selected by the user.

In the implementation, the climate data repository is a folder in the local directory which contains text files of UK locations downloaded from the NASA SSE website. This directory can be expanded by the user. In the current state of the implementation the user needs to select a climate file. However, since the IFC file contains the latitude and longitude of the site in the *IfcSite* entity, this can easily be linked to the appropriate climate file, removing the user input for this completely. This however is not being currently implemented in the prototype.

The technical specification repository is a database of technical specifications of PV system components. Functionality can be developed in RenewBIM by which an interface is developed to access this repository making it easier for the user to select the type of module and inverter and enter the quantity. The technical specifications for the selected components would then be extracted from the repository by the tool and used in the simulation model. In the current version of the prototype this has not been implemented, as the database available in Microsoft Access file was not freely available. The technical specifications therefore have been implemented as user inputs as a 'work around'. In order to automate this process, this 'work around' would be removed from future versions, once these databases are purchased for commercial exploitation.

Depending on the simulation time step chosen by the user, the simulation model outputs the results in a comma separated value (.csv) format for hourly values, and widgets are created to display the annual and monthly energy generated by PV.

*i) OpenIFC Java Toolbox & IFC DemoViewer*

There are a range of freeware tools available currently used for visualising, checking, and translating IFC SPF files (Liebich 2011). Open IFC Tools website provides an Open IFC Java Toolbox, which can read and process IFC files (Riedal 2006). The Toolbox (version V1.0.1) is a library of Java Classes that are stored in packages that can be used for processing IFC SPF files. The website also provides an open IFC Demo viewer WebStart (beta version) which visualises IFC files using Java classes from OpenIFC Java Toolbox. It should be noted that with the latest release of IFC 4, the Open IFC Tools website is no longer maintained, and latest version of the Open IFC Java Toolbox (version 2.0.1), compatible with IFC 2x3 and IFC 4, is available on the IFC Tools Project website (Riedal 2013) .

Three packages are used in the software implementation;

- 'openifctools.com.openifcjavatoolbox.ifcmodel.IfcModel', which contains the 'IfcModel' class which can be used to read and store data from an IFC file.
- 'openifctools.com.openifcjavatoolbox.ifc2x3tc1', which contains java classes that store data from the IFC file from for all the entities, defined types, enumerations and select types in the IFC 2x3TC1 schema.
- 'openifctools.com.viewer.demoviewer.TestModelViewer' which contains the java classes for visualising an IFC file.



*ii) IFC Geometry extraction and Simulation model*

IFC geometry extraction model extracts and processes data embedded in selected host building element (*IfcBuildingElement*) to determine the slope, orientation and surface area. The process to derive the slope and orientation of the building element from the IFC schema has been previously discussed in section 5.2.2. The process is implemented in Java using the Open IFC Java Toolbox by the aforementioned packages.

The solar PV simulation algorithms, embedded in the simulation model, are chosen from algorithms in existing PV simulation tools and from the work of Duffie and Beckman (Duffie and Beckman 1991). The algorithms used and the sequence of tasks running in the simulation model have been given in Appendix G. Factors like mismatch losses, inverter losses soiling and shading adversely affect the performance of PV (Quaschnig 2005). Losses due to mismatch, soiling, and the wiring has been accounted for by assuming a derating factor of 0.77, in accordance to the default value in PVWatts (NREL 1999, 2012). The simulation model however does not contain shading algorithms. These algorithms would be researched and is added in the scope of future work. The simulation model is designed to give outputs in hourly, daily, monthly and annual time steps.

**5.3.2 User interface**

The graphical user interface (GUI) of the RenewBIM is developed by linking a 3-D visualisation window for the IFC file to the simulation model (Figure 5.11). This visualisation feature is important for architects to ‘see’ the buildings they are analysing. OpenIFCtools (Reidal 2009) provided their demo viewer research version developed in Java for linking to the tool. The user loads an IFC file, previously generated by a BIM authoring tool, which is then rendered in the visualisation window. The user then selects a host building element by clicking on the window and loads the selected object. When the selected object is loaded the fields ‘Azimuth’, ‘Tilt/Slope’ and ‘Surface Area’ get populated. The user then loads weather data by browsing in the local directory where the NASA SSE text files are stored. The reference year of the climate file is then automatically populated. In this version of RenewBIM, the PV and inverter databases have not been linked but a provision has been made. Instead, the parameters of PV module and inverter specifications are entered by the user. The user then selects the simulation time period required for the energy generation results. Annual and monthly generation results are displayed in a widget, and daily and hourly results are saved in a CSV file in a user-defined local directory.

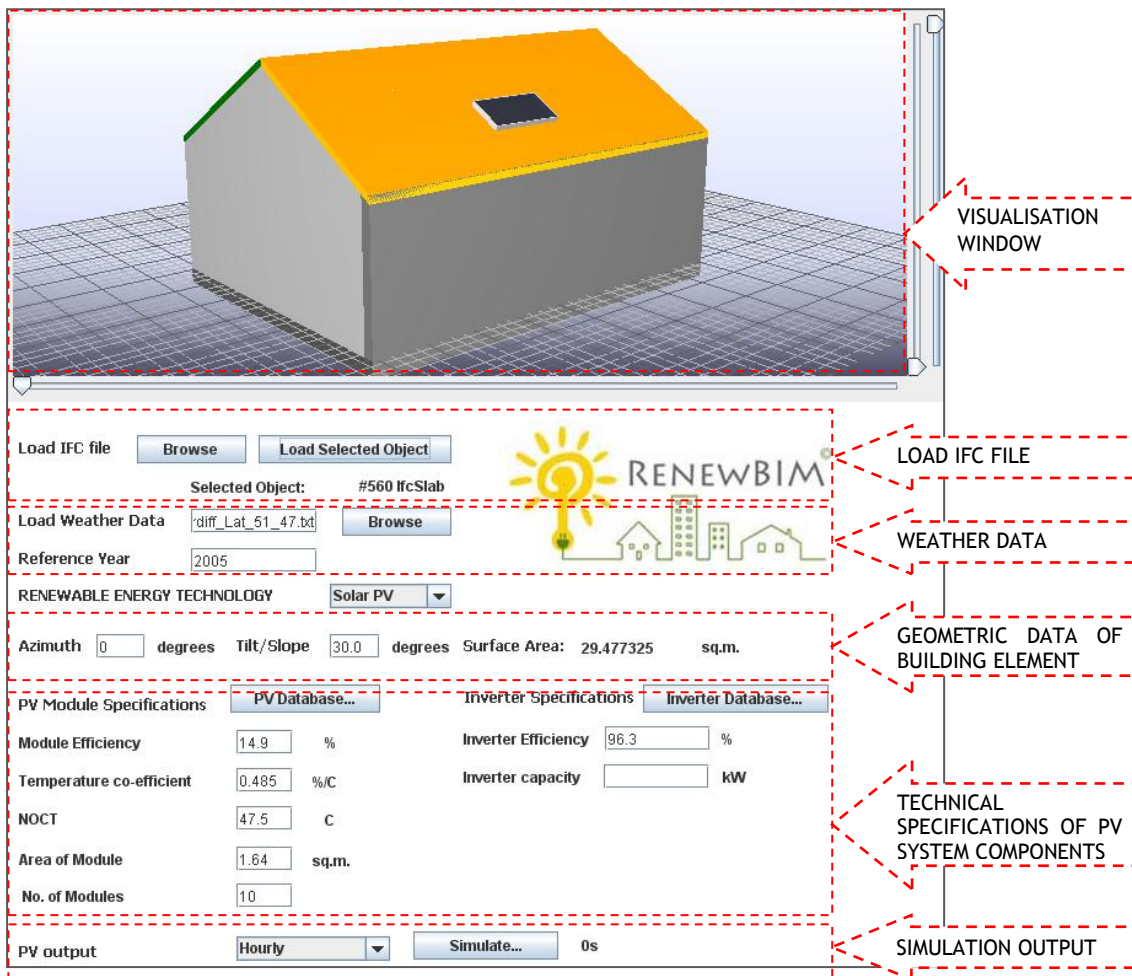


Figure 5.11 User interface of the prototype

i) *User interaction with the prototype*

RenewBIM is primarily aimed to be used by architects (user) in early design phases of their projects. The user interaction with the tool has been explained using a use case scenario (Figure 5.12). The architect's main role in the project team is to create an architectural building model. The development of the building model and its export in the IFC data exchange format occurs in the BIM authoring tool. The architect then accesses the prototype to find out the energy generation potential of the host building element where solar PV modules are installed. The tool can be operated through seven actions by the architect, most of which involve selection from either the IFC data model or external databases for climate, PV modules and inverters. The tool, embedded with detailed time-series simulation models, minimises re-entry of data such as building geometry and manual input of technical data from manufacturer's specifications. The addition of other renewable energy technologies such as solar thermal, biomass boilers and heat pumps using the same conceptual framework will further encourage architects to assess the renewable energy generation potential of their projects.

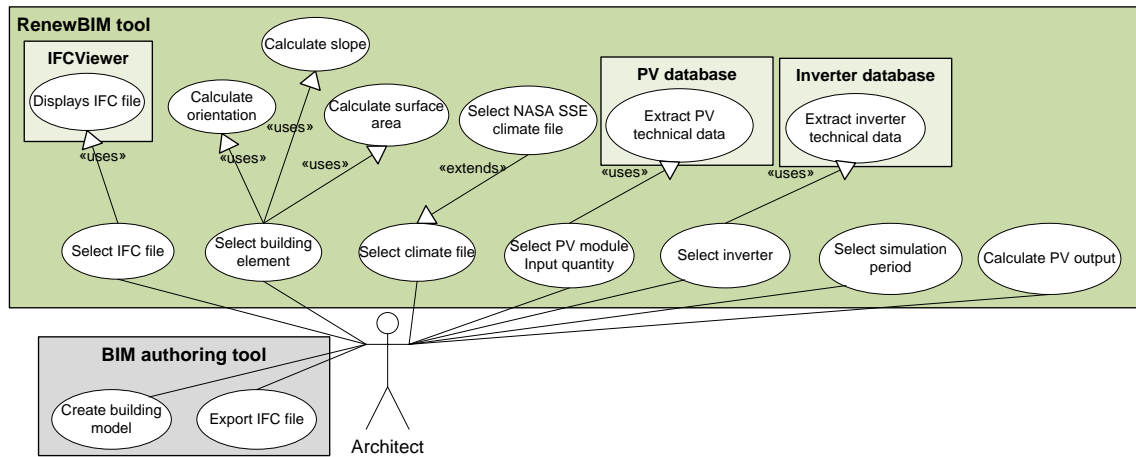


Figure 5.12 UML use case scenario showing the user interaction with the prototype

The user interaction with the prototype is further illustrated with a UML sequential diagram (Figure 5.13). The diagram shows the architect using RenewBIM to calculate the energy generated by a user-defined PV array. RenewBIM is composed of the main class 'PVSimulationModel', 'DemoViewer', the package 'OpenIFC Toolbox', and 'IFCGeometryExtractionModel'. It is also linked to 'ClimateFileRepository'. The diagram explains the following process:

- i. The architect sends a message to Revit requesting an IFC file representation of the BIM model, the IFC file is exported by Revit. The file gets loaded in the 'DemoViewer' where the BIM model is visualised.
- ii. 'DemoViewer' request the user to select a host building element in the BIM model, and selected host building element is highlighted by the viewer.
- iii. The IFC file, the selected host building element are then called by the class 'PVSimulationModel' in order to calculate the energy generated by PV. The class 'PVSimulationModel' also requires these additional inputs;
  - Climate file: The architect selects a climate file from the 'climatefilerepository' which is then utilised by the 'PVSimulationModel'.
  - PV module and inverter technical specification: The user needs to input this data manually in this version. In later versions, these inputs will be linked to a 'TechnicalSpecificationRepository' wherein the user will select the type of PV module and inverter and the technical specifications will be automatically called from the repository.
- iv. When the 'PVSimulationModel' receives the IFC file, it uses package 'Open IFC Toolbox' to read and parse through the IFC file. All entities, properties and relationships in the IFC file are then represented by the Java classes in 'Open IFC Toolbox'. The IFC file is converted to a Java Class which can be read by RenewBIM.

- v. 'IFCGeometryExtractionModel' class requests 'ifcModel.java' class generated by the OpenIFCToolkit and processes the geometrical information (slope, azimuth and area) in the file in a format compatible with 'PVSimulationModel'.
- i. The user then selects the simulation time step (hourly, daily, monthly or weekly). The energy generated by PV for the selected time step is then calculated by the 'PVSimulationModel' class and the results are returned to the user.

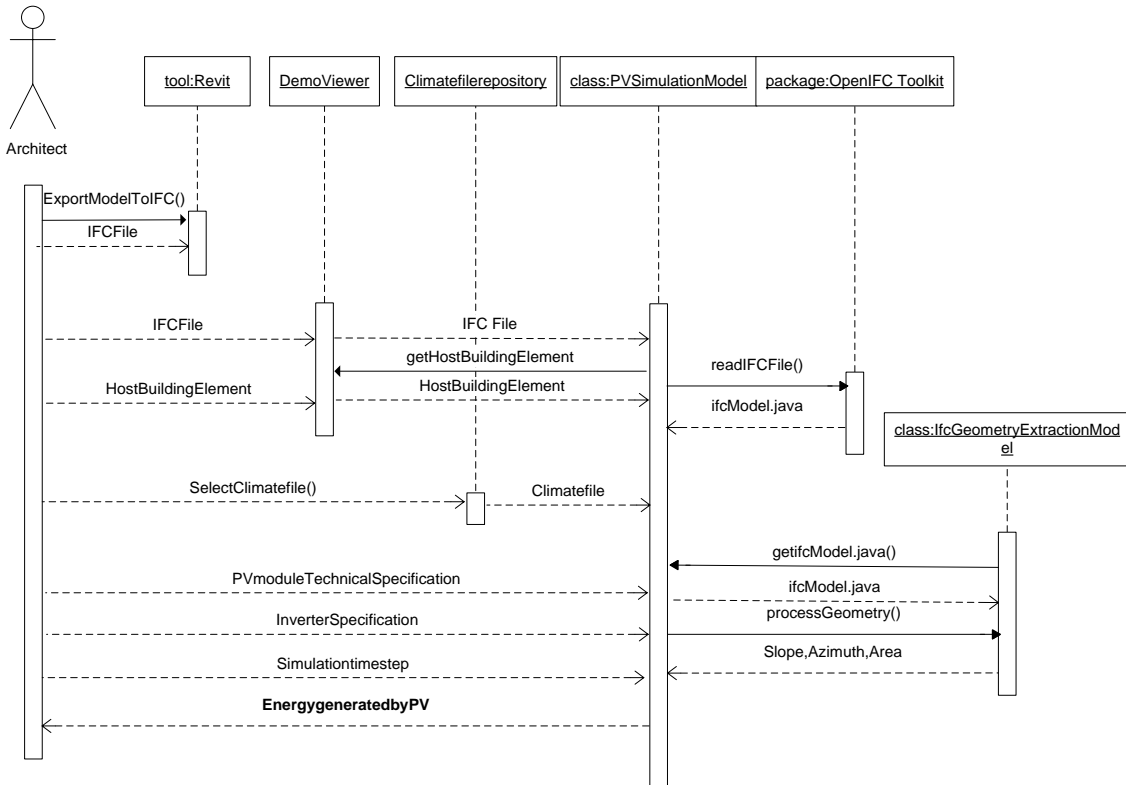


Figure 5.13 UML diagram showing the sequence of tasks conducted by the architect, Revit and RenewBIM Java tool.

### 5.4 Conclusion

A standardised process for adding IFC compatibility to RES simulation models has been proposed in this chapter by means of a conceptual framework. It is standardised to allow the flexibility of linking any RES simulation model or develop compatibility with other open-BIM data exchange schemas (for ex. XML based schemas).

The conceptual framework has been implemented in a solar PV simulation model in order to make it compatible with the IFC by means of the RenewBIM prototype. It is found that the IFC schema does fulfil partial input data requirements of solar PV simulation model, especially geometric data. The IFC schema has entities that contain the site location information of the building that can be linked to the site’s climate data. PV simulation model also require non-geometric input data such as technical specifications of PV components to run the analysis. It

is found that climate data is available in a range of formats, however there isn't a standardised specification to represent climate data that can be read by all analysis programs. Technical specifications of RES system components are stored in databases that are proprietary and its use is restricted to specific simulation tools. From the implementation in the prototype, it is evident that climate data and technical data of system components need to be represented in a common standardised exchange format that can be read by all analysis programs.

However, the prototype does provide a proof-of-concept that the conceptual framework can be implemented in RES simulation model, using an open-BIM data exchange schema. It automates the input of the geometric data of the building and technical data of PV components for conducting PV simulation thereby minimising the erroneous data-entry task for the user. The saved time can then be used to develop design alternatives to optimise the output received from the prototype (energy generated by PV). The prototype works for simple geometry and there is scope for improvement in the prototype for processing all geometry represented by the IFC schema as well strong linkages to climate and technical data repositories, as and when their specification gets standardised.

The successful adoption of the prototype in the industry is dependent on its validation against other existing tools, and unique applications that is currently lacking in tools. Hence, the prototype is tested and validated against existing tools in the market and applied for building level and district level energy assessments in the following chapter.

## CHAPTER 6. RENEWBIM TESTING AND VALIDATION

The testing and validation of the RenewBIM tool and its possible applications has been done using two case studies. The first case study is for a building level solar PV assessment (section 6.1) and the second case study is for a district level solar PV assessment (section 6.2). For the building level assessment, the testing has been done addressing two components of the tool; one the PV simulation model itself and second the IFC Geometry Extraction Model that deduces geometric input data (slope, orientation and surface area) from the IFC SPF file for the PV simulation model. The main purpose of testing the prototype on a district level application is to show the possibility of the prototype to provide solar PV assessment for not just single designed BIM models, but for ‘as-built’ BIM models and city wide models.

### 6.1 Building level Solar PV assessment

A building level solar PV assessment was conducted using a case study of a residence in Cardiff with a 2.45 kWp PV system installed in 2011. The performance of the solar PV system was monitored from the installation date, hence has over a year’s collection of monitored data. The house was surveyed and an architectural BIM model of the house was constructed in Revit (Figure 6.1) and exported as an IFC file. The IFC file was then loaded in the prototype. The weather file format currently compatible with the tool is a text file (.txt) downloaded from NASA Surface meteorology and Solar Energy website (NASA 2012). The results from the testing and validation have been presented in the following sections.

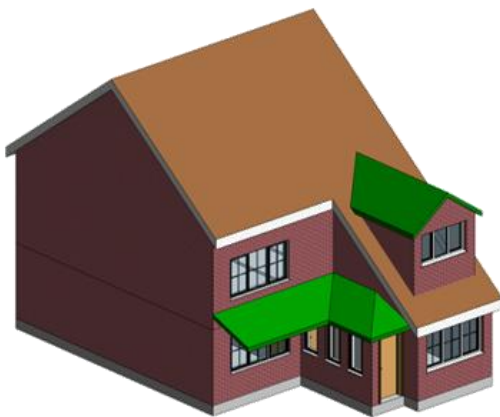


Figure 6.1 Revit Model (Left) and image (Right) of the house with a 2.45 kWp array

### 6.1.1 Performance against existing tools

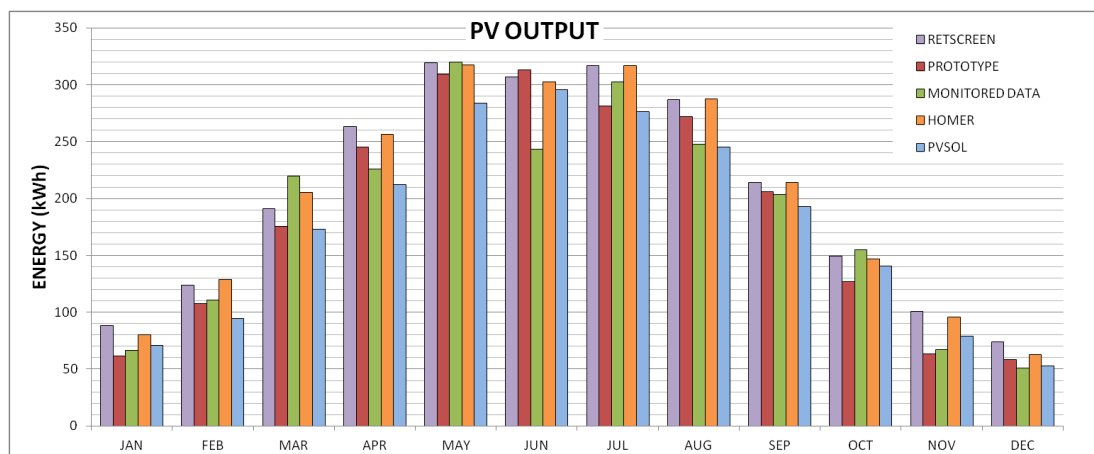
The accuracy of commercially available energy simulation tools against actual monitored data and comparison with existing tools is crucial for their large-scale adoption. Hence the prototype has been validated against three tools; PV\*Sol, RetScreen and HOMER, using the case study.

The 2.45 kWp solar PV system was commissioned on 16th June 2011. The roof upon which the system is installed has an azimuth angle of 40° east of due south and tilt of 38° accurately measured by a theodolite. The PV system and inverter specifications required by the model are shown in Table 6.1.

**Table 6.1 PV module and inverter specifications**

PV MODULE SPECIFICATIONS	INVERTER SPECIFICATIONS
Nominal Output: 245 Wp	Rated power (AC): 2.5 kW
Quantity: 10 (1 string- connected in series)	Quantity: 1
Efficiency at STC: 14.9%	Efficiency (max.): 96.3%

Daily average clearness index and outside ambient temperature of a location specified by latitude and longitude are extracted from the weather file and used as input data. Monitored hourly inverter output data was logged from June-2011 to May 2012. PV simulations were carried out in PV\*Sol, RetScreen and HOMER with the installed system specifications, the results of which are presented in (Figure 6.2).



**Figure 6.2 Monthly output of various PV simulation tools against monitored data**

Figure 6.2 shows considerable agreement of the results of the prototype against monitored data in winter months Nov-Feb with a percentage error of 7.4%. In September, all simulation tools show reasonable agreement with the monitored data with an average error of 4.2%. In the month of June however, actual output is considerably lower than the simulation results. The outputs are similar with an average error of 25%. Since solar radiation data of the site

was not monitored and recorded for this period, the discrepancy could be attributed to the over-estimated simulated solar radiation data as against actual monitored data.

The percentage errors for all tools are within a range of 10% in the months of June, July and September (Figure 6.3). When the average of the monthly percentage errors for all tools is calculated, the prototype is remarkably comparable to PV\*Sol as they show an average error of 10.57 and 10.6% respectively.

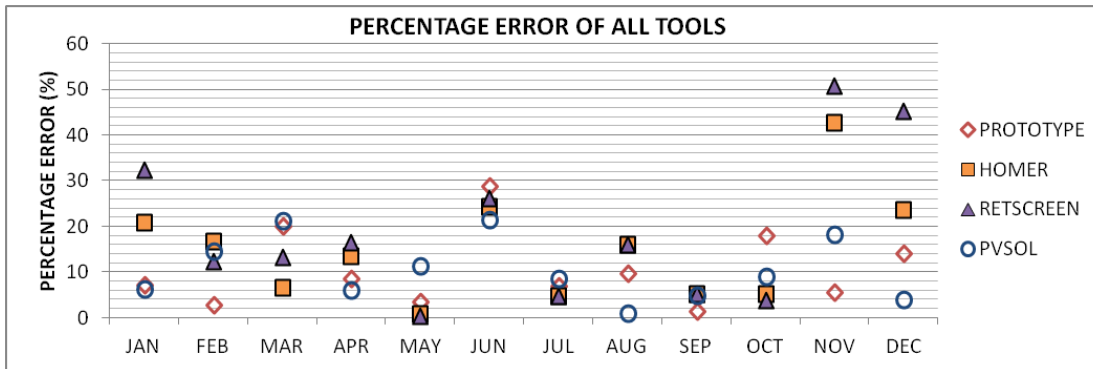


Figure 6.3 Monthly percentage errors for various PV simulation tools

In the annual generation figures (Table 6.2), it can be observed that the results of the prototype were similar to actual data showing a percentage error of 0.36%, while simulation tools RetScreen, Homer and PV\*Sol, show 9.1%, 8.4% and 4.3% error respectively. The system is largely un-shaded hence, the monitored and simulated data does not account for shading losses.

Hence, this validating exercise indicates that the solar PV simulation model of the prototype has a sound physical basis. The case study has also been used to compare the monitored data with PV simulation software PVWatts and PVGIS (Sweet et al. 2013).

Table 6.2 Annual output of various PV simulation tools against monitored data

	MONITORED DATA	RETSCREEN	HOMER	PV*SOL	PROTOTYPE (RENEWBIM)
ANNUAL OUTPUT (kWh)	2212	2434	2414	2117	2220
ERROR (%)		9.1%	8.4%	4.3%	0.36%

### 6.1.2 Challenges in the processing geometric data from IFC file

The roof of the case study, even though drawn as a single 'Extruded Area Solid' in Revit, has an asymmetrical shape made more complex by the insertion of a dormer roof. Hence, this shape is represented by a 'BRep' in the IFC SPF file, instead of a 'Swept Solid' (Figure 6.4). A 'BRep' is a list of faces which are defined by coordinates. In this case, *IfcRoof* is represented by a group of 29 faces (*IfcFace*) described under *IfcFacetedBrep*. These faces were not displayed in the IFC Model Viewer. The IFC SPF file was imported back in Revit to check



whether the faces would be displayed. The faces were displayed in the imported model (Figure 6.5).

For 'Extruded solids' the local placement of the 'rectangular profile' is required to analyse and deduce the slope and orientation of the solid. The 'Brep' is placed with respect to the local placement of the roof and the individual faces do not possess their own local placements. This makes it difficult to deduce slope and orientation of the surfaces using the same algorithms used for 'Extruded Area Solids' shape representation. Hence, the prototype does not process 'Brep' shape representations. However, the tool would be extended to be able to process all roof shape representations.

```
#68170= IFCROOF('3z2pwyDUj1pBcC32_QDqVG',#52,'Basic Roof:Pitched - warm Timber - Ins
Over:242091',$,'Basic Roof:Pitched - warm Timber - Ins
Over:45400',#67959,#68168,'242091',.NOTDEFINED.);
#68168= IFCPRODUCTDEFINITIONSHAPE($,$,(#68166));
#68166= IFCSHAPEREPRESENTATION(#44,'Body','Brep',(#68161));
#68161= IFCFACETEDBREP(#68159);
#68159=
IFCCLOSEDSHELL((#68017,#68022,#68027,#68032,#68037,#68042,#68047,#6805
2,#68057,#68062,#68067,#68072,#68077,#68082,#68087,#68092,#68097,#6810
2,#68107,#68112,#68117,#68122,#68127,#68132,#68137,#68142,#68147,#6815
2,#68157));
#68017= IFCFACE((#68016));
#68016= IFCFACEOUTERBOUND(#68014,.T.);
#68014= IFCPOLYLOOP((#67968,#67970,#67972,#67962));
#67968=
IFCCARTESIANPOINT((0.,8.35428436194738,6.52708229173936));
#67970=
IFCCARTESIANPOINT((0.,3.73000000000001,2.91419538687007));
#67972=
IFCCARTESIANPOINT((0.,3.73000000000001,3.23208444974575));
#67962=
IFCCARTESIANPOINT((0.,8.35428436194737,6.84497135461504));
```

Figure 6.4 IFC SPF file showing geometric shape representation of *IcfRoof* '3z2pwyDUj1pBcC32\_QDqVG'

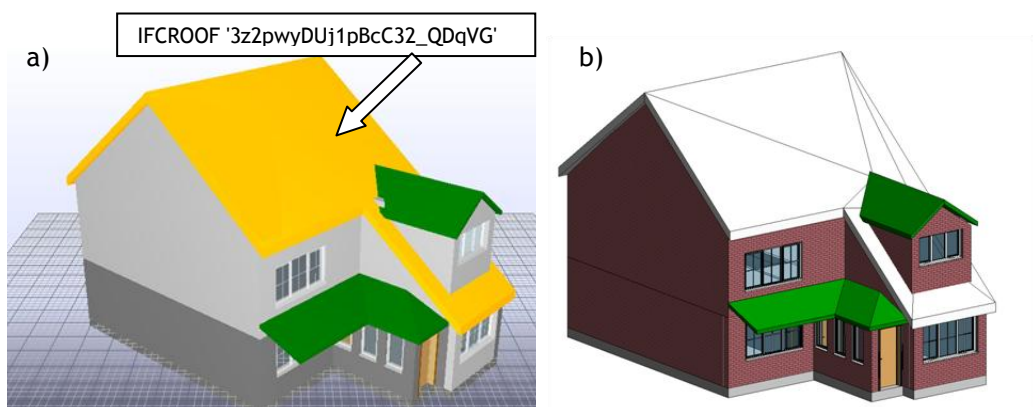


Figure 6.5 The case study IFC SPF file in IFC Model Viewer (a) and imported in Revit (b)

As a work around, the roof is constructed in two parts in Revit, one is the pitched roof over the house, and another sloping roof over the extension. When exported as an IFC file the

pitched roof is displayed in the IFC Model viewer composed of two slabs (Figure 6.6). This is confirmed when the IFC file is imported back into Revit. Since the shape representations of these slabs are ‘SweptSolid’(Figure 6.7), these can now be processed by the prototype.

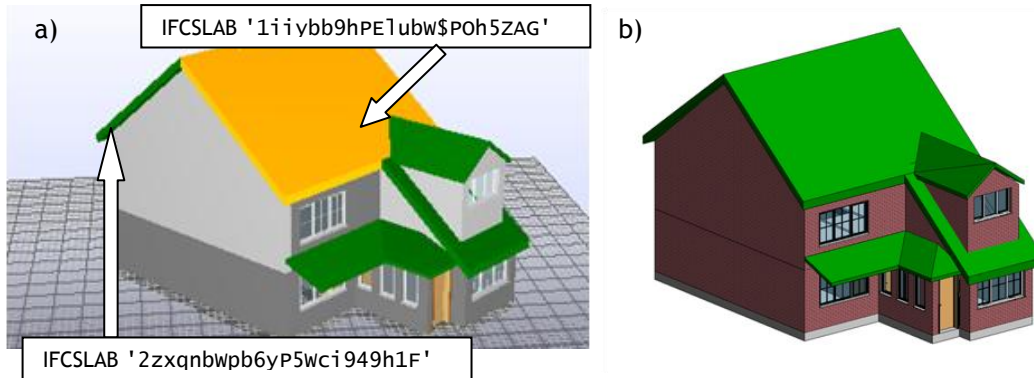


Figure 6.6 Revised IFC SPF file in IFC Model Viewer (a) and imported in Revit (b)

```
#99467= IFCROOF('2XgtFpGMDDSBsUsBIySlsu',#52,'Basic Roof:Pitched - warm Timber - Ins Over:256479',$, 'Basic Roof:Pitched - warm Timber - Ins Over',#99466,$,'256479',.NOTDEFINED.);
#99511= IFCRELAGGREGATES('2EKTUHeFTexHYcuwnZ9T_f',#52,$,$,#99467,(#99490,#99510));
#99490= IFCSLAB('2zxqnbwbp6yP5wci949h1F',#52,'Basic Roof:Pitched - warm Timber - Ins Over:256479',$, 'Basic Roof:Pitched - warm Timber - Ins Over',#99471,#99488,'256479',.ROOF.);
#99488= IFCPRODUCTDEFINITIONSHAPE($,$,(#99486));
#99486= IFCSHAPEREPRESENTATION(#44,'Body','SweptSolid',(#99481));
#99510= IFCSLAB('1iyybb9hPE1ubw$POh5ZAG',#52,'Basic Roof:Pitched - warm Timber - Ins Over:256479',$, 'Basic Roof:Pitched - warm Timber - Ins Over',#99491,#99508,'256479',.ROOF.);
#99508= IFCPRODUCTDEFINITIONSHAPE($,$,(#99506));
#99506= IFCSHAPEREPRESENTATION(#44,'Body','SweptSolid',(#99501));
```

Figure 6.7 IFC SPF file showing geometric shape representation of *IfcRoof* composed of slabs

This validation exercise further highlights the different ways in which a building model will be constructed in Revit or other BIM authoring platforms. These would give rise to IFC files differing from each other containing different shape representations. Hence, it is vital for the prototype to be developed further to handle all types of shape representations.

## 6.2 District level Solar PV assessments

The developed prototype should be usable for conducting RES assessments for not just single buildings, but also for neighbourhoods and districts. Current environmental standards and legislation have driven the demand of sustainable-retrofit solutions. With the announcement of financial incentives like FiT by various governments, an increase in solar PV installations was seen amongst housing associations and governing councils that own most of existing housing stock, particularly in the UK. With the advance of BIM in newly constructed buildings, BIM models would be produced not just for single buildings but for neighbourhoods. Another case study of the village of Hollybush was used to analyse the performance of the tool on BIM models of a district. The PV and inverter parameters selected is summarised in Table 6.3 taken from the work of (Gupta et al. 2011).

The prototype, in its current version, can analyse a single building element at a time for PV generation. A part of the village of Hollybush (35 houses) was constructed in Revit (Figure 6.8) and exported as an IFC file and loaded in the tool. The slope of all roofs is  $30^\circ$ . The prototype processed the azimuth and slope of all the roofs (*IfcSlab*) selected (one building element at a time) and simulated the energy generated by PV for an annual time step. The climate data for Rhymney valley where the village is located (Latitude:  $51.7^\circ$ , Longitude:  $-3.3^\circ$ ) was downloaded from the NASA SSE website.

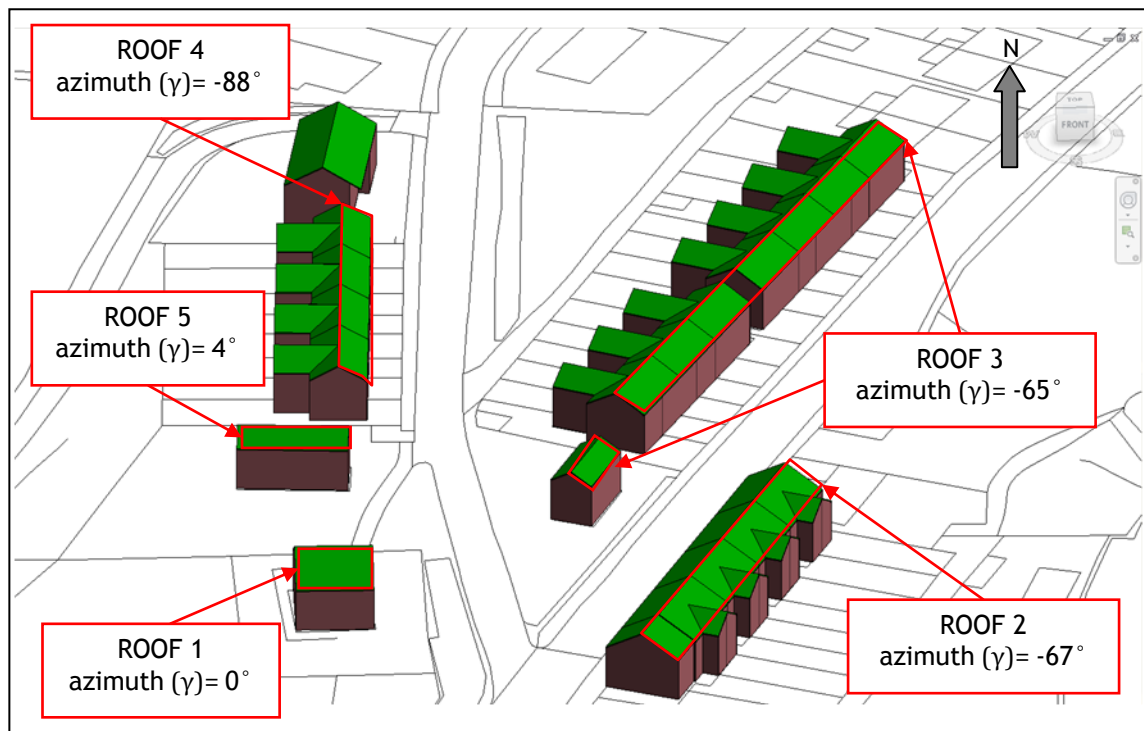


Figure 6.8 Revit model of houses in Hollybush showing different roof orientations

**Table 6.3 PV module and inverter parameters**

PV module parameters	
Module capacity	235 Wp
Size of array	1.88 kW
No. of modules	8
Area of module	1.64 m <sup>2</sup>
Module efficiency	14.3 %
NOCT	47.5 °C
Temperature co-efficient	0.485 %/°C
Inverter parameters	
Inverter efficiency	95%

**Table 6.4 Annual PV generation results for different roof orientations.**

ANNUAL GENERATION (kWh)	ROOF 1	ROOF 2	ROOF 3	ROOF 4	ROOF 5
Azimuth (°)	0	-67	-65	-88	4
RenewBIM	1764.61	1677.15	1682.18	1618.21	1764.3

As in the earlier case study, the prototype could only process roofs that were composed of slabs. Hence, the prototype could not process the slope and azimuth of roofs over extensions to houses as these were represented by the 'BRep' geometric representation.

### 6.2.1 User interface for district level assessments

Since the prototype can process the geometric data for a number of buildings in the same IFC file, the user interface can be altered for district level assessments. The user interface for district level assessments is illustrated in Figure 6.9. When the IFC file is loaded containing a number of buildings with different orientations, the visualisation interface (1) becomes the main interface where user input is required. When the user guides the mouse to hover over the roofs, the azimuth and slope for each roof is displayed (2). Upon selecting the roof, a pop-up menu opens where they are fields for the user to enter the PV and inverter parameters (3). The user input for weather data and simulation options remains the same as in the earlier GUI (4). Project owners would find the annual simulation time-step most useful. The user also needs to provide additional input data about the energy demand of each households, the total number of households and the carbon emission factor based on the baseline fuel type consumed by the district (5). Upon pressing the simulation button, the energy generated by the PV array, and the associated savings in energy and CO<sub>2</sub> emissions is displayed as outputs (6). The key output displayed by the tool is the percentage reduction (saving) in energy and CO<sub>2</sub> emissions (7). These features of the tool would help governing councils or private owners assess the solar PV potential of their projects. As and when the tool is extended to other RES, these outputs would help guide the owners in meeting their renewable energy targets.

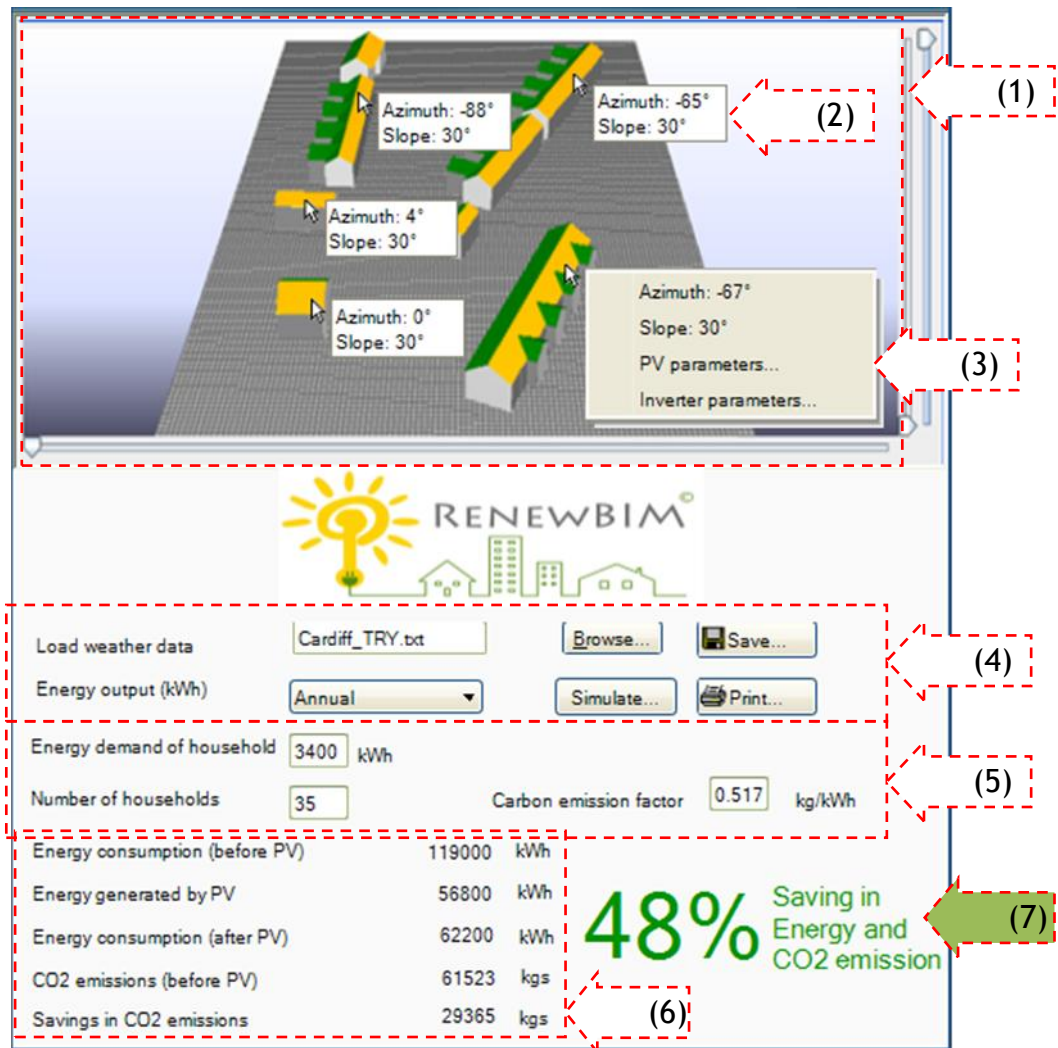


Figure 6.9 User interface of prototype for district level solar PV assessments

Although, the prototype, in its current version, has certain limitations around processing various shape representations defined in the IFC schema, this case study shows the potential application of the prototype at a district level. However, the application is based on the premise that the project team would adopt the IFC-based BIM approach in the design and construction of districts. IFC-based BIM has not only been the focus for the design and construction of new buildings but also for existing buildings and ‘as-built’ building information models.

‘As-built’ building information models has been the focus of recent research which involves the creation of 3D models for existing buildings using technologies such as 3D laser scanning (Tang et al. 2010; Woo et al. 2010; Huber et al. 2011; Diaz-Vilarino et al. 2012). Researchers currently are finding ways of representing ‘as-built’ BIM models and are investigating the IFC schema to represent not only ‘as-designed’ information but also ‘as-built information (Xiong et al. 2013).

For cities, research suggests the usage of cityGML, a XML based format, for representation and exchange of virtual 3D city models (Kolbe 2009). CityGML, is a semantic model like IFC,

but with a different scope and at a different scale. Recent research has been focussing on ways for exchanging of information and bringing IFC and CityGML together towards a unified 3D city model (Kolbe 2009; Berlo and Laat 2011; Isikdag and Zlatanova 2009). It is now possible to convert IFC models to CityGML in different levels of detail preserving most of their semantic information (El-Mekawy et al. 2012).

Hence, the IFC open-data exchange standard is not only the preferred format for representing 'as-designed' building information models, but also is gaining popularity in representing 'as-built' BIM models and in city wide applications. Hence, the prototype can be extended for the assessment of not only designed BIM models, but also for 'as-built' BIM models of existing buildings and city-based models to predict the savings in energy, CO<sub>2</sub> emissions and associated costs by the installation of RES on buildings.

### 6.3 Conclusion

The prototype was tested and validated on two applications; building level and district level assessments. In the building level assessment the prototype was assessed on its performance against existing PV simulation tools in the market as well as on its ability to extract relevant geometric required for PV simulations.

The prototype was validated against three tools; PV\*Sol, RetScreen and HOMER using a monitored case study. In Monthly generation figures RenewBIM was comparable to PV\*Sol showing an average percentage error of 10.57% and 10.6% respectively. The results of the annual generation figure output from RenewBIM was comparable to monitored data as a deviation of 0.36% was found, while RetScreen, Homer and PV\*Sol, showed 9.1%, 8.4% and 4.3% deviation respectively. Thus, RenewBIM has a sound physical basis.

In terms of processing the geometry, RenewBIM can only process 'Extruded Solids' shape representation which was found to be a limitation when applied to the monitored case study. The roof of the case study was asymmetrical hence was represented as a 'BRep'. A work around was devised so that the roof is divided into symmetrical and asymmetrical components in Revit. It was constructed such that the roof component that contains the PV modules is exported as an 'Extruded Solid' in the IFC data model. This work around worked well as the roof geometry could be processed by RenewBIM. This exercise also highlighted the various ways in which a BIM model can be constructed in Revit or other BIM authoring tools. These could get exported as elements possessing different shape representations when exported as an IFC SPF file. Extending RenewBIM's capability to process all geometric representations is therefore made top-priority for future work.

The main purpose of testing the prototype on a district level application was to show the possibility of the prototype to provide solar PV assessment for not just single designed BIM

models, but for 'as-built' BIM models and city wide models. A part of the village of Hollybush was drawn in Revit possessing different orientations and exported as an IFC SPF file. RenewBIM successfully processed the geometry of simple pitched roofs as drawn in Revit. A modified user interface for district level assessments was also proposed that would help owners of large domestic/non-domestic stock develop and meet their renewable energy targets.

In order to gauge the interest from industry in adopting RenewBIM in the building design and construction process, RenewBIM is presented to potential users and their feedback is analysed in the next chapter.

## CHAPTER 7. USABILITY TESTING

The preceding chapter gave an account of the testing and validation of RenewBIM prototype using real-life case studies. This chapter focuses on further testing of the prototype from the user's perspective. The user interaction with the prototype has also been summarised in the earlier chapter. However, to establish the effectiveness of the prototype and plan its future development, usability testing of the prototype is conducted. This chapter provides a short introduction on usability testing (section 7.1), followed by the discussion on the usability testing procedure for RenewBIM (section 7.2). This is followed by results of the testing (section 7.3) and conclusions are drawn on the usability of the RenewBIM prototype (section 7.4).

### 7.1 Introduction

Usability is a software attribute usually associated with the “ease of use and to learn” of a given interactive system (Dumas and Redish 2000). Nowadays usability evaluation is becoming an important part of software development, providing results based on quantitative and qualitative estimations. Usability testing, also referred to as user-centred evaluation is fundamental to the ‘*human-centred design*’ process. ‘*Human-centred design*’ encompasses designing a system which is useful to its target audience (ISO 2010). Usability testing has been largely recognised as “the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use”. There are different components to usability which are converted to its performance metrics or evaluation criteria such as effectiveness, efficiency and satisfaction as described in the ISO standard (ISO 2010) and others such as memorability, error tolerance and learnability.

Usability testing of prototypes has been conducted in recent research which has found it to be indispensable for gauging the prototype's acceptability by the users and future development directions in the works of Cemesova (2013b) and Struck (2012). The former conducted usability testing to validate the BIM integrated Passivhaus design analysis prototype (Cemesova 2013b). And the latter conducted usability testing of prototype that integrated uncertainty and sensitivity analysis in BPS tools to support conceptual design (Struck 2012). Usability testing was also conducted for the validation of a number of prototypes developed to support decision making and design optimisation through the integration of uncertainty and sensitivity analysis in BPS tools (Hopfe 2009; Hopfe and Hensen 2009).

The main benefit of conducted usability testing at the early design stage of a tool's lifecycle is that it is cost-effective when adopted early, and hence can be used to inform future developments of the prototype.



## 7.2 RenewBIM usability testing procedure

Usability testing procedure and tools are categorized differently by different authors. Quesenbery (2008) uses four categories: exploratory research, benchmark metrics, diagnostic evaluation and summative testing. Folmer and Bosch (2004) identify usability testing, usability inspection and usability inquiry. Holzinger (2005) differentiates inspection methods (without end-users) and test methods (with end users). Test methods are subdivided into thinking aloud, field observation and questionnaires, and inspection methods into heuristic evaluation, cognitive walkthroughs and action analysis. The use of inspection-based evaluation and user-based testing have also been confirmed as valid usability testing procedures by the ISO standard 9241-210:2010 (ISO 2010).

The aim of conducting usability testing of the RenewBIM prototype was to find out whether it can support the design team in renewable energy assessment of buildings. Hence, it is integral to involve end users at this stage to analyse to prototype's acceptability and applicability in industry practice, and gauge future directions in prototype development. Hence the approach of user-based testing has been adopted for the usability testing of the RenewBIM prototype.

User based testing is fundamental and indispensable, can be conducted at any point in the design stage and relies on the participation of potential users of the system. There are different components of a usability test which include the methods or mediums by which the usability test is conducted, prototype fidelity, performance criteria and selection of participants. The following sub-sections describe these components in further detail. This is followed by an outline of tasks which determine the RenewBIM usability testing procedure

### ***7.2.1 Methods used for usability testing***

Preston (2004) summarises a range of methods used for conducting usability testing. These include interviews/observations, focus groups, group reviews, heuristic review, prototype test, formal usability test, controlled experiment and questionnaires. In user-based testing, users can either be presented with design concepts in a visual representation (sketch or a diagram) or by means of a prototype (ISO 2010). The methods used for RenewBIM usability testing are summarised in Table 7.1 along with their description. Testing the value of a software concept on feasibility and market acceptance using a paper prototype is considered a valid exercise (Struck 2012).

**Table 7.1 Different methods used for usability testing of RenewBIM**

Methods for usability testing	Description	Application
Interviews/observations	These are one-on one session with users, asking questions like what they do, want, prefer	One to one sessions were conducted with industry experts for their feedback on opinion of the RenewBIM prototype.
Questionnaires	A formal questionnaire is an instrument for gathering information from a group of people. Advantage is that it is not influenced by the interviewer. It can be done remotely (over the internet).	This method was used in Chapter 4, section 3.4 to find out practitioners perspectives on the existing RES assessment tools and methods used in the industry. This method will also be used to conduct quantitative and qualitative analysis of the feedback of RenewBIM usability testing
Paper Prototype Test	Use of realistic scenarios but a fake product for example mock-up interfaces.	The future applications of RenewBIM prototype (mock-up interfaces) have been shown to participants using the prototype test.
Prototype Test	A step up from a paper prototype, this one uses some type of animated prototype with realistic scenarios.	The RenewBIM prototype in its current version has been shown to participants asking for their feedback through discussion and online survey.

### 7.2.2 Prototype fidelity

Since the usability testing of a working prototype is conducted for RenewBIM, it is important to describe the concept of prototype fidelity that has governed the choice of usability testing procedures. The fidelity of a prototype varies from low to high depending on the software stage of development. Only two levels of fidelity of prototypes are commonly recognized in the literature: low fidelity and high fidelity. However, the work of Engelberg and Seffah (2002) found that these two levels are loosely defined and each covers a broad range of fidelity levels. They defined an intermediate ‘mid-fidelity’ level which has properties distinct from the other two extremes. Table 7.2 summarises the characteristics of the three fidelity levels. RenewBIM, in its current version, can be defined as a ‘medium-fidelity’ prototype, as a functional user-interface has been developed with sufficient detail for a usability testing. Since a high-fidelity prototype requires higher degree of functionality and is time-consuming to develop, it would have defeated the purpose of conducting a usability testing for gauging user requirements. Mock-up interfaces for future applications and development of the RenewBIM prototype was also presented to participants as the prototype is in early design stage and would be developed according to user feedback. A mock-up can be described as a low-fidelity prototype (Cemesova 2013b).

**Table 7.2 Different levels of prototype fidelity (Engelberg and Seffah 2002)**

Fidelity	Appearance	Optimal uses	Advantages	Limitations
Low	Rough sketch; highly schematic and approximate. Little or no Interactive functionality.	Early design: conceptualizing and envisioning the application.	Low cost: useful communication vehicle; proof of concept.	Limited usefulness after requirements established; limitations in usability testing
Mid	Fairly detailed and complete but objects are presented in schematic or approximate form. Provides simulated interactive functionality and full navigation.	Designing and evaluating most interactive aspects, including navigation, functionality, content, layout and terminology.	Much lower cost and time as compared to high fidelity; detail is sufficient for usability testing; serves as a reference for the functional specification.	Does not fully communicate the look and feel of the final product; some limitations as a specification document.
High	Lifelike simulation of the final product; refined graphic design. Highly functional, but the back end might be simulated rather than real.	Marketing tool; training tool; simulation of advanced or highly interactive techniques.	High degree of functionality; fully interactive; defines look and feel of final product; serves as a living specification.	Expensive to develop; time consuming to build.

**7.2.3 Performance metrics**

Performance metrics or evaluation criteria are factors based on which the usability of a product is tested. Choosing evaluation criteria is crucial for the identification of usability problems. These include time spent to finish a task, time spent recovering from errors, number of wrong icon choices, observations of frustrations, of confusions and satisfaction(Bastien 2010). However, these performance metrics are not suitable for usability testing of low or mid fidelity prototypes. The performance metrics are instead chosen from the ISO standard definition of usability described earlier (ISO 2010) which are defined as follows;

- Effectiveness- “accuracy and completeness with which users achieve specified goals.”
- Efficiency- “resources expended in relation to the accuracy and completeness with which users achieve goals.”
- Satisfaction- “freedom from discomfort and positive attitudes towards the use of the product.”

### 7.2.4 Selection of participants

Literature gives no clear answer to the question of how many participants to involve. Holzinger (Holzinger 2005) states that inspection methods require 1-5 participants, whilst test methods require 4 to well over-30 participants. In general, five to eight participants are deemed as sufficient, with five being perceived as a general rule of thumb (Faulkner 2003; Dumas and Fox 2012; Nielsen 2012). The usability testing conducted by Cemesova (2013b) considered six participants as the testing was done to gauge the acceptance of the prototype by the user for a low-fidelity prototype. Hence six participants were considered sufficient for the usability testing of the RenewBIM prototype that had a low to mid fidelity level.

The type of participants can depend on several factors such as “competence, attitude, state and personality”(Struck 2012). Participants can also be categorised as ‘expert’ and ‘novice’(Faulkner 2003; Sauer et al. 2010). Sauer et al.(2010) concluded that when aiming at gaining an overview of usability problems, experts provide a more comprehensive list. If the aim was to identify the most severe usability problems as quickly as possible, novice users would perform better. Severe usability problems are considered problems that would prevent the completion of a specific task. It was found that experts would point to problems relating to efficiency and functionality as they were able to adopt compensating strategies by drawing on previously experienced problems. The participants chosen for RenewBIM usability testing were either expert in renewable energy assessments or in BIM/CAD tools. Most of the participants were architects who were the target audience for the RenewBIM prototype. Two participants were novice in renewable energy assessments or in BIM/CAD tools. The level of expertise in BIM and in renewable energy analysis can also be established by following the categories of participants described in the work of Hopfe et al.(2005) as “innovators”, “early adopters” and “conservatives”. Table 7.3 describes these categories in the context of users of BIM and RES analysis tools. Irrespective of the context, the six participants can be categorised as one “innovator”, three “early adopters” and two “conservatives”.

**Table 7.3 Different categories of BIM and RES simulation tools users [Adapted from (Cemesova 2013b)]**

Category	BIM/RES analysis adoption
Innovator	Develops BIM/BIM compatible tools/ RES analysis tools
Early adopter	Uses BIM/RES analysis regularly and is aware of BIM/RES simulation tools and associated standards/methods.
Conservative	Uses BIM/RES analysis tools occasionally Does not use BIM/RES analysis at all

### ***7.2.5 Overview of conducted tasks and selected test methods***

Usability testing procedure for RenewBIM was carried out using these mediums; presentation of the working prototype and mock-up interfaces of future scenarios, and questionnaire to be filled in by participants asking for their feedback. One-to-one interview sessions were also conducted with three participants (experts) to gain more insight on the future market of this tool, and what further improvements would need to be made to increase the tool's usability and acceptability in the construction industry.

Two aspects of RenewBIM tool were presented to the participants; one was the working prototype and the other mock-up interfaces showing future developments of the tool in a Microsoft Office Powerpoint presentation (Appendix H). A discussion session was held after the presentation. After the presentation, the participants were given the opportunity to complete a survey (Appendix I). The participants were also provided with a participation information sheet (Appendix J).

The survey was available online (SurveyMonkey Inc 2013) and was completed anonymously by the participants in the comfort of their own environment. This enabled participants to feel more at ease and leave unbiased remarks. This encourages feedback to be given objectively without the influence of the evaluator. The experience of the evaluator has been found to influence the survey result (Dumas and Fox 2012).

The survey type used for RenewBIM usability testing is 'user evaluation' and 'user opinion'. A user evaluation survey provides data on actual system, for example if product meets expectations. A user opinion will result in more data about the system, for example what they think of the requirements of the system. The first two of the questions asked are on the basis of user opinion. And the next six questions are asked on the basis of gauging user evaluation. Each question contained an open-ended component (comment box) to encourage more feedback from the respondents.

## **7.3 Analysis of results**

The survey results were analysed quantitatively and qualitatively. All of the respondents gave constructive and positive feedback regarding the RenewBIM's applicability in industry today and future development of the tool to increase the RenewBIM's acceptance in the industry.

When asked about the consequences of integrating CAD/BIM tools and renewable energy modelling (Figure 7.1) four of the respondents believed that it would improve design quality and enable RES evaluation in early design stages. This was the basic aim of developing the RenewBIM prototype. Three of the respondents also agreed that it would lead to a competence gain by architects today as they still rely on consultants/ engineers to conduct RES assessments. Three of them also agreed that BIM integrated RES modelling tools would encourage faster adoption of renewable energy technologies in buildings.

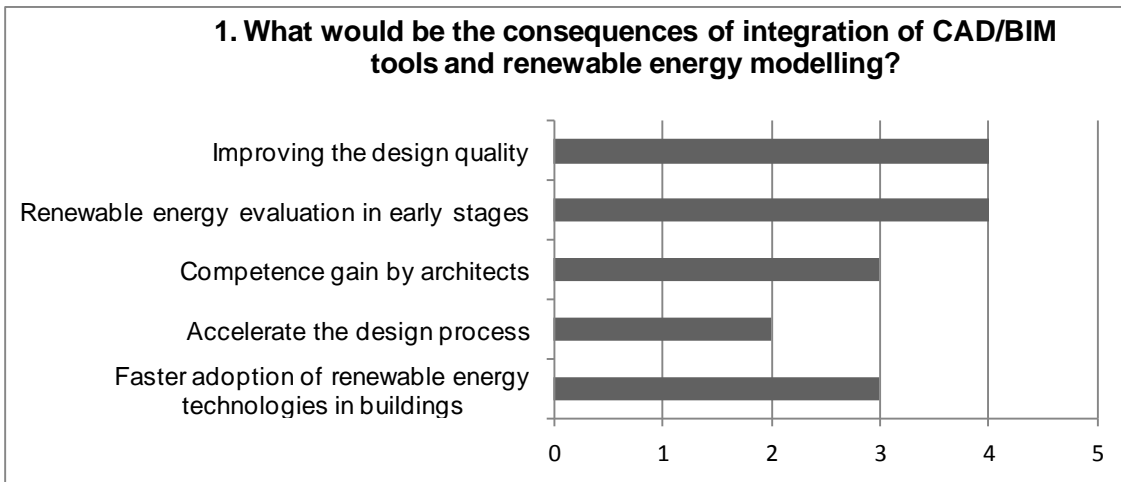


Figure 7.1 Consequences of integration of CAD/BIM tools and renewable energy modelling

The respondents were then asked about the most important criterion for adopting BIM compatible software tools (Figure 7.2). The respondent could select only one answer. Three of the respondents agreed that interoperability with various CAD tools and exchange formats was the main criterion for the adoption of BIM compatible software tools.

One respondent commented “We use mostly software from one software vendor between structural and architectural domains as they guarantee interoperability”. This suggests the use of proprietary tools in the adoption of BIM to increase collaboration between different domains in the project team.

Two of the respondents also stated conformance to regulatory requirements as an important criterion. Only one respondent selected user friendliness as an important criterion. It is important to note that the cost of the software or market standing were not selected as an important criteria, as long as the tool is interoperable with other software.

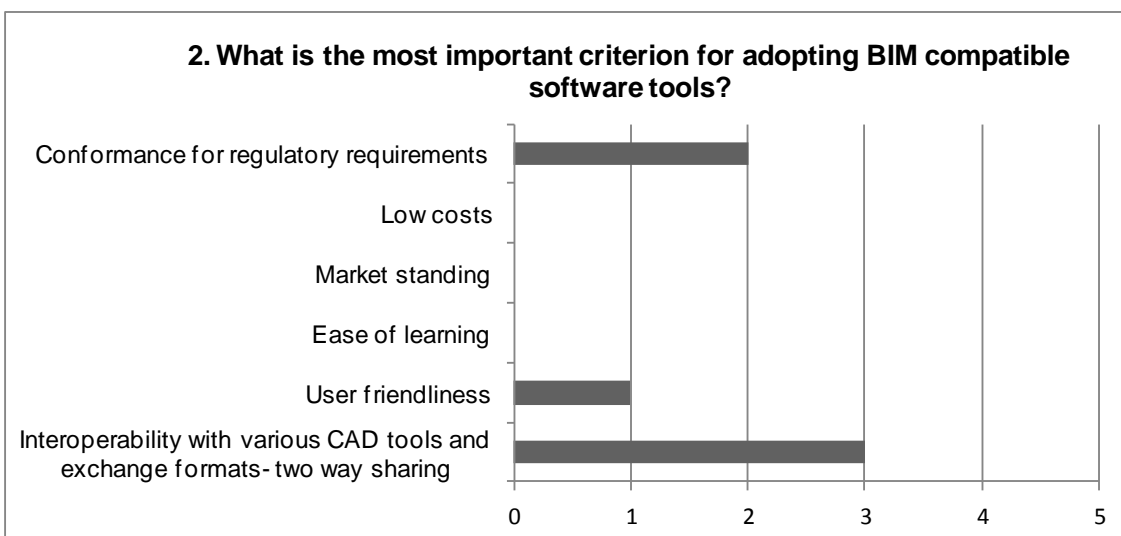
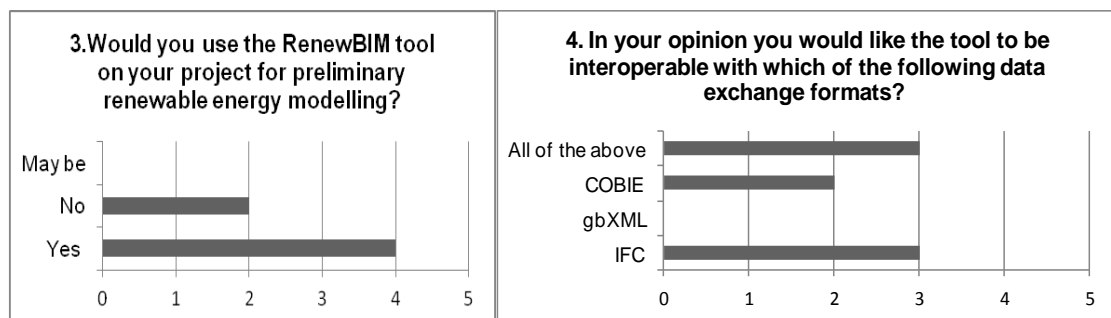


Figure 7.2 Important criteria for adopting BIM compatible software tools

The respondents were then asked questions about evaluating the tool. On asking whether they would use RenewBIM tool as presented on their projects for preliminary renewable energy modelling (Figure 7.3 left), the respondents were generally positive once the limitations of the current version and the likely developments in future versions were presented. An ‘expert’ respondent was hesitant to adopt RenewBIM as they used their own developed tools for RES assessment in practice. For another respondent, the limitation in the current version for not processing all geometric representations was a major reason for not adopting the tool. However, in future versions this limitation would be removed and RenewBIM would be able to process all geometric representations that can be instantiated by the IFC schema.

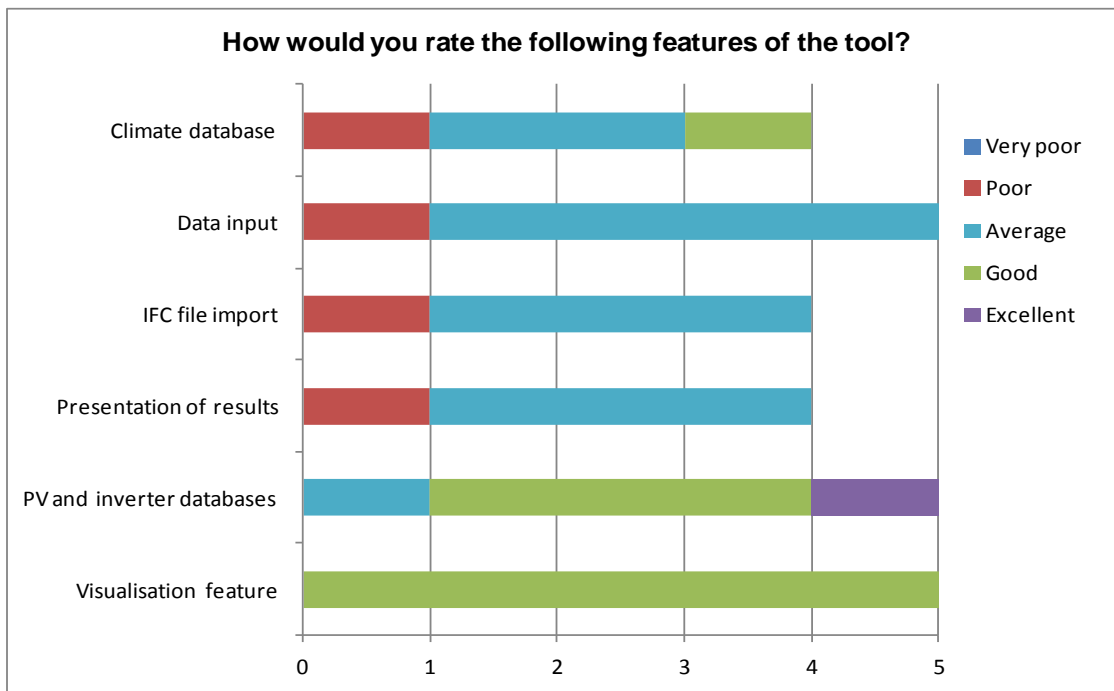


**Figure 7.3** Respondents feedback on using RenewBIM on their projects (Left) and on the data exchange formats they would want the tool to be interoperable with (Right).

This was followed by asking about their opinion on which of the data exchange formats would they want RenewBIM to be interoperable with (Figure 7.3 right). The respondents could choose more than one answer. The respondents knew the limitations of gbXML as a data exchange standard only in the energy analysis domain. They were positive about IFC as it is an international standard as three of them agreed RenewBIM should be interoperable with IFC. Two respondents suggested that interoperability with COBie was required for current adoption of RenewBIM. The results of the tool, including the energy generated by PV, choice of PV components and their location, etc. can be exported in a COBie spreadsheet. Three respondents selected that RenewBIM be interoperable with all three exchange formats for a wider industry adoption.

The respondents were also asked to rate the features of the tool on a five point Likert Scale (Allen and Seaman 2007). Around 3-4 of the respondents found the linkage of climate and PV/inverter database in the tool good or excellent. One respondent commented that;

*“The marketability of PV simulation tools currently relies on the richness of their product databases. These databases should not only be provided but should be regularly updated as new products are launched in the market. Linking to various climate data formats and especially monitored climate data is crucial for a realistic output from the tool.”*



**Figure 7.4 Rating on the various features of the tool by respondents**

The features of data input, IFC file import and presentation of the results were not given a higher rating. The reasons given were the current inability of the tool to process IFC files containing complex geometry, the tedious process of data input for technical specifications as the PV/inverter databases were not procured and linked in the current version. These limitations would be dealt with in future versions followed by another usability test in which higher ratings are anticipated.

***Overall from questions 3, 4 & 5 (Figure 7.3 and Figure 7.4) there is a certain level of satisfaction with all the features of RenewBIM tool and a positive response to its adoption by the construction industry.***

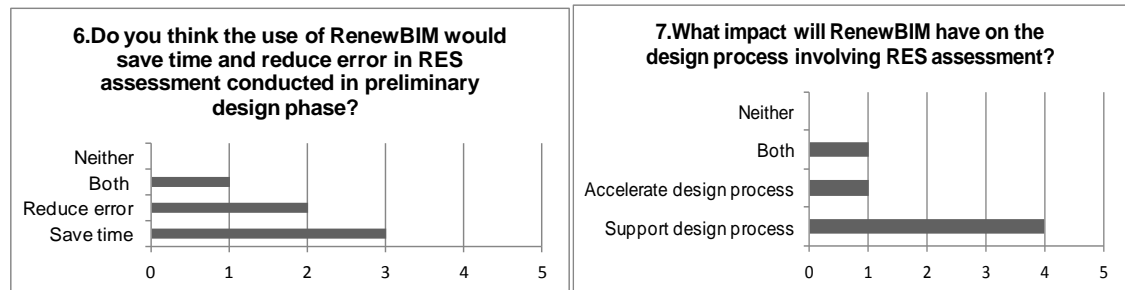
The next two questions were asked to gauge the efficiency and effectiveness of RenewBIM tool. The respondents were asked if there were any benefits in using RenewBIM in saving time or reducing error in RES assessment in the preliminary design phase (Figure 7.5 left). Three of the respondents agreed that the tool would save time in RES assessment. The respondents commented that since the tool would have linked climate and RES component databases, these data input would not have to be entered manually saving time.

*“The automation of building geometric data import will also save time since the building model would not have to redrawn in the simulation model. However this relies on a successful geometric data exchange between CAD and the simulation tool via IFC.”*

Two types of error were stated by some of the respondents; tool-based error, and user-based error. Tool-based error would be the error contained in the simulation model or geometric data import feature of the tool itself. User-based error would be the error made by the user in populating the user-interface. In its current version, around two of the respondents agree



that using RenewBIM in RES assessments would reduce user-based error as most of the user input manually entered in conventional RES analysis tools is automated. However, further testing and validation of the simulation model and geometry import via IFC would have to be conducted to obtain reliable results from the tool and reduce tool-based error.



**Figure 7.5** Feedback on the use of RenewBIM in saving time and error (Left) and feedback on the impact of RenewBIM on the design process involving RES assessment (Right)

One respondent's comment was;

*“Since the tool will be developed to cater for all renewable energy technologies apart from PV, automate data entry for building geometry and link to component databases it will surely save time. Currently, this data is procured from various sources, building drawings, manufacturer’s literature for technical specifications, etc.”*

The respondents were also asked about the impact RenewBIM will have on the design process involving RES assessment. Four of the respondents agreed that the use of the RenewBIM would definitely support design process. Only one respondent agreed that the use of the tool could accelerate the design process. The respondents stated that since the tool was not checked for IFC files containing complex geometry, issues in geometric import may arise which may lead to altering the model in CAD for a successful import in RenewBIM which will slow down the design process. A trial of the tool with various IFC files would give a more conclusive answer.

***Overall, from questions 6 and 7, it is suggested that RenewBIM can prove to be efficient tool for RES assessment in the early design stages and its use definitely supports the design process proving its effectiveness.***

The final question was an open-ended question which asked the respondents to describe what would be an ideal BIM-compatible renewable energy modelling tool. They were asked to list the features of this ideal tool. Further developments of the tool were also discussed in one-one interview sessions with two of the respondents.

The first respondent is an ‘early adopter’ in BIM and RES simulation from the architectural profession. The need for a more graphical interface which appeals to architects was highlighted in the discussion. It was suggested that even though the tool is IFC based, in order to improve efficiency, the tool needed to be developed as a plug-in or an add-on in

architectural CAD/BIM tools that would encourage making iterative changes in the design to gain maximum performance from renewables all within the same BIM software environment.

*“The ideal tool would be one through which design alternatives could be tested fairly early in design process, enabling various design iterations, digitally prototyping and optimising the design.”*

The use of key performance indicators in a radar chart (Figure 7.6) was encouraged, since it’s a graphical method to show best performing design alternatives.

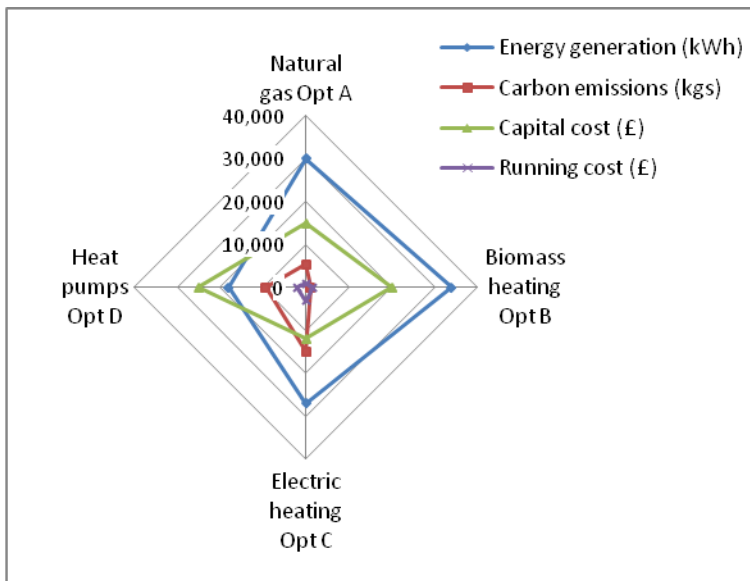


Figure 7.6 Radar chart showing performance of different heating options

The second respondent is an ‘expert’ in the BIM domain. Concerns were raised around the processing of various geometrical representations that can be instantiated using IFC schema. The expert pointed out that the external shell of the building was the only requirement for the RenewBIM tool. IFC data models can be large files with complex data within them about the building with entities ranging from a chair to a building storey or a wall cladding panel. The use of middleware software, for example BProCom server, xBIM server or openBIM server, was suggested that filter elements (for example external shell only) in the IFC data model, and provides a condensed IFC SPF file that contains only the entities required by the RenewBIM prototype. These further points towards the development of an MVD, which involves creating a subset of the IFC schema concerned with a specific exchange model.

*“The ideal tool is the one that would read and process any IFC geometry model and be able to interpret the information to carry out the analysis without having to modify the model”*

Another suggestion made was to establish a method of sharing the output of the tool with the project team. Currently, the tool does not link the results of the simulation back to the IFC file since the IFC schema does not have an energy analysis domain. The output of the tool

such as the choice of PV components and PV generation could be linked to a COBie spreadsheet. With extension to the IFC schema proposed for the energy analysis domain (Cemesova 2013b), the tool could be extended using the same energy analysis concepts of the IFC schema, and the outputs can be stored in the IFC file as well.

Another respondent was critical about the tool's output to be credible as it did not contain shading algorithms. The research in shading algorithms and its subsequent addition to the RenewBIM simulation model is now in scope of future work.

## 7.4 Conclusions

Usability testing of the RenewBIM was conducted to gauge the performance of the prototype from the user's perspective and inform future development directions. The chapter outlined a range of methods that can be used for usability testing of prototypes out of which the prototype test, paper prototype test, interviews and questionnaires were selected to test the RenewBIM tool. The prototype was presented to the respondents and their comments and feedback were recorded. An online survey was also given to respondents which included questions to deduce the user's evaluation of the RenewBIM tool and their opinion on integration of BIM and renewable energy modelling.

Majority of the respondents agreed that integrating CAD/BIM tools and renewable energy modelling would improve design quality and enable RES evaluation in early design phases. Another consequence of developing BIM-integrated RES analysis tools would be faster adoption of RES in buildings and competence gain by architects today who still rely on consultants/engineers to conduct RES assessments.

Interoperability with various CAD tools and exchange formats was agreed as the main criterion for the adoption of BIM compatible software tools by a majority of respondents.

The 'user-evaluation' based survey results were analysed on the following performance metrics, effectiveness, efficiency and satisfaction.

**Effectiveness:** The respondents found RenewBIM to be an effective RES analysis tool as it is based on a neutral IFC-exchange format that is independent of proprietary BIM authoring tools such as Revit or ArchiCAD. Respondents agreed that the tool aids in renewable energy assessment of buildings and supports the building design process. It has the potential of becoming a 'one-stop-shop' solution to meet all requirements needed to conduct RES assessment of buildings for a range of technologies apart from solar PV.

**Efficiency:** RenewBIM's capability of reducing time taken to conduct RES assessments of building in the early design phases was confirmed by the respondents. This was possible due to automation of the external data input for climate and technical specifications of RES components as well as the building geometry via the IFC data exchange format.

**Satisfaction:** Overall, the participants responded positively to RenewBIM tool and saw its potential to be accepted by the building design and construction industry. Respondents were satisfied with the provisions made to link the tool to external databases of climate and RES component (PV and inverter) specifications. Four out of six respondents indicated that they would be happy to adopt the tool in their practice.

The respondents also provided certain directions on the future development of the tool through one to one discussion sessions and open-ended questions in the survey. The future development directions included creation of a MVD for meeting exchange requirements from architectural BIM model to RES analysis. All geometric representations instantiated using the IFC schema would have to be processed by the tool to gain industry-wide acceptance. These future directions for tool development are described in detail in the final concluding chapter.

## **CHAPTER 8. CONCLUSIONS AND FUTURE WORK**

The aim of the thesis is to develop a methodology to support RES by using open-BIM data exchange standard thereby enhancing the interoperability between BIM models and RES analysis tools. This was fulfilled by achieving the objectives stated in Chapter 1, and by addressing the research questions. This chapter starts with a summary of the research steps taken to fulfil the research objectives and associated findings (section 8.1), followed by concluding remarks on the proof of the hypothesis (section 8.2), and finally ending with future work and research opportunities (section 8.3).

### **8.1 Summary**

In order to fulfil the aforementioned aim, an analysis of industry practice was conducted in Chapter 1 that provided the motivation for this thesis. It was aimed to understand current methods and tools used by the project team for RES analysis of buildings and their level of integration in the early design phase. It was found that there is a lack of tools that can be used for a complete assessment of all renewable energy technologies in terms of energy, carbon emissions and financial analysis. The current approach of RES assessment includes using a variety of tools some of which have either a statistical, steady-state or dynamic simulation logic. A variety of tools were used in the industry case studies that took a considerable amount of time of the consultants. Finding the input data sources required for the RES simulation tools to operate was a long and cumbersome process when CAD drawings of the building were not available. The time spent on these projects varied from 3-6 months respectively only for RES feasibility assessments.

Thereafter, in Chapter 2, an analysis of BIM adoption approaches worldwide was conducted in a literature review and industry case studies. It was also important to analyse the political drivers that have encouraged BIM adoption, for the practical implementation of the methodology to develop BIM-compliant software. The policy for making it mandatory to adopt BIM at a maturity level on construction projects is often met with mixed reactions and ambiguity from the industry; however, it acts as important driver to adopt BIM early on in the building design process. The BIM implementation case studies showed the inclination of the construction industry to adopt proprietary BIM software made available by a single vendor for a variety of domain specific applications. This approach poses a threat to the adoption of open-BIM standards such as the IFCs in software implementation. Adopting open-BIM data exchange standards would permit flexibility in the use of proprietary software. For true collaboration between project team members, the shift from 'Level 2' to 'Level 3' maturity seems inevitable. Software implementation based on IFCs is crucial to adopt BIM at 'Level 3' maturity.

In Chapter 3, the existing scenario of RES integration in buildings was presented through literature review, where the drivers, benefits and barriers in adoption were captured. A ‘state-of-the-art’ review of existing RES and BPS tools used for RES simulation was conducted on the basis of their interoperability with CAD/BIM model and integration in the building design process. There are political and financial drivers in place for the rapid adoption of renewables. The review revealed that there is a gap in the market for simple tools that can quantify and illustrate the influence of various solar applications. The online survey conducted revealed that although RES simulation was adopted early in the design process, the respondents were using their own developed toolkits or assessment methods. Architect’s knowledge in this domain was found insufficient and they relied upon consultants or engineers for RES performance assessments of their projects. The review of existing tools and methods concluded that there either specialised tools available that conduct assessment of a specific RES, or tools that conduct a holistic RES assessment are statistical and lacking a detailed simulation logic. Furthermore, very few tools are developed to be used in the EDP of the building design process and are far from integration with BIM processes. Lack of interoperability between RES and CAD/BIM models was deemed to be one of the factors for the low adoption of RES in the EDP, in the online survey. In order to enhance the interoperability between BIM models and RES simulation tools, the structure of the RES simulation model was synthesised. The input data requirements for RES simulation model consist of building geometry, properties, climate data, technical specifications of RES components and other parameters such as internal loads and operating schedules.

In Chapter 4, the interoperability standards used in BIM were analysed through a literature review and their implementation was shown through a case study. It was found that IFC has become the international standard for data exchange and integration in the building construction industry, and has been successfully implemented in projects worldwide. Hence the IFC was chosen as the public data exchange standard for enhancing interoperability between tools in this thesis. Existing BIM-compliant analysis tools and their development approaches based on methodologies were also analysed. It was concluded that rather than inflating the IFC schema further through analysis extensions, using the schema ‘as-is’ would be the approach that would have the best chances of industry adoption. This was approach was further reaffirmed in the HESMOS project and by LBNL.

Chapter 2-4 fulfilled the first two research objectives of analysing the ‘state-of-the-art’ literature in BIM (adoption, interoperability standards and implementation)(Chapter 2) and RES simulation tools (and methods)(Chapter 3), and successfully identified a problematic area in interoperability between architectural BIM models and RES simulation tools (Chapter 4).

In Chapter 5, a methodology was developed based on IFC to enhance the interoperability between RES tools and architectural BIM models. A conceptual framework was proposed that provides a standardised process of establishing BIM (IFC)-compliance in RES simulation models. Although IFC is the chosen schema, ‘standardising’ the framework offers greater use

in software implementations using other data exchange schemas (XML based) and simulation models. This fulfilled the third research objective of developing an open-BIM based methodology to enhance the interoperability between architectural BIM models and RES simulation tools. The methodology was implemented in a solar PV simulation model. It was found that the IFC schema was capable of representing building geometry that can serve as partial input data for solar PV simulation. Other input data such as climate and technical specifications could be sourced from external data repositories. The specification standard for climate and technical specifications data has not been developed in recent research. The entities in the IFC schema have a hierarchical sub-typing structure that allows geometric data to be extracted from the IFC data model. A prototype called RenewBIM was developed in Java as 'proof-of-concept'. This fulfilled the fourth objective of implementing the methodology by developing the RenewBIM prototype.

In Chapter 6, RenewBIM was validated using two application case studies in order to fulfil the fifth research objective. The first application was on building level assessments. Using a case study of a house with monitored PV generation data, the tool was tested and validated on two factors. The first factor was the performance of the tool against existing PV simulation tools in the market. The PV simulation model performed better against all other tools and it showed deviation of 0.36% from monitored data (annual PV generation). It was proven that the PV simulation model has a sound physical basis. The second application was on district level assessment, in which the village of Hollybush, was taken as the case study and tested in the prototype. The prototype simulated the annual PV generation of a number of roof with differing orientations. This case study was conducted to show the application of the tool to provide RES assessment for districts and potentially cities. This would prove to be useful to large public sector owners with a large domestic or non-domestic building stock.

A usability testing for RenewBIM was conducted in Chapter 7 to gauge the performance of the prototype from user's perspective and inform future directions in the tool's development in order to fulfil the sixth and final research objective. The testing was conducted using a range of methods such as prototype test, paper prototype test, interviews and questionnaires. A quantitative and qualitative analysis of the survey findings were presented in section 7.3. Majority of the respondents agreed that integrating CAD/BIM tools and renewable energy modelling would improve design quality and enable RES evaluation in early design phases. It was also agreed that the tool aids in renewable energy assessment of buildings and supports the building design process. Respondents believed that RenewBIM has the potential of becoming a 'one-stop-shop' solution to meet all requirements needed to conduct RES assessment of buildings for a range of technologies apart from solar PV.

## 8.2 Concluding remarks

The underlying hypothesis governing this research has been that existing open-BIM data exchange standards can be used *in their current state*, by virtue of a *methodology*, that *enhances interoperability* between building information models and RES systems analysis, thereby *facilitating decision-making* and encouraging early integration of renewable energy technologies in the building design process.

The following research questions were formulated to in order to prove this hypothesis.

*a) How can interoperability with BIM models support RES assessment of buildings?*

The following research methods were used to answer this research question;

- i. Analysis of interoperability standards and their implementation through literature review and case study.
- ii. Analysis of existing BIM-compliant analysis tools and their development approaches through a literature review.

Various data exchange standards used to enhance interoperability between BIM model and analysis tools were investigated and IFC was chosen as the data exchange standard for implementation in this thesis (Chapter 4; section 4.1). IFC as a data standard has been developed over the years and has become an international standard today. Various projects owners worldwide have successfully implemented IFC-based BIM on the design and construction of the projects (Chapter 4; section 4.2). On further investigation on the data structure of the IFC schema, it was realised that the schema has rich semantic content specially to represent geometry, location and orientation of buildings that serve as partial input data requirements for RES analysis tools. External data repositories were also required apart from information from the IFC data model to execute RES analysis. This fulfilled the requirements of i).

In order to use the information embedded in the IFC data model and from external data repositories to develop BIM-compliant RES analysis tools, an overarching methodology was required that links various data repositories and analysis models to the IFC data model. An analysis was conducted in existing approaches in developing IFC-compliant analysis tools which found that various domain analysis extensions to the IFC schema were proposed, as one approach (Chapter 4; section 4.5). Another approach was to leave the IFC schema 'as-is' and did not believe in extending it further for faster adoption of IFC-based interoperability. This analysis fulfilled task ii) and laid the ground for answering the next research question;

*b) How can a methodology based on public (open-BIM) data exchange standards be developed and implemented to make RES tools interoperable with BIM models?*

- i. Development of a methodology to enhance interoperability between open-BIM and RES simulation.



- ii. Implementation of this methodology on a RES simulation tool (Solar PV) by developing a prototype.
- iii. Validation of the prototype against existing RES tools to test the simulation model.
- iv. Analysis of the interoperability achieved between open-BIM and RES through the prototype.

A conceptual framework was developed as part of the methodology which showed the process and data flow and tasks required between BIM model (based on IFC), external data repositories and RES analysis tools (Chapter 5; section 5.1). The main tasks involved were LISTing the input data requirements (IDR) of the analysis model, MAPping the IDR against information contained in the IFC data model, EXTRACTing information from the IFC data model that fulfils partial IDR, EXTRACTing remaining information from external data repositories and SIMULATing to generate OUTPUT. Though IFC is chosen as the schema in this conceptual framework, the tasks are standardised to suit the needs of other schemas and analysis models. This fulfilled task i).

The conceptual framework was implemented in a solar PV simulation tool in order to test the methodology (Chapter 5; section 5.2). The tasks outlined above were carried out for the BIM model based on the IFC schema and a self-developed solar PV simulation tool (since most specialised RES simulation tools are proprietary and hence black boxes). The software implementation is called 'RenewBIM' developed in Java (Chapter 5; section 5.3). The geometric data embedded in the IFC data model was processed to fulfil IDR of the solar PV simulation model. Climate data and technical specifications repositories helped fulfil the remaining IDR. This fulfilled task ii).

The prototype was tested on two parameters (Chapter 6; section 6.1), firstly, performance of the simulation model against existing PV simulation tools; secondly, the interoperability between architectural BIM model and RES analysis. In the performance against existing tools, the prototype was comparable to PV\*Sol, but the annual PV generation result proved that the performance RenewBIM surpassed that of PV\*Sol, as the deviation from monitored data was really low. RenewBIM can currently handle geometry of 'Extruded Solids' of different slopes and orientations. RenewBIM was applied successfully for a building level RES assessment and a district level assessment (Chapter 6; section 6.2). This fulfilled tasks iii) and iv). Given that IFC-based geometric models of districts and cities would be available in near future, RenewBIM would be readily adopted by owners possessing a large building stock, to conduct RES assessment of their individual buildings or a group of buildings encompassing housing estates or business parks.

The prototype also required to be tested by users in order to gauge RenewBIM tool's acceptability by the industry in the building design process as well as formulate future directions for tool development. This led to the following final research question and research tasks;

c) *Does the developed prototype support the design team? What can be improved?*

- i. Analysis of the prototype's applicability in practice by presenting it to a target audience.
- ii. Quantitative and qualitative analysis of the responses of the target audience

The prototype was presented to a target audience and their feedback was captured through online questionnaires and one to one discussion sessions. The survey findings were then analysed quantitatively and qualitatively (Chapter 7; section 7.3). Overall, it was agreed that RenewBIM can prove to be efficient tool for RES assessment in the early design stages and its use definitely supports the building design process. Additionally the respondents were satisfied with all the features of RenewBIM tool and gave a positive response to its adoption by the construction industry. This fulfilled tasks i) and ii).

The feedback on future directions for the tool's development, have been described in detail in the following section.

As a final remark, it can be concluded that the hypothesis has been proven correct. This thesis has proposed an overarching methodology that is used to enhance the interoperability between architectural BIM model represented by IFC (open-BIM data standard) and RES simulation tools. It is important to note that the IFC data exchange has been used in its current state without proposing any extensions for RES analysis models. Instead analysis models and their associated data repositories have been linked to the data exchange schema and a prototype 'RenewBIM' has been developed to enhance solar PV simulation. However, it is envisaged for RenewBIM to not only conduct solar PV simulations, but also become a holistic tool capable of conducting energy, carbon and financial analysis of all renewable energy technologies.

### **8.3 Future Challenges**

The development of the methodology and its implementation (RenewBIM) in developing IFC-compliance in RES analysis tools have presented the following future challenges. The first two challenges overcome the RenewBIM's current limitations by extending the tool to incorporate more technologies and process all kinds of shape representations to extract geometric data from the IFC data model. The next two challenges have been formulated as the methodology was developed after an analytical review of current approaches in developing IFC-compliant analysis tools.

### ***8.3.1 Tool extension for the assessment of other renewable energy technologies***

As represented by the user interface presented to the expert panel, the tool would be extended to incorporate energy, carbon and financial assessment of three major renewable energy technologies (building integrated); solar thermal, biomass boiler, heat pumps. The solar thermal extension would be simple as the input data requirements especially geometric and climate data is similar to solar PV. For renewable heating technologies, as reviewed in Chapter 3 (section 3.4), currently WBEA tools are used to predict the performance of these technologies. Most of these tools provide energy and carbon emissions analysis only, and the project team has to rely on manual methods to conduct financial calculations. There have been interoperability issues in IFC-compliant energy analysis tools. As IFC-compliant energy analysis tools are developed further, linking these developed analysis models to RenewBIM and extending their capabilities in the financial analysis domain would be required to incorporate renewable heating technologies. The tool would have to undergo further testing and validation after this tool extension is complete using real-life case studies of building with monitored data available of renewable energy generation from various RES.

### ***8.3.2 Tool integration in existing IFC-based energy analysis tools***

When RenewBIM is extended to other renewable heating technologies it would rely on BPS tools for the building heating demand to size the RES. Hence, RES assessment tools should ideally be integrated within BPS/WBEA tools in which RES sizing is also possible. Cemesova (2013b) proposed a PassivBIM system with an energy analysis extension of the IFC schema. Even though PassivBIM was implemented for Passivhaus assessments, it is a generic system that could be applied to any energy analysis model. For RenewBIM, since the geometry extraction process from the IFC data model has closely been in accordance with the PassivBIM system, the integration of PassivBIM and RenewBIM would give the industry one holistic IFC-based BIM compatible energy analysis tool capable of sizing and assessing the performance of RES.

### ***8.3.3 Extraction of geometric data from all shape representations contained within IFC 2x3 schema.***

Currently, RenewBIM processes the geometric representation of 'Swept solids' that is 'Extruded solids'. As the IFC schema is capable of representing more complex shapes, the tool needs to be extended to enable extraction of geometric data from all shape representations especially for roofs and walls. Once this is accomplished, the tool would be able to be applied to other building integrated PV applications for example; roof tiles, shading devices, windows, etc. The tool would have to undergo further testing and validation after this tool extension is complete. This would involve a thorough usability testing by releasing an alpha

version to the market and gaining user-feedback on the user-friendliness and analysing problems encountered while processing various architectural BIM models stored as IFC files containing complex building geometry.

#### ***8.3.4 Development of a specification standard for external data repositories; climate data and technical specifications of RES components.***

As outlined in Chapter 5, synthetic climate data is available in a plethora of formats compatible with associated energy analysis applications. In recent research, a data schema has been proposed for describing climate data to be used for energy simulation. Likewise, currently the technical specifications of RES components are either sourced from manufacturer's literature or from licensed proprietary databases that hold this data in their chosen format. A similar endeavour needs to be made in developing a data schema or a specification standard for technical specifications of all RES components. This will require the collaboration of manufacturer, RES components testing labs and institutes. The thesis outline the specific data required from technical specification databases, which can be seen as a starting point to standardise the format of this data to be used by RES analysis applications.

#### ***8.3.5 Addition of shading algorithms in the simulation model***

The usability testing pointed out the need for RenewBIM to incorporate shading algorithms in its simulation logic, which is contained within tools like PVsyst, and PV\*Sol. Research has been done in the past (Quaschnig and Hanitsch 1995b, a; Quaschnig 2005; Alonso-García et al. 2006) and is continuing in order to investigate the effect of shading on the performance of solar PV systems and calculate the corresponding system losses (Dolara et al. 2013; Rodrigo et al. 2013; Tian et al. 2013). Future work would involve investigating these shading algorithms and incorporating them into the simulation model of RenewBIM to further establish its credibility.

#### ***8.3.6 Development of an MVD for architectural BIM model and RES analysis.***

The buildingSMART organisation advises the use of the MVD process in order to fulfil exchange requirements between two domains. As outlined in Chapter 4, a start has been made to develop MVD for 'architectural design' and 'energy analysis' domains. The development of an MVD, was not the focus of this thesis since the process is started with forming a working group comprising of domain experts, software engineers, etc. However, the input data requirements listed in Chapter 3 (Tables 3.8-3.11) can form the basis of the exchange requirements model that can be developed to enhance the interoperability between architectural BIM model and RES performance analysis. By establishing the input data requirements the subset of the IFC Schema has been identified in this thesis that can partially fulfil the IDR. Hence, an effort in

the development of a MVD for exchange model; 'Architectural design' to 'RES analysis' can be made aligned with existing efforts in MVD development for the energy analysis domain.

### ***8.3.7 Integration of BIM-based analysis tools in the building design process to minimise impact on the surrounding of buildings***

A rapid development of architectural building systems, BIM software, and Building integrated RES, leads to an increase in unforeseen design issues during the construction of the building. As architects design their buildings in unconventional shapes using 'state-of-the-art' facade or glazing systems, a lack of analysis tools to tackle issues such as glare effects on the surrounding can cause severe consequences (Yang et al. 2013). Examples, include the 'Walkie Talkie Tower' in London (Roger 2013), the Vdara Hotel in Las Vegas and Museum Tower in Dallas (Winston 2013). Building Integrated Photovoltaic systems can also cause glare issues (Chiabrando et al. 2009; Wybo 2013). These glare issues can be minimised by adjusting the slope and azimuth angle of PV array during the design phase (Shea 2012). The Fraunhofer Institute is currently working on analysis software that can provide a 3D visualisation of a building with PV array and predict the reflection of sunlight from PV panels for a given location and period of time (Rose 2013).

With the evolution and rapid adoption of BIM, these analysis tools would in future be required to be BIM-compatible. RenewBIM as a prototype tool does not solve all design issues but stresses the need for using analysis tools early in the building design process in order to avoid design issues surfacing during the construction or post-construction phase of the building as given in examples stated above. RenewBIM can however be extended to tackle more design issues especially pertaining to the impact caused by the installation of RES on its surroundings.

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## APPENDIX A BIM OVERLAY TO RIBA OUTLINE PLAN OF WORK

	RIBA Work Stage	Description of Key Tasks	Core BIM Activities
Preparation	A Appraisal	<p>Identification of client's needs and objectives, business case, <b>sustainability, life cycle and Facilities Management aspirations</b> and possible constraints on development.</p> <p>Preparation of feasibility studies and assessment of options to enable the client to decide whether to proceed.</p>	<ul style="list-style-type: none"> <li>Advise client on purpose of BIM including benefits and implications. Agree level and extent of BIM including 4D (time), 5D (cost) and 6D (FM) following software assessment. Advise client on Integrated Team scope of service in totality and for each designer including requirements for specialists and appointment of a BIM Model Manager.</li> <li>Define long-term responsibilities, including ownership of model.</li> <li>Define BIM Inputs and Outputs and scope of post-occupancy evaluation (Soft Landings).</li> <li>Identify scope of and commission BIM surveys and investigation reports.</li> <li>Data drop 1.</li> </ul>
	B Design Brief	<p>Development of initial statement of requirements into the Design Brief by or on behalf of the client, confirming key requirements and constraints. Identification of procurement method, <b>project sustainability and BIM</b> procedures, <b>building design lifetime and project</b> organisational structure and range of consultants and others to be engaged for the project, <b>including definition of responsibilities</b>.</p>	
Design	C Concept	<p>Implementation of Design Brief and preparation of additional data. <b>Agreement of Project Quality Plan including BIM and Change Control protocols</b>.</p> <p>Preparation of Concept Design including outline proposals for structural and <b>environmental strategies and services systems, site landscape and ecology</b>, outline specifications, preliminary <b>cost and energy plans</b>.</p> <p>Review of procurement route.</p>	<ul style="list-style-type: none"> <li>BIM pre-start meeting.</li> <li>Initial model sharing with Design Team for strategic analysis and options appraisal.</li> <li>BIM data used for environmental performance and area analysis.</li> <li>Identify key model elements (e.g. prefabricated component) and create concept level parametric objects for all major elements.</li> <li>Enable design team access to BIM data.</li> <li>Agree extent of performance specified work.</li> <li>Data drop 2.</li> </ul>
	D Design Development	<p>Development of concept design <b>using project BIM data</b> to include structural and <b>environmental strategies and services systems, site landscape and ecology</b>, updated outline specifications and <b>cost and energy plans</b>.</p> <p>Completion of Project Brief.</p> <p><i>Application for detailed planning permission.</i></p>	<ul style="list-style-type: none"> <li>Data sharing and integration for design co-ordination and detailed analysis including data links between models.</li> <li>Integration/development of generic/bespoke design components.</li> <li>BIM data used for environmental performance and area analysis.</li> <li>Data sharing for design co-ordination, technical analysis and addition of specification data.</li> <li>Export data for Planning Application.</li> <li>4D and/or 5D assessment.</li> <li>Data drop 3.</li> </ul>
	E Technical Design	<p>Preparation of technical design(s) and specifications, sufficient to co-ordinate components and elements of the project, <b>BIM data and information for statutory standards, sustainability assessment and construction safety</b>.</p>	
Pre-Construction	F Production Information	<p>F1 Preparation of production information</p> <p><b>Development of BIM data in sufficient detail to conclude co-ordination of design team inputs, to enable performance specified work to commence and enable a tender or tenders to be obtained.</b></p> <p><i>Application for statutory approvals.</i></p> <p>F2 Preparation of further information for construction required under the building contract.</p> <p><b>Development of BIM data to integrate performance specified design work into model.</b></p> <p>Review of <b>BIM</b> information provided by contractors and specialists, <b>including integration into project BIM data.</b></p>	<ul style="list-style-type: none"> <li>Export data for Building Control Analysis.</li> <li>Data sharing for conclusion of design co-ordination and detailed analysis with subcontractors.</li> <li>Detailed modelling, integration and analysis.</li> <li>Create production level parametric objects for all major elements (where appropriate and information exists this may be based on tier 2 supplier's information).</li> <li>Embed specification to model.</li> <li>Final review and sign off of model.</li> <li>Enable access to BIM model to contractor(s).</li> <li>Integration of subcontractor performance specified work model information into BIM model data.</li> <li>Review construction sequencing (4D) with contractor.</li> <li>Data drop 4.</li> </ul>
	G Tender Documentation	<p>Preparation and/or collation of tender documentation in sufficient detail to enable a tender or tenders to be obtained for the project.</p>	
	H Tender Action	<p>Identification and evaluation of potential contractors and/or specialists for the project.</p> <p>Obtaining and appraising tenders; submission of recommendations to the client.</p>	

RIBA Work Stage		Description of Key Tasks	Core BIM Activities
Construction	J	<p><b>Mobilisation</b></p> <p>Letting the building contract, appointing the contractor. Issuing of information to the contractor. Arranging site handover to the contractor.</p>	<ul style="list-style-type: none"> <li>• Agree timing and scope of 'Soft Landings'.</li> <li>• Co-ordinate and release of 'End of Construction' BIM record model data.</li> <li>• Use of 4D/5D BIM data for contract administration purposes.</li> <li>• Data drop 5.</li> </ul>
	K	<p><b>Construction to Practical Completion</b></p> <p>Administration of the building contract to Practical Completion. Provision to the contractor of further information as and when reasonably required: <b>Clarification and resolution of design queries as they arise</b>. Review of information provided by contractors and specialists. <b>Assist with preparation for commissioning, training, handover, future monitoring and maintenance.</b></p>	
Use	L	<p><b>Post Practical Completion</b></p> <p>L1 Administration of the building contract after Practical Completion and making final inspections. L2 Assisting building user during initial occupation period.</p>	<ul style="list-style-type: none"> <li>• FM BIM model data issued as asset changes are made.</li> <li>• Study of parametric object information contained within BIM model data.</li> <li>• Data drop 6.</li> </ul>
R&D	M	<p><b>Model Maintenance &amp; Development</b></p> <p>L3 Review of project performance in use <b>and comparison with BIM data</b>. <b>Analysis of BIM data for use on future projects following feedback and research.</b></p>	

## APPENDIX B POLICIES IN CLIMATE CHANGE MITIGATION

Policy/directive	Brief description	Impacts/ Current status
<b>Kyoto Summit (1997)</b>	Led to an agreement linked to the United Nations Framework Convention on Climate Change, which commits its parties by setting internationally binding emission reduction targets. EU commitment (2008-2012)- 5% reduction in GHG emissions from 1990 levels.	The Kyoto protocol was adopted for the first commitment period (2008-2012). This is now replaced by 'Doha Amendment to the Kyoto Protocol' enforced in 2012, for the commitment period (2013-2020). EU commitment (2013-2020) - 18% reduction in GHG emissions from 1990 levels.
<b>Climate change Levy (2001)</b>	A tax on commercial businesses which supply electricity, natural gas, petroleum and hydrocarbon gas in liquid state, coal and ignite, coke and semi-coke or coal or ignite and petroleum coke.	Currently in force.
<b>Ratification of the Kyoto Protocol (2002)</b>	The targets set out in the Kyoto agreement were formally agreed and made a legal requirement for 15 countries which signed within the EU including the UK. Since then a further 10 countries in the EU have made a commitment of 6-8% reduction. The UK committed to a 12.5% reduction in emissions below 1990 levels between 2008-2012.	
<b>EU Emissions Trading Scheme (ETS)(2005)</b>	The ETS is a mechanism through which energy intensive industry sectors can receive or buy emission allowances which they can trade with one another, if they exceed or fall under a 'cap' set on the amount of green house gas emissions an installation can produce. The sectors include electricity generation, iron and steel, Mineral processing, pulp/paper processing and aviation (European Commission 2013).	The ETS limits around 45% of the total EU's greenhouse gas emissions and covers more than 11,000 heavy energy-using installations in power generation and manufacturing industry in 27 EU member states.

Policy/directive	Brief description	Impacts/ Current status
<b>Climate Change Act (2008)</b>	The UK created a legally binding target to reduce greenhouse gas emissions by at least 26% below 1990 levels by 2020 and subsequently 80% by 2050. (UK Parliament 2008)	The act requires the Secretary of State to set “carbon budgets” representing UK emissions for five year periods beginning with the period 2008-2012. The carbon budgets limit our greenhouse gas emissions to: <ul style="list-style-type: none"> <li>• 3,018 million tonnes of carbon dioxide equivalent (MtCO<sub>2</sub>e) over the first carbon budget period (2008 to 2012)</li> <li>• 2,782 MtCO<sub>2</sub>e over the second carbon budget period (2013 to 2017)</li> <li>• 2,544 MtCO<sub>2</sub>e over the third carbon budget period (2018 to 2022)</li> <li>• 1,950 MtCO<sub>2</sub>e over the fourth carbon budget period (2023 to 2027) (UK Parliament 2009)</li> </ul>
<b>Carbon Emissions Reduction Target (CERT) (2008)</b>	The CERT legislation requires gas and electricity suppliers to achieve targets for a reduction in carbon emissions generated by the domestic sector. The government had set the overall carbon emissions reduction target, to be collectively achieved by suppliers between 1 April 2008 and 31 December 2012, of 293 million tonnes of CO <sub>2</sub> (lifetime).	The scheme closed on 31 <sup>st</sup> December 2012. 265 million tonnes (lifetime) CO <sub>2</sub> reductions achieved in CERT by the end of September 2012. (Ofgem 2012a). Currently, replaced by the Green Deal.
<b>Community Energy Saving Programme (CESP) (2009)</b>	CESP was developed as part of the government's Home Energy Saving Programme. It required gas and electricity suppliers and electricity generators to deliver energy saving measures to domestic consumers in specific low income areas of Great Britain. It was targeted at ‘fuel-poor’ households. The CESP target is 19.25 million tonnes (lifetime) CO <sub>2</sub> emission reduction.	The scheme closed on 31 <sup>st</sup> December 2012. 66,977 dwellings were treated with 122,337 carbon saving measures by the end of June 2012. The scheme achieved an estimate 6.1 million tonnes of CO <sub>2</sub> emissions reduction by June 2012. (Ofgem 2012b)

Policy/directive	Brief description	Impacts/ Current status
Green Deal (2013)	Green Deal is another financial mechanism that enables building owners to make energy-saving improvements without having to pay all costs upfront. They pay the costs through instalments charged in their energy bills. The improvements include; insulation (loft or cavity wall), heating, draught-proofing, double glazing, renewable energy technologies - eg solar panels or wind turbines. (DECC 2013a)	In progress.

## APPENDIX C ONLINE QUESTIONNAIRE 1

1. How often do you use BIM in construction projects?

- Often
- Sometimes
- Rarely
- Do not use it now, but will consider using it in future
- Would like to but don't know how to

2. Which level of BIM do you use on projects?

- Which level of BIM do you use on projects? Level 0- The use of 2D CAD files for production information.
- Level 1- The BIM model usually 3D models constructed using BS1192:2007 by individual disciplines but not used collaboratively between team members
- Level 2- Production of managed 3D models using BS1192:2007 by all members of the project team
- Level 3- Single integrated model to be shared by all members. Requires advance interoperability

3. How often do you use renewable energy modelling in the early design phase of your projects for earlier integration?

- Often
- Sometimes
- Rarely
- Do not use it now, but will consider using it in future
- Would like to but don't know how to

**4. How often do your projects include?**

	Often	Sometimes	Rarely	Don't use at all
Solar Photovoltaic	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Solar thermal	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Biomass heating	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Heat pumps	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Wind turbines	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

**5. What are the reasons for not adopting renewable energy modelling in early design phase of projects?**

- Perceive no need
- Do not feel motivated to use- Renewable energy modelling tools can be specialist requiring technical expertise
- Not in architect's competence domain
- Does not accelerate the design process
- Lack of interoperability-for ex. CAD import
- High costs (purchase, maintenance)

Other (please specify)

▲

▼

◀

▶

**6. At what stages of a project (RIBA plan of work) do you integrate the following renewable energy technology?**

	Solar PV	Solar thermal	Wind turbine	Biomass boiler	Heat pumps
Preparation	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Design	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Pre-construction	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Construction	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Use	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
R&D	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

**7. Which renewable energy modelling software do you currently use?**

Solar PV      Solar Thermal      Wind turbine

Software tools

PVsol  
PVsyst  
PVWatts  
Polysun  
Other

Polysun  
TRNSYS  
TSol  
Transol  
Other

Tools hosted on manufacturers website  
Other

Biomass boiler      Heat pumps      RetScreen      HOMER

Industry-rule of thumb  
Biomass sizing tool- Carbon Trust  
Biomass sizing tool- ESRU, Strathclyde  
Tools hosted on manufacturers website  
Other

Geo-Sol  
TRNSYS  
EnergyPlus  
Other

Yes  
No

Yes  
No

Other (please specify)

**8. What are the 3 factors that most influence the choice of software you use?**

- User-friendly design interface
- Cost
- 3D interface
- Quality of output (images)
- Simulation capacity
- Interoperability with other softwares
- Availability of plug- in(s)
- Other

Other (please specify)



**9. How would you evaluate the state of architects knowledge regarding renewable energy simulation tools?**

- Good
- Sufficient
- Insufficient
- Don't know

**10. In which construction phase is renewable energy simulations used in your office?**

- Preliminary/concept design
- Detailed design
- Pre-construction
- Construction
- Use

## APPENDIX D INVESTIGATION OF PROPERTY SETS TO DETERMINE SLOPE OF SLABS (IFCSLAB)

Pitch Angle for the slab (IfcSlab) was added as a property definition in IFC 2x3 (Liebich et al. 2007). The property definition was added as part of the property set PSet\_SlabCommon (Table D.1).

Table D.1 Property definition of PSet\_SlabCommon in the IFC 2x3 schema

Name	Property Type	Data Type	Definition
Reference	IfcPropertySingleValue	IfcIdentifier	Reference ID for this specified type in this project (e.g. type 'A-1')
AcousticRating	IfcPropertySingleValue	IfcLabel	Acoustic rating for this object. It is giving according to the national building code. It indicates the sound transmission resistance of this object by an indexation (instead of providing full sound absorption values)
FireRating	IfcPropertySingleValue	IfcLabel	Fire rating for this object. It is given according to the national fire safety classification.
Combustible	IfcPropertySingleValue	IfcBoolean	Indication whether the object is made from combustible material (TRUE) or not (FALSE).
SurfaceSpreadOfFlame	IfcPropertySingleValue	IfcLabel	Indication on how the flames spread around the surface, It is given according to the national building code that governs the fire behaviour for materials.
ThermalTransmittance	IfcPropertySingleValue	IfcThermalTransmittanceMeasure / THERMALTRANSMITTANCEUNIT	Thermal transmittance coefficient (U-Value) of a material. Here the total thermal transmittance coefficient through the slab (including all materials).
IsExternal	IfcPropertySingleValue	IfcBoolean	Indication whether the element is designed for use in the exterior (TRUE) or not (FALSE). If (TRUE) it is an external element and faces the outside of the building
LoadBearing	IfcPropertySingleValue	IfcBoolean	Indicates whether the object is intended to carry loads (TRUE) or not (FALSE).
Compartmentation	IfcPropertySingleValue	IfcBoolean	Indication whether the object is designed to serve as a fire compartmentation (TRUE) or not (FALSE).
PitchAngle	IfcPropertySingleValue	IfcPlaneAngleMeasure / PLANEANGLEUNIT	Angle of the slab to the horizontal when used as a component for the roof (specified as 0 degrees or not asserted for cases where the slab is not used as a roof component).

Using Revit Architecture (version 2013) , three test cases were drawn with pitched roofs of slope 30 degrees, 45 degrees, and 60 degrees and exported as IFC files (Figure D.1), in order to determine whether their property set definitions have explicit data written in IFC SPF regarding their slope.

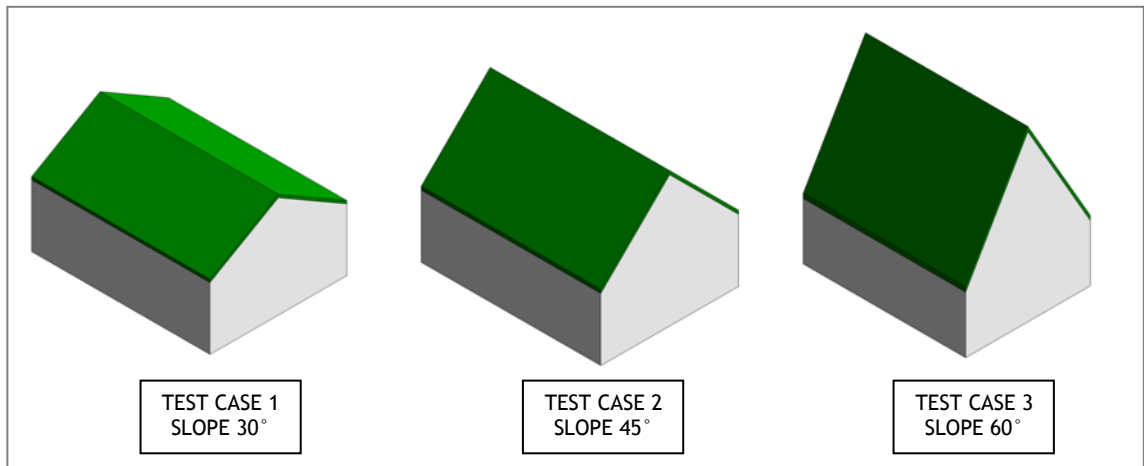


Figure D.1 Test cases for pitched roofs of slope 30°, 45° and 60° in Revit.

As mentioned earlier a pitched roof (IfcRoof) maybe composed of slabs (IfcSlab) connected through the relationship (IfcRelAggregates) .

For TEST CASE 1, The Roof and the composed slabs are denoted in Figure D.2. The IFC SPF file is analysed to find the associated property sets of IfcSlab.

```
#562= IFCROOF('2LQpsqhX99jBdLa1Yp4VLC',#52,'Basic Roof:Generic - 125mm:212434',$,'Basic Roof:Generic - 125mm',#561,$,'212434',.NOTDEFINED.);
#614= IFCRELAGGREGATES('33TYN0mgf9VQYEtFR5SLkk',#52,$,$,#562, (#591,#613));
#591= IFCSLAB('3C7Tzs00j4K0v8j5NHdgT6',#52,'Basic Roof:Generic - 125mm:212434',$,'Basic Roof:Generic - 125mm',#566,#589,'212434',.ROOF.);
#613= IFCSLAB('0D4ZU_HML7xQNxQKlgti_V',#52,'Basic Roof:Generic - 125mm:212434',$,'Basic Roof:Generic - 125mm',#592,#611,'212434',.ROOF.);
```

Figure D.2 Instance of IfcRoof and associated IfcSlabs in the IFC SPF file.

For IfcSlabs denoted by step line numbers #591 and #613 the associated property sets defined by IfcRelDefinesbyProperties shown in Figure D.3 and Figure D.4 respectively.

```
#630= IFCPROPERTYSET('0oBJQkYUj3m8nbHyDni1FR',#52,'Constraints',$, (#616,#620,#137,#144,#623));
#634= IFCPROPERTYSET('30LBmESOr8ohCnc8jqat_k',#52,'Dimensions',$, (#617,#619,#622,#624));
#638= IFCPROPERTYSET('3PlWIb1X915hfn9xZvcw3i',#52,'Construction',$, (#618,#621,#625,#626));
#642= IFCPROPERTYSET('24b2Atxaj9VfjRzALbD4os',#52,'Phasing',$, (#138));
#678= IFCPROPERTYSET('3F2r_sHMfCLfrNAisJM9m1',#52,'Pset_SlabCommon',$, (#670,#306,#677));
```

Figure D.3 Property sets for IfcSlab (#591)

```
#630=
IFCPROPERTYSET('0oBJQkYUj3m8nbHyDni1FR',#52,'Constraints',$(#616,#620,#137,#144,#623
));
#634=
IFCPROPERTYSET('30LBmESOr8ohCnc8jqat_k',#52,'Dimensions',$(#617,#619,#622,#624));
#638=
IFCPROPERTYSET('3P1wIb1X915hfn9xZvcw3i',#52,'Construction',$(#618,#621,#625,#626));
#642= IFCPROPERTYSET('24b2Atxaj9VfjRzALbD4os',#52,'Phasing',$(#138));
#678=
IFCPROPERTYSET('3F2r_sHMfCLfrNAisJM9m1',#52,'Pset_SlabCommon',$(#670,#306,#677));
```

Figure D.4 Property sets for IFC Slab (#613)

The property set 'Pset\_SlabCommon' had the following attributes as property set definitions (Figure D.5);

```
#670= IFCPROPERTY SINGLEVALUE('Reference',$,IFCIDENTIFIER('Generic - 125mm'),$);
#306= IFCPROPERTY SINGLEVALUE('IsExternal',$,IFCBOOLEAN(.T.),$);
#677= IFCPROPERTY SINGLEVALUE('LoadBearing',$,IFCBOOLEAN(.T.),$);
```

Figure D.5 Property set definitions for 'Pset\_SlabCommon' as in the IFC SPF file

For this particular IFC SPF file, the 'PitchAngle' has not been stored in the property set definition of 'Pset\_SlabCommon'. Upon further investigation it is found that the property set 'Dimension' contains a 'Slope' property (Figure D.6).

The slope property is a type of *IfcPropertySingleValue* and the data type is *IfcReal*. *IfcReal* is a defined type of simple data type REAL. The domain of *IfcReal* is all rational, irrational and scientific real numbers (Liebich et al. 2007). Here the precision is unconstrained, but in practice it is implementation specific. The data type '*IfcReal*' for the property 'Slope' is misleading as it is suggested that the data type for the slope or pitch angle should be *IfcPlaneAngleMeasure*. There is no indication of its units, due to which it is assumed that the units for this particular instance of *IfcReal* is the same as *IfcPlaneAngleMeasure* which is radians.

```
#634=
IFCPROPERTYSET('30LBmESOr8ohCnc8jqat_k',#52,'Dimensions',$(#617,#619,#622,#624));
#617= IFCPROPERTY SINGLEVALUE('Slope',$,IFCREAL(0.577350269189625),$);
#619= IFCPROPERTY SINGLEVALUE('Area',$,IFCAREAMEASURE(65190235.4749544),$);
#622=
IFCPROPERTY SINGLEVALUE('Volume',$,IFCVOLUMEMEASURE(8148779434.36931),$);
#624= IFCPROPERTY SINGLEVALUE('Thickness',$,IFCLENGTHMEASURE(125.),$);
```

Figure D.6 List of properties under the property set definition named 'Dimension'

Hence the slope of the slab is 0.577350269189625 radians which when converted to degrees is 33.07°. Hence, a 10.2% deviation is found in Test Case 1 (Slope 30°).

A similar process is repeated for all other test cases and the results of the slopes as given in the property set 'Dimension' is outlined in Table D.2.

**Table D.2 Percentage Deviation in slope data in Revit and IFC SPF files.**

TEST CASE	SLOPE	IN	SLOPE IN IFC SPF (Property set)		DEVIATION	
	REVIT				ERROR	
	degrees		radians		degrees	
TEST CASE 1	30		0.577350269189625		33.07	10.2 %
TEST CASE 2	45		0.999999999999998		57.29	27.3 %
TEST CASE 3	60		1.73205080756887		99.23	65.4 %

The results from the test cases show that the property sets containing the slope of a building element have errors when the IFC file is exported from BIM authoring tools like Revit. This error can be attributed to the export functionality in Revit. This however has not been explicitly proven by this investigation. Similar analysis in other BIM-authoring tools like ArchiCAD would have to be conducted to confirm that the errors in ‘Slope’ data are attributed to the export functionality of a particular BIM-authoring tool.

These errors in the slope data in IFC SPF stored in a building element’s property set can produce erroneous results in calculated solar radiation falling on the building surfaces. This in turn has an impact on the building heating demand and the electrical output of solar PV or solar thermal technologies. Hence, the geometric representation of a building element is analysed in order to derive the slope of that element instead of relying on the building element’s associated property sets.

## APPENDIX E      EXTRACTING GEOMETRIC DATA OF IFCROOF

In Chapter 4, a ‘Roof’ entity trace down structure was shown in Figure 4.5. The figure has been shown below for convenience (Figure E.1).

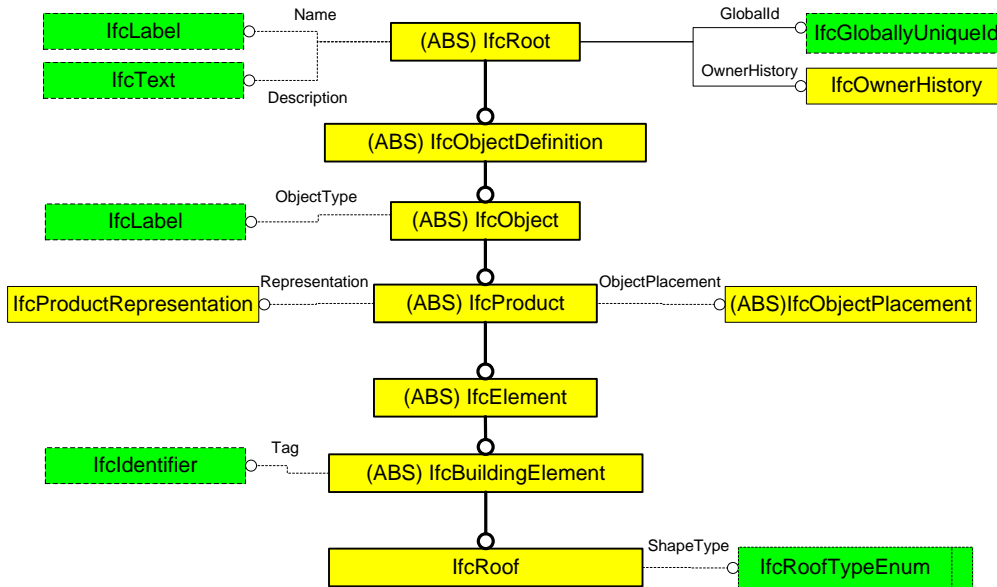


Figure E.1 An ‘IFCROOF’ entity with its attributes shown using EXPRESS-G

The attributes of ‘representation’ and ‘object placement’ provide the basis of defining the geometric description of a building element entity in the IFC schema. These attributes are inherited by the *IfcBuildingElement* entity from the *IfcProduct* entity. The representation attribute (*IfcProductRepresentation*) stores the shape representations of an object. It describes the shape of the element through its subtype entity *IfcProductDefinitionShape*. It contains many different types of shape representations though the IFC entity *IfcShapeRepresentation*. The predefined types for solid models are ‘SweptSolid’, ‘Brep’, ‘CSG’, ‘Clipping’ and ‘AdvancedSweptSolid’ (Liebich et al. 2007). RenewBlm in its current version can only process one type of shape representation extruded solids (*IfcExtrudedAreaSolid*) that come under ‘SweptSolid’.

The Object Placement (*IfcObjectPlacement*) attribute stores the placement information of an object. It could be absolute (relative to the global coordinate), relative (relative to the object placement of another product), or constrained (relative to the grid axes). The default setting for the placement of an object is relative placement, defined by *IfcLocalPlacement* with a PlacementRelTo attribute to specify the referencing spatial context. For example, a roof (*IfcProduct*) is placed relative to a building storey (*IfcBuildingStorey*); a building storey is placed relative to a building (*IfcBuilding*); a Building is placed relative to a site (*IfcSite*) and

a site is placed relative to a project (*IfcProject*). *IfcProject* is placed absolutely within the world coordinate system (WCS)(Liebich 2009).

The object placement attribute is filled by the select type ‘IfcAxisToPlacement’(See Figure 5.4) (Figure E.2)(Liebich 2009). When related to 3D objects, the ‘IfcAxis2Placement3D’ entity is selected. This entity has three attributes, ‘Location’, ‘Axis’ and ‘RefDirection’. It relates the transformation of the coordinate system from a relative placement to a point, which will be the origin of a new coordinate system. This transformation is composed of two parts: a translation and rotation. The ‘Location’ attribute is filled by the entity ‘IfcCartesianPoint’, and forms the translation part of the transformation. It describes the location of a point which is the origin to the new coordinate system. The ‘Axis’ attribute describes the direction of the z-axis of this new coordinate system, and the ‘RefDirection’ describes the direction of the x-axis of the new coordinate system. The direction of the y-axis of the new coordinate system is derived from the cross product of the ‘Axis’ and ‘RefDirection’ attributes.

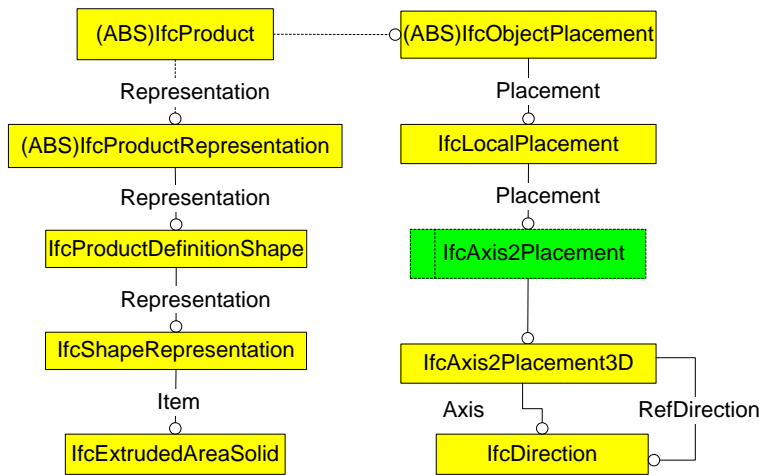


Figure E.2 EXPRESS-G for geometric representation of a product (*IfcExtrudedAreaSolid*)

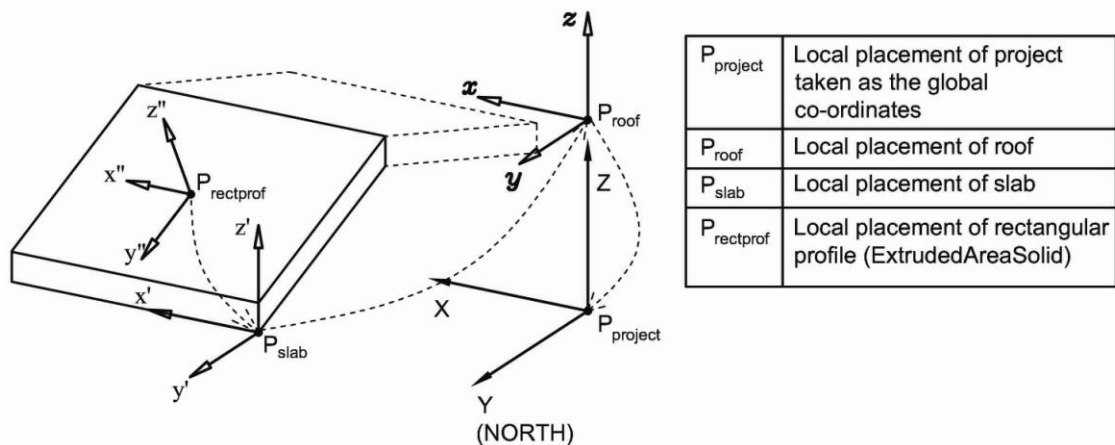


Figure E.3 Local placement of slab relative to building spatial structure

An example of the object placement of the rectangular profile slab ( $P_{\text{rectprof}}$ ) is denoted by the Cartesian point ( $P_{\text{rectprof}}$ ), Axis ( $z''$  direction vector) and RefDirection ( $x''$  direction vector); and is placed relative to object placement of slab ( $P_{\text{slab}}$ )(Figure 5.5)( Figure E.3). The  $y''$  direction vector is derived from the cross-product if  $x''$  and  $z''$  direction vectors. For the deduction of the topological relationship the local placement of an object should be transferred to the placement of the global co-ordinates (Chen et al. 2005; Cemesova 2013b). Transformation matrices have been used to transfer the local placement of an object to the placement of global co-ordinates (world co-ordinate system)(Cemesova 2013b).

### E.1 Derivation of Orientation

In Revit, the north of the project points upwards on the computer screen. Hence, if global co-ordinates are the local placement of *IfcProject*, the Y-axis of the co-ordinates would represent the NORTH direction. It is suggested that buildings that are positioned due north-south-east-west are drawn using this convention, and if the building has any other orientation, that orientation is specified as the ‘project north’ angle in Revit which is then translated to the ‘True north’ attribute of the entity *IfcSite* instantiated in the IFC data model.

A test case building of dimensions (8m (l) X 6m(w)X2.7m(h)) with a pitched roof ( $30^\circ$ ) is drawn in Revit. The local placements of the rectangular profile, slab, roof, and project are shown in Figure E.4.

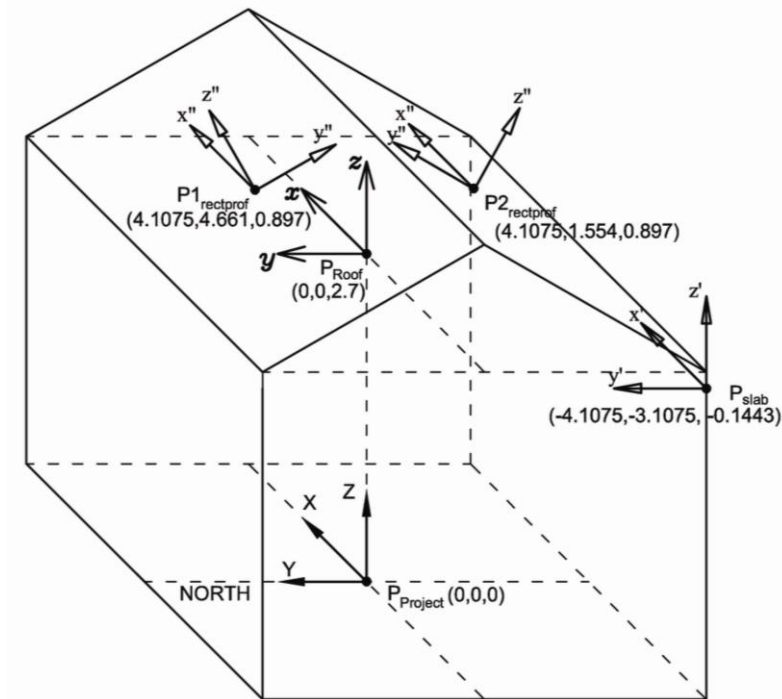


Figure E.4 Local placements of rectangular profile, slab, roof and project base point for test case



The Cartesian points, Axis (z direction vector) and RefDirection (x direction vector) attributes are summarised in Table E.1. The Y-direction vector is derived as the cross product of x and z direction vectors.

**Table E.1 Local placements of rectangular profile, slab, roof and project base point for test case**

Point/Entity	Co-ordinates	X-direction	Y-direction	Z-direction
South rectangular profile (P <sub>2rectprof</sub> )	(4.1075, 1.554, 0.897)	1, 0, 0	0, 0.866, 0.5	0, -0.5, 0.866
North rectangular profile (P <sub>1rectprof</sub> )	(4.1075,4.661,0.897)	1, 0, 0	0, 0.866, -0.5	0, 0.5, 0.866
Slab (P <sub>slab</sub> )	(-4.1075, -3.1075, -0.1443)	1, 0, 0	0, 1, 0	0, 0, 1
Roof (P <sub>roof</sub> )	(0,0,2.7)	1, 0, 0	0, 1, 0	0, 0, 1
Project base point (P <sub>project</sub> )	(0,0,0)	1, 0, 0	0, 1, 0	0, 0, 1

Following the work of Cemesova (cite), the transformation matrix for transferring the placement of a rectangular profile to the project co-ordinate system (global co-ordinates) can be given by;

$$M_{Project-rectprof} = M_{Project-roof} * M_{roof-slab} * M_{slab-rectprof} \dots\dots\dots(1)$$

Solving for Equation (1) for the test case south rectangular profile (P<sub>2rectprofile</sub>), the transformation matrix is ;

$$M_{Project-P2rectprof} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.866 & -0.5 & -0.1554 \\ 0 & 0.5 & 0.866 & 3.453 \\ 0 & 0 & 0 & 1 \end{bmatrix} \dots\dots\dots(2)$$

The transformation matrix is then multiplied by a homogenous co-ordinate (Cemesova 2013b) which is a unit vector in the Z-direction represented by (0,0,1,0) to transform P<sub>2rectprofile</sub> in the co-ordinate system of P<sub>project</sub> .

Transforming P<sub>2rectprofile</sub> in the co-ordinate system of P<sub>project</sub> using the transformation matrix (2)

The resultant matrix is,

$$M_{Project-P2rectprof} * \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ -0.5 \\ 0.866 \\ 0 \end{bmatrix} \dots\dots\dots(3)$$

The resultant matrix in (3) is denotes the direction of the new z-direction vector ( $Z_n''$ ) when transferred in the co-ordinate system of  $P_{project}$  (Figure E.5 -Left ).

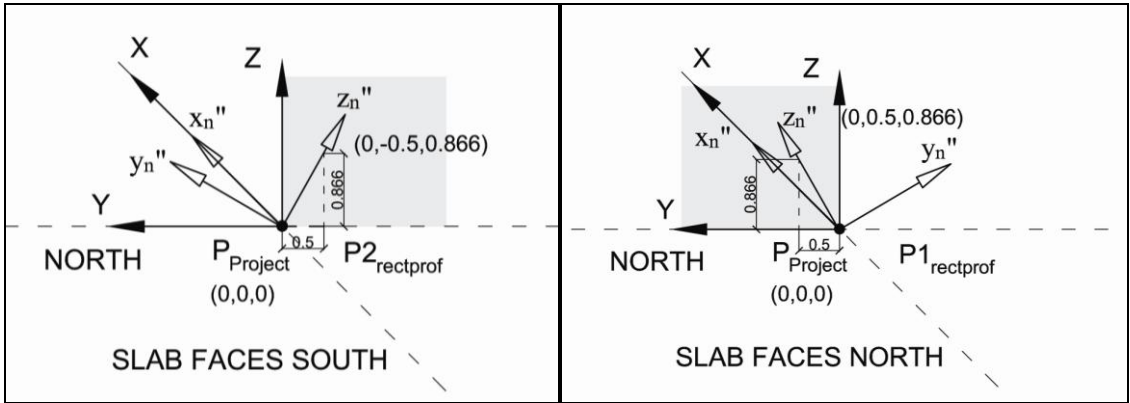


Figure E.5 Representation of the transformed local placements of south (Left) and north (right) rectangular profiles.

Similarly for the transformation matrix for transferring the placement of the north rectangular profile ( $P1_{rectprofile}$ ) to the project co-ordinate system will be;

$$M_{Project-P1rectprof} = \begin{bmatrix} 1 & 0 & 0 & 4.1075 \\ 0 & 0.866 & 0.5 & 4.661 \\ 0 & -0.5 & 0.866 & 0.897 \\ 0 & 0 & 0 & 1 \end{bmatrix} \dots\dots\dots (4)$$

Transforming  $P1_{rectprofile}$  in the co-ordinate system of  $P_{project}$  using the transformation matrix (4)

The resultant matrix is ;

$$M_{Project-P1rectprof} * \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0.5 \\ 0.866 \\ 0 \end{bmatrix} \dots\dots\dots (5)$$

This resultant matrix (5) for the north rectangular profile is represented in Figure E.5-Right.

Similarly, the resultant matrix for east and west rectangular profiles can be denoted by (6) and (7) and respectively (Figure E.6);

$$M_{Project-Eastrectprof} * \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0.5 \\ 0 \\ 0.866 \\ 0 \end{bmatrix} \dots\dots\dots (6)$$

$$M_{Project-Westrectprof} * \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} -0.5 \\ 0 \\ 0.866 \\ 0 \end{bmatrix} \dots\dots\dots (7)$$

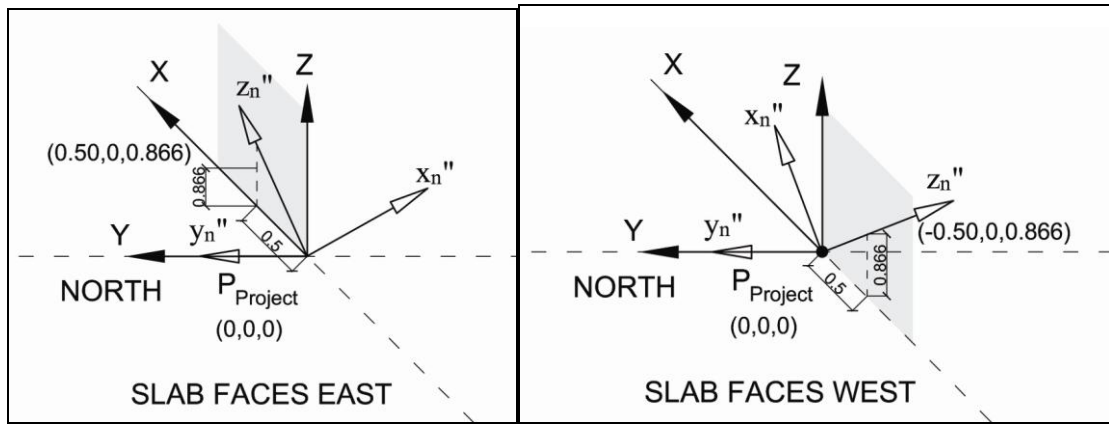


Figure E.6 Representation of the transformed local placements of east (Left) and west (right) rectangular profiles.

**E.1.1 Conventions for azimuth ( $\gamma$ ) in solar radiation calculations**

For solar radiation calculations the orientation is referred to as azimuth ( $\gamma$ ), and is denoted by conventions (Duffie and Beckman 1991)( Table E.2). All azimuth angles are measured from due south taken as  $0^\circ$  (Figure E.7).

Table E.2 Conventions for azimuth in solar radiation calculations

Orientation	Convention value
South	$0^\circ$
North	$\pm 180^\circ$ (taken as positive for due north)
East	$-90^\circ$
West	$+90^\circ$
South East	$-90^\circ < \gamma < 0^\circ$
South West	$+90^\circ > \gamma > 0^\circ$
North East	$-180^\circ < \gamma < -90^\circ$
North West	$+180^\circ < \gamma < +90^\circ$

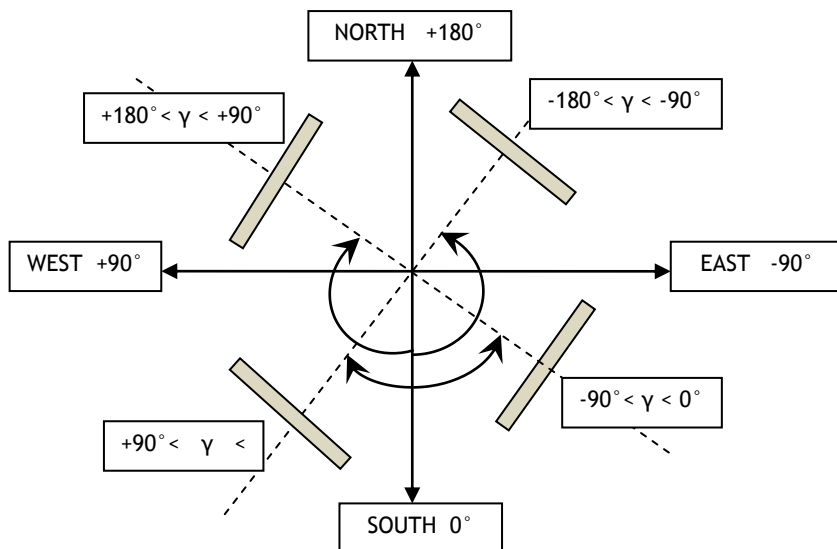


Figure E.7 Representation of azimuth angles for solar radiation calculations

### E.1.2 Conventions to derive azimuth angle from the resultant matrix

From observing the resultant matrices (3),(5),(6) and (7), for slabs facing cardinal directions; south, north, east and west respectively and assuming the matrix to be denoted as  $(x_r, y_r, z_r, 0)$ , the following rules can be made to derive the azimuth angle of slabs (Extruded solids) of a project (Table E.3). These conventions hold true assuming that the building is orthogonal. All surfaces are either horizontal or vertical to each other.

**Table E.3 Conventions to derive azimuth angle for projects for cardinal directions.**

Condition	Orientation	Azimuth angle ( $\gamma$ )	
		Radians	Degrees
If $x_r = 0$ ; $y_r < 0$	South	0	$0^\circ$
If $x_r = 0$ ; $y_r > 0$	North	$+\pi$	$+180^\circ$
If $x_r > 0$ ; $y_r = 0$	East	$-(\pi/2)$	$-90^\circ$
If $x_r < 0$ ; $y_r = 0$	West	$+(\pi/2)$	$+90^\circ$

### E.1.3 Adjustment for 'True north'

In the Revit platform, it is encouraged that the building is drawn orthogonally (the building is aligned vertically and horizontally), the way an architect would like to visualise the building plans on a sheet. The parameter of 'Project north' in Revit, points up towards the top of the screen/sheet. If the building on site is in reality orthogonal and points towards global northing, the 'project north' becomes the 'true north' of a project.

In reality, projects may or may not point be oriented true to global northing. The Y-axis of the global co-ordinates (world-co-ordinate system) may not point towards global northing. The angle made by the Y-axis and global northing is crucial to determine the 'true' orientation of surfaces for solar irradiation calculations. The 'true' orientation of the building on site is mentioned in the 'True north' attribute. The true north angle is the angle made by the Y-axis of the project co-ordinate system with the Y-axis of the global co-ordinates. The true north angle is specified in Revit as positive or negative depending on the orientation of building westwards or eastwards from Y-axis of the global co-ordinates respectively.

When exported to an IFC data model, the information of the 'True north' attribute is stored under the entity of *IfcProject* under the sub-entity *IfcGeometricRepresentationContext*. An IFC data model will always contain one instance of *IfcProject*. If the True north attribute is kept as default in Revit as  $0^\circ$ , this will mean that the project north matches true north, that is the positive Y-direction of the global co-ordinates will point toward global northing. The true north attribute is instantiated by the entity *IfcDirection*  $(x,y,z)$ .

Cemesova(2013b) pointed out issues with the IFC exportation of the 'True North' attribute from Revit Architecture. A default value of True north angle of  $0^\circ$  gets exported as

*IfcDirection* (2, 6.1230E-17, 1) approximated as (2, 0, 1) instead of (0, 1, 0). Assuming the ‘y’ and ‘z’ values as ‘x’ and ‘y’ values;

$$\text{True north angle (TNa)} = \left[ \tan^{-1} \frac{y}{z} \right] * \frac{180}{\pi} \text{ degrees} \dots\dots\dots (8)$$

Equation (8) hold true for all IFC SPF files exported by Revit Architecture software. If IFC SPF files are exported correctly by other BIM authoring tools containing the correct representation of *IfcDirection*, equation (9) should be used.

$$\text{True north angle (TNa)} = \left[ \tan^{-1} \frac{x}{y} \right] * \frac{180}{\pi} \text{ degrees} \dots\dots\dots (9)$$

When the orthogonal building model is specified with a true north angle instead of the default value of 0° in Revit and exported as an IFC SPF file, the local placement of the building elements instantiated in the IFC data model indicate the ‘true’ orientation of all elements. The orientation of the elements will now be non-cardinal. Hence the conventions developed in Table E.3 can be extended for all non-cardinal orientations, therefore adjusting for the ‘True North’ attribute.

The ‘IFC geometry extraction model’ uses the algorithms in Table E.4 when the true north angle of a project is specified in a BIM authoring tool.

It should be noted that RenewBIM (IFC Geometry extraction model) has been configured to work with orthogonal buildings only. Buildings of complex shapes cannot be yet processed by RenewBIM and will be added to future versions.

**Table E.4 Conventions to derive azimuth angle for projects for cardinal directions.**

Condition	Orientation	Azimuth angle (γ)	
If -1 < x <sub>r</sub> < 0 and 0 < y <sub>r</sub> < 1	North-West	$+\left[\frac{\pi}{2} + \tan^{-1} \left  \frac{y_r}{x_r} \right  \right]$	$+\left[\frac{\pi}{2} + \tan^{-1} \left  \frac{y_r}{x_r} \right  \right] * \frac{180}{\pi}$
If 0 < x <sub>r</sub> < 1 and 0 < y <sub>r</sub> < 1	North-East	$-\left[\frac{\pi}{2} + \tan^{-1} \left  \frac{y_r}{x_r} \right  \right]$	$-\left[\frac{\pi}{2} + \tan^{-1} \left  \frac{y_r}{x_r} \right  \right] * \frac{180}{\pi}$
If 0 < x <sub>r</sub> < 1 and -1 < y <sub>r</sub> < 0	South-East	$-\left[\frac{\pi}{2} - \tan^{-1} \left  \frac{y_r}{x_r} \right  \right]$	$-\left[\frac{\pi}{2} - \tan^{-1} \left  \frac{y_r}{x_r} \right  \right] * \frac{180}{\pi}$
If -1 < x <sub>r</sub> < 0 and -1 < y <sub>r</sub> < 0	South-West	$+\left[\frac{\pi}{2} - \tan^{-1} \left  \frac{y_r}{x_r} \right  \right]$	$+\left[\frac{\pi}{2} - \tan^{-1} \left  \frac{y_r}{x_r} \right  \right] * \frac{180}{\pi}$

## E.2 Derivation of Slope

The resultant matrix that is derived by transforming the rectangular profile local placement from the rectangular profile co-ordinate system to the project co-ordinate system also assists in deriving the slope (β) of the rectangular profile trigonometrically (Figure E.8). ‘IFC Geometry Extraction model’ uses the following algorithm to deduce the slope of a selected building element.

$$\beta \text{ (degrees)} = \tan^{-1} \left| \frac{y_z}{z_z} \right| * \frac{\pi}{180} \dots\dots\dots (10)$$

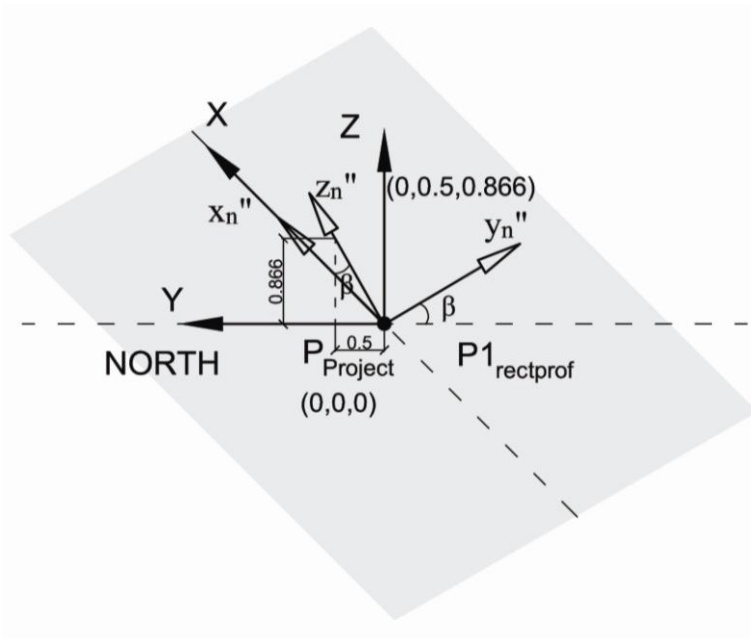


Figure E.8 Derivation of slope of rectangular profile from the resultant matrix obtained by transforming the local placement

### E.3 Derivation of Surface Area

An 'IfcSlab' can have the 'Representation' of an *IfcExtrudedAreaSolid* for standard slabs (Figure E.9) or an *IfcBooleanClippingResult* for slabs with cut edges (Liebich 2009). Currently, RenewBIM only deals with 'Extruded Area Solids' shape representation.

'Swept solids' have the following constraints;

- 1) Solid- instantiated by any one of *IfcExtrudedAreaSolid*, *IfcRevolvedAreaSolid* and *IfcSurfaceCurveSweptAreaSolid*
- 2) Profile- instantiated by any one of *IfcArbitraryClosedProfileDef*, *IfcRectangleProfileDef*, *IfcCircleProfileDef*, *IfcEllipseProfileDef*. The location of the profile like any other shape representation is defined within the context of object placement denoted by the entity *IfcAxis2Placement3D*.
- 3) Extrusion- consisting of extrusion direction and depth attributes.

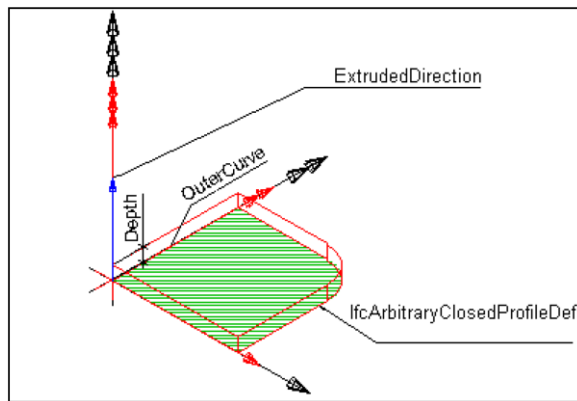


Figure E.9 Representation of a standard slab in the IFC schema (Liebich et al. 2007)

*IfcRectangleProfileDef* contains the following attributes; XDim and YDim

XDim : The extent of the rectangle in the direction of the x-axis.

YDim : The extent of the rectangle in the direction of the y-axis.

Hence the surface area of the slab can be found out by the product of the attributes of *IfcRectangleProfileDef*; XDim and YDim. The IFC geometry extraction model for RenewBIM can only handle 'Rectangular profile' definitions currently. However, the IFC geometry extraction model will be developed in future to process all shape representations of slabs. It is important to note that recent research has developed Java classes that derive the surface area of building elements from the IFC data model for thermal analysis (Cemesova 2013b) which can be incorporated in the RenewBIM prototype.

## APPENDIX F    EXTRACTING    GEOMETRIC    DATA    OF IFCWALLSTANDARDCASE

The IFC specification provides two entities for wall occurrences (Liebich et al. 2007):

*IfcWallStandardCase* used for all occurrences of walls, that have a non-changing thickness along the wall path and where the thickness parameter can be fully described by a material layer set. These walls are always represented geometrically by ‘SweptSolid’ geometry, if a 3D geometric representation is assigned.

*IfcWall* used for all other occurrences of wall, particularly for walls with changing thickness along the wall path (e.g. polygonal walls), or walls with a non-rectangular cross sections (e.g. L-shaped retaining walls), and walls having an extrusion axis that is unequal to the global Z axis of the project (i.e. non-vertical walls).

*IfcWallStandardCase* is a more useful wall representation since it consists of more parametric description and allows more intelligent data to be exchanged (Solihin 2010). Hence, only *IfcWallStandardCase* is analysed further and implemented in the prototype.

### F.1 Derivation of Orientation

The geometric representation of *IfcWallStandardCase* is simplified and restricted to ‘Swept Solids’ (and CSG) only, the attributes that would help determine its orientation are object placement and usage of the material layer set (*IfcMaterialLayerSetUsage*).

#### F.1.1 Usage of material layer set

Building elements are related to a material using the relationship *IfcRelAssociatesMaterial*. The attributes of *IfcRelAssociatesMaterial* include the inherited attribute ‘RelatedObjects’ and a direct attribute ‘RelatingMaterial’. Typical elements are walls and slabs. Materials can be arranged by layers and applied to layered elements instantiated by the following two entities;

*IfcMaterialLayerSet*, - for layered elements with an indication of the layering direction and individual layer thicknesses

*IfcMaterialLayerSetUsage*- i.e. a material layer set with positioning information along the reference axis or surface of the element.

*IfcMaterialLayerSetUsage* determines the usage of *IfcMaterialLayerSet* in terms of its location and orientation relative to the associated element geometry (Figure F.1). The attributes of *IfcMaterialLayerSetUsage* are *ForLayerSet*(*IfcMaterialLayerSet*), *LayerSetDirection* (*IfcLayerSetDirectionEnum*), *DirectionSense* (*IfcDirectionSenseEnum*) *OffsetFromReferenceLine*(*IfcLengthMeasure*) (Liebich et al. 2007). The *DirectionSense* attribute is of particular important for determining the orientation of standard walls.



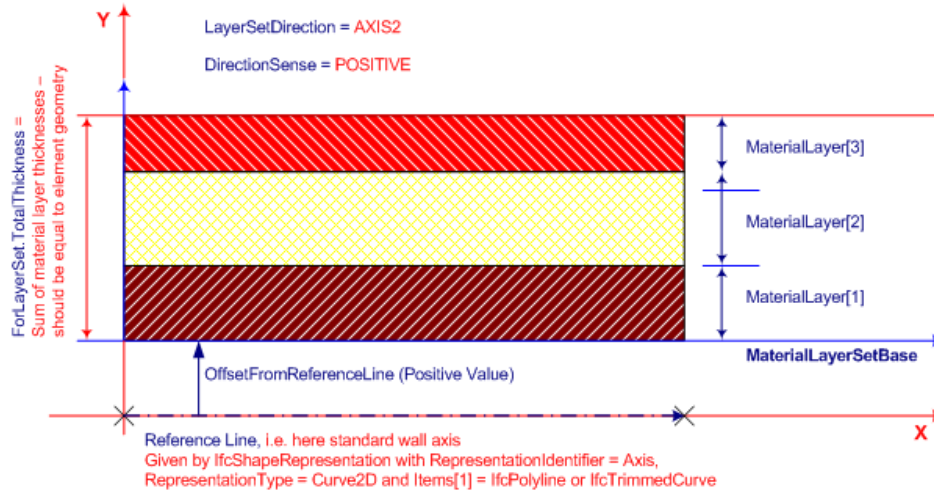


Figure F.1 Illustration of the use of *IfcMaterialLayerSetUsage* for *IfcWallStandardCase*

**F.1.2 Local placement and DirectionSense of standard walls drawn in Revit**

The local placement and direction sense of the walls can change according to the direction in which the walls have been constructed in Revit Architecture. An example of a room of dimensions 8m x 6m measures from wall centrelines, and wall thickness 0.215m is shown in Figure F.2 showing the walls drawn in different directions.

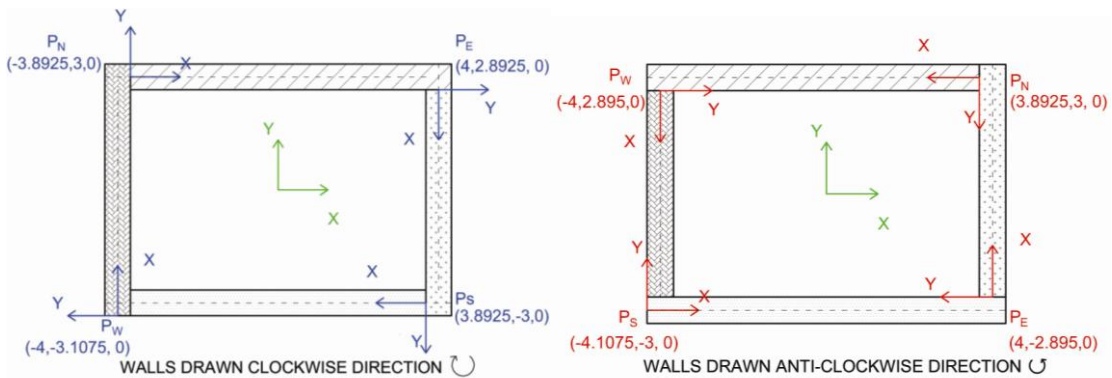


Figure F.2 Illustration of standard walls drawn clockwise and anticlockwise in Revit

Table F.1 Local placement and DirectionSense of walls in room example

WALL	CLOCKWISE		ANTICLOCKWISE	
	Local Placement	Direction Sense	Local Placement	DirectionSense
NORTH	$P_N = (-3.8925, 3, 0)$	Negative	$P_N = (3.8925, 3, 0)$	Positive
EAST	$P_E = (4, 2.8925, 0)$	Negative	$P_E = (4, -2.8925, 0)$	Positive
SOUTH	$P_S = (3.8925, -3, 0)$	Negative	$P_S = (-4.1075, -3, 0)$	Positive
WEST	$P_W = (-4, -3.1075, 0)$	Negative	$P_W = (-4, 2.8925, 0)$	Positive

The local placement and direction sense for all walls of the room example drawn clockwise and anti-clockwise are summarised in Table F.1. The direction sense of all walls drawn clockwise is negative and anticlockwise is positive. This rule only holds true if the wall

orientation in Revit is specified 'outside' and materials of the walls are specified from external to internal. This is the usual way in which the wall templates in Revit are specified and should be applied while drawing the building in a BIM authoring tool. RenewBIM assumes that all wall material layers are specified from external to internal.

The same method developed in the work of Cemesova of using transformation matrices to transform the local placement from the wall co-ordinate system to the global co-ordinates (WCS) has been applied to find out the orientation of the wall. In the case for walls however, the homogenous co-ordinate is a unit vector in the Y-direction and will depend on the wall's DirectionSense attribute. If the 'DirectionSense' of the walls material is positive, the homogenous coordinate to be used is  $(0,1,0,0)$ . If it is negative, the homogenous coordinate is  $(0,-1,0,0)$ . This is further illustrated in Figure F.3.

The orientation of the wall can be found out by the resultant matrix.

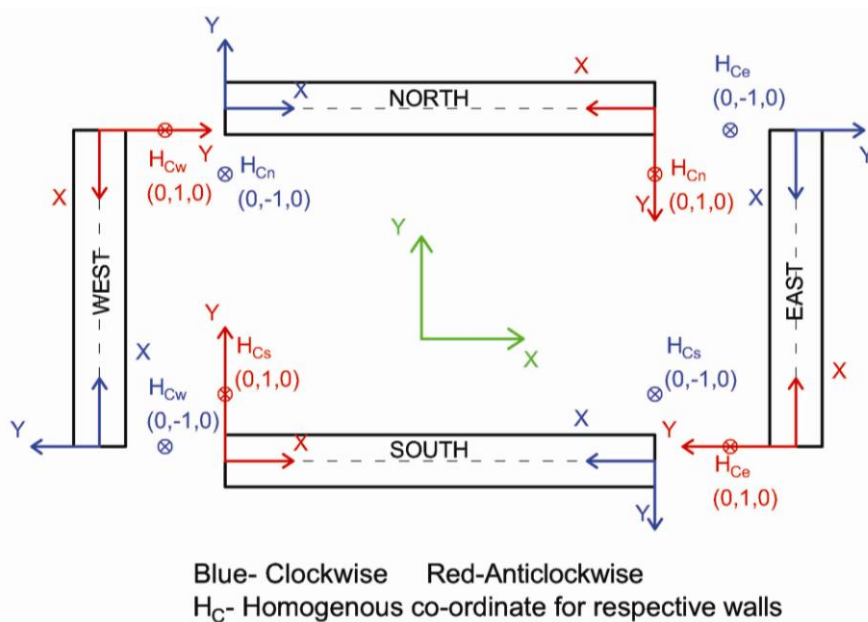


Figure F.3 Homogenous co-ordinates considered according to the local placement and direction sense attributes of standard walls.

### F.1.3 Conventions to derive azimuth angle from the resultant matrix

With the resultant matrix represented by  $(x_r, y_r, z_r, 0)$ , Cemesova (2013b) developed the following conventions (Table F.2) for cardinal orientations for orthogonally shaped buildings. The conventions are then extended to non-cardinal orientations to account for a specified True North attribute (Table F.3).

**Table F.2 Conventions for cardinal orientations for orthogonal buildings (Cemesova 2013b)**

Orientation	Convention
North	$x_r = 0$ and $y_r = -1$
South	$x_r = 0$ and $y_r = +1$
East	$x_r = -1$ and $y_r = 0$
West	$x_r = +1$ and $y_r = 0$

**Table F.3 Conventions for azimuth angles of cardinal and non-cardinal orientations for orthogonal buildings**

Condition	Orientation	Azimuth ( $\gamma$ ) Degrees
If $x_r = 0$ and $y_r = +1$	South	0
If $x_r = 0$ and $y_r = -1$	North	180
If $x_r = -1$ and $y_r = 0$	East	-90
If $x_r = +1$ and $y_r = 0$	West	+90
If $0 < x_r < 1$ and $-1 < y_r < 0$	North West	$+\left[\frac{\pi}{2} + \tan^{-1}\left \frac{y_r}{x_r}\right \right] * \frac{180}{\pi}$
If $-1 < x_r < 0$ and $-1 < y_r < 0$	North East	$-\left[\frac{\pi}{2} + \tan^{-1}\left \frac{y_r}{x_r}\right \right] * \frac{180}{\pi}$
If $-1 < x_r < 0$ and $0 < y_r < 1$	South East	$-\left[\frac{\pi}{2} - \tan^{-1}\left \frac{y_r}{x_r}\right \right] * \frac{180}{\pi}$
If $0 < x_r < 1$ and $0 < y_r < 1$	South West	$+\left[\frac{\pi}{2} - \tan^{-1}\left \frac{y_r}{x_r}\right \right] * \frac{180}{\pi}$

## F.2 Derivation of Slope

The rule for the geometric representation of *IfcWallStandardCase* is a ‘Swept Solid’ extruded vertically long the positive z-axis of the wall local placement coordinate system and WCS. Hence a default value of 90° for the slope is considered for all occurrences of *IfcWallStandardCase*.

## F.3 Derivation of Surface Area

The algorithms to extract the surface area of standard walls have been developed by Cemesova (2013b). Same algorithms have been implemented in the RenewBIM prototype.

*IfcWallStandardCase* can have the ‘Representation’ of ‘SweptSolid’ or ‘Clipping’ (Liebich 2009). Currently, RenewBIM only deals with ‘SweptSolid’ shape representation instantiated by ‘Extruded Solid’. The constraints of ‘Swept Solid’ shape representation has been previously described in section E.3. as the following;

1) Solid- instantiated by any one of *IfcExtrudedAreaSolid*, *IfcRevolvedAreaSolid* and *IfcSurfaceCurveSweptAreaSolid*

2) Profile (Swept Area)- instantiated by any one of *IfcArbitraryClosedProfileDef*, *IfcRectangleProfileDef*, *IfcCircleProfileDef*, *IfcEllipseProfileDef*. The location of the profile like any other shape representation is defined within the context of object placement denoted by the entity *IfcAxis2Placement3D*. *IfcRectangleProfileDef* contains the following attributes; XDim and YDim.

3) Extrusion- consisting of ‘Extrusion Direction and ‘Depth’ attributes. The ‘ExtrudedDirection’ for an *IfcWallStandardCase* has to be the Z-axis.

The external area of a ‘SweptSolid’ wall is calculated by multiplying the value of the ‘Depth’ and ‘XDim’ attributes (Figure F.4).

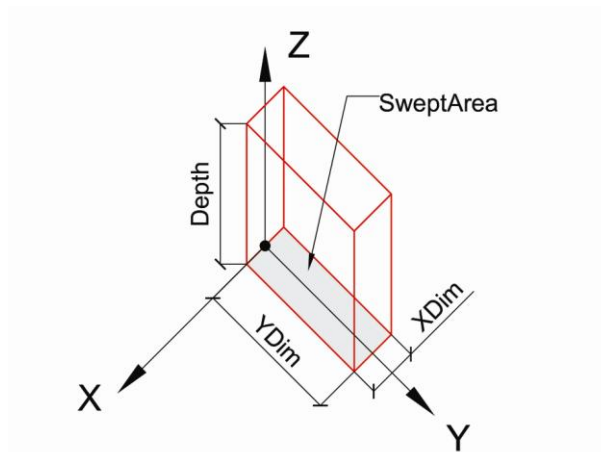
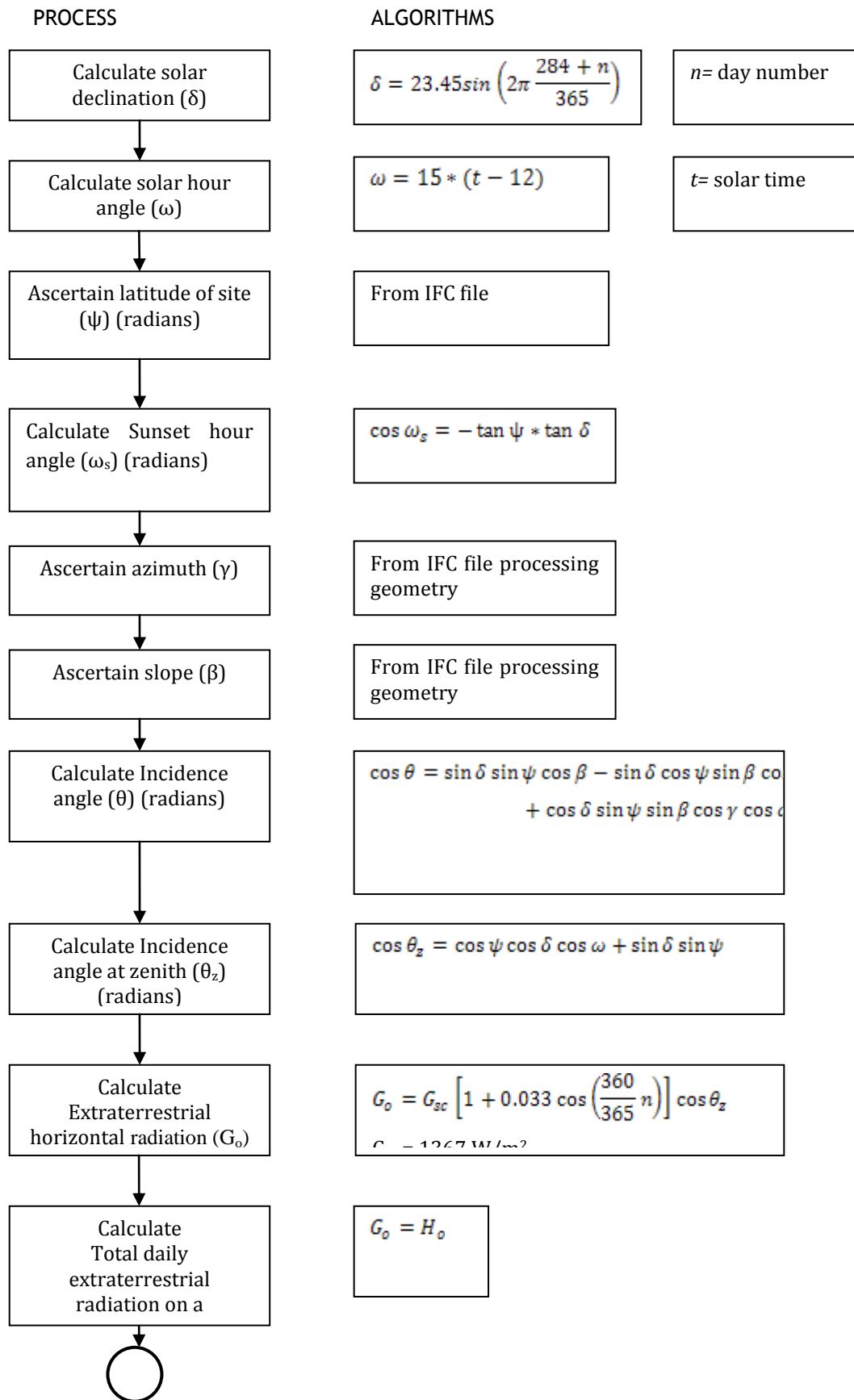
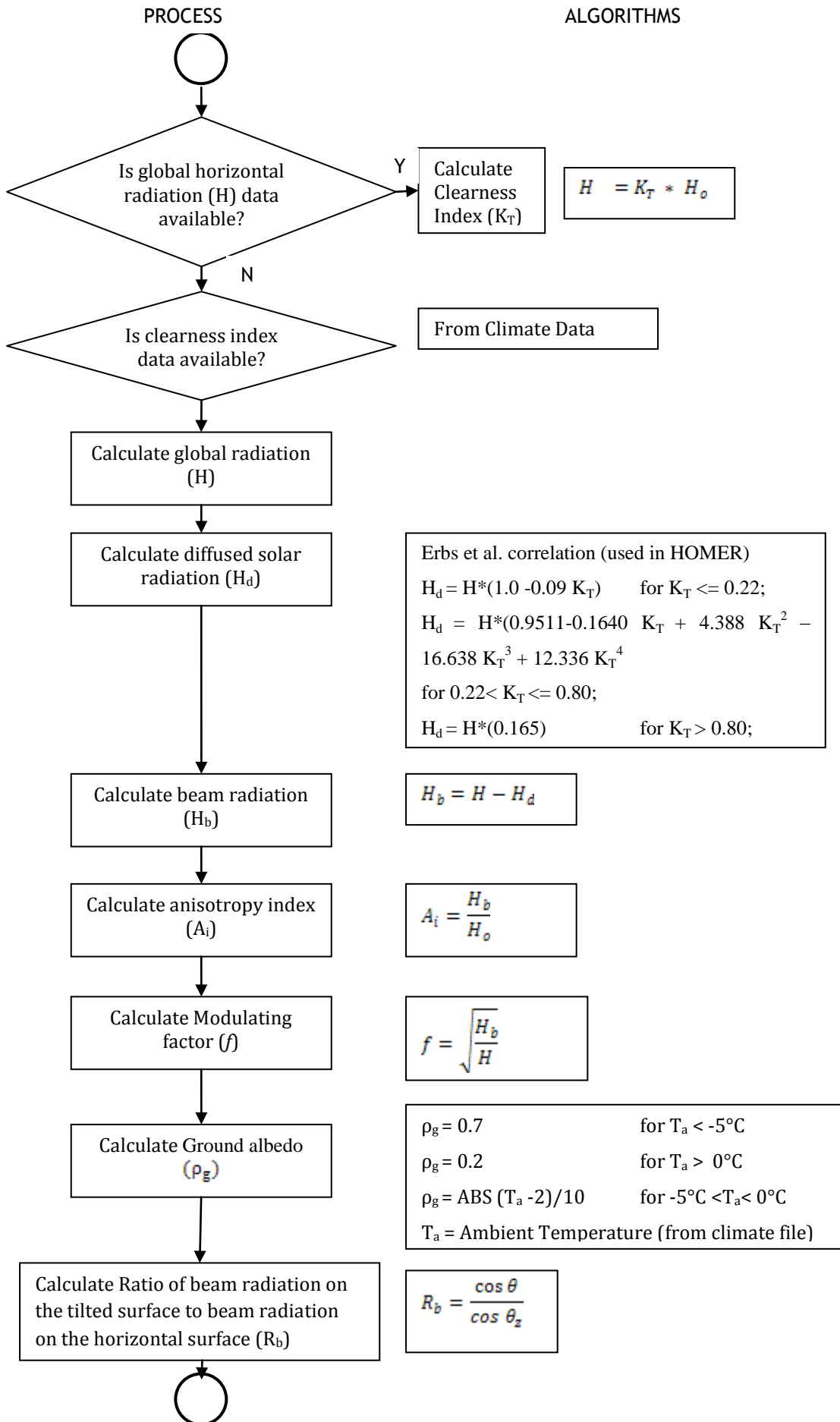
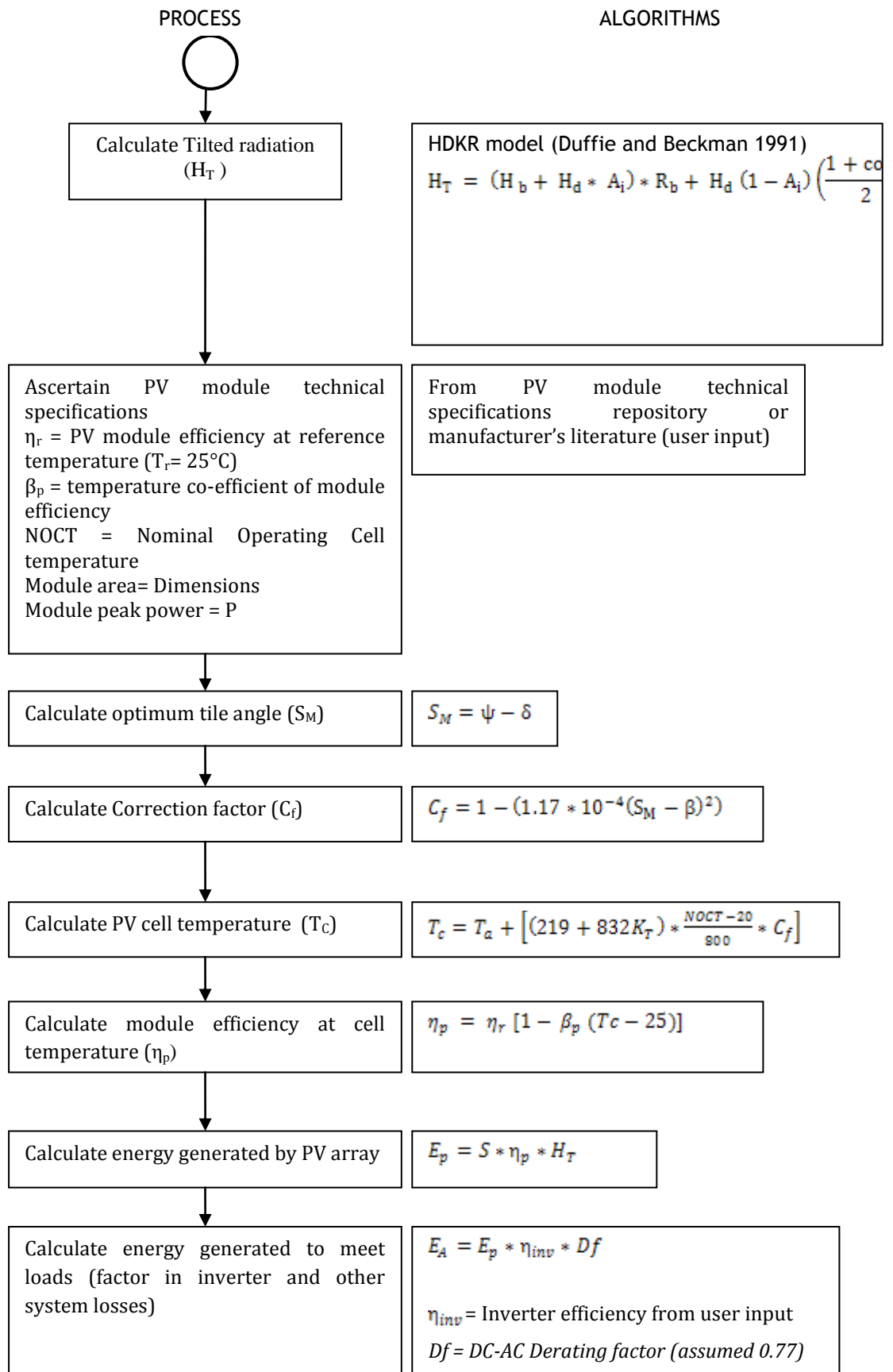


Figure F.4 Constraints of Swept Solids- *IfcExtrudedAreaSolid*

## APPENDIX G SOLAR PV SIMULATION MODEL







## APPENDIX H USABILITY TESTING PRESENTATION

### RenewBIM

IFC compliant renewable energy modeling tool



bre

Knowledge Transfer Partnerships

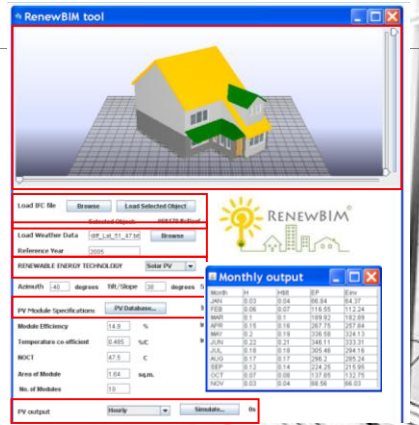
### What is RenewBIM?

- A renewable energy modeling tool
- Solar PV, Solar thermal, Biomass boilers, Heat pumps and wind turbines
- Compliant with Industry Foundation Classes
- Aid to architects for incorporating renewables in the preparation and design phases (RIBA plan of work)



### User interface- Currently

- 3D visualisation feature
- IFC-compliant
- Weather data: NASA SSE files
- Technologies: Solar PV only
- PV and inverter specifications are user inputs
- Output in hourly, daily, monthly, time periods



### User interface- What it could be ?

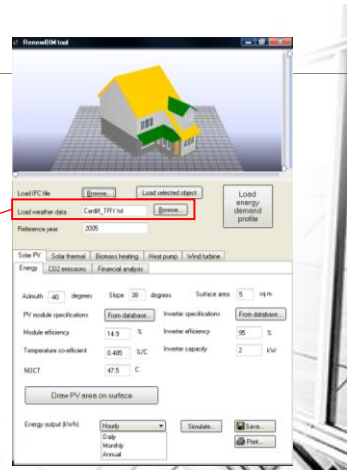
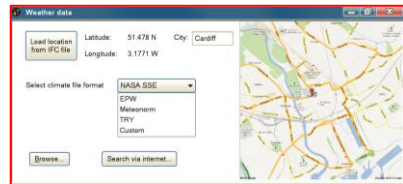
- Demand supply matching





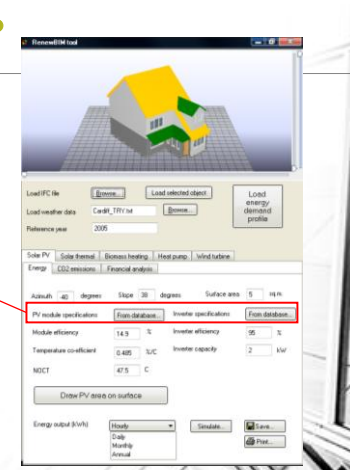
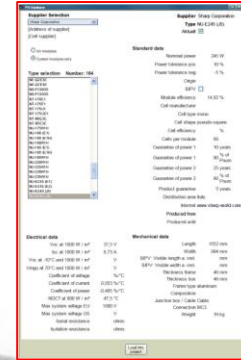
### User interface- What it could be ?

- Compatibility with various weather data formats (via internet) and monitored data



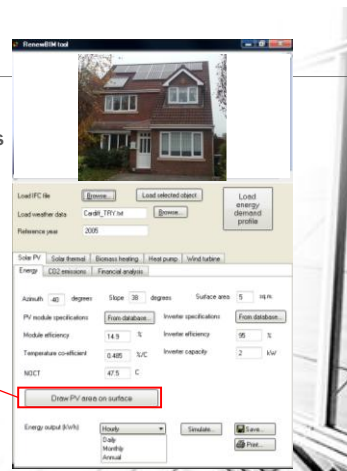
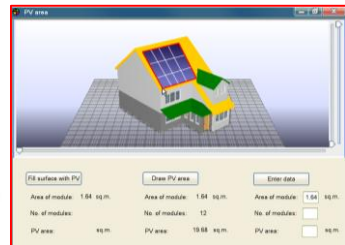
### User interface- What it could be ?

- Linked to PV module and inverter database



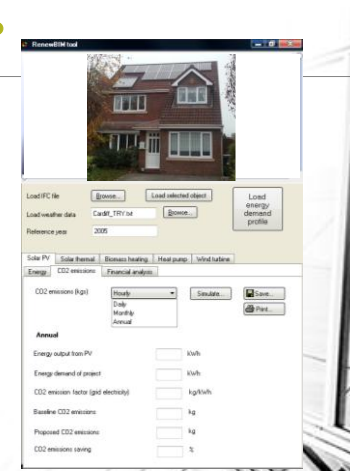
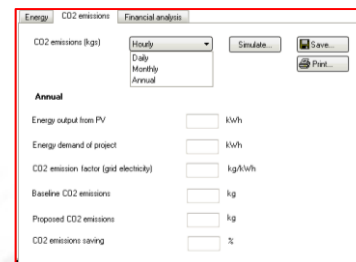
### User interface- What it could be ?

- Draw PV area on surface
- Realistic render of modules on project images



### User interface- What it could be ?

- CO<sub>2</sub> emissions analysis



## User interface- What it could be ?

- Financial analysis
- FIT, payback period, RHI

The screenshot shows a software window with several input fields and buttons. A red box highlights the 'Financial analysis' section, which includes:

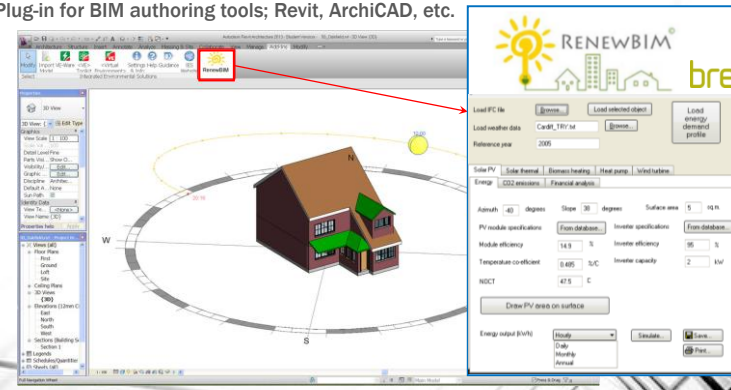
- Feed-in Tariff:** System size (kW), Rate structure (Higher rate, Medium rate, Lower rate), Energy generated by PV (kWh), Energy exported to grid (kWh), Tariff: generation (£), Tariff: export (£).
- Financial parameters:** Inflation rate (%), PV modules (£), Annual savings (£), Project Life (yr), Inverter (£), Simple payback (£), Debt ratio.
- System cost:** Total system cost (£).
- Payback period:** Annual savings (£), Simple payback (£).

Buttons for 'Save...' and 'Print...' are visible at the bottom.



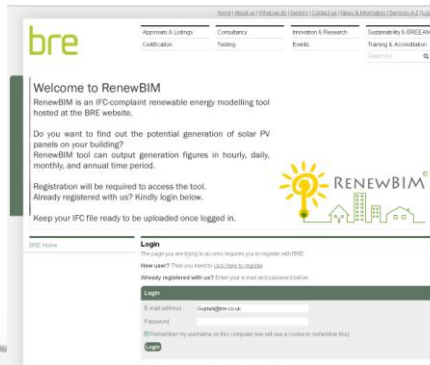
## Potential applications

- Plug-in for BIM authoring tools; Revit, ArchiCAD, etc.



## Potential applications

- Tool hosted at the BRE website to be used on a per-project basis.



## RenewBIM

IFC compliant renewable energy modeling tool

Thank you!

Any questions?

Apeksha Gupta  
Renewable energy KTP Associate  
Guptaa@bre.co.uk; Guptaa29@cardiff.ac.uk



Knowledge  
Transfer  
Partnerships

## APPENDIX I USABILITY TESTING QUESTIONNAIRE

1. What would be the consequences of integration of CAD/BIM tools and renewable energy modelling?

- Faster adoption of renewable energy technologies in buildings
- Accelerate the design process
- Competence gain by architects
- Renewable energy evaluation in early stages
- Improving the design quality

Other (please specify)

2. What is the most important criterion for purchasing BIM compatible software tools?

- Interoperability with various CAD tools and exchange formats- two way sharing
- User friendliness
- Ease of learning
- Market standing
- Low costs
- Conformance for regulatory requirements

Other please specify

3. Would you use the RenewBIM tool on your project for preliminary renewable energy modelling?

- Yes
- No
- Not sure

Comments

4. In your opinion you would like the tool to be interoperable with which of the following data exchange formats? (Please explain why in the box below)

- IFC
- gbXML
- COBIE
- All of the above

Why?

5. How would you rate the following features of the tool?

	Very poor	Poor	Good	Excellent
Visualisation feature	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Data input	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
PV and inverter databases	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Presentation of results	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
IFC file import	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Climate database	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Comments

6. Would the use of RenewBIM save time and reduce error in RES assessment conducted in preliminary design phase?

- Reduce error
- Save time
- Both
- Neither

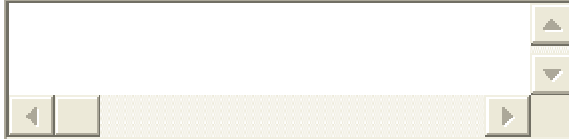
7. What impact will RenewBIM have on the design process involving RES assessment?

- Accelerate the design process
- Support the design process

Neither

Both

**8. In your opinion, what would be the ideal BIM-compatible renewable energy modelling tool?  
Please add 'must-have' features of the tool in the box below.**



## **APPENDIX J PARTICIPATION INFORMATION SHEET FOR USABILITY TESTING**

### **Participant Information Sheet**

#### *Study Title: Presentation and online survey of 'RenewBIM' prototype*

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You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask me if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

#### *What is the purpose of the study?*

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There are still issues with interoperability between Building Information Modelling (BIM) authoring tools and renewable energy modelling. The renewable energy in the market today are not BIM-complaint leading to a decrease in adoption of these technologies in the building sector. A prototype 'RenewBIM' has been developed which facilitates the transfer of data from BIM tools to solar PV simulation model via the IFC exchange format. The solar PV simulation model has been created with algorithms used by existing tools in the market. A through literature review has been done in this.

The aim of this study is to establish the usability of the prototype RenewBIM tool. The study will be done in two parts; a 10-15 mins presentation followed by a 5-10 minute discussion, and an online survey that should take no longer than 15 mins.

#### *Why have I been chosen?*

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The study is aimed at leading architects, engineers/energy consultants and BIM experts. The aim is to have between 4-8 participants in total.

#### *Do I have to take part?*

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Your participation is completely voluntary. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. You are also free to withdraw from participating at any time and without giving a reason.

#### *What will happen to me if I take part?*

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You will be only participating in the presentation feedback and online survey after which you will not be contacted. Your contact details will not be taken or stored.

Participant Information Sheet      Version 1      19/2/2013

### *What about confidentiality?*

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The feedback will be stored and analysed in Ms Office software with no data linking it back to you.

### *What do I have to do?*

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A presentation on the RenewBIM user interface and its features will be made, after which you will be asked to fill an online survey and give feedback. Discussions during the presentation will be manually recorded (not video recorded) by taking notes and will be used in the thesis chapter.

### *Are there any risks?*

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There are no risks.

### *What will happen to the results of the research study?*

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RenewBIM tool is a prototype/prrof of concept developed as a part of the PhD. The feedback from presentations and online surveys will be published as a thesis chapter. You will be able to access the results by downloading a copy of the thesis from Cardiff University. The results will go through quantitative analysis and will be presented as graphs. Your name will not be included in the Thesis.

### *Who is organising and funding the research?*

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The research is organised by a Ph.D student Apeksha Gupta, and forms a part of the KTP project between BRE Wales and Cardiff University.

### *Contact for Further Information*

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For further information, please contact Apeksha Gupta at: [Guptaa29@cardiff.ac.uk](mailto:Guptaa29@cardiff.ac.uk).

Participant Information Sheet      Version 1      19/2/2013

## **CURRICULUM VITAE**

Apeksha Gupta was born on 22<sup>nd</sup> October 1984 in Mumbai, India. She studied architecture and urban design from Kamla Raheja Vidyanidhi Institute for Architecture (KRVA) in Mumbai, India.

After gaining work experience in India as an architect she pursued an MSc in Sustainable Building Technology at University of Nottingham, UK. She also won a scholarship from the University of Nottingham to complete her Master's degree. After graduating, she got an opportunity to work as a Knowledge Transfer Partnership (KTP) Associate for Building Research Establishment (BRE) Wales and South West in 2010 and simultaneously pursue a PhD degree with the BRE Institute of Sustainable Engineering at Cardiff University.

She has excelled both academically and professionally, her latest achievement being the winner of the 'Duke of Gloucester Young Achiever Award' for the field of architecture (2013).