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Retrospective use of building information modelling for information management of existing buildings

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Retrospective use of Building Information Modelling for Information Management of Existing Buildings

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List of Abbreviations and Acronyms

3D – 3 Dimensional
AEC - Architecture, Engineering and Construction
AUDE - Association of University Directors of Estate
BEP – BIM Execution Plan
BIM – Building Information Modelling
CAD – Computer Aided Design
CDE – Common Data Environment
CIBSE - Chartered Institution of Building Services Engineers
CIC – Construction Industry Council
CO_2 - Carbon Dioxide
COBie - Construction Operations Building Information Exchange
EA – Energy Analysis
GBS – Green Building Studio
gbXML – Green Building Extensible Markup Language
GE – George Eliot Building
Gov – UK Government
GSC - General Space Check
HC – Heating and Cooling
IES – Integrated Environment Solutions
IES VE – Integrated Environment Solutions Virtual Environment
IFC – Industry foundation Class
ISO – International Standards Organisation
MEP - Mechanical, Electrical, and Plumbing
PAS - Publicly Available Specification
PIP – Project Implementation Plan
RESSEEPE - *REtrofitting Solutions and Services for the enhancement of Energy Efficiency in Public Edification*
RICS - Royal Institution of Chartered Surveyors

Glossary of Terms

BIM – Building Information Modelling (BIM) can be described as a combination of technology, people, process and policy, which enables all of the design details, decisions and characteristics to be held within a collaborative data package

BEP – A BEP is a BIM specific project-planning document, which encompasses a number of critical planning criteria when embarking on a BIM project.

CDE – The CDE is a means of providing a collaborative environment for sharing work and can be implemented in a number of ways. The CDE is described in detail within the PAS 1192/2.

Data Sustainability - Refers to the accessibility and accuracy of building data across the life span of an asset or information directory.

gbXML - The Green Building XML schema, was developed to facilitate the transfer of CAD building information models between design models, a variety of engineering analysis tools, and other types of models.

IFC - Industry Foundation Classes (IFC) are the open and neutral data format for OpenBIM.

Interoperability – Relates to systems, especially of computers or telecommunications, that are capable of working together without being specially configured to do so.

OpenBIM - Open BIM is a collaborative approach to the design and management of buildings based on open data standards and workflows. It prescribes that data should be interoperable.

PIP – The Project Implementation Plan is a project plan utilised to configure how a project is implemented. In regards to BIM it particularly focuses on the resource adequacies and readiness of a team or company prior to taking on a BIM project.

Abstract

The Association of University Directors of Estate (AUDE) identified a number of key challenges in the management of large portfolio of existing buildings dating back to the 1960s, these challenges includes poor performance of out-dated building components, a lack of flexible functionality to spaces and a complete lack of accurate and reliable data necessary for efficient building management. These challenges are findings of AUDE commissioned and published paper entitled "The Legacy of 1960's University Buildings". The paper highlights that much of the building stock held by Universities is progressively becoming out of date and unfit for purpose. The report considers "how to renew (refurbish/replace) a very large proportion of the property portfolio that was built in the 1960's."

Building Information Modelling (BIM) is a technology that can improve the way in which building data is created, collated and utilised to improve how buildings are designed and managed from cradle to grave. A critical review of the literature was carried out investigating the role of Building Information Modelling in Construction Management.

A case study approach has been used to investigate the various aspects of information collection and modelling. The George Eliot building, part of Coventry University Estate has been identified and selected as the main case study. A number of experimental processes and techniques were tested using experimental data collection focusing on key themes of relevance to BIM: 3D BIM modelling, Data interoperability, Data Sustainability and Model Validation.

The result of the study recognised an existing problem in information management regarding a lack of accurate building data. The study establishes critical components to consider within the adoption of BIM practices to improve information management such as the need for robust model validation. Additionally the research highlights a number of existing issues within the interoperability of information management tools, which should be considered when adopting BIM. The improvement in interoperability is intrinsically intertwined with good BIM practice. The processes experimented within the research demonstrate the potential that BIM can have to improve information management. The findings of the investigation consequentially informed into the creation of informed process maps designed to facilitate information management within organisations with large built assets portfolio.

Acknowledgements

1. Chapter 1: Introduction to Research

1.1. Introduction to the Topic Area

The knowledge of Building Information Modelling (BIM) within the construction industry is on the rise, the recent NBS National BIM Report 2013 (NBS 2013) states that only '6% of the industry were neither aware nor using BIM' in 2012, compare this to previous years of 21% and 43% in 2011 and 2010 respectively it is clear that the awareness of BIM amongst construction professionals is rising. This statistics have improved in the NBS National BIM Report 2016 with 54% aware and currently using BIM, 42% only aware and down to only 4% neither aware nor using BIM (NBS 2016).

However following on from this, in the same NBS BIM Report 2013, the statistic that '74% of the industry is not clear enough on what BIM is yet' (NBS 2013) did indicate that in 2013 the industry was not completely past the 'What' stage for all construction professionals. However again these figures can be countered through the NBS National BIM Report 2016 with statistic recording that 73% of participants agreed, "BIM is the future of project information" (NBS 2016). Knowledge of BIM is rising but gaps are still present such as with the retrospective application of the techniques to existing buildings. In the context of construction Building Information Modelling (BIM) can be best described as a combination of technology, people, process and policy, which enables all of the design details, decisions and characteristics to be held within a collaborative data package. All of the design and project information can then be shared, accessed and altered live, facilitating an efficient and fluid collaborative design and management process across the whole life of a building. A significant observation is that 'Information' aspect of BIM is just as important as any design model. Working within a BIM environment, adopting BIM information sharing protocols, collating the data in an interoperable format, and utilising standards such as PAS1192 (BSI 2013) aims to improve how information is shared amongst all varying parties involved in an efficient interoperable manner.

A core feature of working within a BIM environment is the drive towards encouraging multi-disciplinary collaboration from the very outset of a project. A major issue that is experienced within non BIM design processes is the matter of conflicting design issues; the ethos of having a core central BIM model is to facilitate a smoother transition through these issues by identifying conflicts earlier on in the project stages thus reducing the negative effects on schedule and costs (Mustafa et al, 2014). From an early stage projects can be visualised and interrogated using BIM and simulation software allowing the client and designer alike to gain an appreciation of how the design is going to materialise, this allows for important design decisions and alterations to be made at an early stage where the cost repercussions are reduced. The efficiency of the effects of changes within documentation or design is greatly improved, as any changes made which are linked to the main BIM model will be carried through automatically.
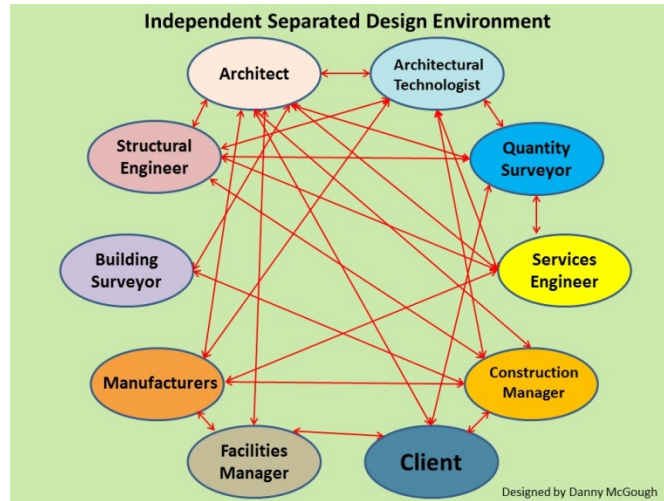
Figure 1 - Traditional Collaboration Diagram

Figure 1 represents graphical representation expresses the chaos when all parties are working independently outside of a core integrated project environment. Having the design process completed within a BIM environment with federated models at the centre of the project can lead to multiple benefits post model creation. The models can be analysed allowing for a multitude of model interrogations and analysis to take place. It is argued that by using BIM processes for building projects it will improve the energy efficiency, improve the scheduling, and facilitate a reduction of waste and possibly paramount to this, a reduction in costs (Clifford 2013).

Figure 2 shows a 'BIM Collaborative Design Environment' showing how a BIM federated model and CDE can assist the project team to deliver a fluid fully collaborative project.
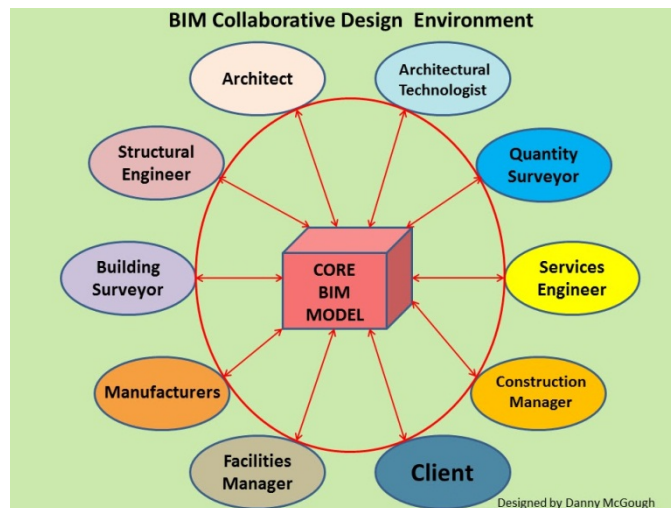
Figure 2 - BIM Workflow Collaboration Diagram

In summary, through carrying out all of this pre-construction design analysis and interrogation it is argued the result will be a reduction waste in terms of time, cost, process and material. At the same time the stringent energy analysis that can take place in the early stages of a BIM project aims to improve the performance of a project in regards to low impact design. And finally post project completion the BIM model can continue to be utilised by the FM team to assist in the management of their assets in an environmentally conscious manner.

1.2. Research Questions

Research questions developed from the research objectives, which will be critically evaluated and answered as part of this research.

a. What is the effect of BIM processes and technology on the data management of existing buildings?

b. What are the challenges of retrospective application of BIM for information management of existing buildings?

1.3. Aim

The aim of this research is to investigate the use of Building Information Modelling processes and techniques for information management of existing buildings.

1.4. Objectives

The objectives of the study are such:
- Objective 1: Carry out a literature review on the role of Building Information Modelling in information management;
- Objective 2: Develop Building Information Model of selected case study building;
- Objective 3: Evaluate experimental processes to investigate and test the application of BIM to existing buildings
- Objective 4: Establish the critical paths when adopting Building Information Modelling tools for information management;
- Objective 5: Develop process maps to summarise the findings of the research in adopting Building Information Modelling processes for information management;

1.5. Breakdown Discussion on Aim and Objectives

1.5.1. Aim

The aim of this research is to investigate the use of Building Information Modelling (BIM) to optimise the information management of existing buildings.

A significant focus was the use of BIM software, techniques and processes to assist the information management of existing buildings. As stated by Attia et al (2012) building design companies and industry as a whole will be galvanised by mandatory codes and standards which aim the drive towards neutral or zero energy buildings. Establishing the best design option for either new build or refurbishment and combining all of the various design options is a difficult task. This research focuses on existing and developing processes within BIM, by critically evaluating their adoption to improve the data management of buildings. The UK government realised this potential and mandated the use of BIM for public sector projects from 2016 for new builds however this work argues that the benefits are transferable to existing building information management.

This research will explore the application of Building Information Modelling within the context information management providing awareness and guidance for the adoption of Building Information Modelling tools.

1.5.2. Objectives

Objective 1: Carry out a literature review on the role of Building Information Modelling in information management

A comprehensive literature review was carried out evaluating the role of BIM software, techniques, processes and protocols in construction has been evaluated. This objective investigates the current position of industry in regards to the use of BIM within new builds and existing built asset management. This objective was fulfilled within the literature review chapter 2, section 2.2.

Objective 2: Objective 2: Develop Building Information Model of selected case study building:

This objective investigates the use of BIM for existing buildings. A case study building from Coventry University estate was used as the focus of a study to carry out the implementation and evaluation of BIM techniques, simulations and measurements. A full BIM model of the building was created using BIM and 3D modelling techniques, with a critical analysis of the processes involved in achieving this.

Objective 3: Evaluate experimental processes to investigate and test the application of BIM to existing buildings:

A number of experimental processes were investigated including model validation, data exchange and preparation for model analysis. A significant aspect was to investigate the interoperability and collaboration of the processes adopted. This objective has primarily been fulfilled within chapter 3 Data collection and Analysis.

Objective 4: Establish the critical paths when adopting Building Information Modelling tools for information management:

This objective evaluates and establishes the critical paths for adopting the techniques and processes investigated. This objective draws together the previous evaluations and investigations with the aim of contextualising the evidence. A significant output of the objective was to establish good practice in the use of BIM tools and identify key lessons learnt through the use of a robust case study experimentation approach. This objective has been fulfilled throughout the thesis with particular relevance within chapter 3 where the data was collected and analysed and further in chapter 4 where the wider context of the processes were discussed in the context of the project as a whole.

Objective 5: Objective 4: Develop process maps to summarise the findings of the research in adopting Building Information Modelling processes for information management:

This objective is to develop a critical methodology for the adoption of BIM processes and techniques. The thesis has used a phasing of experimental and case study approaches to establish recommendations on BIM adoption for information management. Selections of process maps have also been created, which will provide an accessible platform to assist and inform future users in the adoption of BIM techniques and processes.

1.6. Methodology

1.6.1. Methodological Description

The grounding of this work has been underpinned through the understanding of its paradigm context. Possible alignments of the work can be seen in the pragmatic paradigm. As defined by Cresswell (2003), Pragmatist researchers will focus on the what and the how, not necessarily devoted to any specific system, which would support the problem centred, practical, real world focus of this thesis. As stated by Mackenzie et al (2006) within pragmatism, "The research question is 'central', data collection and analysis methods are chosen as those most likely to provide insights into the question". However this work fits more firmly in the interpretivist paradigm as the case study, qualitative, experimental and descriptive approach in which the observations, testing and experiments have been centred around naturally fit with the interpretivist philosophy, such as the description by Cohen et al (1994) attempting to understand "the world of human experience". The breakdown of the specific approaches mentioned above will be discussed in greater detail later within this section. The role of the interpretivist paradigm tends to rely heavily upon the "participant' views of the situation being studied" (Creswell, 2003). With this it is important to acknowledge and recognise the impact of the researcher. This reference is extremely poignant to this work as the data collected throughout the work and later the descriptive analyses of this data are influenced by the interaction of the researchers interface with the processes.

The structure of the thesis will be expressed as it progresses through the levels of research, Figure 3. As stated above the methodological design begins with the interpretivist paradigm. This can be defined as "exploring a research object on the basis of your use of abstract theoretical structures and philosophical concepts" (Routio, 2007). The thesis uses 'Empirical research' which will encompass case studies and experimental techniques adopted. Routio et al (2007) can define empirical research, "when the object of study belongs to empiria, the tangible world of people, objects and events, the study is called, empirical."

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Figure 3 - Research Strategies (Research Strategies, 2015)

A qualitative method has been adopted. As stated by Stake (2012), qualitative method is an iterative and reflexive process that begins as data is being collected rather than after the data collection has ceased. This strategy will suit, as the aim is to provide a qualitative view as a result of descriptive analysis, which will be discussed in detail later. Data has been gathered through the experiments and the observation of processes. This data has then been interpreted using 'progressive focus' technique, which was used to analyse the data gathered. Author interaction with the data will be a factor throughout with an aim of refining the final objectives of the work. Anderson (2003) defines 'Progressive focus' when the observed thoughts "represent theoretical insights that emerge from engagement with the data… focusing on events that might bring alive research interests and concerns" (Anderson, 2003).

The research experiments were carried out in such ways that the success or failures of the experiments affected the strategy of the research going forward and theoretical observations were made throughout which informed the structure and approach of the following experiments.

A specific component of the method will be the case studies primarily focused on Coventry University's George Eliot building. To provide a scientific spread of testing a number of other case study models of low, medium and high complexity were used within the tests to ensure robustness throughout the experiments, results and observations. The additional models will provide continued controls to the experiments to help ascertain why and how issues or results are affecting the data and results. The additional case study models varying degrees of complexity will provide a means of credibility and validation of the process. The processes and techniques worked through, as part of the experimental phase of the research will be critically evaluated to ascertain functionality, potential benefit and accessibility.

To provide further context to the case study selection as the main case study focus it is important to reference the interface with an on-going research project at Coventry University. The case study project is linked to RESEEEEPE project, which is a European Union funded FP7 refurbishment project. The project titled RESSEEPE stands for, REtrofitting Solutions and Services for the Enhancement of Energy Efficiency in Public Edification. The project focuses on the refurbishment of existing buildings. Building typology analysis and a critical selection process was carried out through the RESSEEPE project to select buildings which offered the best opportunity for refurbishment within Coventry University estate. Once the building options available for refurbishment were critically evaluated the selection for refurbishment was narrowed down to two buildings with George Eliot being selected as a case study demo building for the project. The RESSEEPE project highlighted the need for real world implementations of BIM ethos and the link between that project and this thesis was grounded via the sharing of the BIM models created within this research.

The case study method has been selected to provide an in-depth investigation into a focused area of research. The case study provides a means to evaluate a focused typology of building in detailed context working through a sequential standard process of applying BIM modelling and analysis techniques. By using this in-depth approach a limitation result is such that the wider context of the processes has not been fully explored, however the justification for this is that the in-depth approach into the main case study building provides a focused wealth of data, which can be investigated fully. The case study building was selected due to the replicability of the building typology, which brought strong possibilities for the extrapolation of results and findings. At this stage of the research this extrapolation will provide best practice guidance for future and similar projects and case studies beyond the scope of this research.

The case study approach utilises experimental and descriptive data collection techniques. These techniques cover a number of practical experiments into the use of BIM in building management and performance assessment. As discussed by Fellows et al the case study approach used within this research will provide a 'theoretical generalisation for the experiments, rather than empirical or statistical generalisation' (Fellows et al, 2005). Interpreting that statement the results of the case study investigation aim to inform into future adoption providing assistance, but with the significant note that any findings of the work have been discovered and proposed as the result of a focused case study with limitations on the reliability of the extrapolation of the results to far wider context. Discussing this limitation in the research it can be proposed that further testing on wider case studies and applications of the proposals investigated in this study should be carried out to strengthen the validation of the outputs of the research.

Experimental data collection methods have been adopted to investigate the processes. Whilst an experimental approach is traditionally better suited to a bonded approach, as stated by Fellows et al, "the experimental research approach is, perhaps, best suited to 'bonded' problems or issues in which the variables involved are known", (Fellows et al, 2005) its use within this research can be justified by the need to test the investigations in as close to scientific manner as possible within the practical nature of the research. It could be argued that a control over the independent variables is required to carry out the investigations into the selected BIM processes. However as the nature of this research is to evaluate and test new and existing approaches to BIM processes and technical applications with unique bespoke case study models not all variables can be known from the outset as the source data, in this case the case study BIM models are all created as per the one-off source designs. It is important to reflect on this point to identify how the experimental data collection approach within this research may differ from the commonly understood use of experiments. The experiments rely far greater on the observation and interpretation of the processes within the experiments adopting BIM technology and processes rather than the traditional scientific experiment which focuses on the numerical or otherwise results of laboratory style work or social observations focusing on critical historical data. This differentiation is important for understanding the reasoning behind the research placement within the interpretist paradigm and the research design as described. This approach can be defended by an example study where the focus of the project and 'experiments' were outside of the traditional lab context. In the case of Elton Mayo's 'Hawthorne Experiments' (Mayo, 1949) the research was carried out in a 'live' manufacturing workplace housing an electrical company. The nature of the 'experiment' was that it had to respond to the live workplace and the continuing shifting variables.

The information gathered through the experiments within the case studies will be analysed using Descriptive Analysis, Descriptive Analysis is tradition based on an interpretative philosophy. As discussed by Yin (2009), when evaluating the suitability and planning to adopt descriptive analysis it is important to recognise 3 critical questions.

 a. The purpose of the descriptive effort? - *Response - To ascertain best practice in the selected process adoption*

 b. The full but realistic range of topics that might be considered a 'complete' description of what is to be studied – *Response – The BIM processes tested within the experiments have been fully described in an open and critical manner. Each process has been tested in sufficient detail to provide a complete description of the 'experience'.*

 c. The likely topics that will be the essence of the description. - *Response – The topics within the description have been selected to provide a wide base of data and analysis, which define experiments within a number of industry relevant BIM processes. These 'topics' that have been selected as part of the experiments are analysed descriptively to provide a foundation for the final output within the process methodology of best practice.*

The practical investigations in themselves will lead the study into areas unknown from the outset. The critical paths will be observed throughout the experiments. Descriptive analysis will be adopted to reflect on the results and process experience with the aim to propose best practice in response. Patterns, which describe the use of descriptive analysis, can be found as "descriptions of objects or phenomena, explanations of processes, and predictions on the future behaviour of the object of study" (Routio, 2007). These patterns align with the suitable structure of this research.

The reliability and creditability of the research is grounded in the lead researchers trained skill and ability in the use of BIM technology and processes adopted. The lead researcher is a successor of the BRE BIM fundamentals course and has access to BRE as a BRE BIM Member as a result (BRE 2015). Additionally the researcher has held degree with

honours qualification in Architectural technology with embedded Autodesk and BIM software training certified by CIAT. This experience has provided the researcher with the fundamental background to carry out the research in an informed and credible manner.

As part of the experimental procedure a number of software platforms were used. For validity and repeatability it is important to specify the exact versions used as well as the hardware platform specifications. Table 1 and 2.

Hardware – Specification	Version
Windows PC system	
Operating system	Windows 7 Professional Service pack 1
Processor (CPU)	Intel core - I5 4690k
Graphics card (GPU)	NVidia GTX 980ti
Motherboard	ASUS gamer pro Z170
Memory (RAM)	Hyper fury X 16 gb (2 x 8 GB) 1866 MHz
System Cooling/Fans	3 system fans (deep cool UF 140 silent)
CPU cooling	EVO 416s CPU cooler heat sink plus 2 CPU fans (Corsair air series 120mm)
Power unit - PSU	EVGA 850w gold rated

Table 1 - Hardware and operating system specification

Software	Version
Autodesk REVIT	REVIT 2015
IES VE Ware	V 2015.0.0.0.
Green Building Studio	Cloud based accessed in 2015
BCF plug in	V2.2 2015
Rapid Energy Modelling	Embedded into REVIT 2015
REVIT Heating and Cooling Analysis	Embedded into REVIT 2015
Solibri	V9.1

Table 2 - Software Version

1.6.2. Specific Methodological Processes

1. The Paradigm – Interpretivist – The work is grounded in the interpretivist paradigm in that the work is very much centred on the case study method; with a qualitative strategy focusing on the detail of the process experimented. The experimental data collected followed the descriptive and experimental data collection methods, which were then analysed in accordance with the interpretist paradigm using descriptive analysis.

2. Qualitative Method - A qualitative method has been adopted. As stated by Stake (2012), qualitative data analysis is an iterative and reflexive process that begins as data is being collected rather than after the data collection has ceased. This method will suit, as the aim is to provide a qualitative view as a result of descriptive analysis of the case studies. Data has been gathered through the qualitative observation of processes.

3. Desk based study; a critical review was carried out to investigate the role of Building Information Modelling in Construction Management. An Investigation into the use

of BIM tools for information management has been carried out evaluating the topics of data management, interoperability, OpenBIM platforms and data sustainability and the origins of BIM.

4. Case Study - The case study approach has been selected to provide an in-depth investigation into a focused area of research. The case study provides a means to evaluate a focused typology of building in detailed context working through a sequential standard process of applying BIM modelling and analysis techniques.

5. Descriptive Data collection; Descriptive techniques have been used to gather data and information on the existing information collection, storage and sharing processes at Coventry University estates. Focussing on investigating processes and protocols.

6. Experimental Data Generation (Modelling and Simulation): A 3D technical BIM model has been created for the case study building retrospectively. The model has been used to investigate best practice in modelling, simulation and validation, identifying gaps and shortfalls of each software and process. The experimental approach adopted in this research differs from the more commonly understood use of scientific or quasi-experimental design as this research has developed experiments where the data has been collected in using a strong strand of descriptive data collection as well as the experimental data collection. Due to this the experiments rely far greater on the observation and interpretation of the process and experiment rather than the critical historical data or numerical as a result of the experiment.

7. Descriptive Analysis: Case Study has been utilised to critically investigate the role of BIM in information management. The qualitative data has been analysed using descriptive analysis of the processes attempted in the experiments. This data analysis was then used to inform best practice in the future application of BIM processes and techniques. A considerable amount of secondary case study data has been gathered, analysed and shared throughout the project to provide a comparative critical comparison to the central case study.

8. Analytical: Throughout the project the integration and collaboration with the concurrent FP7 RESSEEPE project will be analysed critically evaluating the processes of the wider European project and the impact the findings of this research has had on the European project.

9. Descriptive Analysis Leading to Critical Proposals: Process maps have been produced using the descriptive analysis of the case study experiments which summarise the best practice and critical paths investigated for adopting Building Information Modelling processes for information management. The objective was to create process maps, which provide assistance and inform users when embarking on adopting BIM processes for improved building management and performance strategies of existing buildings in the future. As discussed later on in the final chapter the limitation of these process maps are such that for greater reliability and generalisation a process of greater validation and widening of the case study selections would need to be carried out.

2. Chapter 2: Literature Review: Building Information Modelling

2.1. Introduction to Chapter

This chapter aims to provide an insight into the background of BIM through a number of available definitions of BIM, evaluating modern and historical interpretations. The chapter later focuses on the information management aspects of BIM such as data sustainability and interoperability. The literature review is constructed using a mix sources from literature, academic papers and online material. The researcher recognises a percentage of the review uses online material such as the NBS Surveys (2013-/2016) and UK Government funded items such as the BIM Task Group and BIS BIM Strategy (2011). This is justified through the aim to provide a strong wide insight into current policy and process. However recognition for classical academic support is recognised through the use of historical sources such as the works by Englebart's (1962) and Eastman (1974-) as well as published academic strength through paper journals.

2.2. The background to BIM

To explain the definition of BIM and what the acronym of BIM actually stands for I have utilised the description as set out by BuildingSMART showing the variations in the BIM acronym; Building Information Modelling, Building Information Model, Building Information Management (BuildingSMART, 2013).

BIM is an acronym, which can be seen as representing three separate but linked functions:

BUILDING INFORMATION MODELLING - Is a BUSINESS PROCESS for generating and leveraging building data to design, construct and operate the building during its lifecycle. BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms.

BUILDING INFORMATION MODEL - Is the output of the business process resulting in a DIGITAL PROTOTYPE, a virtual computer model of a project, which holds selected structured data about the asset (design, quantity, time, cost, as built etc.).

BUILDING INFORMATION MANAGEMENT - Is the ORGANISATION & CONTROL of the business process by utilising the information in the digital prototype to effect the sharing of information over the entire lifecycle of an asset. The benefits include centralised and visual communication, early exploration of options, sustainability, efficient design, integration of disciplines, site control, as built documentation, etc. – effectively developing an asset lifecycle process and model from conception to final retirement (BuildingSMART, 2013).

Another definition of BIM, which can help evaluate the acronym is the definition as proposed by Martin Simpson (2013), which dissects the acronym as such;

• 'Building' is the verb 'to build' rather than the noun 'a building'. It is therefore relevant to any asset of the built environment

• Information (or more specifically, 'the sharing of structured information') is the fundamental concept of BIM. This includes both geometric and non-geometric information such as time, cost, fire rating etc.

• 'Model' refers to the 'representation of a system or process' rather than a '3-dimensional representation of a person or thing'. Though there can be no doubt that geometric representation is important, we must be able to simulate the various facets

of the design of an asset (structural, architectural, building services etc.), the construction of the asset and the operation of the asset.

A particular significance of this definition is the identification of the 'Building' aspect of BIM in the context of a verb as in 'to build' rather than the noun of 'a building'. Whilst the use of the noun 'building' in BIM restricts the acronym to identify BIM as purely focusing on the buildings within projects where as explaining the 'building' aspect of BIM as a verb allows for a wider appreciation of BIM involvement with the wider construction sector focusing on building as a process, i.e. 'to build'. It could be argued that to take an acronym and then later amend it to suit the direction or perception that the source above is indicated is a bias play on words. The ethos and BIM bridges beyond whatever any breakdown of the acronym. A criticism is that the industry and its participants in and around BIM have spent far to long debating inconsequential aspect such as, 'what does the M stand for in BIM?' BIM practice in reality is or should be concerned with how to practically adopt better collaborative practices and improve how the construction industry performs.

BIM tools can purely be used to enhance the communication of 3D designs in an isolated design environment however BIM can go far beyond that limited use. The level of collaboration, where BIM software is used simply for 3D visual design representation or 'silo'd' design as it can sometimes be referred to, would be in between Maturity level 0 and 1. 'Maturity Level 1', which is signified by users still preferring to work in 2D yet adopting the 'Information' protocol aspects of BIM to enhance file based collaboration. According to the NBS National BIM Survey 2013 (NBS 2013), 47% of participants have already at some point reached BIM 'Maturity Level 2', which was positive news, reinforcing the stability and future prospects of BIM. Within the same NBS National BIM Survey 2013, 8% stated that participants had reached the BIM Level 3 of maturity at some point, working within a fully collaborative and integrated environment. Looking at the progression of these statistics against the latest 2016 result of the NBS survey (NBS 2016) we can see a continued rise in the apparent height of the maturity levels of BIM reached with 30% reaching level 1, an increase from 47% to 65% reaching level 2 and 4% reaching level 3. These statistics indicate that the competence and relevance of BIM is on the increase. Critiquing the data an interesting drop in statistics can be seen in the apparent 'level 3 achievements'. We can see a drop from the 8% stated in 2013 to 4% stated in 2016. It could be argued that this drop is a result of a greater understanding amongst the industry as to what level 3 actually entails and thus the unrealistic claims in 2013 that 8% of the industry had already reached the heights of level 3, at a time before a tangible understanding of what level 3 would actually be in a practical sense.

Additional definitions have been presented by leading industry participants, which hold robust value such as those of NBS who define BIM as "the means by which everyone can understand a building through the use of a digital model. Modelling an asset in digital form enables those who interact with the building to optimize their actions, resulting in a greater whole life value for the asset" (NBS 2016). A critical aspect of this statement is that NBS is using the term of a 'digital model' as the primary focus of the definition; the definition does not take account of the crucial policy and standards aspects of what encompasses BIM. A crucial aspect of what BIM actually is from especially from a UK perspective is the collation of a number of standards and regulations, which form the policy framework to support BIM.

RICS however define BIM as a useful tool to "help us to save both money and carbon by cutting out wasteful processes/activities and making more informed decisions at the right time" (RICS 2016). Understandable the perspective from RICS is concerned with the reduction of waste in regards to cost and carbon. RICS go on to state that "models offer a better visual representation of design/construction and can therefore be used to help inform decision making" (RICS 2016). The consideration that a BIM model can help to inform

decision making is positive support for the technology. Its important to highlight however that for models to support accurate decision making a critical understanding has to be developed in regards to ensuring that models a produced to a high quality and accuracy which should be achieved via a robust understanding of the correct procedures to ensure that models are validated. Additionally a critical area moving forward is a greater understanding of interoperable environments to ensure that data is transferred accurately thus allowing for the 'informed decision making' to be robust.

It could be argued that BIM as a process is not as new as some may perceive. The concept of integrated project delivery (IPD) has clear roots in the history of Architecture. Historical builds right back to the Empire State Building and even further beyond that to the construction techniques adopted for the Egyptian pyramids have had an element of IPD embedded within them. The Empire State Building consists of 102 floors and was constructed in the 1930's. Surprising to some may be the schedule of works and completion time; the building was completed in just 13 months, which was an achievement in the 1930's (Construction Company, 2015). It is argued that they achieved this through various ways; one process was by having a collaborative and integrated design environment in which all of the various design and construction teams worked in close proximity of each other. This would enable decisions and alterations etc. to be made live without any lengthy delays for information exchange. A critique of this statement however has to be highlighted, such that the context of the previous examples of 'IPD' are proposed out of an industry state based in a completely different context in regards to the construction industry. In Egyptian and early American 1930's the relation to the modern construction industry is not comparable.

Attempting to reach the source or birth of the concept of BIM could be seen in the early accounts of Douglas C. Englebart's research into his '*Augmenting Human Intellect study*' (Englebart, 1962), who had the insight to imagine a world where design was completed within a visualisation on a screen proposing that "the architect next begins to enter a series of specifications and data–a six-inch slab floor, twelve-inch concrete walls eight feet high within the excavation, and so on. When he has finished, the revised scene appears on the screen. A structure is taking shape. He examines it, adjusts it… These lists grow into an evermore-detailed, interlinked structure, which represents the maturing thought behind the actual design" (Englebart, 1962). Englebart was clearly a visionary and the argument that this perception is closer to the origins of BIM is far stronger than that of the empire state building as Englebart is not making claims the industry of his time is taking credit for BIM rather it's a philosophical and theoretical view looking forward to the future beyond 1962. Perhaps a greater critical turning point in the origins of BIM come from the work from Charles Eastman (1974) whose work on the Building Description System (BDS) which introduced the use of library component or elements which could be integrated into the building model. At the time the software was difficult to navigate but comparisons can be made between the use of pre defined library components and the infrastructure of modern BIM software such as REVIT. Eastman goes onto to produce the GLIDE system in 1977, discussed within his paper titled '*GLIDE: A Language For Design Information Systems*', highlighting the significance of his work, "We expect GLIDE to be used as a laboratory for developing a variety of design information systems. Initial application areas under investigation include building design, with interfaces to a variety of performance analyses" (Eastman 1977). Within the paper and model we can begin to see clear relations to the modern understanding of BIM. Additionally Eastman goes onto later discuss "the implementation and operating environment… these are particularly critical to an interactive database system, since speed and convenience are essential if the full advantages of direct interaction are to be obtained" (Eastman 1977). It is at this point the indication of the significance of the interactive database is represented, positively contradicting the out dated and unsustainable nature of hard copy plans due to their 'decay' and 'failure to represent the building post renovation' (Eastman 1974). The research carried out by Eastman is crucial in understanding the evolution of BIM, what is found most indicative by the research is the fact that Eastman, as early as 1974 had seen the inadequacies

of hard copy plans. Without AutoCAD being in essence a digital representation of a hard copy plan is surprising to see that the industry took so long on mass to respond to these significant observations. It could be argued that there is still a resistance to the culture change of BIM today despite the positive evidence in support of it.

Over the last few years the UK Government has made significant moves outlining where they expect the construction industry to be in 2016. The UK Government has mandated that all public building projects will have to be using BIM design processes at level 2, fully collaborative 3D BIM, or higher by 2016. As Maude (2012) Minister for the Cabinet Office states, "The Governments four year strategy for BIM implementation will change the dynamics and behaviours of the construction supply chain, unlocking new, more efficient and collaborative ways of working. This whole sector adoption of BIM will put us at the vanguard of a new digital construction era and position the UK to become the world leaders in BIM". The Cabinet Office states in the Government Construction Strategy (2011) "there is a detailed programme of measures Government will take that will reduce costs by up to 20% by the end of this parliament"; it is believed that BIM will be one of the key factors in achieving this target.

The UK 2016 deadlines for level 2 BIM established by the UK Government (2011) target is to push the UK as a potential leader in BIM policy and standards. The 2016 policy and supporting statements have a critical relevance to the research topic highlighting the implication that Government targets have on industry and research.

It's important to assess what data is required or useful to Operations and Management, and then in respect of the findings the handover requirements of data can then be established. It's becoming increasingly clear through various drives such as the UK Governments Soft Landings policy (GSL) that the handover of relevant data from the design and construction phases over to the FM team is being increasingly recognised as a crucial step in the whole life of a building. The Cabinet Office FM Category Team led the development of the Soft Landings policy in 2011 with an aim of improving the aforementioned link between the actual design and construction of a project with the operations asset management of the project (civilservice, 2013). These aspirations fall into part of a wider emphasise of evaluating actual building performance against predicted performance utilising actual data post completion to test out whether the projects are actually performing as previously claimed during design. The hope is that by further interrogating building post-completion the industry can begin to evaluate scientifically whether the projects and methods of design being used today are the projects and methods that should be used for future designs.

The focus of the GSL as outlined by the Civil Service (2013) will be on the following:
- To ensure that the GSL policy becomes a standard ethos for Government projects
- To improve the integration of FM in the early phase of a construction project. This is to ensure that FM can have a constructive input into a project from an early stage with a clear focus on how the building is going to perform in the real world across its whole life.
- Ownership and accountability of a project post completion from the design and construction team.
- Improved and appropriate handover process from the construction teams to the end user client and FM.
- The emphasis to carry out Post Occupancy Evaluation/Monitoring, which will lead to lessons, learnt from a project being evaluated.

As discussed by Chasey et al (2000), "Because of restrictive construction schedules, sequencing and coordination of different construction activities will also become a big issue. Constructors will need to develop new ideas and methods to be able to design and construct a

fab that ramps up quickly and works efficiently in an uncertain and changing environment." Whilst this reference is concerned with construction activities it does give a recommendation for the need to explore new avenues of working to cope with the demands of a modern industry. Whilst is originates from 2000, the impact of the coordination of activities is just as relevant with current industry processes, new build or refurbishment, with the development of BIM a possible 'modern' solution to these issues.

2.3. Information Management in BIM

The management processes and time that it takes for a facilities management team to continually assess and maintain their asset stock can be considerable. For instance if you focus on a University estates team with numerous of buildings to manage trying to find a detail specifications of a fixture or fitting in a building that was built 40 years previous, it is reasonable to state that this can be difficult task. Having all of the information available within one core data package could be invaluable, at the click of a button the details, manufacturer, performance criteria and cost could be accessed almost instantaneously which BIM can facilitate. Another key component that BIM systems can assist in is by giving the decision-making teams the correct tools and right information when they need. The information is up to date and applicable to the requirements of the call off of information. A key problem that exists within asset management is access to information; a core ethos of BIM is to provide an easily and readily accessible access point to all of the required Estates and Facilities Management teams information. BIM is establishing itself firmly in the strategy of the future of FM, Operation and Management. At current BIM for FM is focused around the handover of viable and relevant data to the FM team post completion. A future prospect is for the data to be held directly within the model and big data package, which can then be accessed through interoperable platforms.

The benefits of using BIM for facilities management as outlined in Adopting BIM for Facilities Management (Balestry et al, 2007) broadly include:

- Quicker and more effective facilities management – This is done through providing information that can be shared easily and reused efficiently by the many contractors working within the AEC and FM industries.
- Easier performance of simulations - For upgrade and refurbishment projects, BIM helps to analyse the designs thoroughly and, consequently, perform simulations easily.
- Predict building performance – BIM allows managers to control costs through the life of a facility by capturing data that helps to predict the performance of the building and enables more accurate budget planning

Project Execution Plans (BEP) and Project Implementation Plans (PIP) are an area where quick, cheap and effective steps can be made in the early stages of BIM adoption. Small or large companies can use these tools or documents during the implementation stages of project at relatively small costs as compared to actually implementing the technology platform needed to run a BIM project. The documents are not a radical new concept; there are clear similarities to any existing planning documents that firms have set up internally for projects. Other BIM protocol documents such as the PAS 1192-2:2013 have additional reference and guidance for a BIM strategy outlining project planning, structure, sharing and modelling protocols etc.

To briefly outline BIM protocols; BIM protocols are the setting up and adherence to processes and procedures that are part of BIM. Documents such as the Implementation Plans and the Project Execution Plans are used to outline the goals, skills, protocols, responsibilities and many other aspects of a BIM project at an early stage (BIS, 2011). Whilst in their current reference these types of documents are often referred to as BIM projects tools or plans they

could have a wider use across a multitude of projects, from basic standard construction projects right the way through to international research projects. Protocols and Executions Plans can be used to take a team beyond the initial brief into and through a project from start to finish providing clarity on what rules and procedures the team should adhere to, in a pre-agreed and documented format. As stated by BuildingSMART (2013), "To successfully implement Building Information Modelling (BIM) on a project, the project team has developed this detailed BIM Project Execution Plan. The BIM Project Execution Plan defines uses for BIM on the project (e.g. design authoring, cost estimating, and design coordination), along with a detailed design of the process for executing BIM throughout the project lifecycle."

One of the major benefits of adopting BIM protocols early on is that initial outlay can be reduced, resulting in the leap into BIM being less of a leap and more of a steady transition. Another factor to consider is that by tackling the people and organisational aspects first you can skip the nervous and often ill-informed leap of purchasing a costly full software package deal before even knowing what the firm or organisation wants to get out of BIM, which can lead to multiple problems further down the line. It could be argued that by prematurely making the decision on technology software packages and tools increases the probability of encountering issues such as being tied into a proprietary vendor with little scope to utilise OpenBIM approaches or not considering the actual companies or clients (depending on who's the driver into BIM) requirements for future BIM projects. Making these leaps into the technology aspects of BIM before fully understanding what the organisation hope to achieve, or maybe more importantly what they actually need to achieve with BIM could be extremely costly. Organisations that wish to invest in BIM should be prudent to ensure that they have sifted through the initial stages of the BIM wash to ensure that they fully investigate what BIM will mean to the organisations specific requirements.

BIM protocols and Project planning hold particular significance to this work due to the coordination and planning requirements of the project. Protocols and project plans are an important factor when considering information management, as it is within these documents that the information requirements for the management of a project are set. The immediate relevance to the study will be the agreement of data standards such as industry foundation classes (IFC) and open BIM authoring tools to create the case study model.

Within BIM there are two standards of sharing and coding data, which in general terms are regarded as OpenBIM and Closed BIM. Closed BIM generally refers to when BIM processes are carried out on a single platform or proprietary software package. Data is produced to a closed standard, which can only be accessed and interrogated using certain software packages, as the coding of the data is not interoperable with multiple formats. Whereas OpenBIM refers to when the BIM environment crosses multiple platforms regardless of the software vendor, in essence creating an 'open' shareable design environment using an open standard data. This is achieved through the use of adhering to Industry Foundation Class (IFC) standards (OpenBIM Network, 2013).

To achieve an OpenBIM project environment information needs to be shared/exported to a non-proprietary format, such as IFC. The debate between Open and Closed BIM is a heated topic at present amongst the varying parties involved in shaping the future of BIM. The UK Government is pushing the drive towards OpenBIM. One way in that they are doing this is through specifying in the BIS-BIM-strategy-Report (2011) that Maturity Level 3 BIM should achieve "Fully open process and data integration enabled by IFC/IFD." Many individual BIM experts such as those who are part of the OpenBIM Network are also pushing for the drive towards an open standard BIM future. As stated within their mission statement at OpenBIM Network, (2013) "The primary function of the OPEN BIM Network is to inform industry about open BIM, what it means, why it is increasingly becoming the global solution of choice, how it can be done and what, collectively, industry can do to accelerate its

adoption" (OpenBIM Network, 2013). The OpenBIM Network is working in alliance with BuildingSMART (2013) who are an integral part of developing the IFC standard.

Figure 7 shows data integration of COBie and IFC in respect of the BIM Maturity Level stages.

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Figure 4 - BIS-BIM-strategy-Report (BIS, 2011)

The reasoning's behind 'open' BIM are to actively encourage BIM practitioners to utilise the IFC data formats and open BIM standards, with part of the hope that no one software vendor will have a monopoly on the market. This would lead to market lead and market driven of software options, which are being continually improved, increasing competition. According to the NBS National BIM Survey 2013 (NBS 2013), within the scope of their research pool Autodesk currently hold a 63% share of the CAD drawing market so clearly they have a large proportional share of the market. However over recent years this proportion has fell to 31% (NBS, 2016).

As stated by Taylor et al (2009) issues of BIM standards and interoperability have been predominantly addressed so any research moving forward should ensure that the current established knowledge base is utilised. As proposed by Jung et al (2010) "Rigorous efforts including industry foundation classes (IFC) and others by several international organizations have also developed various practical details". As early as 2009/2010 before recent UK drives for adoption, IFC was being referenced as a solution interoperability, yet it could be argued that only with the impending BIM level 2 2016 deadline the UK industry has begun to wake up to the concept.

Interoperability can be defined in computer science terms as "the ability to exchange and use information (usually in a large heterogeneous network made up of several local area networks" (Wordnetweb, 2013). The international Standards Organisation with the ISO/IEC 2382-01 defines interoperability as "The capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units" (ISO, 2015). This statement places greater focus on the intention of the users position within the data transfer process. The emphasis is on 'little or no knowledge of the unique characteristics'. This is a particular

concern to this research as the role of the user in the experimental processes will be paramount.

Interoperability is a significant word in the evolution of BIM and will play a significant part in defining the future of BIM. For files and models to be shared and merged amongst multiple analysis tools and offices they need to be 'interoperable'. If software packages have the ability to be interoperable then it means that time can be saved through not having to continually redevelop new building geometry for each tool that needs to be utilised to carry out various analysis and interrogations. The importance of this interoperability of files and models across all the teams involved within a BIM project is a pressing concern within BIM, which is continually being intensely developed and debated. Interoperability is a key factor that is directly stated in the BIS-BIM-strategy-Report by the BIM task Group (2011), "A Building Information Model (BIM) should be the central hub for all information about the facility from its inception onward. This information takes on many shapes and has many roles to play. Accurate geometric and intelligence about the planning, Design, construction, and operation of a facility are needed by current and future tools for analysis and reporting. Information must interoperable be able to support all the (multiple) opportunities."

When considering BIM, interoperability is a key component, which needs to be carefully considered at every step. If the work produced by varying teams is carried out and outputted in an interoperable manner then it allows for multiple teams to work collaboratively on a project without necessarily holding the same software skills and licences. As stated by the BIM Task Group (2011) BIM is "essentially value creating collaboration through the entire lifecycle of an asset, underpinned by the creation, collation and exchange of shared 3D models and intelligent, structured data attached to them." Having an interoperable Open database with all of the schedules, materials data, costs, energy performance information in one accessible package will enable an Estates and Asset Management team to make whole life planning decisions in an efficient manner for all built asset management.

Through the statements made which have been included in this section by the BIM Task Group in the BIS-BIM-strategy-Report (2011) and by the OpenBIM Networks mission statement (OpenBIM Network, 2013) it can be derived that OpenBIM is clearly being encouraged by Governments BIM Task group as well as large sectors of the industry. The BIM task group (2015) stated that "Information must interoperable be able to support all the (multiple) opportunities" this along with the UK Governments directives on attaining the higher BIM maturity levels indicates that that future BIM practitioners will need to utilise IFC data formats and open BIM standards to ensure that they are working in an interoperable integrated BIM environment.

As discussed interoperability is a critical concern in BIM, especially in light of the recently passed Level 2 Maturity target as per UK Government mandate. For interoperability to be a reality and a cohesive drive the adoption of an open data standard had to be agreed. This has been done through the adherence to industry foundation classes (IFC) which has been established and developed by BuildingSmart and embedded into ISO:16739:2013, the ISO is defined as 'Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries' (ISO, 2013)

IFC data standards are crucial to the sustainability and interoperability of data. The use of this data standard will be adopted throughout the project as often as feasible with the aim of adopting an 'open' process for carrying out the investigations and disseminating the results. To briefly explain what IFC data formats are, they are in essence an 'open' and neutral data format which set a data standard which if utilised can assist in the 'interoperability' between software packages. As stated by BuildingSMART, "Industry Foundation Classes

(IFC) is an open and neutral data format for OpenBIM" (BuildingSmart 2015). The data standard that has been developed by Building SMART international, if adhered to enables for the exchange of models and information between multiple software types, in essence achieving interoperability.

London et al (2010) stated that due to the interoperability that is offered as part of IFC, BIM is beginning to enhance the design environment creating an environment where information exchange can be synchronised using the centralised and single core model data model. This statement follows a similar suit to Taylor et al (2009) discussed above which eluded that issues with interoperability had been 'predominantly addressed'. A significant question arise from this in regards to, 'is interoperability really a past issue which has been solved?' These statements will be evaluated through the experiments carried out as part of this project and within the discussion.

A key feature of BIM is that it needs to be interoperable > hold current data > easily accessible > Have the ability to be analysed. Once data is gathered and collated in an interoperable format it can then be drawn off and analysed efficiently. Any data stored and accessed can then be used as a key facilitator to inform and assist the decision making process. This is expressed in Figure 8:
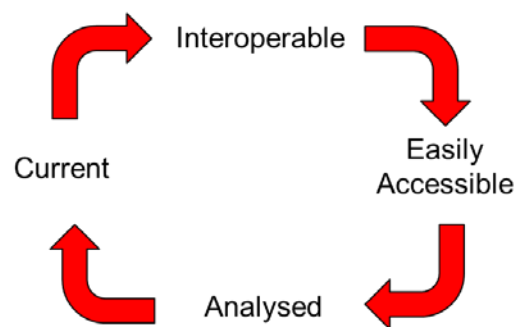
<p style="text-align:center">Figure 5 - Sustainability of data</p>

Choosing a proprietary software package may hinder the longevity of data accessibility, as over time software changes and updates will continually come out. Software, if maintained correctly is always in a state of evolution. The risk with choosing a single proprietary software package is that the system may get left behind the wider industry standard as the competitors continue to develop their systems. It is in this respect that the sustainability of data has to be considered. Data Sustainability for the purpose of this study is referring to the accessibility and accuracy of building data across the life span of an asset. Data, which is inaccessible due to out-dated data standards or redundant software libraries, is as such lacking in data sustainability. Locking down to proprietary software standards can directly impact the sustainability of data, as any loss in access to a proprietary format will result in a los in data access. As stated by the AIA (2010) "An open standard, if acceptable, will result in a greater ability to maintain data accessibility over time. Mandating a proprietary single software solution may limit the number of qualified designers and contractors but improve internal post-construction data use." Data sustainability can be achieved if data is accessible and has a secured life span. To provide an example hard copy plan drawings lack data sustainability due to the fact they are susceptible to damage and locked away in physical achieved systems preventing easy accessibility. On the contrary digital media can be backed up multiple times and be accessible via a number of platforms.

An important consideration on data is the factor of data security. Recent developments in the PAS 1192/5:2015 aims to provide the framework to "specifies the processes that will assist organisations in identifying and implementing appropriate and proportionate measures to reduce the risk of loss or disclosure of information which could impact on the safety and security" (BIM Task group, 2016).

It could be argued that part of the drive to push an OpenBIM future is to ensure that no one Software vendor will have a monopoly on the market. This then in effect will help to push market competiveness between the development and sales of BIM software packages, which may lead to improved systems in the future. According to the recent NBS National BIM Survey 2013, within the scope of their research pool Autodesk, which is predominantly a proprietary software package, held a 63% share of the CAD drawing market, which at that point clearly held a large proportional share of the market. However in NBS National BIM Survey 2016 this figure has fell to 31% showing a gradual spreading of the BIM authoring tool market. Questions, which will be need to be addressed in the future of BIM but are beyond the scope of this research, will be to see 'how does this large market share affect the progression and evolution of OpenBIM?' And 'Will Autodesk's share open up or close down the interoperability of BIM?' Are Autodesk going to be happy to push forward with open BIM or is it in their interest to actually tie practitioners into their product package, which at current is a relatively closed package?

Within the Sustainability of Digital Formats report carried out by digitalpreservation.gov the importance of looking at data in terms of whole life-cycle was expressed "Sustainability and retrieval of digital information over time is an imperative to life-cycle uses of BIM. Software programs come and go and so do digital file formats. For digital data to remain retrievable over time, procedures for archiving and updating must be in place" (Sustainability of Digital Formats, 2013). Whilst developing this project this concern has been continually address and considered.

A tool or process, which will be evaluated, will be the use of COBie to collate and organise the case study information. COBie is another tool that is also vastly becoming synonymous with BIM. COBie is a tool, which allows for a multitude of non-graphical data and information to be stored in an organised manner, in essence a SpreadSheet. All of this data can then be handed over to the client/facilities management department allowing for easy access to a multitude of details post-completion without having the unenviable task of sifting through a mass of fragmented documentation looking for very specific details, which may be hard to find in traditional documentation. With COBie the intention is that all of this information can be kept in an up-datable database that can be easily accessed and kept up to date throughout the whole life cycle of a building, from concept through to demolition. A full detail of information should be handed over at completion of the project with additional data drop post occupancy to further inform operations and management. The drops as outlined by the BIM task group (2015)

COBie – Data Drops for Standard

- CIC 1: Drop 1: Brief/early design - When project is initiated by Client
  Model represents
  REQUIREMENTS and CONSTRAINTS

- CIC 3: Drop 2a: Design development issued for tender- Requirements & Constraints
  Model represents
  OUTLINE SOLUTION

- CIC 4: Drop 2b: Tender submission - Model Represents Outline Solution

- CIC 5: Drop 3: Contractors design development and planning - Construction Information)
  Model represents
  CONSTRUCTION INFORMATION

- CIC 6: Drop 4: Handover - Operations & Maintenance Information
  Model represents
  OPERATIONS and MAINTENANCE INFORMATION

- Data Drop 5 (and subsequent drops):
  Model represents
  Post occupancy validation information and on-going operation and maintenance

As stated by the BIM Task group (2015) the COBie data can then "be kept as delivered, or held in ordinary databases, or they can be loaded into existing Facility Management and Operations applications, either automatically or using simple copy-and-pasting." According to the BIM Task group this process is a 'simple' process however in reality the process can often be thwart with challenges and interoperability issues. Data needs to be specifically aligned within the models for the COBie system to receive data in its required structure. It's important for a client or owner to assess as early as possible as to what information they require to be held and handed over in the COBie data sheets to ensure that the handover of data is useful and relevant to post completion management, as represented in Figure 9.
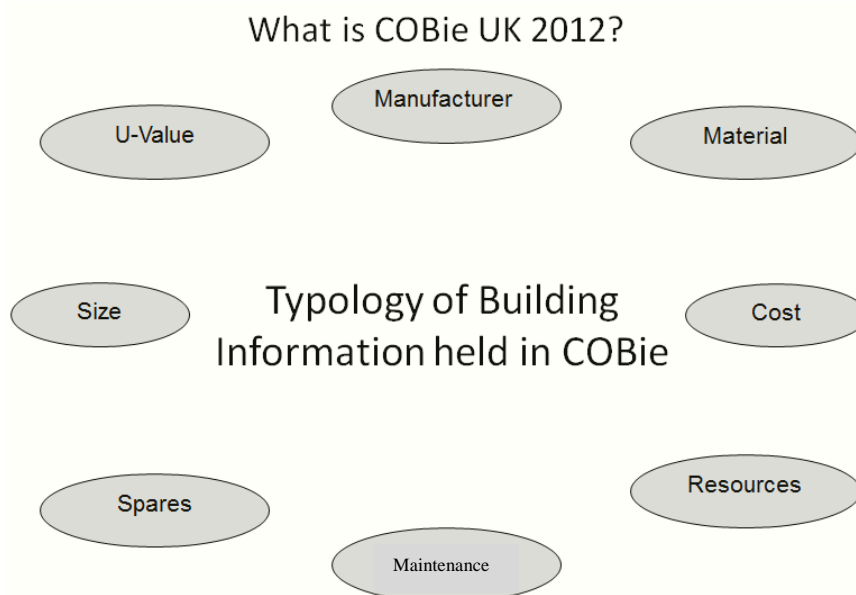
Figure 6 - Typology of information held in COBie

A varied array of information can be attained from BIM models and processes. Once the case study model has been completed the model will be interrogated and analysed. Part of the output from the model will be to evaluate the value of creating schedules and takeoffs from the case study model. To explain this process further, once a model goes beyond the state of simply holding 3D geometry it becomes an intelligent model. It's the intelligent data that's held within an intelligent BIM model, which becomes the key to getting the most out of

the BIM process. As highlighted by Kulusjarva et al of Solibri (2010) BIM information is often fragmented across traditional information storage and exchange processes and to a lesser but still paramount extent across BIM platforms. One of the results of intelligent BIM model is the huge mass of information and data that is produced from the process. Kulusjarva et al (2010) reflects on this aspect with the quote of, "you can't see the forest for the trees" which is a fitting analogy. An example of the importance of making sense of this data is explained as such by Kulusjarva et al, (2010) "Some things are easier to see than others. For example, through visualising geometrical information and by looking at it problems can be discovered. Through this process elevated detail information can be attained to a level more understandable, and usable, for all. A similar result is achieved when quantity takeoffs are generated from a BIM file, as the 'total numbers' gives greater understanding about the building structure" (Kulusjarva et al, 2010). It's significant to note at this point however that the data that can be derived from a BIM model is only as accurate and reliable as to what is put into the model in the first instance.

The Building Information Modelling tools available today to industry practitioners have begun to help operatives optimise design and retrofit strategies. However, it's significant to recognise that these tools will only be accurate in predictions and outputs if the data and models used within them are validated and accurate. It's important to understand within BIM modelling that the quality of data that goes into a BIM model directly influence the quality of data that you can draw, the two are intrinsically intertwined. It is important therefore to ensure that processes of model validation and data validation takes place throughout a project.

As stated by Haug et al (2011), it is critical for the information to be used to be accurate and correct as inaccurate data and information can result in increased cost and time delays. Haug goes on to argue that poor quality data can significantly impact the efficiency of an organisation negatively. Madncik et al (2004) take this further stating that a high quality of data is often critical to a company's success. It is argued that model validation is a crucial step in assuring quality of data.

2.4. Drivers for Refurbishment and Existing Strategies

The Association of University Directors of Estate (AUDE) commissioned and published a paper titled "The Legacy of 1960's University Buildings" (AUDE 2008). The relevance of the paper is significant to this research as it focuses on the refurbishment of post 1960 higher education university buildings. The paper highlighted a common issue that many universities are facing in that much of the building stock that is held is progressively becoming out of date and unfit for purpose. The choice that owners are facing is whether to condemn the buildings refurbish them or carry out a full demolition and rebuild. As stated within the AUDE report, the "report considers one of the big issues in Higher Education today – how to renew a very large proportion of the property portfolio that was built in the 1960's." With the substantial all-encompassing question being, "refurbish or replace?"

Four key points that were identified as a significant part of the study;

- Academic buildings can often be refurbished more successfully than residential;
- While the financial case for refurbishment might look poor, with costs in some cases as high as 80% of a new build option, there are often significant other benefits from the refurbishment route, particularly environmental ones;
- High standards of environmental performance can be achieved on refurbishment projects, provided that the objective is at the core of the design from the outset; and
- Architectural excellence can still be achieved in refurbishment projects.

As stated within AUDE reports from the legacy project, (AUDE 2008) the demand for the need to re-evaluate how pre-assessments of higher education building refurbishments are carried out rose from discussion in regional meetings with Estate Directors. An example of the demand for the project was expressed through the indication that the University of Bath alone had earmarked "£40M of investment decisions that will need to be taken which directly impact 1960's buildings" (AUDE 2008). The experimental phase of this thesis aims to improve pre-assessment techniques.

In regards to the statistics of what Era University buildings were built in data can be gathered from the Estate Management Statistics (Estate Management Statistics 2014); which are collated nationally for the HE sector. Focusing on post war buildings around 25% of HE buildings were built pre 1940, 10% of HE buildings were built between 1940 and 1959, over 40% of HE building were built between 1960 and 1979, and around 25% of building were built since 1980. This equates to around 75% of higher education building being built since 1940 with a very significant proportion of 50% of them being built between 1940 and 1979. The proportion built pre 1979 and post 1940 are significant as this represents a large proportion of building stock which it's reasonable to assume will require refurbishment in the near future and thus this research will focus on existing buildings to pre-empt this trend of refurbishment. This data supports the selection of the George Eliot Building for the case study and experimental phase of this thesis.

Its reasonable the state that many Universities have similar significant investments planned for many buildings from the post war era which require attention and refurbishment, therefore it could be argued that any research scope which proposes to inform the spending of these funds in an efficient and optimised way would benefit the institutions. Objective 3 focuses on supporting the decision-making process in performance management through the proposed process methodologies.

2.5. Chapter Critical Appraisal

This chapter set out to fully explore the current trends and standards within BIM practices and process. A crucial aspect of this research was to theoretically and practically ascertain the impact of modern BIM processes and techniques on information management for existing buildings. To be able to carry out the experimental phase of the project a full understanding of the wider context of BIM theory and processes should be demonstrated. This chapter set out the framework to provide a grounded foundation of theory and current industry practice in regards to BIM focusing on a number of significant areas such as Drivers, BIM theory, interoperability, sustainability of data and OpenBIM. Sustainability of data in the case of the is research is focused on the accessibility and life span on the data held on asset information in regards to building design, plans and geometry.

When considering BIM in an overview perspective it can be helpful to consider the critical significant factors. These can be expressed as the people, the process, the technology and the policy. It is argued that it is only when these elements are working collaboratively and integrated when the true value of BIM will be experienced. If all four elements are fully considered within BIM adoption then it sets the initiative with a solid foundation of understanding. The key components are what will set a successful project apart from an unsuccessful adoption, as represented in Figure 10.
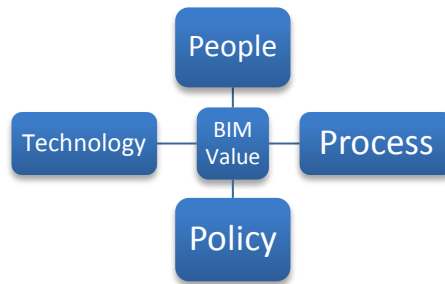
Figure 7 - BIM factors

Additionally the chapter has signified the importance of ensuring high quality data and the negative impact that poor data can have on information management as covered by Haug et al (2011) and Madncik et al (2004). The impact of this on the research design of this project will be to establish clear measures to ensure the quality of data being exchanged as part of the experimental process.

Perhaps the most significant findings of the chapter is the support for the requirement for open data standards as discussed with the relevance of the Building Smart IFC standard and the establishment of UK and Internationally recognised BIM standards such as the PAS 1192 series and the ISO/IEC 2382-01 and ISO:16739:2013 setting out the guidelines for IFC and interoperability standards. It will be a critical component of this research to ensure that the impact of the interoperability and IFC standards is recognised. When constructing the case study analysis IFC standards will be adhered to as a significant requirement of the processes.

3. Chapter 3: Data Collection and Analysis

3.1. Case Study - Coventry University - Geographic Context

The city that the case study buildings were selected from is Coventry, West Midlands. Coventry is the 21st in the list of district size in relation to population. The city has a population estimated as 316,900. The University Public District occupies a purpose built 33-acre (133.346 m2) campus in the heart of Coventry city centre. The campus buildings and environment are constantly being developed and enhanced. The Coventry City Council is investing £160m in the campus over the next ten years Lynch et al (2008) including construction of a new Student Enterprise Centre and a high-tech faculty building for Engineering and Computing. Figure 11 shows the location of Coventry and Coventry University within the United Kingdom (RESSEEPE, 2013).
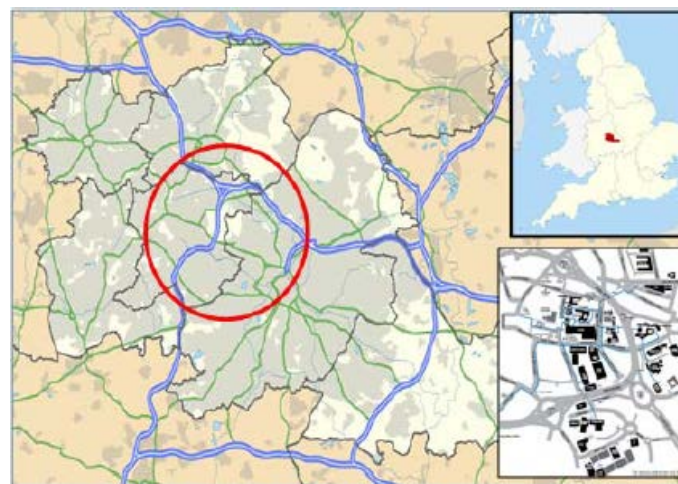
Figure 8 - Coventry University – Coventry – UK

3.1.1. Building Selection

With the support of the Coventry University RESSEEPE team a thorough process of building typology analysis to assess the suitability of the estates building stock in relation to the aspirations of the European refurbishment project was carried out. The six buildings were identified as requiring upgrade in many respects, which matches current Coventry University building improvement master Plan. The six buildings that were selected to participate in this project are Alan Berry, Ellen Terry, George Eliot, John Laing Building, Richard Crossman and Student Centre Building. A full set of building information was collected and analysed for the initial feasibility study, which can be found in Appendix A. The analysis that was carried out and informed this decision includes evaluation of energy consumption and carbon emissions, scope for improvement and planned investments strategies by the Universities estates. Once this study analysis was completed, it was concluded that the best building suitable for this intervention and provided the best opportunity for optimisation was the George Eliot Building. As it can be seen in Figure 12 this building is a six storey building constructed in 1960. The Gross external area of the building is 6089 m/2 with a net internal area of 2799 m/2 and a gross internal area of 5,325 m/2. The electricity, gas (for heating purposes) and water consumption for each square meter in one year are 89kWh/m2 and 185kWh /m² respectively.

| Image 1 : Alan Berry Building | Image 2: Ellen Terry Building | Image 3: George Elliot Building |
| Image 4: John Laing Building | Image 5: Richard Crossman | Image 6: Student Centre Building |
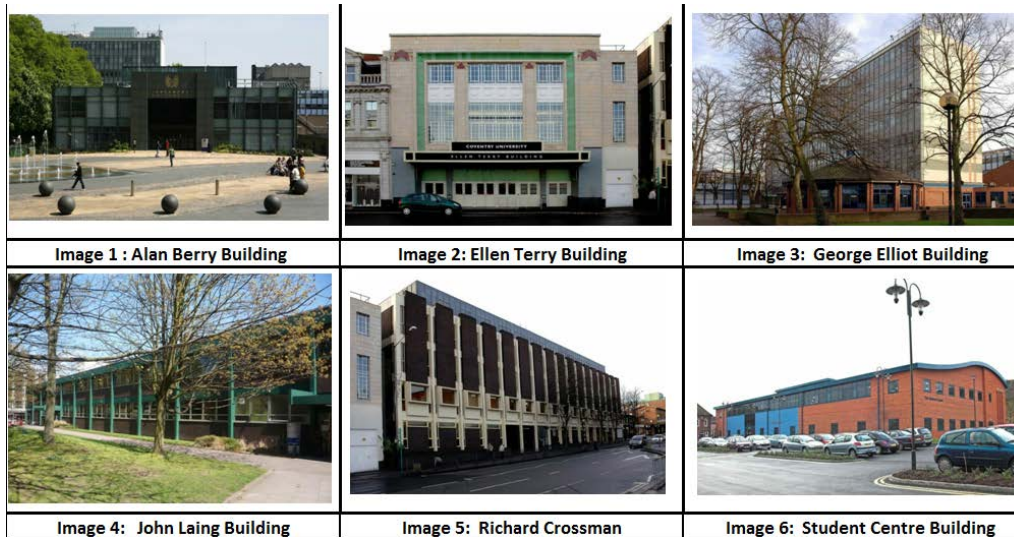
Figure 9 – Six-options/George Eliot Building

The building has a Curtain system, which was refurbished in 1993 with a 30% glazed proportion. The window frame type for the office and workrooms on the West and East façade is UPVC with 6 mm glass in a double-glazed, which is embedded into the curtain system fixed to the frame. A small proportion of the facade varies from the norm, around 10% on the East elevation, which houses a stairway, toilet and storage areas where windows are constructed of a metal frame with a 6mm single glazed panel. Above and below this are fixed rendered panels. The domestic hot water to George Eliot (GE) building is served through a single 700 KW boiler located in Charles Ward (CW) plant room. The source of heating in this building is from the heat generators in the plant room with the power of 7400 KW.

Figure 13 shows external views of George Eliot building in Coventry:

Figure 10 - External view of George Eliot Building

3.1.2.Benchmarking

Benchmarking is an important process in driving building performance management and prioritizing various intervention measures. The relevance to this study is to establish a process to evaluate the current building stock within Coventry University to establish the best option for integration into the RESSEEPE project. CIBSE set out a procedure for benchmarking building performance with similar buildings in the sector (CIBSE 2008). There is always budgetary limitation in terms of the ability of organization to invest in significant way in a large number of property portfolios over short, medium and long term perspective. Therefore the refurbishment process have to take into consideration a process of prioritizing the intervention using a number of indicators such as cost, energy, environment factors and feasibility of such intervention. In organizations with large portfolio of old building it is essential to plan and prioritise the building stock relative to the urgency for refurbishment action. The selected case study buildings in this project have been benchmarked against each other using overall electrical and gas energy consumption ($kWh/m^2/year$).

Figure 14 shows the energy consumption for both electricity and gas for the six case study buildings. The results reveal Ellen Terry Building as an outlier in terms of gas consumptions. The building is the oldest among the selected buildings and is constructed in 1931, which means it has very poor levels of fabric insulation. Initial site survey also reveals poor level of heating controls within the building. The building is also surrounded by other commercial spaces. This building is one of the most challenging in terms of areas of low carbon intervention. The lowest gas consumption is in the Student Center Building, which is fairly new building constructed in 2005 therefore insulation levels are based on Building Regulation Part L 2002. The second highest gas consumption is the George Elliot Building with about 180 Kwh/m^2/annum of gas consumption. Electricity consumption varies from 63 – 116 kWh/m^2/year, the variation in electrical energy consumption can be attributed to the difference in use and the application of mechanical air conditioners in parts of the buildings.
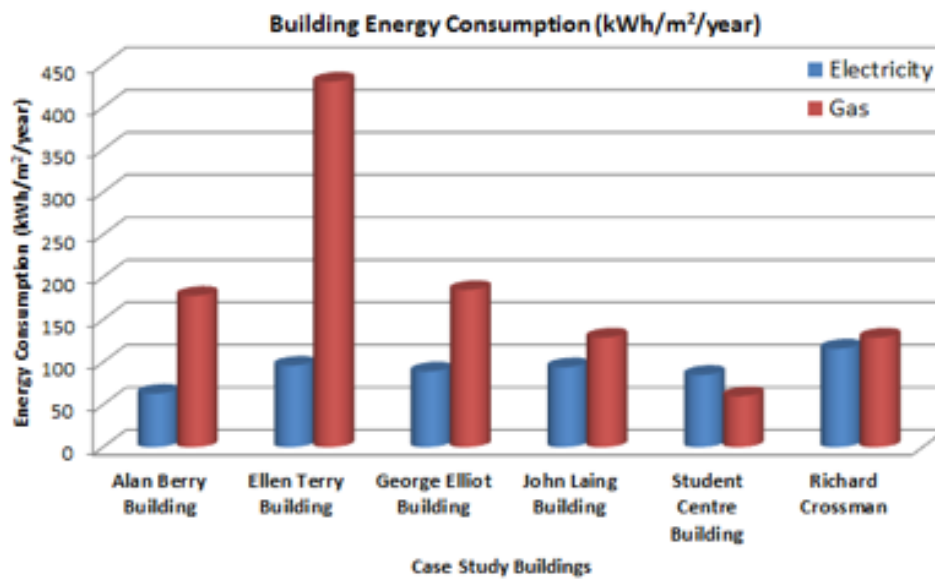
Figure 11 - Case Study Energy Consumption

Figure 15 shows the carbon emission associated with the SIX case study buildings based on both electricity and gas consumption using CO_2 conversion factors of 0.55 and 0.19 for electricity and gas respectively. The total CO_2 emissions from these buildings reveal as expected Ellen Terry Building to have the highest emissions followed by Richard Crossman and George Elliot Buildings. The energy consumption and emissions have been used in conjunction with other factors such as available technologies, site access, internal access to space, internal flexibility, opportunity for interventions, planned investments by the Estate Department in Coventry University and risk of interventions in order to inform the selection of the best option for the current intervention. In regards to these factors Ellen Terry had considerable access issues as well as existing planning restrictions on the North façade system discouraging retrofit. The Alan Berry and John Laing building's expected life span negatively impacts the financial investment consideration. Likewise due to the recent modern construction methods used in the student centre this option was also discarded as opportunity for further investment on a relatively young building was unlikely. Richard Crossman has been identified for refurbishment as part of a different proposed project. Therefore George Eliot has been selected as the best option for the current intervention, according to the parameters above-mentioned. GE has good surrounding access. The internal spaces have a mix of open and closed volumes providing a platform to test technologies in closed controlled spaces. The façade and envelope has potential for alteration due to a current non-structural façade and accessible load bearing capable frame. Due to the good accessibility and selective

isolated nature of spaces within GE the risk factor is also reduced. Additionally the GE building marries up with current investment plans from the University.
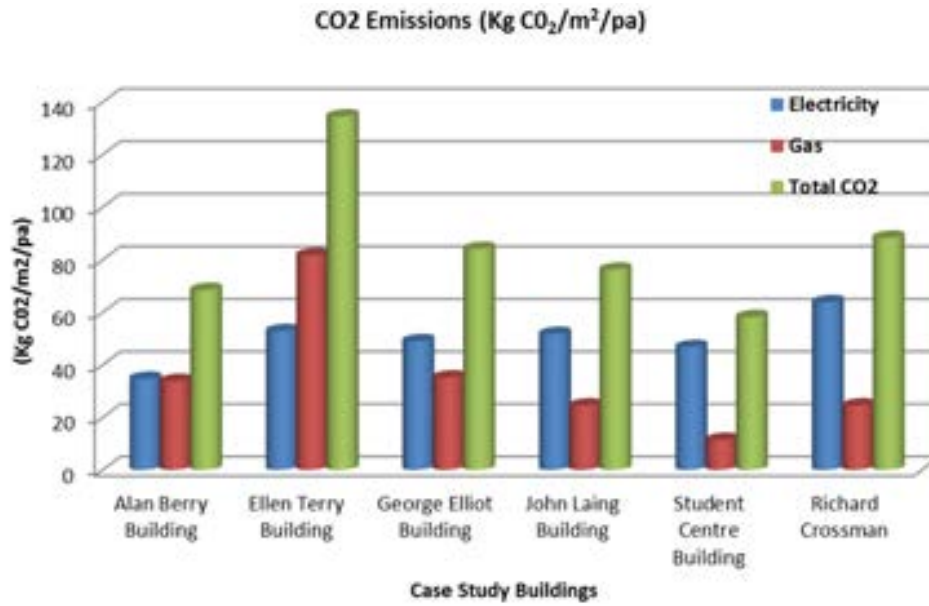
Figure 12 - Carbon Emissions Associated with Case Study Buildings

3.2. Rationale for Building Information Modelling and Management

The lack of data and the lack of a 3D model in the RESSEEPE refurbishment project have led to multiple slowdowns and delays; the argument is such that BIM processes would help to optimise these processes. As discussed earlier within the literature review of this thesis a BIM execution plan can be a valuable asset to a project to ensure collaboration is efficient where required. From evaluating the approach of GE as a case study it was clear early on the sharing of information and collaboration was weakened by the lack of clarity in regards to file sharing, information access and validation of data. A BIM execution plan was retrospectively developed to improve the retrofit collaboration.

By using BIM processes it is proposed that it will remove a lot of the data searching and repeat work by multiple partners as discussed within the initial approach for data collection of the George Eliot Building. However, coming from a current asset management perspective, models for each of our buildings are for the most part not currently held by many UK estates, so this 'ideal' is often not possible. This retrospective realisation of the benefits and need for BIM models and BIM processes when investigating the refurbishment of buildings is a significant aspect of this investigation which should will be further analysed during the discussion and conclusions of this thesis when proposing future optimization of building refurbishment.

3.3. Site Data

Information on site data was provided through existing CAD plans, although similar to later issues to be discussed there was a clear issue with out of date information. Ordinance CAD plans and wider topographical information on the surrounding site was limited. A significant issue is identified with the reliability and standard of existing site data, which highlights the need to gather up to date information prior to any construction. In regards to refurbishment contrary to new builds the surrounding context has a reduced impact. However building orientation and neighbouring building geometry will have an impact on the optimal solutions when considering the refurbishment of a building. Therefore it's important to consider the subject building within a project in the context of its surrounding environment. This will ensure that any simulations such as, solar paths, day lighting and façade detailing will represent an 'as close as reasonable' representation of the actual geometry of the project site as possible.

3.4. Building Data

A significant challenge when attempting to model most existing buildings is the discrepancies within the data held. As with older buildings the data held may be very out dated using original plans. A particular area of concern with this is in regards to design plans. During the early 1990's there was a trend to migrate original hand drawn plans over to CAD plans, although an issue with relying on this data is that the information is only as accurate as the original plans. Additionally there is also a level of error when considering the human interface transferring the plans. Drawing this point into focus with the George Eliot case study building, it was clear when first embarking on the modelling that the discrepancy between plans was going to be an issue, which would have to be taken into consideration. A particular error was found when transposing plans onto the correct floor levels in a 3D environment and aligning the plans. It's important to note that geographic coordinates were not included within any plans so an automated positioning was not possible. The issues that arose was such that each floor plan, of which there were 8 in total including the Ground, first to sixth and roof plan, did not align correctly from floor to floor. Multiple attempts were made to use key features within the plans such as lift shafts, stair shafts and structural columns as key indicators to align upon one another. However, each of the aforementioned key indicators, which in general should be consistent across all levels, did not all align from floor to floor. In summary it was impossible to align all three key indicators on every floor at once. The

solution at this stage when considering the level of detail required for the proposed technical tasks in this investigation was to make a best assumption when positioning the floor plans. This now leads onto the next topic of discussion, which is accuracy of information. GE Building Data such as the source plans and GE BIM model can be found in Appendix B.

3.5. Accuracy of Information and the Effect on Performance Gap

Whilst making numerous approximations the consideration has to be made as to the level of detail that is required for any output. In this case the model will be utilised for multiple applications. Focusing on energy analysis it may first appear that the accuracy of a model is not too significant as many simulation models are simplistic in nature. However when you consider the extent that a 'small error' (10mm) has when multiplied across the full volume of a space the error can be extended to a considerable level causing large discrepancies in analysis (an exterior wall position 10mm out multiplied by the full volume of a room 3500mm in height and then again multiplied across six floors is a considerable amount of error). The result is such that it moves the analysis further away from accurate foundations of data. It could be argued that this 'approximation' of details is one of the factors that influence the gap between virtual and actual performance. It's clear that an unassuming error once considered in a volumetric process can easily become a considerable parameter.

3.6. Level of Detail

When considering the retrospective application of modelling techniques to existing buildings stock, as with new builds that integrate BIM processes it's important to consider the level of detail. To attain what level of detail is required for a particular BIM model it is imperative to assess what the model is going to be used for before any modelling takes place. The aim of this evaluation process is to ensure that no time is wasted on modelling details that are not going to be required within any simulation, investigation or by the local estates management teams. Below you can see a table that has been set up to indicate the goals set out for the investigation along with the level of detail required within a BIM model to achieve these goals. It important to note that this table is process designed to be bespoke in nature to each individual project as every projects goals and target will be unique and set by the key stakeholders. Table 1 evaluates the desired outputs for this project which has been created to provide a breadth of experiments and procedures ranging from Model validation to energy simulation.

Goal	Type of Analysis	Level of detail required in model	Software platform	File Format of source and export requirement
Energy Simulation	Heating and Cooling Loads (H&C loads)	Geometric Spaces and material components identified	REVIT	.RVT, gbXML
Energy Simulation	Interoperability	Geometric Spaces – External and internal, Window position and size, solar shading detail, building orientation	REVIT, IES VE	.RVT, .IFC
Model validation	Validation of model for clashes	As set by other goals, to include: Geometric Spaces and material components, wall positions, feature positions, doors, windows, dimensions.	Solibri	.RVT, .IFC
Model validation	Validation of model for General Space Check	As set by other goals, to include; Geometric Spaces and material components, wall positions, feature positions, doors, windows, dimensions.	Solibri	.RVT, .IFC
Model	Validation of	As set by other goals, to include;	Solibri	.RVT, .IFC

validation	model against building code rule sets- pre-check for energy analysis	Geometric Spaces and material components, wall positions, feature positions, doors, windows, dimensions.		
Energy Simulation and design optimisation	Optimisation of option strategies for refurbishment	As set by other goals, to include; Geometric Spaces and material components	Green Building Studio	gbXML

Table 3 - BIM Software Matrix

Previous History of Retrofit

When considering refurbishment or modelling of existing buildings an important factor to consider is the previous history of retrofit. As discussed in the previous sections the accuracy of existing information may at times be lacking. One direct contributing factor to this inaccuracy can be proportioned down to the on-going maintenance and upgrade of a building. Over the life cycle of a building many changes often occur. This may for the most part be minor cosmetic change but on occasion the interventions may be considerably larger. Examples of this may be such as; Internal floor layout changes, building regulations or code amendments (to align the current building with evolving regulation changes), lighting changes, façade and glazing changes, mechanical upgrade, insulation density. To elaborate on this point using the GE building, some key interventions took place since the building's primary completion, which has to be considered when assessing the buildings information and data.

For example, the building has had a major overall of the facades on the east, south and west. Within the last 3 years the floor layouts for the ground and sixth floors have been completely refurbished to suit ever-changing occupant demands. Contractors carried out this work and plans of the work have been handed over and stored by estates in the form of electrical schematics. This will enable the modelling process to replicate these changes with little issue. In contrary, in 1993 the curtain system and glazing on the east and west elevation was replaced from the original single glazed steel frame to a UPVC double glaze units and the information on specific details such as insulation is not held on current plans however it is believed that the insulation is at best minimal. Around the same date the south façade had a major aesthetic alteration to install a decorative panelled system, which was attached to the structure via a steel bracket system. This particular alteration is significant as it highlights a key issue in the management of assets and respectively the retrospective modelling of assets.

A contractor employed by the estates teams carried out the work on the south façade, however no design plans were handed over post completion. This has resulted in a void of information on a major component of the building. These observations highlight a substantial challenge when considering the management of existing asset stock. If the building information in the first instance isn't accurate, and aligned with as built records and if any alterations made to the asset are not sufficiently recorded then it can greatly hinder the efficiency of the management of existing stock. If asset management and estates teams were to hold up to date, validated and accurate models of asset stock then this issue would be somewhat countered.

3.7. Building Survey's

As discussed in the previous section there is a considerable amount of data and information that is required to not only model an existing building but possibly more importantly to carry out low impact refurbishment often absent for existing buildings. In response to this there is a clear indication that to accompany any retrofit or modelling process a full building measurement survey aligned with any required structural investigations should take place to ensure that the modelling process and thus the analysis of the building is as accurate as reasonably possible. Unfortunately it is beyond the scope and budget of this

project, however the requirement for the best practice is highlighted. An example survey outline has been produced in Appendix B.

3.8. BIM Execution Plan

To assist all internal parties within the refurbishment project in regards to BIM processes and practices a Implementation plan (PIP) and BIM Execution Plan (BEP) template were created (see appendix D). The aim of the document was to investigate the process of using a BxP within a refurbishment project. As discussed in the literature review chapter the need for BxP documents within new build BIM projects is clearly required to successfully transverse through a BIM project. The use of a BEP in a refurbishment project is less understood. This project has investigated the process by creating a bespoke BxP for the internal research project based around the refurbishment of George Eliot. To create the BxP industry sources on frameworks for BEP documents were utilised such as the template proposed within the BuildingSMART alliance, as developed by The Computer Integrated Construction (CIC) Research Group of The Pennsylvania State University (BuildingSmart, 2013). Additionally the template proposed in the AEC (UK) BIM Protocol Project BIM Execution Plan, '*Implementing UK BIM Standards for the Architectural, Engineering and Construction industry'* (AEC UK, 2013) was utilised. As stated within the document the plan is a "pro-forma and guidance document to developing a Project BIM Execution Plan."

As with the intention of BxP documents a bespoke template was created specifically for the needs of the George Eliot refurbishment research project. An analytical process to establish the goals and detail of the document has taken place using the information with the two referenced sources (BuildingSmart, 2013) as can be seen in Table 4 below:

PEP Goal/Detail	Definition/Aim	Rationale	Format
Project Scope	Briefly describe the project scope in terms of: Project Phasing Approximate Site Area; Approximate Gross Internal Floor Area; Contract / Delivery Type. Location (crucial to include project coordinates), general arrangements, physical environment and design constraints can all be included.	Gives an overview to the project whilst setting out agreements on significant project parameters	Bullet point
Set out project goals	Briefly discuss and agree the project goals identifying a unified understanding as to the overall aim/brief of a project.	Sets a concept stage agreement on project goals	Bullet point
Set out project duration BIM goals (identify high value BIM uses during	Discuss and agree the project BIM goals identifying a unified understanding as to the overall BIM target for the project. The BIM execution plan should document the overall Project BIM objectives.	It's crucial to not just make a leaping statement of 'this will be a BIM project'. Clear agreement and goals need to be set from the outset to ensure that the direction through BIM	Bullet point

PEP Goal/Detail	Definition/Aim	Rationale	Format
the project)	These should be discussed and agreed between all Stakeholders. The selection of these objectives will be dependent on many factors	is collaborative and of a high value nature to the project.	
Set out post completion BIM goals	Identify high value BIM uses for use within the operations and maintenance of a project/building	Setting out post completion BIM goals can assist to ascertain what use BIM will have for those who will use the infrastructure or building post completion. These can vary from project design and construction BIM goals	Matrix table/bullet point
BIM deliverables during project	Significant BIM deliverables for the project. The BIM goals are set, this matrix should deal with the actual outputs to meet these goals	Enables the project team to clearly identify BIM outputs. These outputs will then directly affect multiple other sections such as the technology specifications, modelling and design protocols and the exchange protocols	Matrix table/bullet point
BIM deliverables post project completion	Significant BIM deliverables for the post project completion. The BIM goals are set; the project BIM deliverables should be set, this matrix should deal with the outputs to meet these goals of building management and operations.	Enables the project team to clearly identify BIM outputs to meet post completion goals and operations. These outputs will then directly affect multiple other sections such as the technology specifications, modelling and design protocols and the exchange protocols	Matrix table/bullet point
Organisation, Roles and Responsibilities.	This can be company members, Research team etc. involved within the project.	Sets out a clear easily accessible matrix for organisation, roles and responsibilities within a project. Key information should be included such as contact details.	Table Matrix
Projects resources and team skill sets	Identify the resources available to the project as well as the skill sets of team members	This matrix is crucial in ascertaining what resources and skills are available to a project. This has a direct consequence on the scope of BIM adoption whilst also identifying strong or	Table Matrix

PEP Goal/Detail	Definition/Aim	Rationale	Format
		weak areas within a project.	
Unique project challenges	Identify any unique project conditions/ challenges which may influence the approach to the project design/ delivery	It is beneficial to identify any known challenges from the outset of a project; this will enable the processes within the project to be designed to overcome these challenges.	Bullet Point
Facilitate Collaboration and communication procedures	The PEP document through its nature aims to improve the collaboration and communication procedures by setting out clear protocols from the outset and throughout a project.	BIM is not solely relative to technical processes, optimising the collaborative processes is crucial to the success of projects	Throughout document
General data exchange protocols	Setting out general data exchange protocols for standard data transfer and storage (such as word documents and SpreadSheets)	It's crucial to set out general data exchange protocols to ensure that data is shared in a manner, which adheres to the BIM goals set. An example; If a goal is an interoperable BIM project then the data needs to be shared in a interoperable manner such as (.ifc) or other common file formats (.doc)	General Data Exchange Protocols - Table Matrix - (What is the acceptable format of the required outputs and who will need the files? Do the files need to be shared as PDF's? Word or .dwg for instance?)
Modelling and design protocols	Common modelling standards should be established between all Stakeholders. Areas of consideration could include: -Modelling Methodologies. i.e. 2D, 3D -Software Platforms. i.e. AutoCAD, REVIT, TEKLA, Bentley -Level of detail; i.e. Architectural design, structural design, sustainable CAD documents etc. -Checking processes. I.e. Who checks whose work and how often etc.? This is to ensure simple mistakes are eradicated.	Setting out the modelling and design protocols ensures that all processes in relation to the area adhere to the agreed standards set within the project. Points such as the agreed level of detail are crucial in ascertaining what depth of BIM adoption is to be targeted	Bullet point
Model/design	Setting out model/design exchange protocol for	It's crucial to set out model exchange	Model/design

PEP Goal/Detail	Definition/Aim	Rationale	Format
exchange protocol)	standard data transfer and storage (such as word documents and SpreadSheets)	protocol to ensure that data is shared in a manner, which adheres to the BIM goals set. An example; If a goal is an interoperable BIM project then the data needs to be shared in a interoperable manner such as (.ifc) or other common file formats (.doc)	exchange protocol - Table Matrix -
Project timescales	Key project timescales	This can assist in determining the scope, cost and schedule of a project.	Table Matrix
Approved budget	Significant project budget information	Macro budget information (it's not necessary for a full breakdown of budget, the concentration should be on key budget parameters)	Matrix table/bullet point
Programme and schedule	Significant programming of the project detail	An overview schedule for the project and length of project is crucial to ascertain costs and scope.	Matrix table/bullet point
Set out technology specifications and use	Define the technologies to be adopted within a project and what the use of those technologies aims to achieve in regards to outputs.	A common mistake with the adoption of BIM is to purchase and select a technology prior to establishing the goals of BIM adoption for the company or project. Once those are set the technologies can then be selected as per the BIM goals and project requirements	Matrix table
Quality control	Ensuring the quality of information as well as the quality and optimisation of processes	To ensure the standards set out in the project/BIM goals are met	Matrix table
Meeting and Agenda structure/templates	Minutes template and Agenda templates	Efficient and regular communication is essential to the running of a BIM based project.	Template
Risk assessment for the internal research project.	Matrix assessing the risks that may occur as part of the project	During the early stages of a project it can be beneficial to attempt to predict and evaluate the possible risks within a project. The aim is to reduce the likeness of risks occurring before the fact through specific planning. Following on from the	Table matrix

PEP Goal/Detail	Definition/Aim	Rationale	Format
		identification of the risk measures to pre-empt or overcome them should be identified.	

<div align="center">**Table 4 - Execution Plan Matrix**</div>

Critical Analysis BIM Execution Plan Process

To assist to overcome issues in regards to the collaborative processes within the project a section within the internal BEP was created which outlined all of the relevant protocols and processes for data handling and sharing. The document, as with the nature of BxP documents was to be used as a road map for users outlining how to proceed and collaborate in a unified manner.

Additional to this as part of the wider FP7 RESSEEPE project it was highlighted by the author that the project was not fulfilling responsibilities in regards to adoption of BIM processes and practice. In the early stages of the project BIM protocols and a BxP document were not set up. This resulted in the data sharing and collaboration within the project being fragmented. One example of this in practice was through the identification that 'repetition of work' was taking place in regards to the drawing of CAD plans and 3D models. There were multiple parties repeating work that other partners had already progressed on due to the lack of informative collaboration and an understanding of what stage all parties were at in regards to CAD drawings, 3D models and documentation. To overcome this it was evident that 'pre-activity' planning collaboration had to take place to ensure that all parties were aware of other partner's progress and thus could collaborate more efficiently. Part of this process led to a multiple partner teleconference to discuss BIM within the project and a direct result of this was to utilise the process of a BEP. A document was set up by one of the partners within the project to assist in the collaboration of information.

3.9. BIM Authoring Tool Requirements and Selection

As part of the software selection process for this study a main BIM authoring tool had to be selected. Autodesk REVIT platform has been selected as a capable tool to produce a detailed BIM and Mass models. Autodesk REVIT has the ability to produce and export in the required file outputs defined in the BIM objectives and tools matrix such as IFC and gbXML. Additionally the research has prior skills and experience in using REVIT thus it was an efficient decision to carry out the design and BIM modelling work within the tool. OpenBIM and interoperability were of key concerns, which needed to be considered additionally to the skillset of the operative. The REVIT tool has the capability to export to the IFC data standard, which is what gives it the ability to work within an interoperable environment. This process is by no means perfect and investigations into the success rate of the IFC export function will be explored later within this thesis.

3.10. Investigation into BIM Simulation and Interrogation Software Used Within Project

Table 10 is matrix analysing the software to be used within the simulation and interrogation of the BIM 3D model;

Goal	Type of Analysis	Level of detail required in model	Software platform and file format	File Format	Weakness and challenges	Minimum software expertise required
Energy Simulation	Heating and Cooling Loads (H&C loads)	Geometric Spaces and material components identified	AutoCAD -REVIT	.RVT, gbXML	A lot of data is exported through the H&C simulations. Analysing this data for relevant information is required and takes time. The REVIT process takes additional modelling preparation specifically for the H&C simulation. Software expertise	Software expertise to; :set up 3D model - medium :Run H&C simulation - Low :Analyse H&C data - Medium > High
Energy Simulation	Day lighting	Geometric Spaces – External and internal, Window position and size, solar shading detail, building orientation	REVIT, IES VE	.RVT, .IFC	Import into IES VE requires any model to be set up and prepared for IES VE import. Variations to model may be required to suit the import process, such as a reduced level of detail. Import process from REVIT to IES VE can be slow depending on file size.	Software expertise to; :set up 3D model - medium :Run VE simulation - High :Analyse IES VE data - Medium > High
Model validation	Validation of model for clashes	As set by other goals, to include; Geometric Spaces and material components, wall positions, feature positions,	Solibri	.RVT, .IFC	Issues need to be manually resolved. Is an iterative long process Coordination of models is required Models need to have a relatively high detail to draw valuable results	Software expertise to; :set up 3D model – high User of Solibri – Low> Medium

		doors, windows, dimensions.				
Model validation	Validation of model against building code rule sets	As set by other goals, to include; Geometric Spaces and material components, wall positions, feature positions, doors, windows, dimensions.	Solibri	.RVT, .IFC	Issues need to be manually resolved. Is an iterative long process Coordination of models is required Models need to have a relatively high detail to draw valuable results	Software expertise to; :set up 3D model – high User of Solibri – Low> Medium
Energy Simulation and design optimisation	Optimisation of option strategies for refurbishment	As set by other goals, to include; Geometric Spaces and material components	Green Building Studio	gbXML	Interoperability a key issues High level of detail and complexity of models can halt progress.	Software expertise to; :set up 3D model – high User of Solibri – Low> High (depending on the requirements of analysis) Green Building Studio Low> High (depending on the requirements of analysis)

Table 5 - BIM Software Application Matrix

3.11.   Processes

A particular choice when modelling buildings retrospectively is the decision on whether to model with individual components and families, masses or a selection of the two. When considering components and families the benefits are such that it offers a lot of flexibility in regards to sizing of components and placement. Adjusting the position of the components is simply a shift and drag motion. The drawbacks however are that it restricts the speed of interrogation and design optioning that can take place. With the use of massing on the other hand multiple design options and simulations can be carried out with relative speed and ease. In new build design this particular process is or should be crucial as it enables a designer to simulate multiple mass models in quick succession investigating varied volumetric changes and building orientations with few resources used. As this project has an aspect of focus on the investigation into retrospective modelling either approach could be used. The choice was made to use a selection of both techniques to enable the most valuable and efficient process. Using components allow for a large amount of control in editing bespoke and 'off the shelf' families, whereas having a mass base for the model allows for far greater simulation and geometric analysis.

3.12. Description of Challenges

A particular hurdle when modelling retrospectively was the accuracy of available data. As discussed previously the data available on existing building stock can on occasion be sporadic and often low in accuracy. This difficulty was evident when modelling the curtain system façade of the case study building. All of the current elevations only showed indicative sizing with no clear dimensions. There were typical detail plans available for the 1994 upvc refurbishment windows and curtain system, but these were early stage drawings and it was not specified whether the plans were as built. Clear indication of the proposed dimensions for the glazed proportions was present. The opaque sections however lacked clear dimensions. With further investigation and measurement carried out on site it became clear that the typical details were not reflective to 'as built'. To model the curtain grid geometric analysis was used. (Through analysing the sizes of various neighbouring components to the curtain system and grid it became clear that the size of the metal frame windows on the east stairway were the same size as the opaque section of the main curtain system. With further on site dimensioning of the windows it was then possible to approximate the size of the opaque section with the main East and West curtain system).

The issue with the curtain grid highlights the problematic nature of retrospectively modelling old buildings. It's significant to note though that the same absence in information in regards to curtain system design required to produce a 3D model a building may also be required in many building retrofit cases. This particular aspect drives a need for up to date building data and surveys. Without the latest information the use of approximations is all too apparent and could easily become a significant issue. A number of assumptions had to be made in regards to building details and structure due to the nature of the project. A full invasive survey was not possible therefore exact layers of facade materials were not known. Nor were detailed structural plans containing structural slab dimensions available. Therefore calculated assumptions had to be made in respect of this. The slab was estimated using known exterior heights and internal floor to ceiling heights and the façade material layers were estimated as per standard construction techniques during the era of construction. The intention of the document would be to inform future users of the assumptions made within the model at a glance. This would allow future users to be fully aware where assumptions have been made in regards to modelling and absence of finite data. It will be crucial for the assumptions made within the modelling processes in this project to be validated against a full building survey. This will ensure that as much as reasonable the model data can be utilised in future building management processes. The investigation into the building modelling process prior to the building survey, whilst not ideal, has allowed for significant gaps in building data to be highlighted prior to the building survey taking place.

3.13. Process Map for Preparation for Modelling and BIM Modelling Adoption

Figure 16 shows the result of the experiment into the preparation for modelling identifying the critical steps. The process map will be discussed in detail within the discussion chapter. (Note all images can be seen enlarged in the appendix of this thesis)
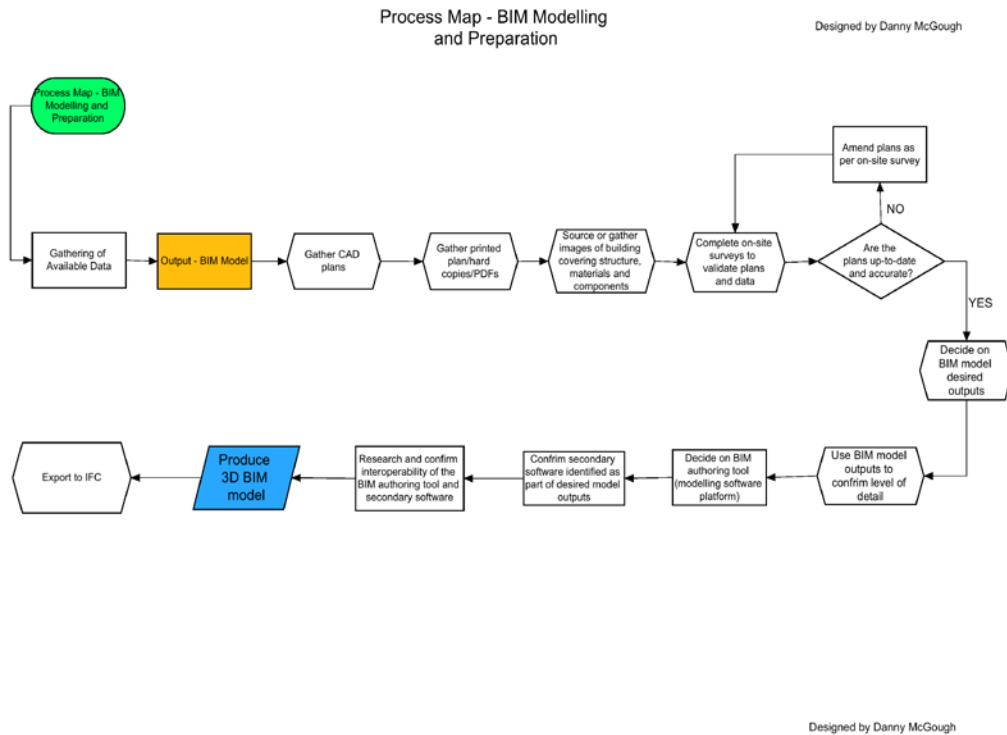
Figure 13 - Process map - Preparation for modelling and BIM modelling adoption

3.14. Rooms and Spaces Definition

Throughout the following sections a number of reference will be made to spaces and room volumes. To clarify the difference between the two they can be explained by Autodesk as, "Rooms and spaces are independent components used for different purposes. Rooms are architectural components used to maintain information about occupied areas. Spaces are exclusively used for the MEP disciplines to analyse volume" (Autodesk, 2014). Within this case study both definitions of spaces have been incorporated into the George Eliot REVIT model.

3.15. Model Validation Data Collection and Analysis

To first enable the validation process to begin the REVIT model created for the George Eliot building had to be exported via IFC format. As discussed within the literature review chapter of this work IFC file format is a crucial factor in ensuring and enabling interoperability within BIM processes. The process to import from REVIT to Solibri was smooth with the use of REVIT's IFC export option. However when using the standard built in IFC exporter which comes with the standard REVIT install unusual graphically anomalies appeared which indicated that certain components such as stairs and railings were not exported correctly with the coordinates and position of the component wrong. To resolve this issue the IFC export functionality was updated within REVIT using the 'Autodesk IFC export plug-in tool' (Autodesk, 2014). The IFC plug in tool for REVIT has been designed to provide greater accuracy when exporting via IFC. This then resulted in a cleaner IFC export

functionality. The Clash detection source files can be found in Appendix E – Model Validation

3.15.1. Model Validation – Clash Detection

The first checks to take place in the model validation phase was to analyse the George Eliot model in clash detection. To begin the process rulesets for the checking process had to be selected. For this demo investigation the 'Intersections between architectural components' ruleset was used, Figure 17. Its crucial to carry out the initial clash detection checks prior to running any other analysis to ensure the robustness of BIM models.
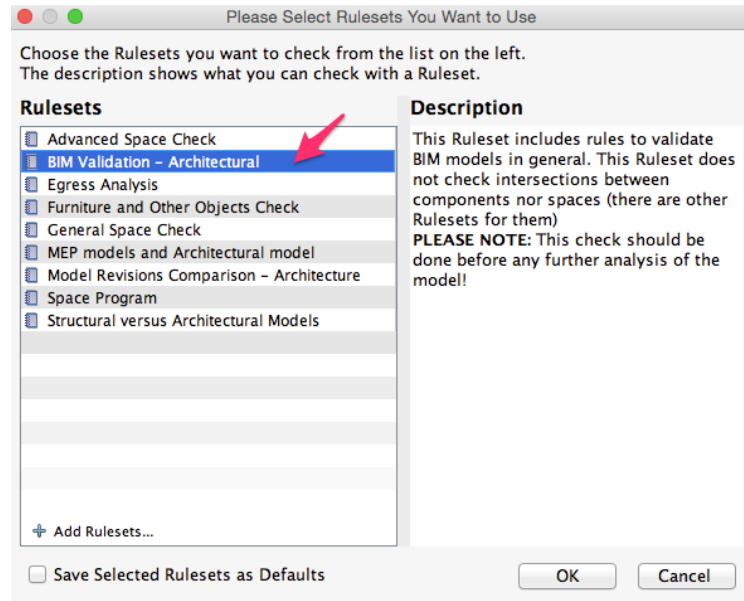
Figure 14 - Clash Detection - Intersections between architectural components

Once the ruleset is loaded into the checking window the checking process can be run. Results are displayed within the Solibri windows. Issues or clashes with the 'same kind of components' result showed 22 issues/clashes in total, with 15 being classified as critical, which is a reasonable figure for first clash run. In contrary to this the ruleset of 'intersections – Different kind of components' flashed up a total of 443, with 18 being critical. Further investigations were needed to work through the results. The results need to be worked through slides added for communication reports, Figure 18.
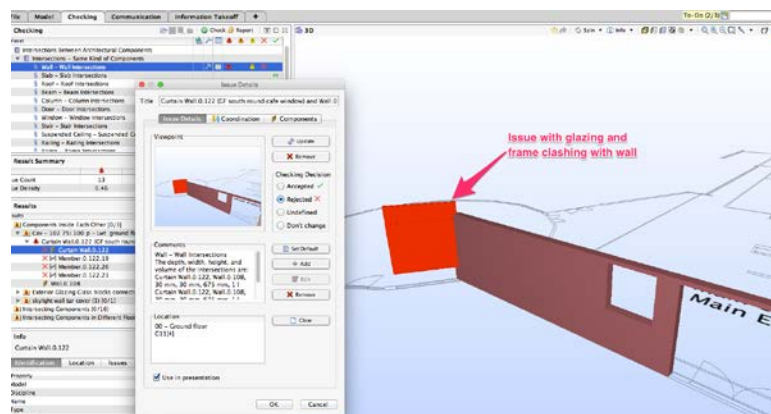
Figure 15 - Reporting clashes - Adding Presentation Slides

For the demonstration of this process within this project it was determined to work through the critical errors first and then work through the lower alert issues. A number of yellow issues were raised in regards to walls intersecting into slabs, these error were also

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noted in the report produced. Once all the clashes are visually checked and reported and report presentation can be created within the communication tab in Solibri. This report can be displayed internally within Solibri, exported to SpreadSheet or exported in the form of a BCFZIP, which will be discussed later on.

3.15.2. Fixing clashes - BCFZIP Analysis and Integration

Once the clash detection validation was completed an iterative modelling process was followed. In this study a process of taking the clash detection results from Solibri into REVIT was used. To allow this an additional BCF import/export app had to be sourced and installed, which was free. The BCF plugin add on enables the user to exchange BCF files importing and exporting. This enabled a workflow link between Solibri and REVIT by supporting the exchange of the clash detection report that was previously created during the model validation clash detection phase. The add on is presented in a number of ways, including a simple visualisation of the report in a standalone viewer, the visualisation of the report within REVIT which can be seen in Figure 19 and additionally a very useful quick zoom to each clash via a quick link between the clash report viewer in the plugin and the REVIT model which can be seen in Figure 20. This results in an efficient process to seek out clashes with the coordinated data interoperable between packages rather than having to rely solely on a visual identification and locating of the clashes.

Using this process the clashes can be worked through one by one until the clashes are resolved. It is important to note here however that it shouldn't be assumed that all clashes have been eradicated and fixed. Therefore an iterative round of model validation should take place to check the latest IFC export for clashes post the model fixing stage.
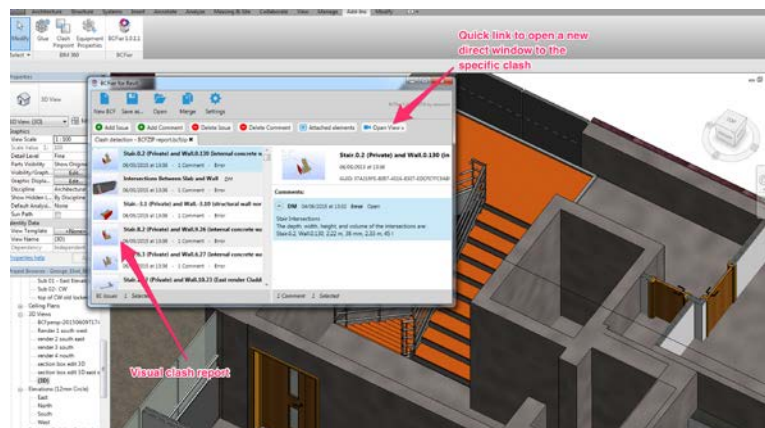
Figure 16 - BCF viewer and link to viewing clash
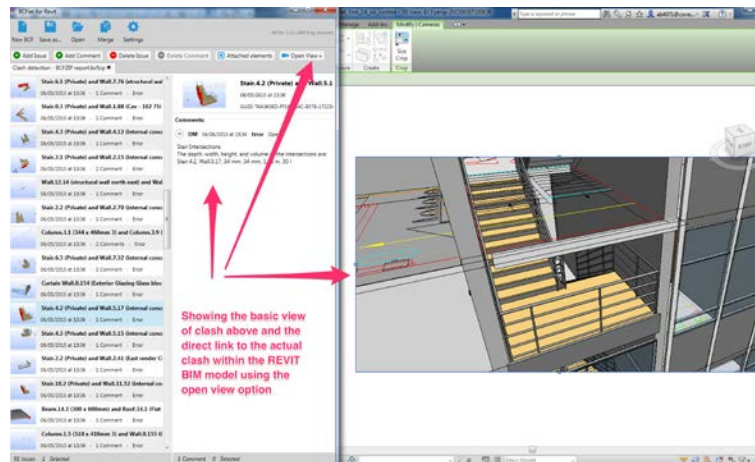
Figure 17 - BCF - Opening the specific view to identify clash
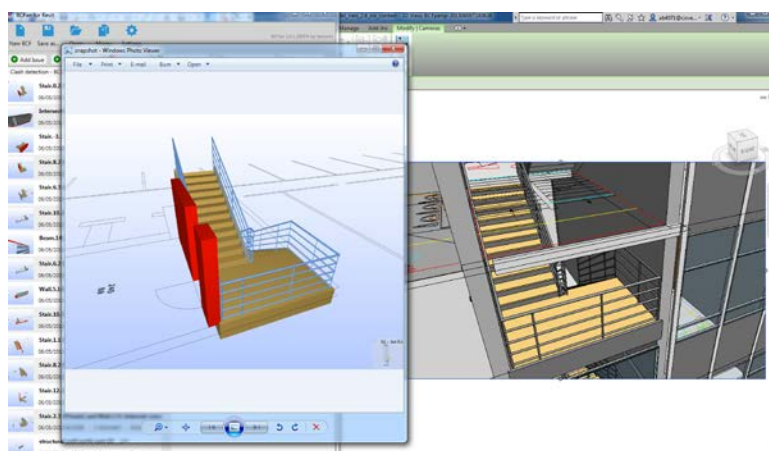
Figure 18 - BCF - The visual clash viewer within BCFier and the linked model view in REVIT

Due to issues with locating exact positions with clashes even with the visual report in BCFier and the quick link to the location, the Solibri report and communication layout was used as a back up support. The reasoning behind this is that the visual BCFier report did not carry over any visual notes on the location of issues whereas within Solibri it held the location, floor, height and offset details that can help to further locate issues. When attempting to find it via the quick link it in essence draws you to the image snapshot you created in Solibri. This transition is not exact and often the view can be obstructed by building components, which are automatically hidden within Solibri when attempting to isolate issues. That said using BCFier for the most part with the occasional use of the source Solibri report has made the process of eliminating clashes more efficient than just using the standalone Solibri report. On a limited occasion there can be an inconsistency between clash issues reported and the model representation. For instance a clash may be flagged up in the clash report, which in relation within the model is not an issue. In the case of this study a door was showing as not having cut through a wall appropriately, whereas in the model the standard door insertion was working correctly Figure 22. This highlights an awareness required when using 'automated' technology, signifying the importance of a professional user with relevant construction skills knowledge to interpret results and data.
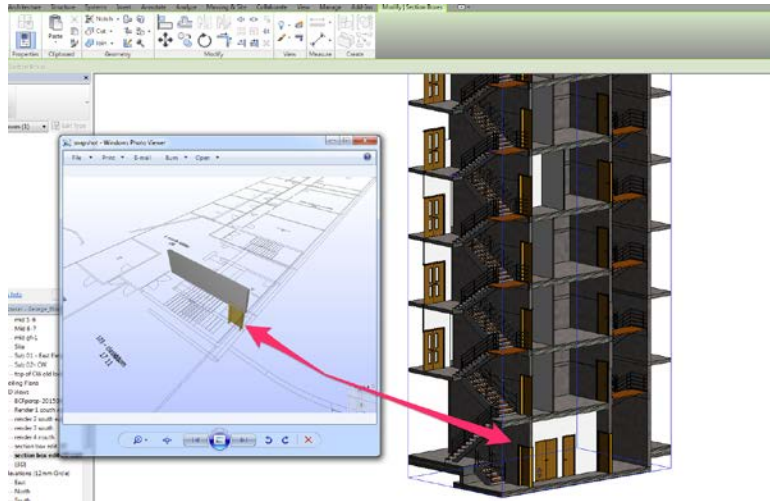
Figure 19 - Clash report inaccuracy

3.15.3. Iterative Design Approach

Once the clashes have been dealt with within REVIT and the user is content that all issues have been resolved then two processes can begin. The first is that the Solibri model should be updated through the file tab within Solibri where the latest IFC file can be selected and uploaded. This means that any internal progress done already within Solibri is not lost and the connection in the checking process is continuous. The visual location of the option, Figure 23.
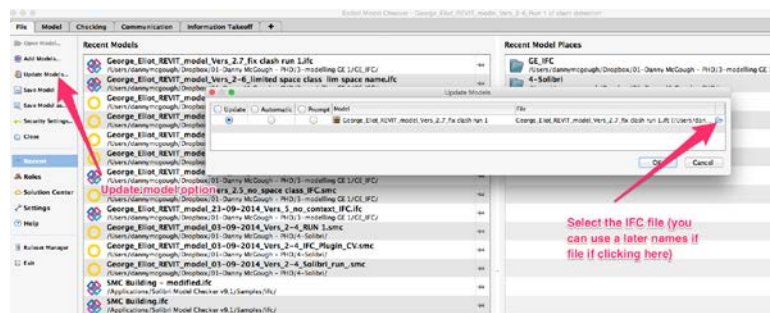
Figure 20- Clash detection - update models

Again the results are displayed within the Solibri results window. Issues or clashes with the 'Intersections - same kind of components' result showed 10 clashes compared to the 22 issues/clashes in run 1, with 3 being critical compared to 15 in run 1, which is a reasonable reduction for one run. The ruleset of 'Intersections – Different kind of components' flashed up a total of 235 in run 2 compared to 443 in run 1, with 5 being critical compared to 18 in run 1. Further investigations were needed to work through the results. These are reasonable reductions but further investigation is required to evaluate the issues.

An unusual occurrence with the second run was that it actually found new issues in areas that hadn't been touched or altered since the first run, which anomalously weren't highlighted in run 1. This highlights the need for multiple runs. It is noted that a full structural survey will be required to accurately model the structure therefore any structural components in regards to columns. The stairs in preparation for run 2 had been radically improved therefore the clashes were limited down to 7 which have been reported for run 2 model amendments. Repeating the previous process the run 2 clash report was exported via BCFzip and then opened within REVIT using BCFier. The issues were then worked through. Similarly the latest IFC file was updated within Solibri repeating the steps in run 1 and 2. The checking was run again for a third time, run 3 results can be seen in comparison in Table 7.

The results have again markedly improved in run 3 with a total of 5 clashes in 'Intersections - same kind of components' compared to the 10 issues/clashes in run 2, with 0 being critical compared to 3 in run 2, which is a reasonable reduction for the second run. The ruleset of 'Intersections – Different kind of components' flashed up a total of 59 in run 3 compared to 235 in run 2, with 1 being critical compared to 5 in run 2. The report is then worked through again as previously explained. As can be seen in the Table 7 the clash detection was run through 5 runs in total to ensure that all modelling errors were removed.

Ruleset	Run 1		Run 2		Run 3		Run 4		Run 5	
	Total	Critical	Total	Critical	Total	Critical	Total	Critical	Total	Critical
'Intersections - same kind of components'	22	15	10	3	5	0	0	0	0	0
Intersections – Different kind of components'	443	18	235	5	59	1	5	0	0	0

Table 6 - Clash detection results run 4 and 5

Figure 24 shows the clear set of clash results.
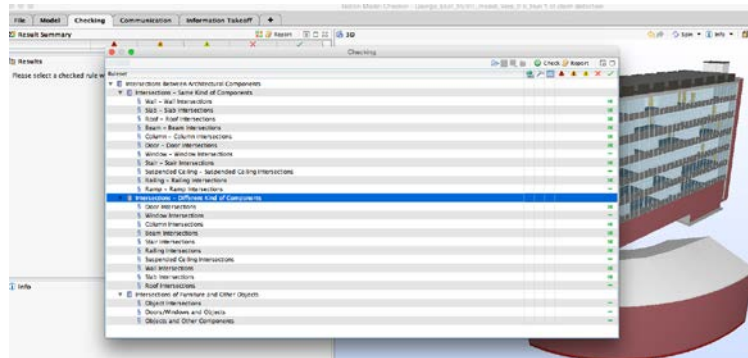
Figure 21 - Clash detection - full set of clear results - no issues

3.15.4. Process Map for Solibri Clash Detection

Figure 25 shows the result of the experiment into the Solibri Clash detection process identifying the critical steps. The process map will be discussed in detail within the discussion chapter.
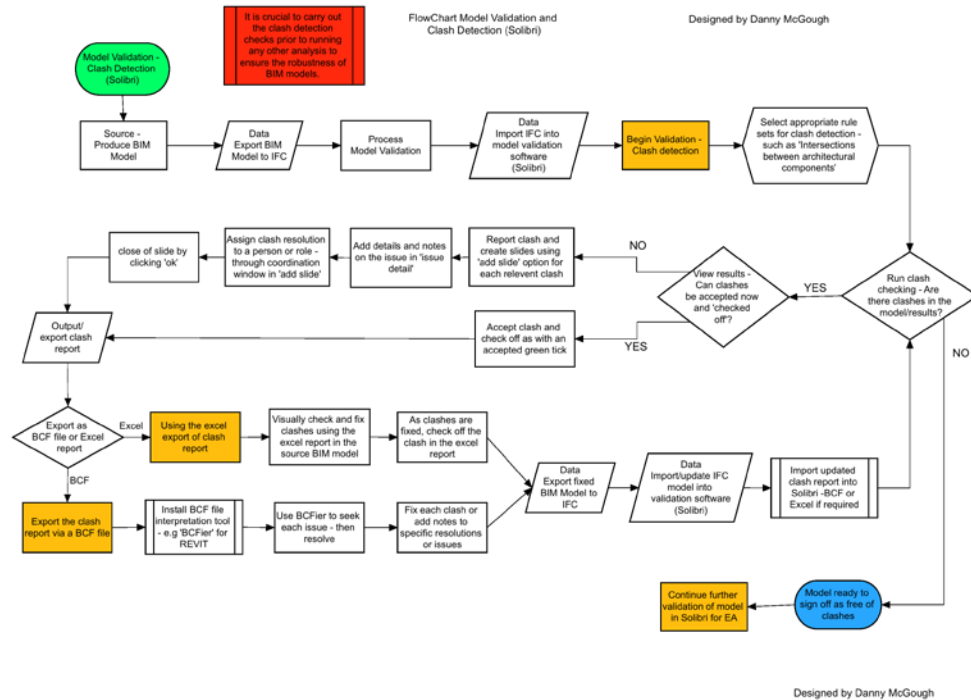
Figure 22 - Process map - Solibri clash detection

3.16. Model Validation General Space Check

The next phase was to set up the software to run checks on the models readiness to run energy analysis using the 'pre-check for energy analysis' ruleset, a number of issues were encountered. The issues were regarding space allocation and building envelope definition. Before proceeding with the pre-check, classification data had to be assigned. These issues were not success defining but if overcome would ensure better validation. The solution was relatively simple to redefine rulesets that match the analysis output required, as this will add the classification rules automatically.

A common thread error appeared throughout the check warning that spaces had not been assigned to the SMC (Solibri file save model), however spaces were defined before export/import from REVIT into Solibri. This highlighted a lack of interoperability between the programs. This highlights an issue either within the Solibri analysis software or an issue residing within the initial model and export. Evaluating the source model a solution was found, spaces needed to be correctly defined within the BIM authoring tool prior to export/import into Solibri. This step highlighted the justification for the use of validation software, as it not only picks up subtle issues but also more prominent issues. The issue if left unresolved would undoubtedly slow down any energy analysis process. Significantly this highlights the need for BIM models to be designed with outputs envisaged to allow for sufficient data to be inputted into the models during design and creation phase. If energy analysis is defined as an output from the outset then it is crucial that spaces are defined within the modelling phase. This signifies the importance of the Software Application Matrix in Table 4.

Once spaces are defined within BIM model then the 'space usage' will need to be defined with the classification parameters in Solibri. This process is another added step that should be automatically carried over within the IFC data from REVIT, however in the first run this classification data was not present. This again highlighted a required step missing. It is possible to address this issue directly within the validation software as can be seen in Figure 26 however it was decided to explore rectifying this problem at source within REVIT. The link between the space date > IFC > Solibri is not clean and allocated space type within REVIT did not automatically add space classification over to Solibri. A process is available within Solibri to apply space name 'classification rules' to help Solibri recognise and realign spaces from their name, its important to highlight that this differs from space type however and is using the name of a space not the space type classification data within REVIT.

This process was successful in part however a limitation of the space classification matching was discovered between the software. Each room within REVIT had a room name, the identifier for this name was a room number i.e. G04 or 104 or 504. The numbering/naming of rooms within the UK in large education buildings and campus' is relatively standard and conventional. Such that the first letter or digit denotes the floor, i.e. G, 1 or 5 in the above example is Ground Floor 1 and Floor 5. When this data is carried over into Solibri via IFC this numbering convention is not recognised by any of the space classification system. This is logical as Solibri is looking for key words such as 'CLASSROOM' or 'OFFICE'. The issue is that in UK building management it's not logical to just have 100 'CLASSROOMS', each room needs a unique identifier. Working with this issue an attempt was made to add '1-4 – classroom' to the REVIT room name, this still resulted in the space not being recognised by the classification system even with the keyword 'classroom' added. Multiple attempts were made to persuade the classification rules within Solibri to recognise the spaces automatically and thus efficiently but none were successful. Figure 26 shows a screenshot of the pre-set classification rules and the window to alter the classification in Solibri.
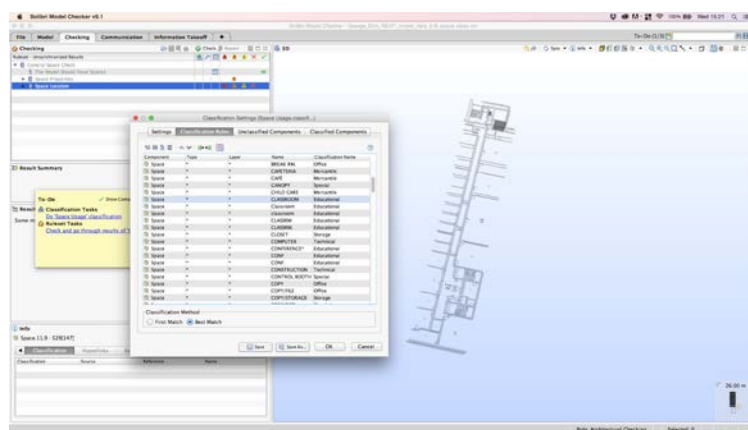
Figure 23 - Issue with classification rules with REVIT

Considering that Solibri will not recognise the 'space type' option within REVIT analysis options, nor will it recognise space names unless they are exactly matching, with no numbering system as discussed above a decision was made to allocate space classification manually once the REVIT IFC model was imported into Solibri. Figure 27 shows adding of classification manually.
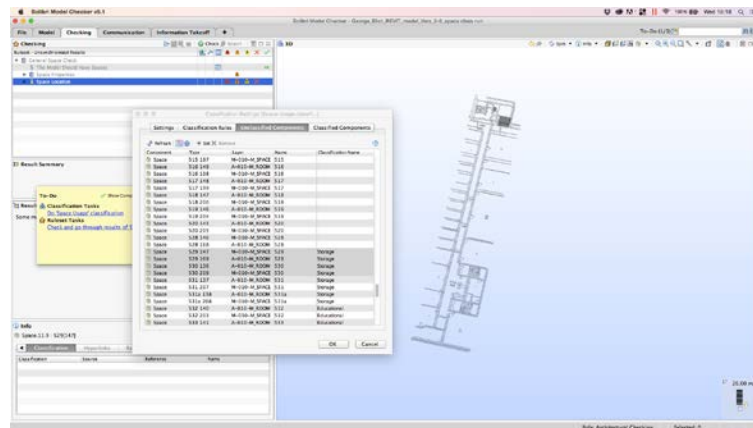
Figure 24 adding classification manually

The process to go through the classification of spaces manually on such a large building can be an extensive task, however it is not complicated. Once the process is complete a wealth of analysis can then take place within Solibri such as space usage and percentage of circulation per floor. Figure 28 shows the process aligning existing REVIT classification within the Solibri rules.
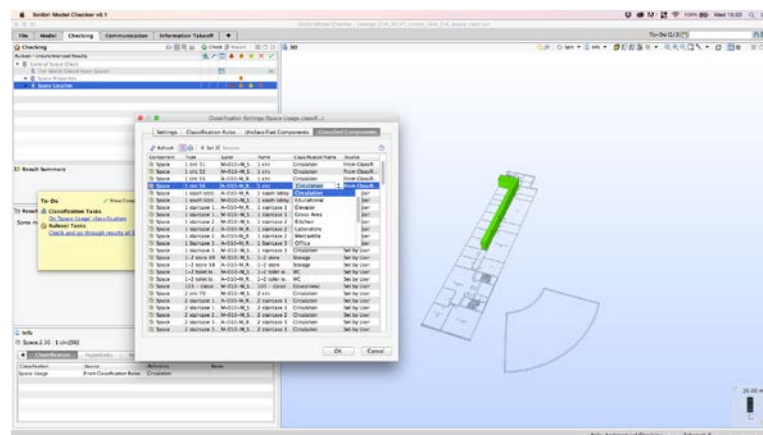
Figure 25 - Classification aligned with Solibri rules

Another notable issue encountered was the fact that Solibri was interpreting both REVIT room tag spaces and REVIT Heating and cooling spaces as 'Spaces' within Solibri. The software was then warning that these were duplicate components when in fact they are both different definitions of spaces within REVIT. REVIT room tags are used to define architectural spaces and REVIT heating and cooling spaces are used to define volumetric spaces for use in energy analysis. Additionally the later provide the correct constraints to enable gbXML export to external analysis software.

During the 'General Space Check', a number of issues can be resolved; it is beyond the scope of this research to outline each and every issue in detail. Instead a typical scenario of the process will be outlined. In this instance the results summary has highlighted a number of issues in regards to space validation, as can be seen in Figure 29.
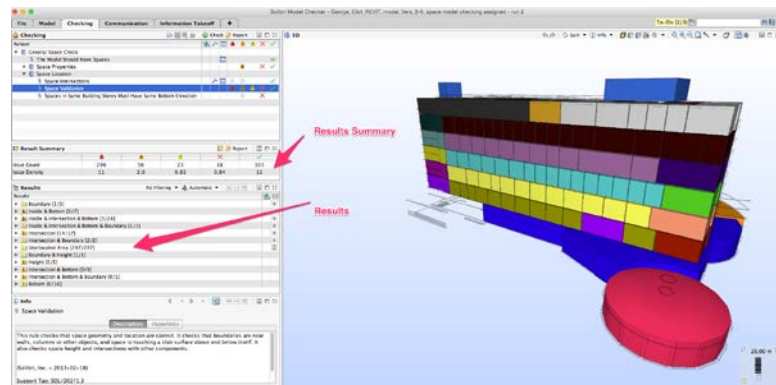
Figure 29 - Solibri Space Validation result summary

Once the checking process is completed results section shows specific issues in Figure 29. These issues can then be inserted into an internal presentation format within Solibri's 'communication' tab, or exported into a presentation report, as presented in Figure 30:
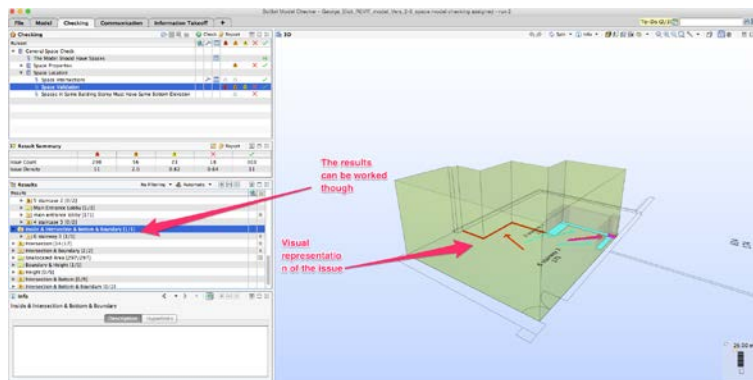
Figure 26 - Checking through individual results
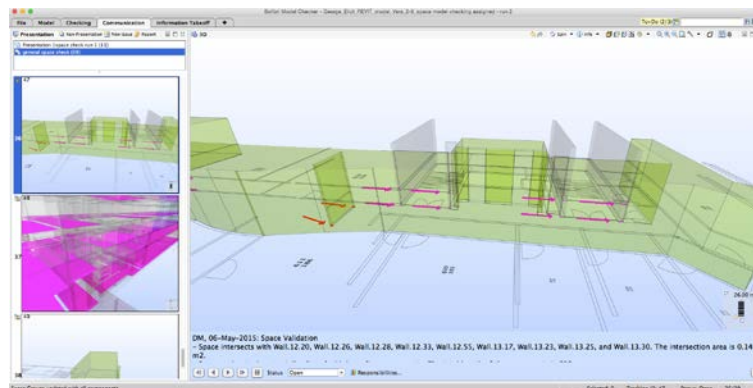
Figure 27 - Internal communication of slides

Once the general space checking process is completed appropriate reports can be created which demonstrate the processes and information that can be derived from 'space usage' validation as presented in Figure 31. Figure 32 demonstrates space usage take-off which can be accomplished once the space classification is aligned. Also see appendix E for exported reports on the general space check issue SpreadSheet as well as the spaces take-off SpreadSheet.

Figure 28 - Space successfully added and takeoff

3.16.1. Process Map for General Space Check

Figure 33 shows the result of the experiment for the general Space Check identifying the critical steps. The process map will be discussed in detail within the discussion chapter.

Figure 29 - Process map - General space check

3.16.2. Process Map for Pre-Check for Energy Analysis

Figure 34 shows the result of the experiment into the pre-check for Energy Analysis identifying the critical steps. The process map will be discussed in detail within the discussion chapter.
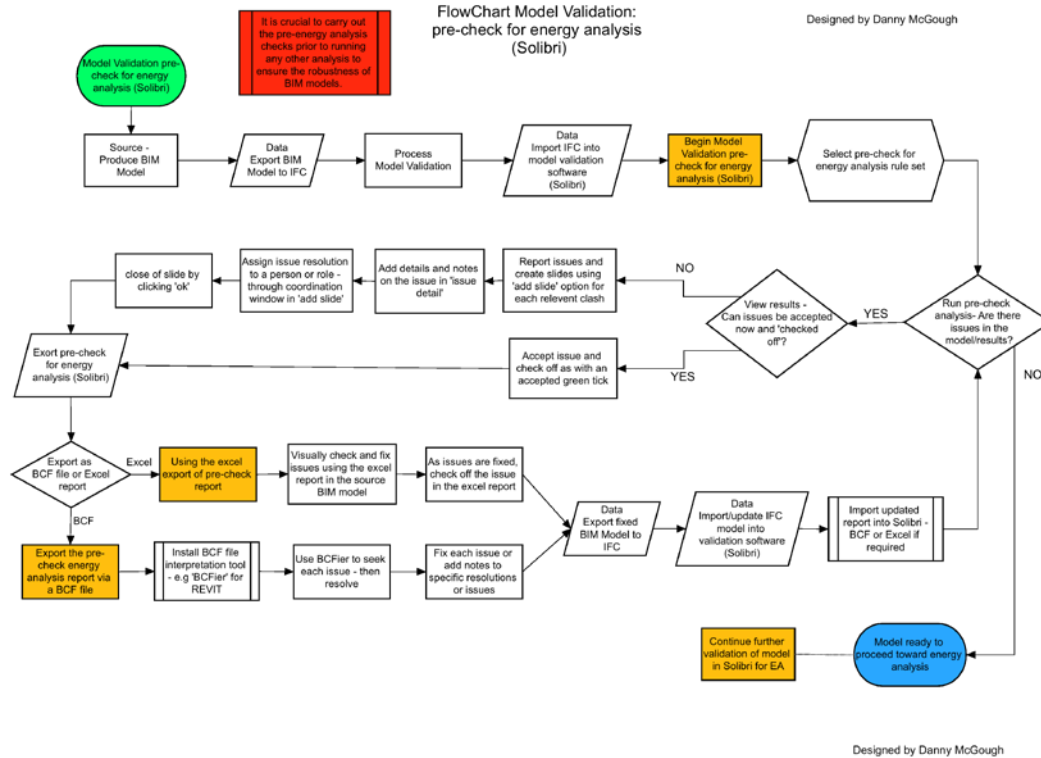
Figure 30 - Process map - Pre-check for energy analysis

3.16.3. Quantity Takeoff – (Solibri)

Once a model is validated, the model can be used for takeoffs, such as quantity takeoffs. Skilled professionals to assist in the costing and management of building can use the takeoff. Within this case study Solibri will be utilised to demonstrate quantity takeoff. When first attempting to carry out takeoffs the first step is to ensure that any outstanding prompts are worked through. In this case study a number of components remained unclassified, which had to be manually checked and classified through to windows, as presented in Figure 35.
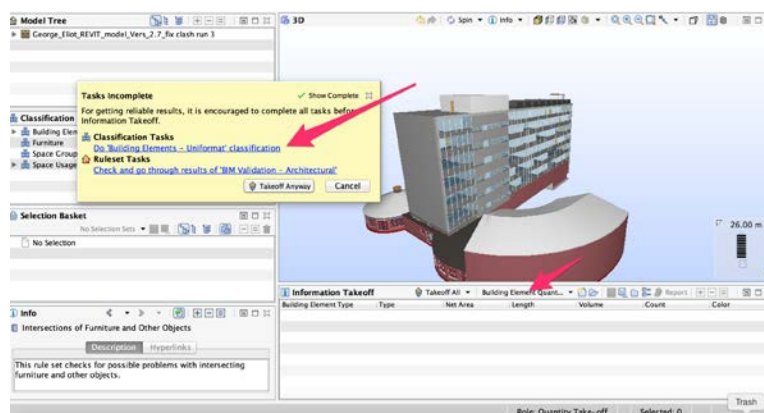
Figure 31 - Solibri complete classification for missing elements

Once in the classification settings window, any issues with classification can be seen. The unclassified components should be aligned with he correct classification as seen in the

step, in Figure 36. Once the classification of components is completed results can be drawn off from the model, as presented in Figure 37. It is important to note here that during many steps and processes within Solibri there is an option to ignore prompts. In doing this there is a risk of analysing or drawing off data that is incorrect as the source data may be incomplete or inaccurate. The prompts are there to act as a warning sign highlighting possible issues, a professional has to decide whether they are relevant to the integrity of the analysis or not. Once takeoffs are drawn off from the model the report can be exported through the Solibri export option, as presented in Figure 38. Again the benefit of this option is that reports can be exported to PDF or excel, removing the requirement for propriety software to be used to view results or reports as seen in Appendix E. This in essence helps to drive the software towards an open approach.
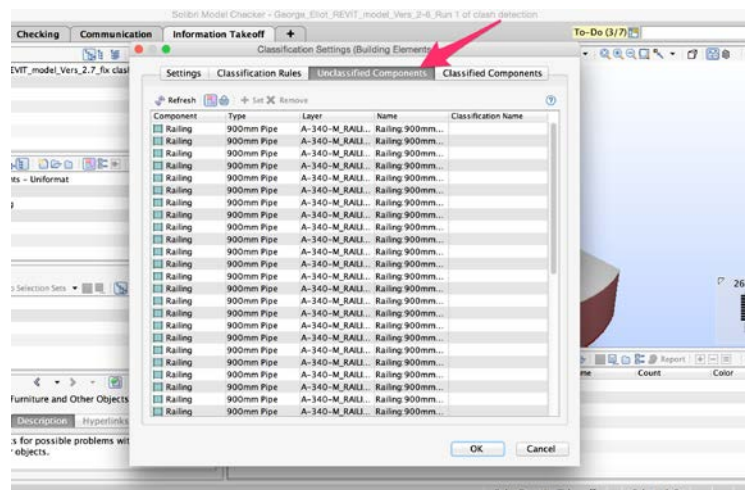
Figure 32 - Solibri unclassified components
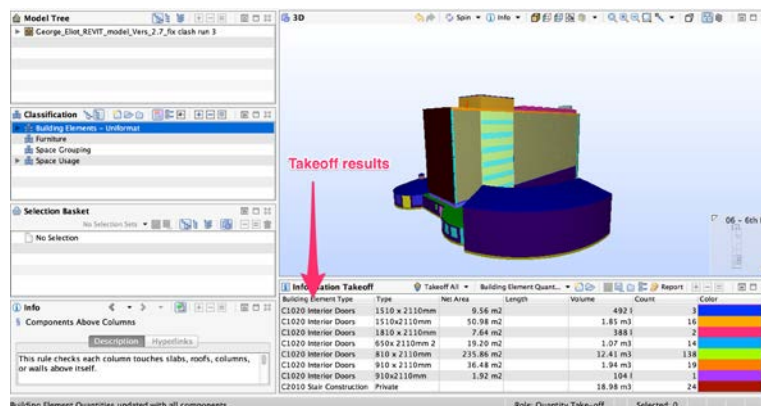
Figure 33 - Internal Solibri Takeoff Results
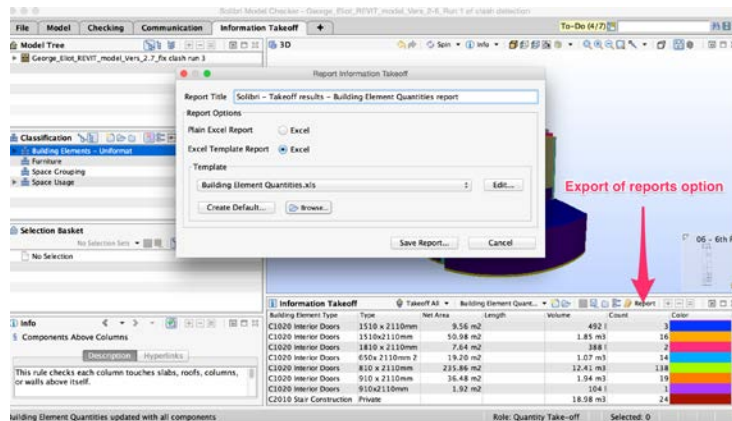
Figure 34 - Export Solibri Takeoff Results

3.17.   IES: IES VE ware

Additional to the collaborative processes of BIM and model validation a selection of simulation and performance software will be investigated as part of the project. IES VE has been selected as a tool capable of carrying out energy simulations and performance analysis, however the relevance to this study is on it capability to accurately import BIM models from the source BIM authoring tool. The simulation capabilities will not be tested as part of this project and are determined and outside of the scope. Autodesk 'heating and cooling' and Autodesk 'Green Building Studio, (GBS)' will be also be investigated to explore a wider pool of energy analysis software platforms. The process relies on using a central core model to base the simulation around. Within this project the import of data in the form of the GE BIM model from the REVIT authoring tool will be investigated. IES VE has been selected as a tool within this project due the reputation and interoperability of the simulation software with relevant authoring tools used within the project such as Autodesk REVIT with interoperability of gbXML, IFC & dxf imports.   The IES support files can be found in Appendix F.

3.17.1.   IES: IES VE ware Analysis

Whilst investigating the IES VE process the focus will be on the interoperability of the systems. Therefore, selections of runs evaluating the import of IFC files into IES VE from REVIT will be evaluated. Taking a scientific approach a number of models will be run through the process testing the impact the complexity and level of detail have on the interoperability. Another additional experiment will be carried out to assess the impact that model validation has on the interoperability. The first stage of the experiment was to run the final REVIT model, which had been validated to zero issues. The reasoning behind this is to evaluate an opening benchmark test. If this model is transferred seamlessly into IES VE then it will immediately set a high benchmark level for data accepted complexity. If it was to fail then the process will be drawn back to a much lower level of detail.

3.17.2. IES VE Benchmark Run

The initial benchmark run was a limited success but the import displayed many issues. Immediately using the model viewer initial errors can be seen with an absence of the ground floor and other spaces distorted and misshapen, as presented in Figure 39.
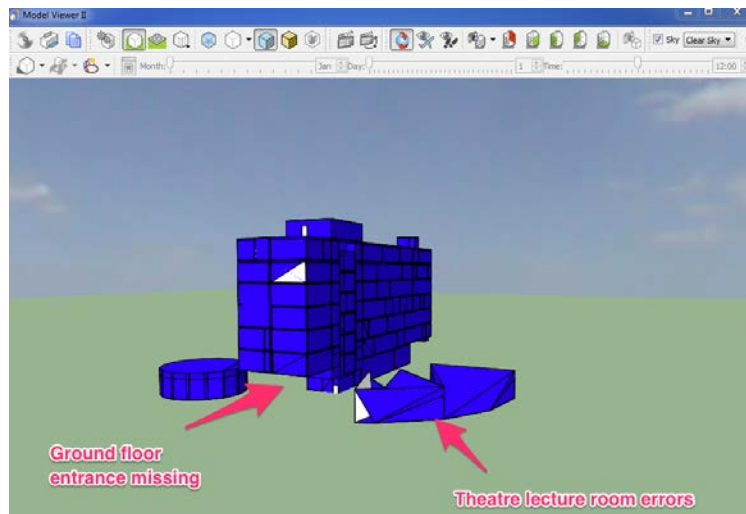
Figure 35 – IES VE - Benchmark run model viewer

Many spaces have parametric massing issues in that the volumes of spaces have multiple uncoordinated and misshapen spaces, as presented in Figure 40 and 41. These are not typical volumetric forms and are clearly errors within the communication between the REVIT IFC export and the IES VE import. An additional error can also be identified in that IES VE is recognising both the room tag spaces with REVIT as well as the analysis spaces within REVIT. This has resulted in two volumetric spaces per room/space within IES VE. This will lead to further inconsistencies and errors during interrogation.
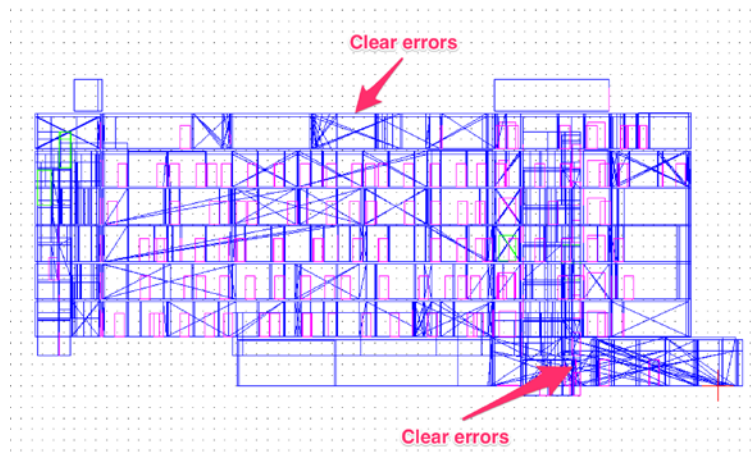
Figure 36 - IES VE- Clear modelling errors within the import
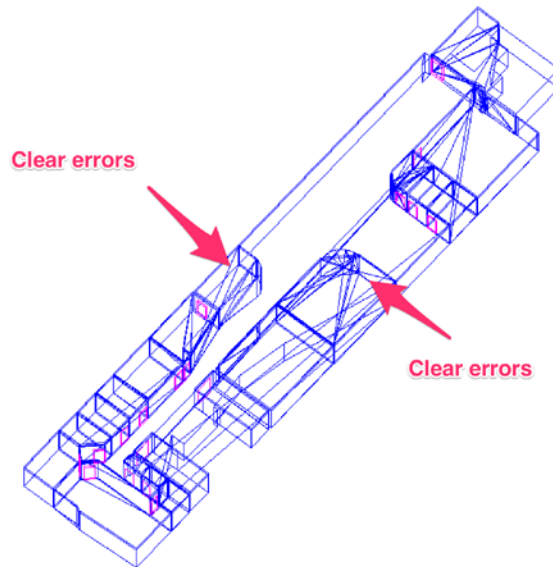
Figure 37 - IES VE - Clear modelling errors within the import 2

The errors have been identified as room bounding issues, which have been identified through the 'BIM Import' report, which is created during the import process. These errors will be discussed in greater depth within the discussion chapter of the research.

3.17.3. IES VE Benchmark Run with IFC level Space Boundaries

The next test to run was to evaluate what impact changing of the space boundaries[1] level has. For this run the space boundaries have been set to level 2 when exporting IFC from REVIT, Figure 42.
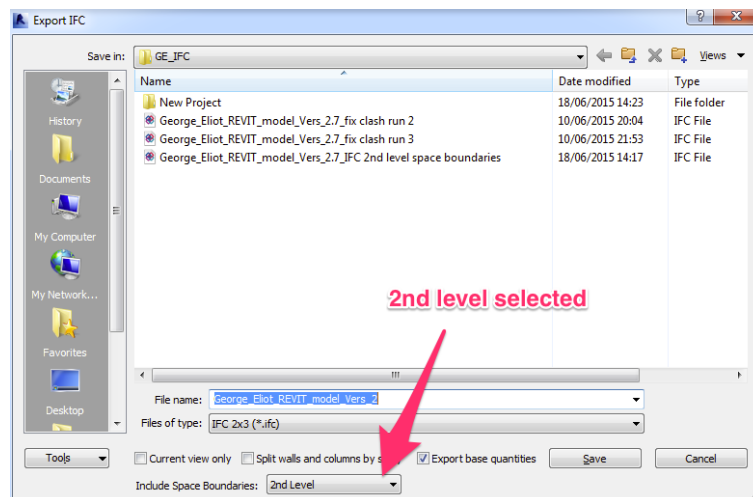
Figure 38 - REVIT IFC export 2nd level selected

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[1] The level space boundaries can be defined by building smart as:

1st Level Space Boundaries

1st level space boundaries are used e.g. in quantity take-off and facility management as they describe the surfaces for finishes. They cannot be directly used for thermal analysis. However middleware or pre-processors to the thermal analysis software may take 1st level space boundaries and perform the necessary transformation into 2nd and 3rd level space boundaries that are required for energy analysis.

2nd Level Space Boundaries

2nd level space boundaries are used by many analysis packages that require a surface view of the building that can be transformed into the various simple topological models. Examples of such analysis packages include: (1) energy analysis, (2) lighting analysis, (3) fluid dynamics. Adding the differentiation of the different types of 2nd level space boundaries is a special pre-processing of space boundaries for the use by some energy analysis packages (e.g. Energy+ from Lawrence Berkeley National Laboratory (LBNL)".[1]

During the benchmark run 2, setting the IFC export to level 2 space boundaries the run failed to transfer and stalled at 're-building adjacencies'. The program was left for 20 minutes at the same freeze screen until the program was manually terminated due to lack of progress. The test was run again to establish consistency in results. The third benchmark run and the second run with the level set at 2 for space boundary failed again. This time the program displayed a 'not responding' warning and requested shutdown. The tests were halted.

3.17.4. Process Map BIM Model Import into IES VE via IFC

Figure 43 shows the result of the experiment into the BIM model import from IES VE via IFC identifying the critical steps. The process map will be discussed in detail within the discussion chapter.
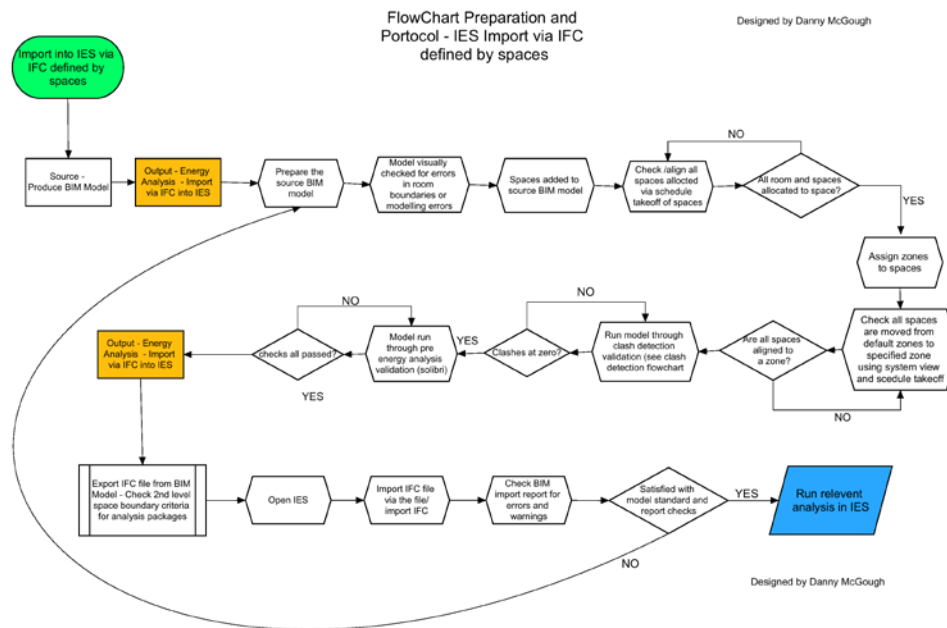
Figure 39 - Process map - BIM model import into IES VE via IFC

Figure 44 shows the result of the experiment into the BIM model import into IES VE via IFC using room volumes as the definition for spaces identifying the critical steps. The process map will be discussed in detail within the discussion chapter.

Figure 40 - Process map - BIM model import IES VE via IFC - room volume

3.17.5. IES VE Import via gbXML file from REVIT

Once 'spaces' have been created and identified within the model the heating and cooling analysis can take place. Figure 45 shows the option of adding spaces within REVIT. Spaces within REVIT define the volumetric parameters and are used primarily for MEP modelling and analysis. This step is mandatory before any gbXML file can be exported. Using the gbXML export function the gbXML file can be exported from REVIT for use in third party applications, as presented in Figure 46.
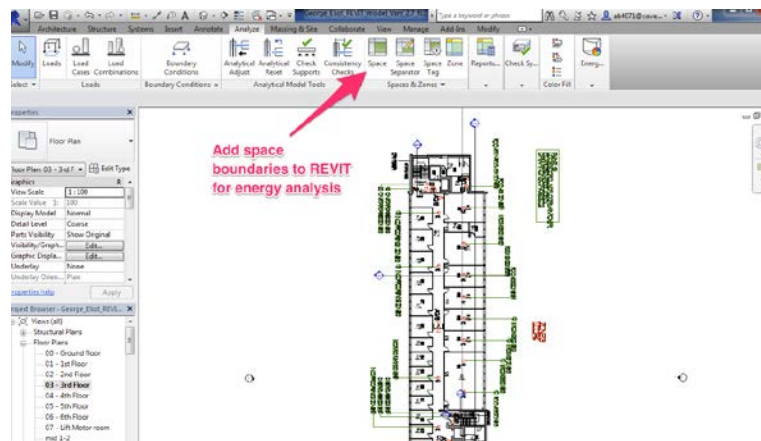
Figure 41 - REVIT - gbXML adding spaces for energy analysis
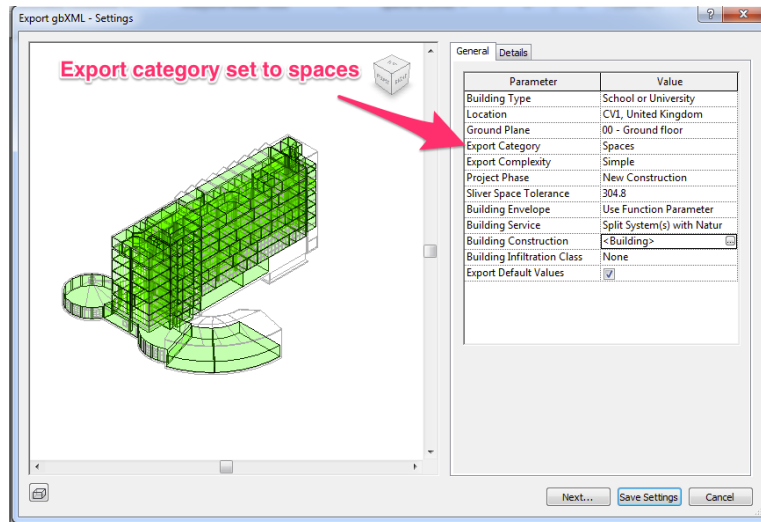
Figure 42 - gbXML export using the Spaces 'export category'

Using the import option through IES VE the GE gbXML file can be imported. There are a number of options, which can be changed. For the first import run via gbXML the import checks were left unchecked, as presented in Figure 47. Again a BIM import report was created which can be seen in Appendix F. The model successfully imported into the recipient IES VE software. As gbXML notates that a selection of room volumes or spaces have to be defined, in this case 'spaces' was selected as the export category.
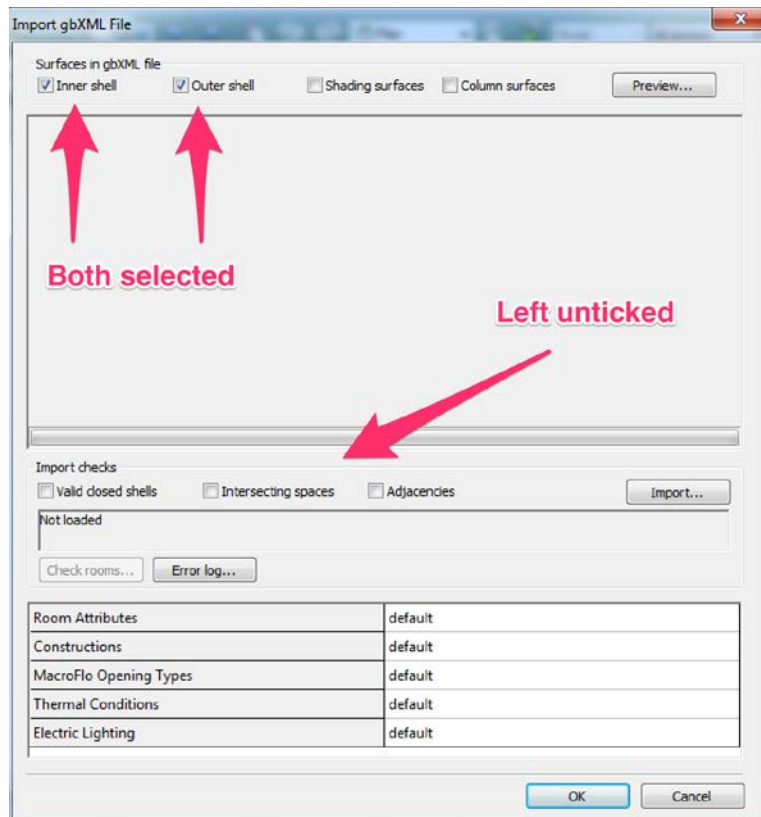
Figure 43 - IES VE gbXML import

When evaluating the import process it is still visually clear that errors are present, as illustrated in Figure 48, 49, 50. It can be identified that IES VE is struggling to interpret the

curved walls, which are being imported. However when comparing Figures 48, 49 and 50 to Figures 40 and 41 clear improvements can be seen within the models accuracy.
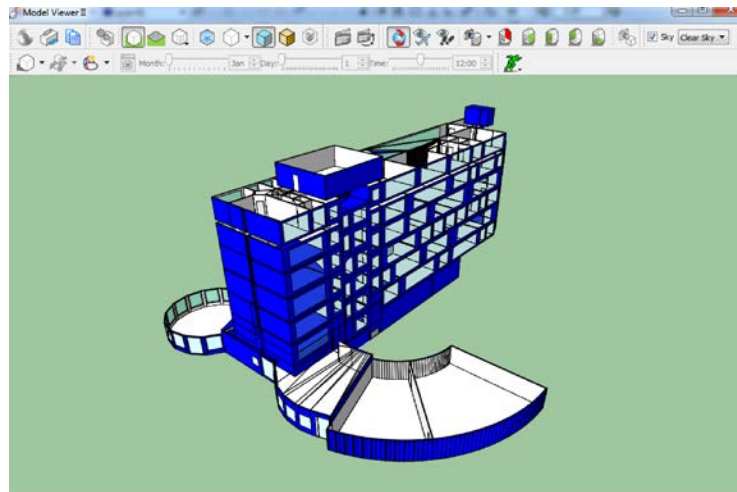
Figure 44 - IES VE gbXML import errors still present
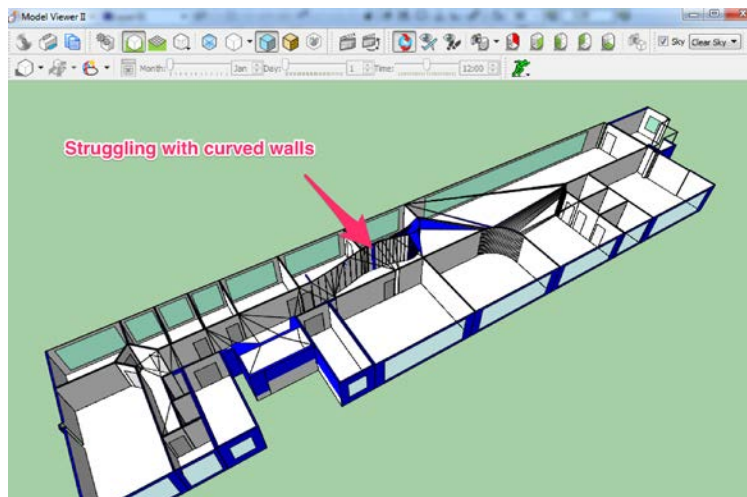
Figure 45 - IES VE gbXML Struggling to model curved walls
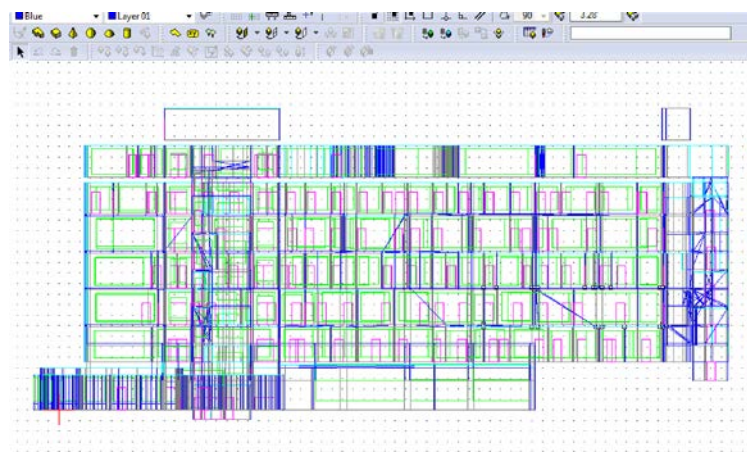
Figure 46 - IES VE gbXML less visual errors compared to IFC import

The next gbXML import into IES VE run will evaluate the impact of checking the 'import checks' boxes. This run will evaluate whether the checks are able to clearly highlight

the issues reviewed previously during import. The gbXML import criteria, as presented in Figure 51.
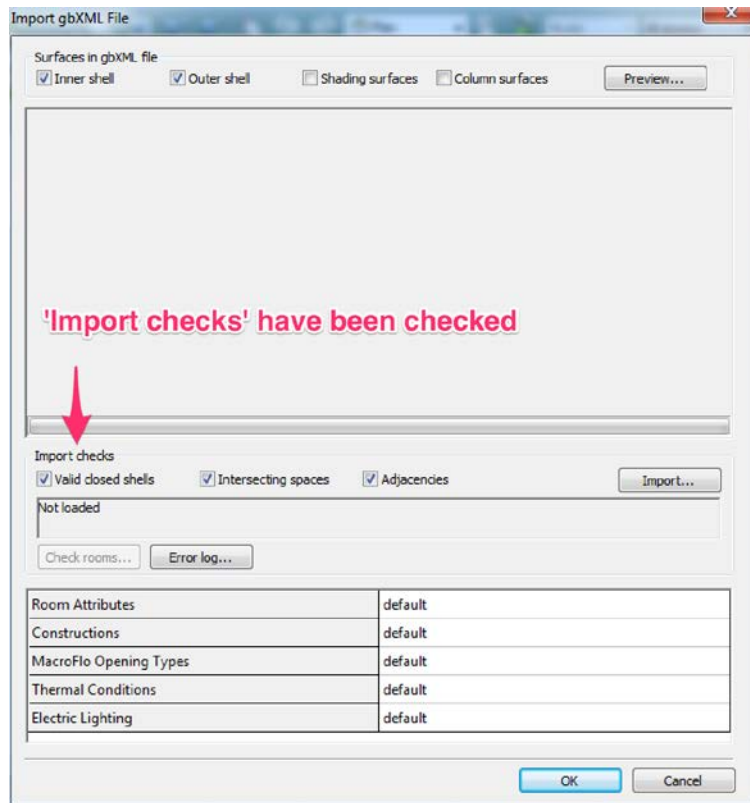
Figure 47- IES VE gbXML 'Import checks' have been checked

The number of spaces that are not fully bounded was 30 and the number of spaces that were intersecting was 67. These results showed a number of errors with interpreting the model and the import process. Focusing on Figure 52 a number of errors can be visually identified. The errors are an exact match to the errors identified in Figure 44 in run 1. In figure 53 and 54 errors can be visually seen in regards to spaces missing the top face. These issues will be discussed in context within the discussion chapter.
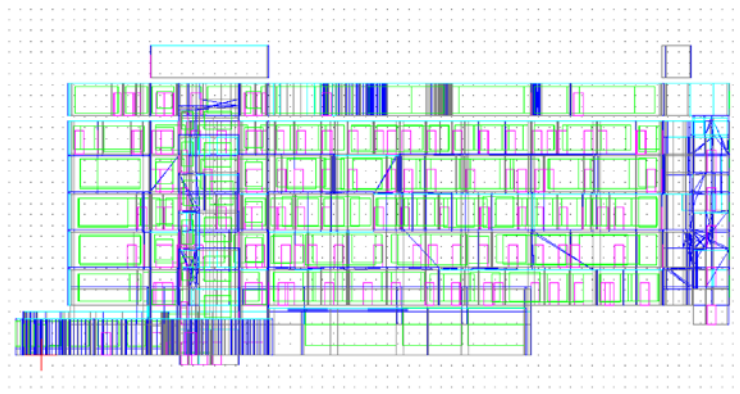
Figure 48 - IES VE gbXML run 2 - Errors can be visually identified
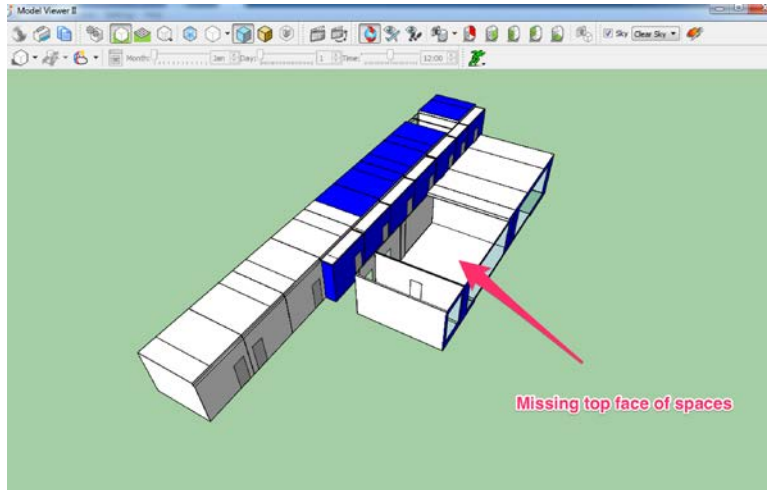
Figure 49 -IES VE gbXML run 2 - Missing top faces of spaces volume
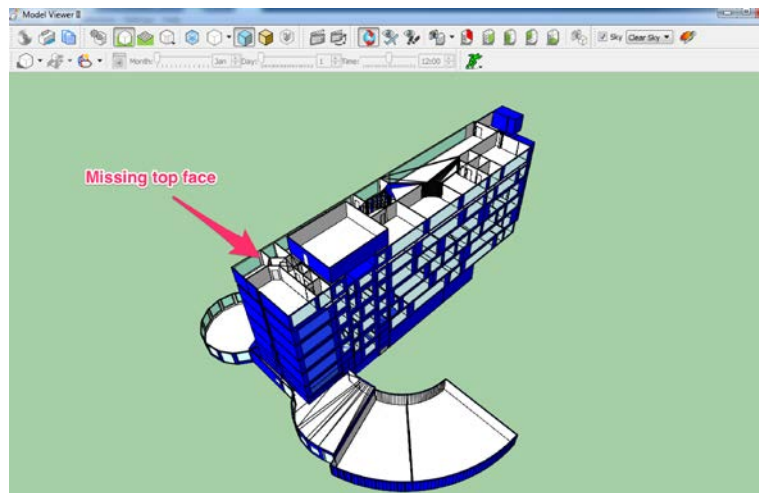
Figure 50 - IES VE gbXML run 2 missing top face of spaces in places

3.17.6. Process Map BIM Model Import into IES VE via gbXML

Figure 55 shows the result of the experiment into the BIM Model Import into IES VE via gbXML identifying the critical steps. The process map will be discussed in detail within the discussion chapter.
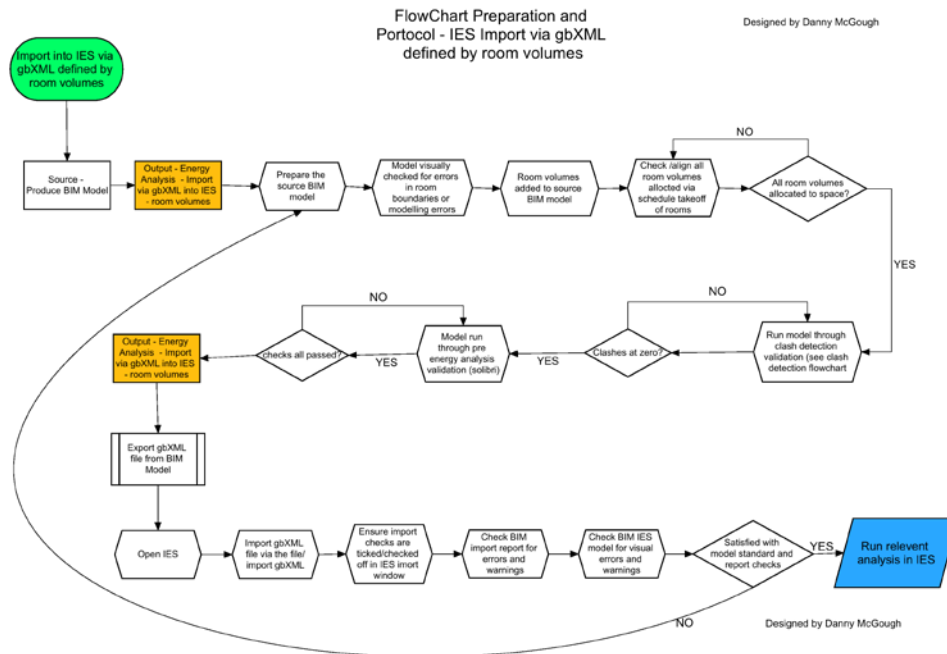

Figure 51 - Process map - Preparation and protocol - IES VE import via gbXML - Room volumes

Figure 56 shows the result of the experiment into the BIM Model IES VE import via gbXML using Spaces definition identifying the critical steps. The process map will be discussed in detail within the discussion chapter.
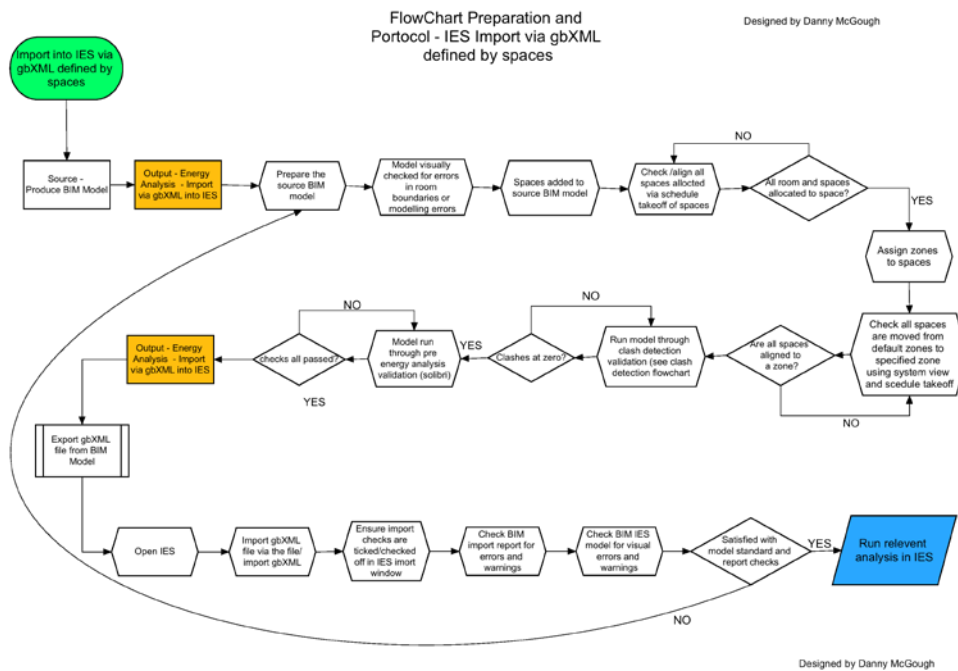
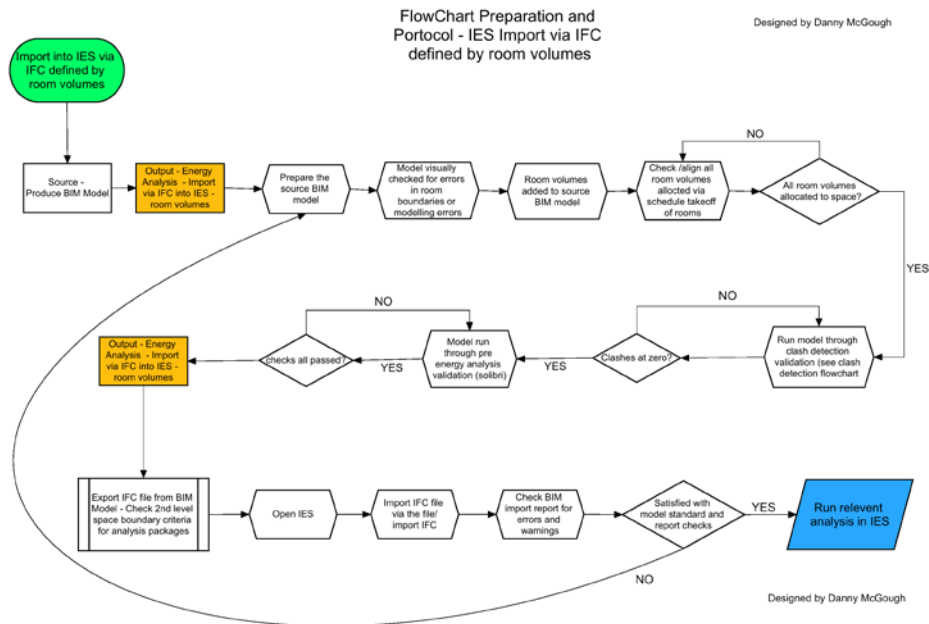Figure 52 - Process map – BIM Model IES VE import via gbXML - Spaces

3.17.7. IES VE Import via gbXML through REVIT Plugin

The next step was to attempt the import into IES VE via the REVIT IES VE plug in. This experiment would be utilised to evaluate and compare the functionality and reliability with the direct import into IES VE via IFC and gbXML. Once the plug in is installed into the REVIT workspace the next step is to use the 'Import Model' option to prepare and transfer the model to IES VE via gbXML to VE, as presented in Figure 57. The initial transfer was successful but errors were present. The outputted report can be found in Appendix F. The immediate warning within the report highlight '**Warning:** Number of spaces that are not fully bounded: 30'. Again this identifies that issues are present with room bounding, similar to the previous tests.

When inspecting the import from REVIT through the IES VE plugin the same errors can be identified, Figure 58 demonstrates this. Once the model was opened within VE the option to link to VE ware directly through the REVIT plugin was tested, this resulted in error warnings stating that the model needed to be imported first. When attempting to do this a warning error was prompted, as presented in Figure 59. This resulted in a failure to fully use the IES VE plugin within REVIT. However the import into IES VE from REVIT was relatively successful, with the above said errors. This would allow for further analysis to take place within IES VE itself. An attempt was made to rectify the issue by searching for research on the matter. The result was a test to reinstall and repair the plugin with the latest version. This attempt did not resolve the issue in Figure 59. Thusly this ended the REVIT to IES VE plugin experiment phase. Despite existing doubts over the performance of the IES plug in within REVIT it is an important factor of this research to evaluate the issues using primary sources.
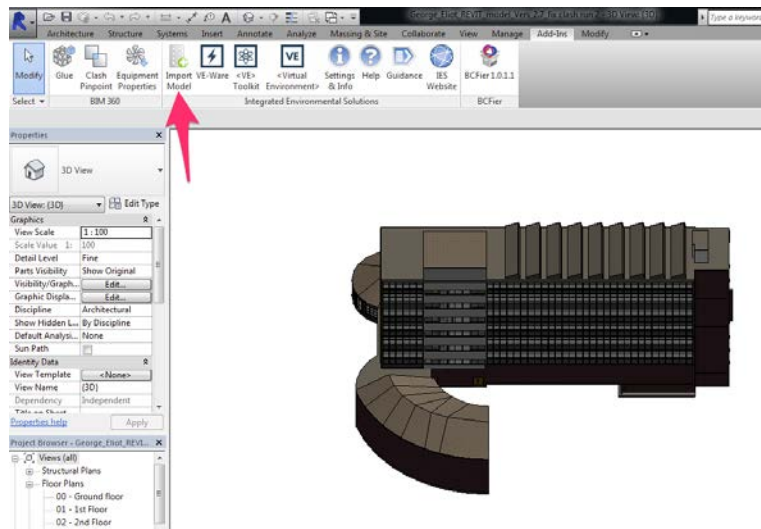
Figure 53 - REVIT to IES VE plugin - Import Check run 3
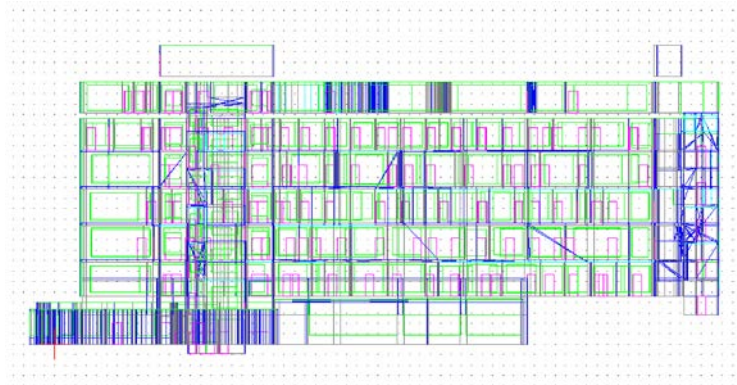
Figure 54 - REVIT to IES VE through plug in run 3
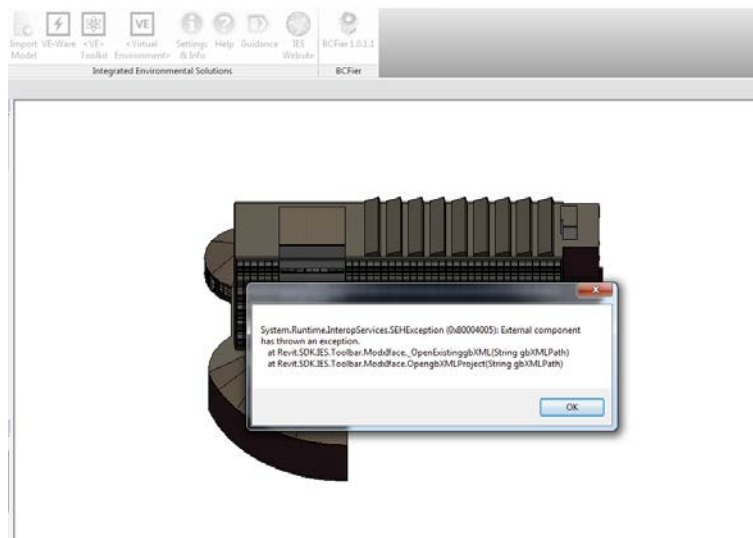
Figure 55 - REVIT IES VE plug in - Consistent error when importing model 43

3.17.8. Resolution of Issues Within gbXML Export/Import REVIT>IES VE

After researching into the issue the answer to the problem was discovered within an IESVE forum. (IES, 2015) The issue is regarding how IES VE interprets the bounding elements within REVIT, "If the space element isn't bounded by a roof (for example if you have set the Space upper limit to be less than the height of the roof) then you will find the room is exported with a big hole where there should be a roof. To correct this the user needs to make sure that all spaces are properly bounded by floor and ceiling/roof elements" (IES, 2015). An experimental test was then commenced to establish if a solution could be found. A number of key issues were worked through in regards to the spaces allocation using the above research prompts. Spaces were correctly aligned with bounding surfaces such as ceilings/slabs. Additionally a number of other errors were worked through using the Solibri report. An anomalous result occurred in that warning were given on 'Number of spaces that are not fully bounded: 40' and 'Number of spaces that are intersecting: 75'. Therefore the errors in regards to bounded spaces had increased. Focusing on Figure 60 a number of visual errors with the gbXML import model can be identified. A number of the errors are a continuation of the previous errors found within import with the addition of further errors. Comparing Figure 61, which is from the run 2 of gbXML import and pre model fixing, and Figure 62, which is of the post model-fixing run 3, a clear improvement can be seen in regards to top faces now being recognised within the model. This will be discussed in context within the discussion chapter.
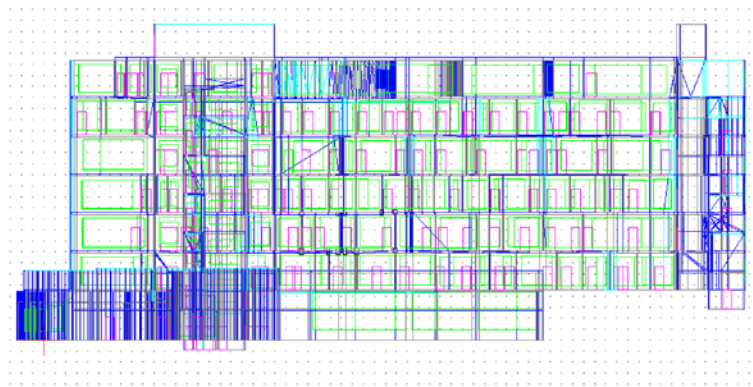
Figure 56 - IES VE gbXML - Run 4 - Visual errors
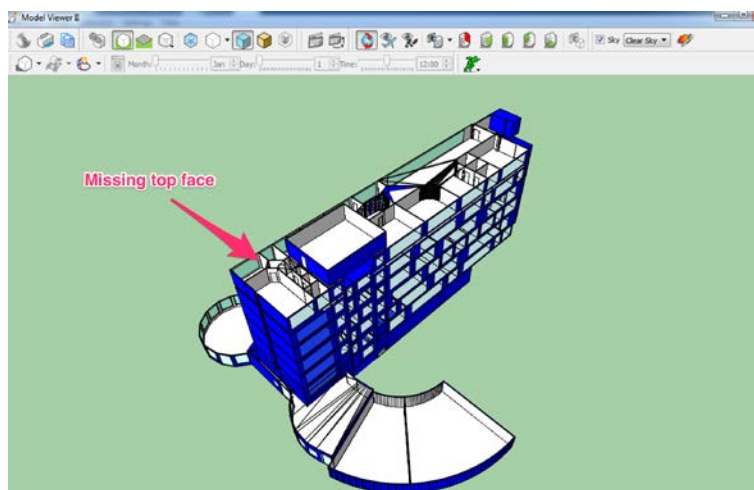
Figure 57 - IES VE gbXML run 2 missing top face of spaces in places
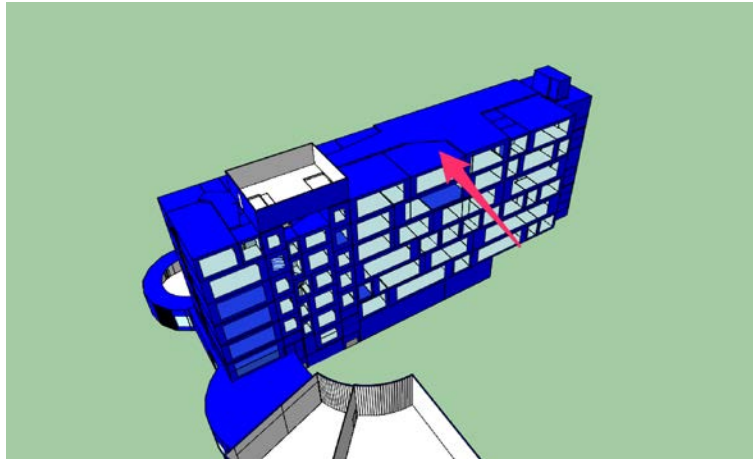
Figure 58 - IES VE gbXML – Run 4 - Multiple issues resolved in top faces

3.17.9. Process Map Import into IES VE via REVIT>IES VE Plugin Toolbar

Figure 63 shows the result of the experiment into the Import into IES VE via REVIT>IES VE Plugin Toolbar identifying the critical steps. The process map will be discussed in detail within the discussion chapter.
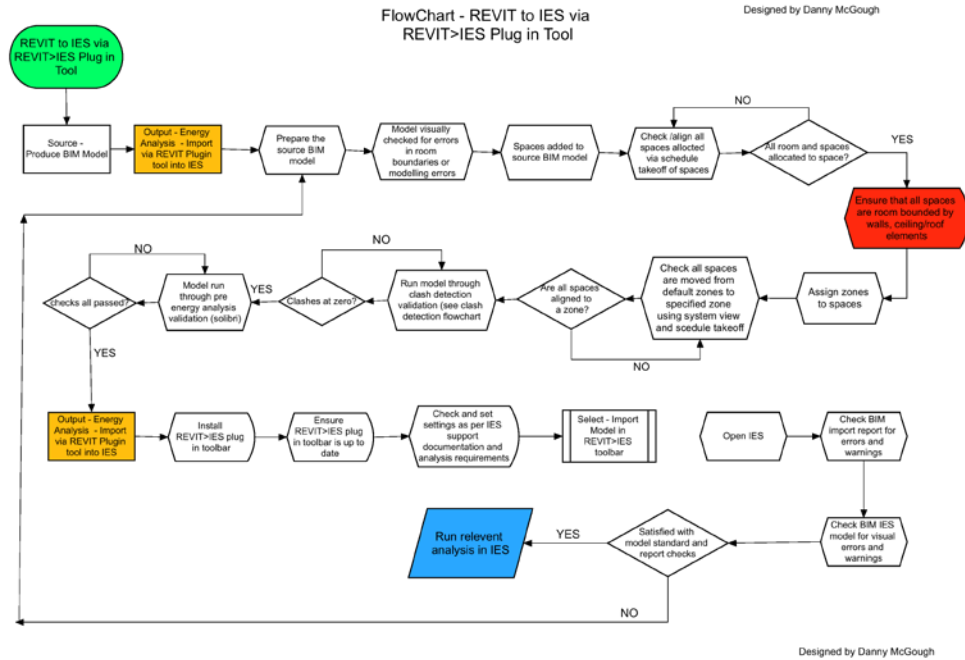
Figure 59 - REVIT to IES VE via REVIT>IES VE Plug in tool

3.17.10.Summary of IES VE Experiments

Table 7 shows a summary of the IES VE experiments.

| Building/Model	Export file type	Process time	Level of detail	Success/Fail - notes
Benchmark run 1- GE–Case study.	IFC file	<4 minutes	Very complex Rooms/spaces/curtain system/6 floors- the model has been validated to 0 issues	Success but with many issues. The spaces are 'doubled' up in that IES VE has read the Room stag spaces from REVIT as well as the Analysis Spaces. This has resulted in two volumetric spaces per room/space within IES VE. Many spaces have parametric massing issues in that the volumes of spaces have multiple uncoordinated and misshapen spaces as per the images below.
Benchmark run 2 - GE–Case study.	IFC file 2nd level space boundary	Fail >20 minutes	Very complex Rooms/spaces/curtain system/6 floors- the model has been validated to 0 issues	Fail – the import failed to transfer and stalled at 're-building adjacencies'
Benchmark run 3 - GE–Case study.	IFC file 2nd level space boundary	Fail <10 minutes	Very complex Rooms/spaces/curtain system/6 floors- the model has been validated to 0 issues	Fail – the import failed to transfer and stalled 're-building adjacencies'
Run 1 - gbXML test	gbXML - Spaces – NO 'import checks' have been checked during import	Success - 65 seconds	Very complex spaces/curtain system/6 floors- the model has been validated to 0 issues	Success – However clear visual errors but far less than the IFC import. Dealt with curved walls far better in comparison to the IFC test.
Run 2 - gbXML test	gbXML - Spaces – 'import checking' HAVE been checked during import	Success - 66 seconds	Very complex spaces/curtain system/6 floors- the model has been validated to 0 issues	Success – However clear visual errors still remain as per run 1.
Run 3 – gbXML import > REVIT IES VE plug in	gbXML - Spaces – 'import checking' HAVE been checked during import	Success one time> failed upon repeat	Very complex spaces/curtain system/6 floors- the model has been validated to 0 issues	The first attempt was in part a success however error could still be seen. Additionally no analysis could be prompted or done using the IES VE plug in options within REVIT. Further attempt to resolve resulted in failure.

Building/Model	Export file type	Process time	Level of detail	Success/Fail - notes
Run 4 – gbXML import post spaces fix	gbXML - Spaces – 'import checking' HAVE been checked during import	Success 90 seconds	Very complex spaces/curtain system/6 floors- the model has been validated to 0 issues. Attempts to resolve known issues with spaces in REVIT model.	The run was a success in part as issues with no 'top faces' were resolved. However further issues were encountered elsewhere.

3.17.11. Autodesk REVIT: Rapid Energy Modelling (REM)

As discussed by Autodesk, "REM is a streamlined, scalable approach for performing energy assessments of existing buildings" (Autodesk, 2011). This terminology may represent a number of processes and solutions, a typical workflow presented by Autodesk could consist of three outline steps: capture, model, and analyse;

- Step 1: First, you capture existing building conditions. Starting from as little as photos, satellite images, aerial images, or laser distance meters, you collect basic information about a building such as geometry, location, orientation, and structural or operational anomalies.
- Step 2: This digital information is calibrated and converted into a simplified 3D building model. Your model can be a:
  - Conceptual massing model that defines the internal volumes of the building (which is all that is necessary for basic energy modelling), or a
  - Detailed model using design elements such as walls, floors, windows, roofs, and rooms or spaces.
- Step 3: In this step, you analyse the building model by performing energy analyses to assess expected building performance.

Figure 58 shows the steps in the REM process.
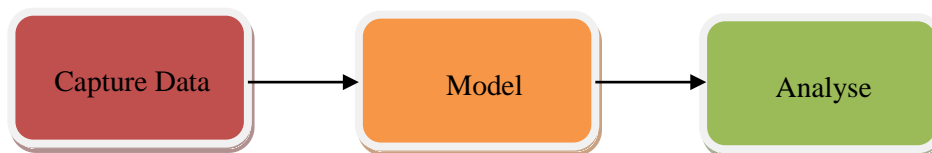
Figure 60 - Rapid Energy Modelling Process

These steps will be followed within the REVIT tool to investigate and run a Rapid Energy Modelling process for the project.

A significant hindrance when investigating the REVIT Conceptual Design platform was the fact that the process, after successfully navigating through the REVIT Conceptual Design processes stalled on the server and remained in the 'processing' stage, without progressing past 0% completion. A warning from the tools expressed that there may be a modelling detail issue therefore the model was refined further checking for errors such as missing walls, gaps in walls and gaps in floors, as these are the likely sources of error when analysing a model for energy simulation as directed by REVIT support documents. Once the initial steps to refine the model were completed the simulation was run again, this time the simulation reached 17% before failing, which was an improvement.

Investigating the issue a process of elimination of factors was undertaken to establish the failure point. The setting to be used within the trial on REM within REVIT software can be seen in Figure 66.
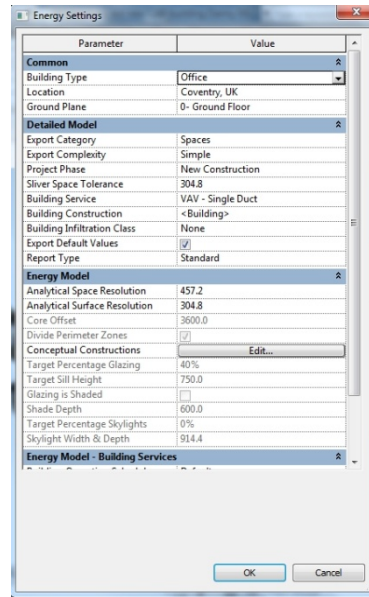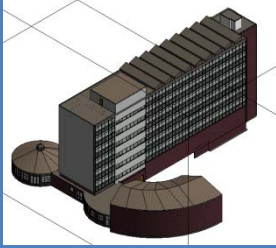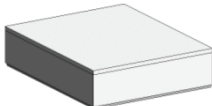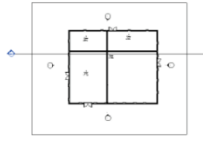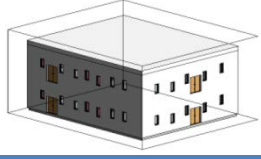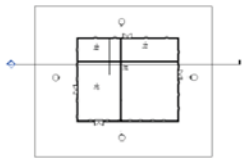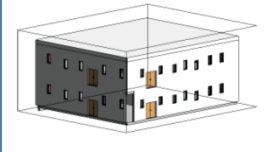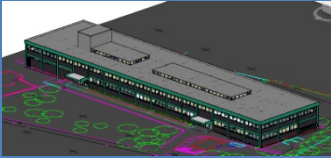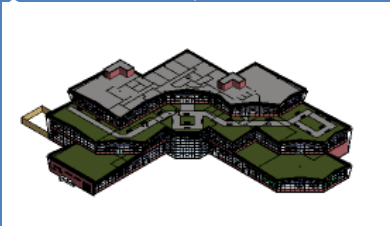
Figure 61 - Energy Settings

As the latest George Eliot model is of a considerable level of detail the investigation began by exploring the process with a simplified model. The matrix below shows the progression.

Building/Model	Success/ Fail	Export Category	Process time	Level of detail
Precursor George Eliot Building- Case study	Fail	Spaces	n/a	Very Complex Rooms/spaces/curtain system/6 floors
Run 1	Success	Spaces	<3 minutes	10m x 10m floor/roof Walls - 4m Internal room-1 Room boundary space set -1 Analytical Spaces set- 1
Run 2	Success	Spaces	<3 minutes	10m x 10m floor/roof Walls - 4m

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Project step 2 Project step 2 Analysis Analyzed at 9/3/2014 1:02:15 PM Energy Analysis Result 				Internal room-1 Room boundary space set -1 Analytical Spaces set- 1 Doors - 4 Windows -20
Run 3 **Simulation begun in plan view not 3D** Project step 3 Project step 2 Analysis Analyzed at 9/3/2014 1:07:05 PM Energy Analysis Result 	Success	Spaces	<3 minutes	10m x 10m floor/roof Walls - 4m Internal room-4 Room boundary space set -4 Analytical Spaces set- 4 Doors - 4 Windows -20
Run 4 Project step 4 Project step 2 Analysis Analyzed at 9/3/2014 1:12:01 PM Energy Analysis Result 	Success	Spaces	<3 minutes	10m x 10m floor/roof Walls - 4m Internal room-4 Room boundary space set -4 Analytical Spaces set- 4 Doors - 4 Windows -20
Run 5 Project step 5 Project step 2 Analysis Analyzed at 9/3/2014 1:24:27 PM Energy Analysis Result 	Success	Spaces	<3 minutes	10m x 10m floor/roof Walls - 4m Internal room-8 Room boundary space set -8 Analytical Spaces set- 8 Doors - 8 Windows -40 Floors -2
Run 6	Success - Therefore wall clash not an issue	Spaces	<3 minutes	10m x 10m floor/roof Walls - 4m Internal room-8 Room boundary space set -8 Analytical Spaces set- 8 Doors - 8

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Project step 6 Project step 2 Analysis Analyzed at 9/3/2014 1:31:28 PM Energy Analysis Result 				Windows -40 Floors -2 Wall placed within a wall to test if a clash is causing GE errors
Run 7 Project step 7 Project step 2 Analysis (1) Analyzed at 9/3/2014 2:00:32 PM Energy Analysis Result 	Success Therefore wall gap and loss of room boundary does not cause major issue	Spaces	<3 minutes	10m x 10m floor/roof Walls - 4m Internal room-8 Room boundary space set -8 Analytical Spaces set- 8 Doors - 8 Windows -40 Floors -2 Gap between ground floor walls, 1 room boundary now not classed as 'enclosed'
Run 8 **John Laing medium level of detail** ⚠ **The Energy Simulation failed.** The exact reason for this failure cannot be determined, however, it is recommended that you do the following: • Open Green Building Studio from the toolbar above, and review the list of simulation runs for failures. • When using Building elements for Energy Analysis, check for limitations in model size, complexity, or quality (e.g. gaps or missing elements may produce a large number of shade surfaces that will exceed DOE2 limits). See Revit wikihelp for more information. • Check your internet connection. If problems persist, please report the problem to Autodesk Subscription Support via the Subscription Center.	Failed - Model too complex	Spaces	<15 minutes	Medium-large building 3000m/2 Rooms 50 + 2 floors 200+ windows Concrete frame
Run 9 **DCEAB large academic concept model (no analytical spaces in model)** 	Success	Spaces	<15 minutes	Large complex building- Room boundaries set. Steel frame Brick walls With large proportion curtain glazing
Run 10 **George Eliot Building- Case**	Fail	Rooms Plus	<15 minutes	Very Complex Rooms/spaces/curta
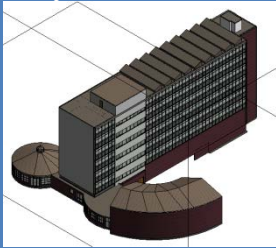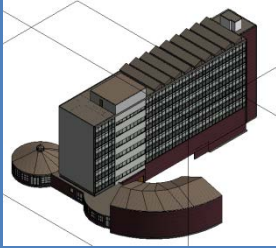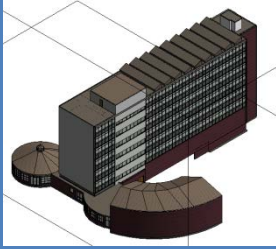
study		thermal properties selected		in system/6 floors
Run 11 **George Eliot Building- Case study**	Fail	Rooms Plus thermal properties not selected	>30 minutes	Very Complex Rooms/spaces/curta in system/6 floors
Run 12 **George Eliot Building- Case study – validated model**	Fail	Rooms Plus thermal properties not selected	>30 minutes	Very Complex Rooms/spaces/curta in system/6 floors. Model validated to zero errors

Table 8 - Rapid Energy Modelling Experiments

As can be seen in the above data difficulties were discovered in the level of complexity and detail that the REM process could handle. Moving up to run 7 the process worked relatively seamless. However when attempting run 8 the process failed. To interpret and analyse this failure it could be assumed that the failure is purely down to the over complexity of the model and the high level of detail within it. However looking at run 9 the building model is the test case is larger than that of run 8, yet in contrary to run 8 the process was successful. Likewise to run 8, runs 10 and 11 both failed. It could be derived from this that the level of detail and complexity of a model is not the only determining factor when running Rapid Energy Modelling. This topic will be discussed in the context of energy modelling and model validation later on in the discussion chapter of this research. REM support files can be found in Appendix G.

3.17.12. REVIT and Heating and Cooling Loads (HC)

HC loads were also simulated within the REVIT platform to gain simulation results, which predict building energy demand. In comparison to the previous energy analysis for REVIT the heating and cooling process encountered less issues. Once 'spaces' have been created and identified within the model so the heating and cooling analysis can take place. The option to add spaces can be seen in Figure 67. This step is mandatory before any heating and cooling loads can be simulated. As discussed in the IES VE experiment using the gbXML

export function enables REVIT data to be used in third party applications, as presented in Figure 68. The setting up of spaces is a requirement for MEP and energy analysis within the REVIT platform and outside of the platform on third party platforms. Once completed the HC analysis can be run, as presented in Figure 69. HC support files can be found in Appendix H.
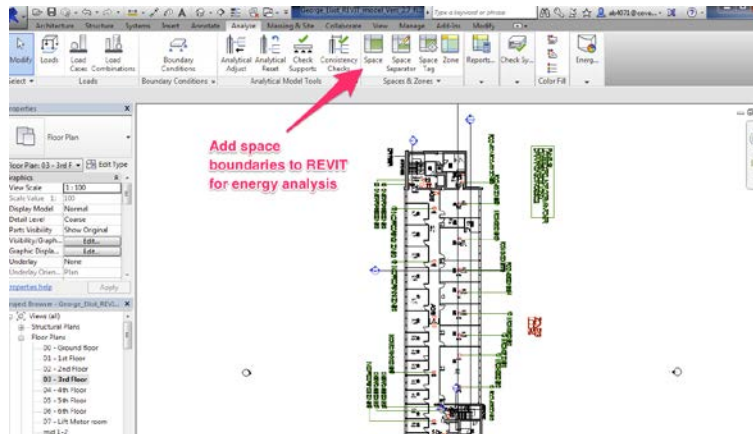
Figure 62 - REVIT - gbXML adding spaces for energy analysis
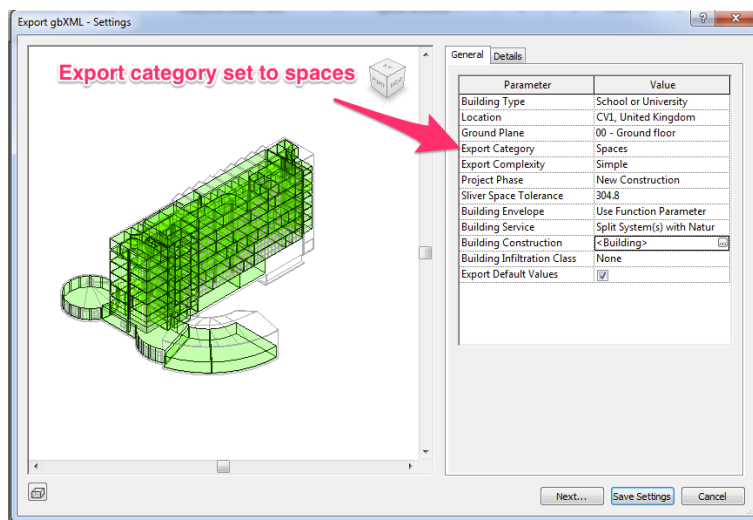
Figure 63 - gbXML export using the Spaces 'export category'
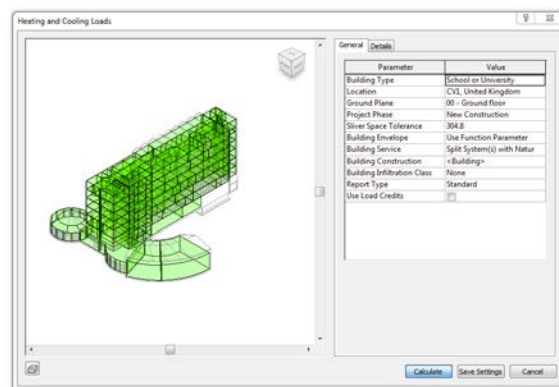
Figure 64 - REVIT heating and Cooling Analysis

3.18.   Green Building Studio

The Case Study model was processed through the Green Building Studio (GBS) tool following on from the energy analysis within REVIT. GBS accepts files either directly from the energy analysis process within REVIT or additionally files directly imported in the form of gbXML file format. As stated by Autodesk "Green Building Studio® energy-analysis software enables architects and designers to perform whole-building analysis, optimize energy consumption, and work toward carbon-neutral building designs earlier in the process" (Green Building Studio, 2014). The process was investigated as a cloud-based process for design optioning and cost and energy impacts of the said optioning processes. The process was completed using the previous protocols utilising gbXML file standard following the same setting up, exporting and validating gbXML files steps. By utilising the gbXML data standard and format further analysis can be completed on the model within GBS. The GBS support files can be found in Appendix I.

3.18.1. GBS - George Eliot Interoperability Investigation

There are two ways to commence the process. Either the gbXML file can be manually imported into GBS or it can be done via REVIT Energy Simulation tool. The former is completed outside of REVIT, directly importing and uploading to the Green building Studio platform. The latter is completed via an internal option within REVIT.

The first process investigated was the manual import directly into GBS. The process begins by first setting up a new project within the GBS platform, once the project information is entered and a location is set the preparation for the first set of analysis run can be commenced. The next step was to upload the gbXML into the GBS platform. The first run was attempted using a non-validated gbXML file from the George Eliot (GE) BIM model using room volumes/boundaries to define the volumes. The run was successfully completed and a selection of results was received as can be seen in Figure 70 (GBS gbXML room volume boundary run 1) and within the appendix I. The second run, (GBS gbXML room volume boundary run 2), used a validated GE BIM model to produce and export a gbXML to evaluate the interoperability with a validated model. The run was a success and results received which can be found within the Appendix I.

The next phase of the investigation was to trial the gbXML interoperability but with a difference in set up regarding using a gbXML file defined via spaces. All runs were attempted via the REVIT energy simulation tool into GBS (nominated with the run abbreviation of 'a') and additionally manually into GBS using the gbXML file import and upload option as a control (nominated by the run abbreviation 'b'). The previous experiment was evaluating gbXML interoperability defined via room volumes or room tags. This experiment will test the interoperability with volume defined via spaces. The first run (GBS gbXML spaces run 1a/b) was attempted using the non-validated model gbXML file. The run failed with the error, 'Invalid gbXML file: This gbXML file contains only one zone'. To have a critical comparison the experiment was rerun, (GBS gbXML spaces run 2a/b) with the validated BIM model to eradicate model validation as a cause. Again the run failed with the same error as above, 'Invalid gbXML file: This gbXML file contains only one zone'. This answered the targeted question that the error was unaffected by the model validation at this stage and the error still remained. Further research was attempted to solve the issue, which highlighted the need for all spaces allocated within the source BIM model to have zones allocated to spaces.

A process was then carried out to revisit the source GE BIM model to add in zones to the current spaces. Once it was believed all spaces were allocated to zones another run was commenced (GBS gbXML spaces run 3a/b). The run successfully solved the issue regarding the need for zones to be allocated within the model but still failed eventually due to an error.

An error prompt highlighted an issue where, 'zone ID aim1119 doesn't have spaces' as seen in Figure 71. All spaces were visually checked to ensure they were aligned with zones, additionally a schedule report was produced which highlighted spaces allocated to the default zone. To elaborate on this process step, spaces are automatically allocated to a default zone until otherwise transferred to a specified zone. The requirement is for all spaces to be allocated into a specified zone leaving the default zone bracket empty. The above process was completed and the test was run again (GBS gbXML spaces run 4a/b). Again the run failed with the same error as run 2. Further research was carried out on the issue and a discovery was made into a significant protocol and process, which can assist in remedying the problem. The resolution was to use a viewing option within REVIT found within view/system browser as can be seen in Figure 72. Using the system browser inline with the schedule takeoff of spaces all zones and allocated spaces can easily be identified. This provides a smooth platform to evaluate the validity of allocated spaces and zones. Once this process was completed a further run was attempted, (GBS gbXML spaces run 5a/b).

Run 5 solved the issue of zones having no spaces allocated to them and for the first time GBS began to attempt to run alternative runs. However after a period of 4 minutes further errors were prompted highlighting issues with the message 'ERROR – Cannot simulate layers aim25649 as given. The wall is too thin'. A substantial amount of research was carried out throughout forums and help pages to try and resolves the issue. A number of attempts were made to resolve the issue and a number of unsuccessful runs were also attempted. Using the codes given with the error warnings an attempt was made to identify the ID of the components causing the issue. A process was carried out using two methods. The first was to attempt to identify the component causing the issue via the 'Select by ID' option within REVIT, as seen in figure 58. No ID within the error could be matched to the source REVIT model. The second process was to use 'AutoDesk, Design Review' as seen in figure 59. Searches were made using the search function with the program; however, again no component could be matched to the errors. This obstacle resulted in a termination of the GE case interoperability tests.

Building/Model	Export file type	Process time (minutes)	Level of detail	Success/Fail - notes
GBS gbXML room volume boundary run 1 - GE–Case study.	gbXML import into GBS – via REVIT internally	<2	Very complex Rooms/spaces/curtain system/6 floors-the model has NOT been validated	Fail - The run failed with the error, 'Invalid gbXML file: This gbXML file contains only one zone'.
GBS gbXML room volume boundary run 2 - GE–Case study.	gbXML import into GBS – via REVIT internally	<2	Very complex Rooms/spaces/curtain system/6 floors-the model has been validated with 0 issues	Fail - The run failed with the error, 'Invalid gbXML file: This gbXML file contains only one zone'.
GBS gbXML spaces run 1a - GE–Case study.	gbXML import into GBS – via REVIT internally	<2	Very complex Rooms/spaces/curtain system/6 floors-the model has NOT been validated	Fail - The run failed with the error, 'Invalid gbXML file: This gbXML file contains only one zone'.
GBS gbXML spaces run 1b - GE–Case study.	gbXML import into GBS – via manual import into GBS	<2	Very complex Rooms/spaces/curtain system/6 floors-the model has NOT been validated	Fail - The run failed with the error, 'Invalid gbXML file: This gbXML file contains only one zone'.
GBS gbXML spaces run 2a - GE–Case study.	gbXML import into GBS – via REVIT internally	<2	Very complex Rooms/spaces/curtain system/6 floors-the model has been validated with 0 issues	Fail - The run failed with the error, 'Invalid gbXML file: This gbXML file contains only one zone'.
GBS gbXML spaces run 2b- GE–Case study.	gbXML import into GBS – via manual import into GBS	<2	Very complex Rooms/spaces/curtain system/6 floors-the model has been validated with 0 issues	Fail - The run failed with the error, 'Invalid gbXML file: This gbXML file contains only one zone'.
GBS gbXML spaces run 3a - GE–Case study.	gbXML import into GBS – via REVIT internally	<2	Very complex	Fail - The run successfully solved the issue regarding the need for zones to be allocated within the model but still failed eventually due to the following error. An error prompt highlighted an issue where, 'zone ID aim1119 doesn't have spaces'
GBS gbXML spaces run 3b - GE–Case study.	gbXML import into GBS – via manual import into GBS	<2	Rooms/spaces/curtain system/6 floors-the model has been validated with 0 issues	Fail - The run successfully solved the issue regarding the need for zones to be allocated within the model but still failed eventually due to the following error. An error prompt highlighted an issue where, 'zone ID aim1119 doesn't have spaces'

Building/Model	Export file type	Process time (minutes)	Level of detail	Success/Fail - notes
GBS gbXML spaces run 4a - GE–Case study.	gbXML import into GBS – via REVIT internally	<2	Very complex	Fail - The run successfully solved the issue regarding the need for zones to be allocated within the model but still failed eventually due to the following error. An error prompt highlighted an issue where, 'zone ID aim1119 doesn't have spaces' (significant protocol discover made as per notes)
GBS gbXML spaces run 4b - GE–Case study.	gbXML import into GBS – via manual import into GBS	<2	Rooms/spaces/curtain system/6 floors- the model has been validated with 0 issues	Fail - The run successfully solved the issue regarding the need for zones to be allocated within the model but still failed eventually due to the following error. An error prompt highlighted an issue where, 'zone ID aim1119 doesn't have spaces'
GBS gbXML spaces run 5a - GE–Case study.	gbXML import into GBS – via REVIT internally	<4	Very complex	Run 5 solved the issue of zones having no spaces allocated to them and for the first time GBS began to attempt to run alternative runs. However after a period of 4 minutes further errors were prompted highlighting issues with the message 'ERROR – Cannot simulate layers aim25649 as given. The wall is too thin'.
GBS gbXML spaces run 5b - GE–Case study.	gbXML import into GBS – via manual import into GBS	<4	Rooms/spaces/curtain system/6 floors- the model has been validated with 0 issues	Run 5 solved the issue of zones having no spaces allocated to them and for the first time GBS began to attempt to run alternative runs. However after a period of 4 minutes further errors were prompted highlighting issues with the message 'ERROR – Cannot simulate layers aim25649 as given. The wall is too thin'.

Table 9 - Interoperability test George Eliot REVIT to GBS

Figure 65 - Run 1 - Green Building Studio non-validated test

Figure 66 - gbXML setting zones error

Figure 67 - REVIT spaces schedule and system browser – zones

Select by ID
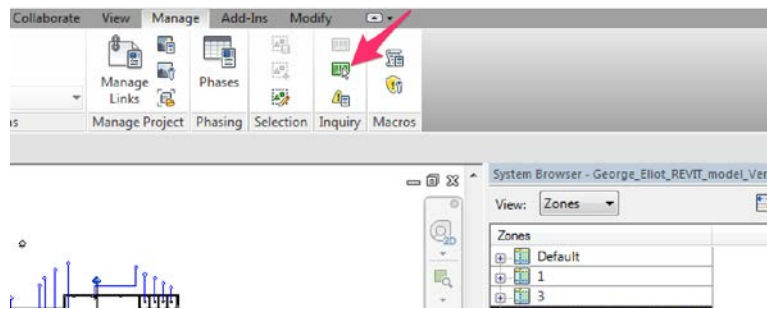
Figure 68 - REVIT 'select by ID'
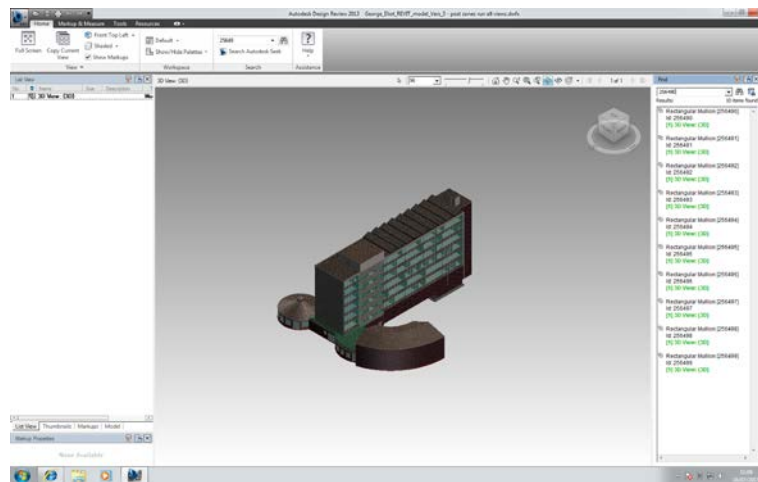
Figure 69 - Design review - Identify component ID with issues

3.18.2. Control test to Validate GBS Processes and Protocol

To provide a critical reflection it was deemed crucial to continue tests to validate the process and protocols using differing models. The target was to provide a control to the case study test runs. The first control test (GBS gbXML spaces run 1 – JL control) was to use the medium sized and level model of the John Laing building. The run failed with the error, 'ERROR – Cannot simulate layers aim0035 as given. The wall is too thin'. Again this issue could not be resolved. To further investigate the issue and to importantly provide a control which will critically evaluate the process and protocols carried out a final test was run using a far less complex model. The run was titled, (GBS gbXML spaces run 1 – Simple model control). The run was a success and critical validated the process carried out and interoperability at a basic level between the systems of REVIT and GBS. This process and results will be discussed in greater depth within the discussion chapter.

Building/Model	Export file type	Process time	Level of detail	Success/Fail - notes
GBS gbXML spaces run 1 – JL control	gbXML import into GBS – via REVIT internally	<3	Medium complex Rooms/spaces/curtain system/2 floors-	The run failed with the error, 'ERROR – Cannot simulate layers aim0035 as given. The wall is too thin.'
GBS gbXML spaces run 1 – JL control	gbXML import into GBS – via manual import into GBS	<3	Medium complex Rooms/spaces/curtain system/2 floors-	The run failed with the error, 'ERROR – Cannot simulate layers aim0035 as given. The wall is too thin.'
GBS gbXML spaces run 1 – Simple model control	gbXML import into GBS – via REVIT internally	<2	Simple model – 2 floors, 8 rooms basic generic construction components	The run was a success. Results were gained.
GBS gbXML spaces run 1 – Simple model control	gbXML import into GBS – via manual import into GBS	<2	Simple model – 2 floors, 8 rooms basic generic construction components	The run was a success. Results were gained.

Table 10 - gbXML control experiments

3.18.3. Process Map for Green Building Studio Protocols

Figure 75 shows the result of the experiment into the Green Building Studio Protocols identifying the critical steps. The process map will be discussed in detail within the discussion chapter.
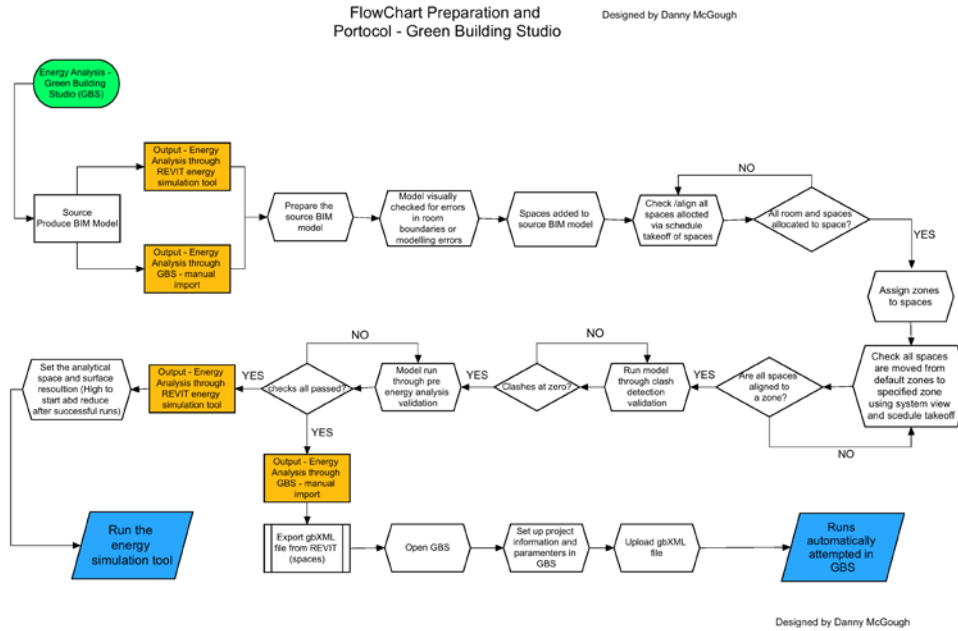
Figure 70 - Preparation and protocol - Green Building Studio

3.19. Chapter Critical Appraisal

Chapter 3 set out to critically investigate a number of varying techniques and processes, which were practically explored using primary investigations. The aim of this chapter was to ensure that new experiments were carried out pushing the investigation of the research to have real impact. The tests were created to ensure that the study did not rely on the findings of existing secondary work, instead the research looked to trial and test new ground in regards to the evolving nature and relevance of BIM. Using the case study and experimental investigations a number of process and techniques were tested providing a platform to analyse crucial topics in the area of data sourcing, collaboration, 3D Modelling, performance simulations, model validation and the interoperability of the said systems. The findings of the chapter support the concept that inaccuracy in data is a major issue when attempting to retrospectively model buildings, whilst this may be understood in sectors of industry this research aimed to prove the case through primary research based around the focused case study. One solution to this but outside of the scope would be to utilise laser-scanning techniques, which are becoming increasingly available. This could provide accurate source data, which could then be harnessed to model correctly. However laser scanning has its own issues and challenges such as the difficulties in easily moving the point cloud data source into a 3D geometric model. The labour involved in processing laser scanning as a solution may outweigh the benefits of the process. Another major issue discovered was the lack of true interoperability between systems. In theory many systems are labelled as interoperable but as can be seen in this investigation it is often not the case in practice. Another limitation encountered was the difficulty that many systems had with accepting and analysing high level of detail models. In many cases this hurdle was not overcome.

4. Chapter 4: Discussion

As discussed within the literature review Taylor et al (2009) reasons that the issues surrounding BIM and interoperability were 'predominantly addressed'. This chapter will discuss in detail the results of the experimental process drawing the content into the context of the literature reviewed. An interesting observation is that a number of the processes attempted within this project contradict the statement made by Taylor et al in (2009), signifying that interoperability has not been predominantly address, 7 years after this quote was first sourced. A number of significant interoperability issues were encountered in regards to the exchange and accuracy of data. Particular to note is the issues encountered with the exchange of the case study model with the Green Building Studio and IES VE platforms.

4.1. Site and Building data

Part of this project has led to retrospectively 'BIM' modelling a large university building, around $5000m^2$. Modelling any existing building can lead to technique refinement to get the software to emulate the building in question, such as a 'new' way to model a bespoke roof design, or massing a particular shape or form in a way that you haven't done before.

A degree of skills development when using software and systems is normal; a greater challenge has been the lack of available information on the existing building stock to make good progress with modelling. This is an issue many Estates and asset management teams will have to endeavour to try to overcome. Much of the information on existing buildings is old, out-dated and/or buried. This issue highlights a limitation in the sustainability of data when focussing on traditional hard copy plans and information systems. As discussed within the literature review the sustainability of data within building management is significant when considering the information management of a building as existing building stocks whole life is often longer than first predicted. The issue is the lack of clear information held on these buildings. One aspect when considering the retrospective application of BIM modelling to existing building stock is that it tackles this issue by providing a level of information on the building in a sustainable format for the future.

For the GE building that has been modelled there has been a close relationship with the local estates team to try and attain the information required to model the current detail of the building. The lack of source data has led to a number of assumptions and estimations. The GE building was designed in 1961 and neither 3D modelling nor BIM was considered when compiling the plans, nor were the requirements of refurbishment strategies. The plans were constructed with one criterion in mind, enough information to raise the building from the ground, quickly and for the right money. Building handover or management was at best an afterthought, if that. In modern years the information being handed over to FM teams is greatly improving with initiatives like softlandings in the UK, as discussed within the literature review but improvements are still required due to rushed handovers as the deadline approaches.

4.2. Accuracy of Data

Another key issue when retrospectively modelling existing stock is the accuracy of the source data. You often can't rely on existing original or CAD plans to hold accurate data because over the years buildings evolve and the records often don't show every detail. It may even be the case that when a plan reaches site, the detail was just not viable and the process or reality of the build altered slightly, this is where the need for 'as built' records derives, again this is key to BIM and softlandings. To counteract this there has been a process of model validation during this investigation through building surveys and onsite visits. The key was to

validate the accuracy of plans, CAD and/or assumptions so that the model is as close to 'as-built' as possible within the scope of this project.

As discussed in the literature Eastman as early as 1974 (Eastman, 1974) had recognised the inadequacies of hard copy plans, yet industry has been slow to progress past this restraint. CAD plans improved the situation somewhat but still remain a restrictive media to store building data through, often becoming out-dated soon after or even before project completion.

Despite the dedicated drive from the local estates team to provide as much relevant data as possible there has always been throughout the project a need for further specific details and information on the case study building. It's imperative to highlight at this point that this event is not necessarily a consequence of how the individual performs their task within the management of a building but rather a reflection on the systems in place for building data collation and management. The project has highlighted significant issues with access to building data and the sustainability of the data at hand.

4.3. Level of Detail and Model Complexity

The research identified the need to establish the BIM goals as early as possible. The crucial factor is establishing clear output within the process, which will help to define the intention, scope and design of the BIM strategy. As discussed earlier within this thesis the execution planning process can assist in defining these statements within the initial stages of a BIM project or implementation. Significantly this process is also crucial when defining the level of detail.

Another key consideration is the level of detail and model complexity; much the same as any BIM new build, in that it needs to be established as to how accurate or refined does the model need to be. This all depends on what information will be required further down the line, i.e. will the model be solely used for energy simulation or is there a desire to use the model for quantities asset management. There is a point where decisions have to be made on the practicalities of entering the detail and specification of every light fitting if that information is never going to be required. The quality of data that goes into a BIM model directly influence the quality of data that you can draw, the two are intrinsically intertwined. A process of model and data validation should take place to ensure quality.

Energy simulations run a complex and intense level of algorithms and data analysis on perspective designs with the aim to optimise design process and strategy. A limitation occurs when trying to use high detail models within this process as the tools struggle to compute simulations with very complex parametric levels. When using simplified models of mass models the process tends to be smooth, however when attempting to use as built models issues are common. When designing new build projects it is standard to have early concept low complexity models or masses, with this simulations can be smooth as the tools can handle the level of detail and complexity. However when working in a retrospective modelling a building is already completed thus to model that building correctly within a BIM authoring tool as close to as built as possible the level of detail increases to a complex level immediately. This highlights the need for a clear path for models progress to be set against defined outputs.

Likewise this aspect is identifiable in the use of quantity takeoffs, the level of detail and skill level of user needs to be appropriate. For instance Quantity Surveyors need sufficient level of detail and skills is required to spot any mistakes or errors before any major cost or disruptions are incurred. The software can only assume what is required; it takes a skilled professional to acknowledge whether the process has been carried out correctly.

If a high level of detail is required for modelling exact building components then challenges can arise in complexity. This issue is compounded if the components are state of the art or bespoke as it further adds to the complexity. One remit can be to ensure the level of complexity doesn't drift above the maximum required. This goal and definition should be set within the Employers Information Requirements (EIR)[2] as early as possible.

4.4. Collaborative Processes

Throughout the early stages of the project data collaboration has been hindered with a lack of information as previously discussed. Eventually the required information was gathered, which was collated and harnessed in an interoperable manner within the model. The investigation moved through a number of collaborative processes ranging from the traditional hard copy transfer of data to the digital cloud based system. A significant issue in regards to the sharing and transfer of data at the start of the project was information being out of date. A logical strategy of setting up information sharing protocols within the BIM Project Execution Plan (PEP) overcomes this issue. The document was set up as a road map for users identifying systems and processes for data handling throughout the project. Ensuring a robust project execution plan is in place early ensures a clear path forward.

The inaccuracy of data is intertwined with the issues of data gathering and both issues led to delays within the modelling. It is reasonable to argue that this challenge will be replicated within other refurbishment projects beyond the scope of this research. Learning from the experimentation in regards to data collation and collaborative processes there is reason to argue that BIM applications hold answers to the issues raised. Through using applications such as A360 or similar common data environments (CDE) the required information for the project could have been placed into the cloud system at the infancy allowing for multiple users from Coventry as well as RESSEEPE immediate access to up-to-date information. Eastman recognised that "the implementation and operating environment… are particularly critical to an interactive database system, since speed and convenience are essential if the full advantages of direct interaction are to be obtained" (Eastman 1977). BIM has evolved to a practically realistic point where true interaction and collaboration can take place between a number of users and software platforms if protocols, planning and software standards are considered in full.

Zoho was explored as part of the RESSEEPE project as a collaborative platform but as discussed previously issues were raised in regards to user control over the information held. Additionally the access to the system was limited to RESSEEPE members, which meant that management collaboration could not take place between the Coventry University Estates team, Coventry research and RESSEEPE teams. By initiating a locally managed system such as A360 the management of the George Eliot was centralised into one platform. To take this system to the next phase the introduction of A360 glue or similar BIM cloud based design and field BIM management platforms would be advised for onsite communication of building data. This would enable BIM processes to be implemented and accessed throughout the whole life of projects/buildings.

4.5. Interoperability

As highlighted within the data analysis aspect of the study, interoperability is a crucial factor. It could be argued that the OpenBIM approach, which aligns BIM practice with interoperable standards, should be the mandatory standard moving forward with BIM. As highlighted earlier in this study, the BIM task group stated that "Information must interoperable be able to support all the (multiple) opportunities" (BIS, 2011). This along with the UK Government's directives on attaining the higher BIM maturity levels indicates that the

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[2] EIR – Is a document, which a client or employer will provide which sets out the standards and requirements that a client expects and demands during tender.

future BIM practitioners will need to utilise IFC data formats and OpenBIM standards to ensure that they are working in an interoperable integrated BIM environment.

If the work produced by varying teams is carried out and outputted in an interoperable manner then it allows for multiple teams to work collaboratively on a project without necessarily holding the same software skills and licences. As stated in the literature review the UK Government is pushing the drive towards OpenBIM. One way in that they are doing this is through specifying in the BIS-BIM-strategy-Report (BIS, 2011) that Maturity Level 3 BIM should achieve "Fully open process and data integration enabled by IFC/IFD." If level 3 is accompanied by a similar mandate as level 2 then investigations into how to improve and evaluate interoperability are crucial. Having an interoperable Open database with the schedules, materials data, costs, energy performance information in one accessible package will enable an Estates and Management to access data efficiently. In reality achieving high level of interoperability is not straightforward. As explored within this research even when systems are proposed as interoperable the success rate of the process may not match up to sufficient standards to achieve critical BIM goals or outputs in information exchange. The alignment of interoperability has been included within the modelling process maps through the adoption of a BIM authoring tool capable of performing in an interoperable format. However not all processes fulfilled this objective as in the case of IES VE.

The above statement is supported by the tests carried out which identified on-going issues with interoperability such as those with IES VE IFC import functionality. As highlighted in the data collection and analysis chapters not every process attempted was successfully interoperable. It is argued that the topic of interoperability of file formats and software packages will be a major factor in determining BIM's success and whether it's a smooth transition from isolated design practices to a truly collaborative BIM environment.

It's a critical point to draw the attention back to the literature in regards to the ISO definition of what are the core requirements of interoperability stated in ISO/IEC 2382-01 which defines interoperability as "The capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units" (ISO, 2015). This statement placed a clear focus on the role of the users position within the data transfer process. The emphasis is on 'little or no knowledge of the unique characteristics'. Many of the processes explored within the data and analysis phase of this research encountered technical breakdowns or issues within the process. As discussed in length within the analysis chapter problems such as the way IES VE reads space identifications and the level of complexity of models required a high level of users exploration and skill to overcome or attempt to overcome the issues. This high user involvement contradicts the ISO definition of interoperability.

This statement was tested in a qualitative manner as software programmes such as REVIT can sometimes be referred to as closed BIM, this however is not a clear defined point as REVIT does have the capability to export file types in the 'open' BIM IFC format which allows for interoperability. For instance REVIT can export all of the model data from REVIT in the IFC data format, which can then be imported into various software packages such as the Solibri validation tests. However, as seen in the experiments the actual performance and reliability of interoperability can often vary, defined by practical results. This highlights the need for organisations to be careful when considering what approach to adopt, as what is truly OpenBIM and what is closed BIM is not clearly signified, the results can often vary away from the 'advertised' claim, as discovered in this research.

A clear inefficiency in working process was identified concerning the space definitions between REVIT and analysis. It is best architectural practice to use room volumes to set room identifiers and tags. And likewise it is best practice in MEP models to use 'spaces' to identify room name and volumetric data. It could be contended that having to

repeat what is in essence the same process is a needless and inefficient process. Non-standard plugins are available to assist in working through this issue however this should not be required as this function should be available as standard. This research proposes that this issue is eradicated directly within REVIT's design of the software by merging the two definitions of room volumes and spaces to encompass a singular room identifier, which encloses all of the room name data, dimensions and volumetric information thus eradicating the need for an additional third party plugin. Until the possible point that REVIT does merge these room identifier methods then this research advises that separate models should be used depending on the desired output. A BIM model containing room volume tags for an asset model and another BIM model containing space volume tags for energy simulation.

Figure 71 below summarises the findings found as part of the data collection and analysis phase of the project. Critical steps within the preparation for modelling adoption include the need for a reiterative modelling process. This should include an initial collation of building data, which is then followed up by visual validation of the data done through on site surveys and visual checks. Further critical steps include the need to decide on the desired outputs before actually beginning the modelling process. A clear BIM strategy should be established through the use of planning meetings and project execution plans to set out the goals. Once the output goals are established the modelling process will be directly impacted in regards to required level of details and model complexity, which will be discussed later in this chapter.
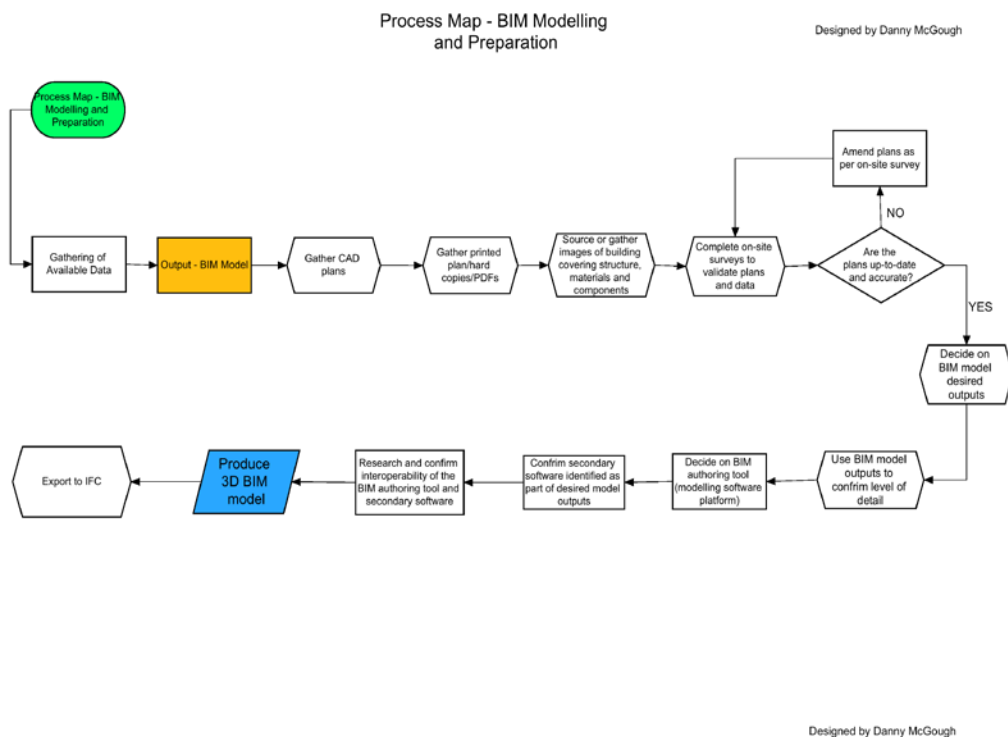
Figure 71 - Process map - Preparation for modelling and BIM modelling adoption

4.6. Model validation and Clash Detection

Throughout the research many technologies and processes have been evaluated such as the model validation. Within the AEC industry today simulation tools have been crucial in revolutionising design processes. The BIM tools available today to industry practitioners have begun to optimise design and retrofit strategies, for accurate results the quality of the model needs to be validated. As discussed in the literature Haug et al (2011) states that its critical for the information to be used to be accurate and correct as inaccurate data and information can result in increased cost and time delays. The process of model validation prior to any

exchange of data in later experiments was crucial to help to ensure accurate information was shared.

Clashes found within models highlight significant and non-significant errors within them, which should be resolved in an iterative nature. Any assumptions or errors made within the modelling phase should be brought to the attention of the model users or building management team. Again relating to the literature review, 'The quality of the information coming out of a BIM model can only be as good as the quality of the information going in'. To ensure quality the GE model was run through model validation. This process has been included in the process methodology developed. As stated by Madncik et al (2004) in the literature review high quality of data is often critical to a company's success, therefore for attempting to ensure this high quality was paramount.

It is significant to note that this model validation phase only validated the information that was contained within the model and cannot validate against human errors in measurement or inaccuracies in source data or plans. The model validation has ensured that the model was built to a good standard of technical quality. If source data is incorrect or assumptions on hidden details have been made then this will remain in the post-validated model. This reiterates that a skilled professional is required to interpret building models and data without relying only on assumptions made within software. This was supported by the results of clashes being reported which didn't exist in the model, which would take a skilled user to recognise this as a nonissue.

As reported in the data phase of the project the clashes within the model was reduced from 443 down to 0. This indicates a clear improvement in the accuracy of the data to be transferred into the recipient software platforms, as represented in Table 11. This reiterative process was adopted to directly alleviate the types of issues highlighted by Haug et al (2011) and Madncik et al (2004) in the literature review by ensure good quality data was produced as a result of a robust model validation process.

Ruleset	Run 1		Run 2		Run 3		Run 4		Run 5	
	Total	Critical	Total	Critical	Total	Critical	Total	Critical	Total	Critical
'Intersections - same kind of components'	22	15	10	3	5	0	0	0	0	0
Intersections – Different kind of components'	443	18	235	5	59	1	5	0	0	0

Table 11 - Clash report figures

In Figure 72, (Enlarged in the appendix F) the process map for the Solibri clash detection can be seen. A primary critical path in completing the clash detection was the recognition for the need for clash detection in spite of the model being created for an existing building. It could be argued that an existing building, which is already constructed and therefore has no clashes should not need running through clash detection, however this does not take account of the errors arising from human or software modelling errors. The case study model initially had 443 errors, which was reduced down to 0. Critical steps in the clash detection process include the requirement for the source model to be exported in IFC format. This critical step has to be considered when choosing the Modelling tool. In the case of this study Autodesk REVIT fulfilled this requirement. Additionally crucial steps include the need to check off some clashes in spite of clash warnings. As discussed previously some clash warnings are false therefore a number of clashes may be reported incorrectly. The overall critical aspect of clash detection is the adherence to the reiterative nature of the process, which if adhered to will impact on project scheduling when attempting to model a project. If sufficient time isn't allowed for the model validation process then significant issues may be carried through the exchange process.
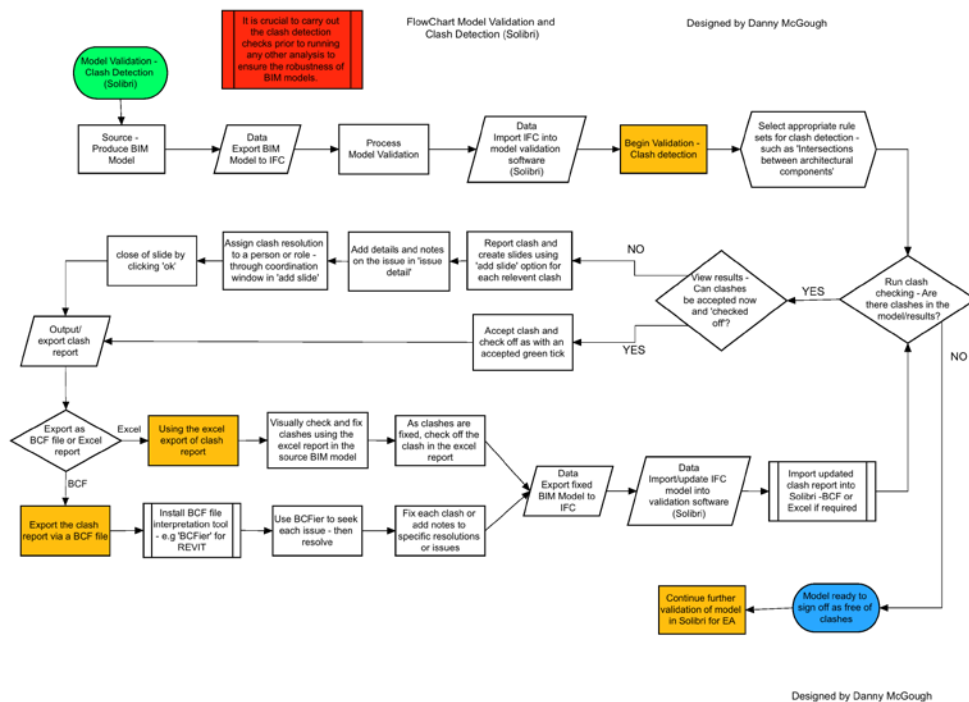
Figure 72 - Process map - Solibri clash detection

4.7. Space Usage Validation (General Space Check)

Space utilisation analysis extracted from the BIM model offered multiple benefits. To complete valid space usage checks the quality of the data within models is again paramount. Additional to this we come back around to the discussion on the level of detail. As discussed within the model validation phase some relatively simple gaps in data were discovered when investigating the practical process. The remedy to this was to manually enter the data directly into the validation software. The investigation into space usage highlighted some key processes to be aware of which impacted the process methodology, with outputs previously aligned and the need for solid data on space usage to be available either in the root BIM model itself, or if not available, a traditional format so the data can be added into the space

validation and analysis software manually. If the process is followed then it will offer many benefits to optimise space management as identified by IWMSNEWS (2010) such as to:

- Identify under-utilised spaces
- Align workplace initiatives with business goals
- Forecast Future Space Requirements
- Simplify Chargeback Process
- Simplify space analysis
- Streamline the move process
- Compare actual with planned space utilization
- Increase efficiency and integration of departments or teams
- Utilise Building Information Modelling

Figure 73 presented below shows the process map outline for the preparation for energy analysis general space check (GSC) validation process. Similar to Figure 71 and 72 a primary critical aspect to the process map begin at the initial requirement for an IFC file of the source model. Another critical step is the requirement to ensure that the model is validated prior to carrying out the energy analysis and GSC to ensure a high quality model as per Haug et al (2011) warnings on the need for accurate data. Before carrying out the GSC it will save time to ensure that the spaces are correctly assigned within the source model prior to GSC validation. The analysis carried out in this research identified critical issues when spaces are not correctly assigned in the source model such as those experienced in the IES VE experiments. One important fact here to highlight is the method for inputted space classification data. If option b is selected and the classification is applied within the validation software then the data is tied to the validation software. This may result in issues if the source data is to be exchanged with other platforms where accurate space classification is required. The decision may be to select option a to align space classification in the source BIM model directly ensuring that the BIM model contains accurate data.
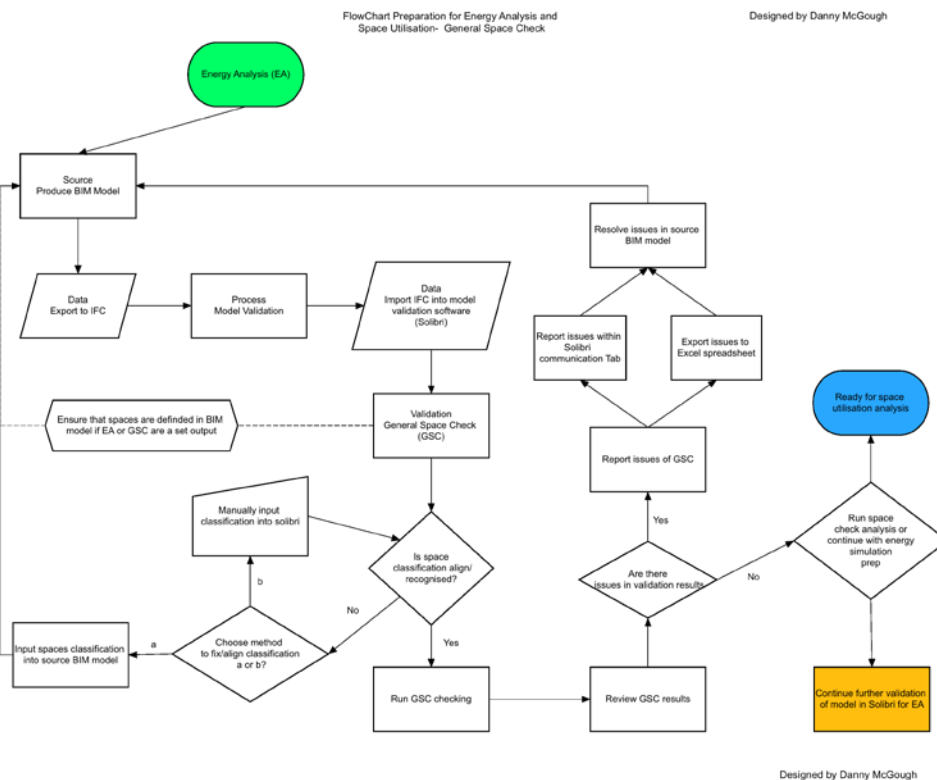
Figure 73 - Process map - General space check

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4.8. IES VE

As covered in the literature review Taylor et al (2009) states that issues of BIM standards and interoperability have been predominantly addressed however the experiments carried out as part of this project indicate that interoperability still has some way to go for some processes. The next section will go into detail through some of the major challenges encountered in regards to data transfer and interoperability of IES VE. A major issue with the level of detail and complexity that IES VE can handle was discovered. Whilst the run tests in Table 7 shows successful runs, looking deeper into the analysis consistent errors could be seen throughout the imported models. It was established that IES VE struggled to handle a complex level of detail from REVIT into IES VE. The impact of this issue is that we are forced to move away from one of the core single model environment. For IES VE to handle the energy simulation process within the building management workflow it demands for a model to be of a low level in detail. Therefore if a detailed model is demanded for building component management and is held, it will need to be stripped back for simulation software, which has a substantial impact on efficiency.

4.9. IES VE and REVIT – Export and Import

A number of interoperability tests were carried out between REVIT and IES VE. The first set of experiments focused on the IFC interoperability. The first clear issue encountered was due to the fact that IES VE was interpreting both room volumes and spaces as analytical volumetric spaces. This resulted in a duplication of volumes spaces and led to IES VE misinterpreting the model. This issue has significant consequences on the reliability of analysis. A simple fix would be to have a BIM model prepared with only volumetric areas defined via spaces[3]. However this quick fix method would completely contradict the 'one model' ethos of BIM.

Interpreting the report whilst using the visual checking of errors the source of errors can be established as bounding issues, which is a result of IES VE attempting to 'heal' misread geometry. An exert from the report reads as 'exceeded unmatched edges limit while healing geometry - extruding from footprint - Outer shell inverted'. During the import process IES VE has misread the IFC data and attempted to reform spaces. This has led to inaccuracies and misshapen spaces. The model imported into the IES VE benchmark test run had been validated, which ensured the model's robustness on a technical level. Therefore these issues can be reasonably interpreted as interoperability issues between REVIT to IES VE through IFC export/import. Unfortunately when attempting to adhere to the guidance discovered in the IFC research on space level boundaries a number of experimental runs resulted in obstruct failure and resulted in the termination of IFC to IES VE interoperability tests. The failures did highlight the need for further development to be progressed in regards to how well IES VE can perform importing BIM models via IFC. To investigate a resolution to these issues the next phase was to experiment with different forms of data export from REVIT evaluating other IFC settings, gbXML export and the REVIT to IES VE plugin.

During the IES VE gbXML import tests a significant issue arose with spaces missing the top face of the volume. This issue was evident within the BIM import reports produced as well as visually apparent within the IES VE model. The answer to the problem was discovered within an IESVE forum, (2015) regarding how IES VE interprets the bounding elements within REVIT, "If the space element isn't bounded by a roof (for example if you have set the Space upper limit to be less than the height of the roof) then you will find the

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[3] To recap spaces are the primary volumetric definition for MEP and analysis and room volumes are generally used for architectural purposes such as quantities.

room is exported with a big hole where there should be a roof. To correct this you just need to make sure that all spaces are properly bounded by floor and ceiling/roof elements" (IES Forum, 2015). All room bounding elements that specifically required to be classed and checked as room bounding elements were correctly assigned, the issue was that the spaces defined in REVIT were not in direct contact with the top room bounding elements such as floors, ceilings and roof elements. The modelling procedure in REVIT is to have the room volume, for purposes of energy analysis restrained by what would be the ceiling tile height. This would give a true calculation of the spaces relevant to analysis. However IES VE required the space volume to be closed by the above floor slab. The fix was to ensure that all space top face limits were set to the exact height of the floor-to-floor heights, thus being in direct contact with room bounding elements above. It is important to note however that spaces should not clash or encroach into the actual room bounding elements, as this will cause validation errors.

Using this data an attempt was initiated to resolve the issues, which were highlighted within the data collection and analysis phase within IES VE. The 3D BIM model was revisited to carry out further improvements in regards to spaces design using the information provided through the Solibri checking process and IES VE analysis. A number of identifiable issues were resolved using the methods above. Each space was in fact not in contact with the bounding slab above thus resulting in the top faces of slabs being absent when analysing the models within IES VE. As highlighted within the data chapter clear improvement could be seen in regards to this issue, which would result in far greater accuracy when analysing the model within IES, however due to the complexity of the model and issues with interoperability not all issues were resolved.

Presented in Figure 74 and 75 is the process map summary of steps to taken when attempting import to IES VE via gbXML. The primary critical step is for the source model to be created in a tool capable of exporting in gbXML. For Figure 74 a critical step is to ensure that room volumes are correctly aligned within the source model. This should be done in two ways, by visually checking rooms volumes have been set visually and then checking all areas have a room volume aligned via the schedule takeoff of rooms. Whereas in Figure 75 the importance is on checking that spaces are moved from default zone and aligned with the created zones. As per the above discussions this error of spaces not aligned correctly caused a number of failures in the test runs. Both process maps then link onto the previous process map for clash detection and pre energy analysis validation indicating the prior need for the process.
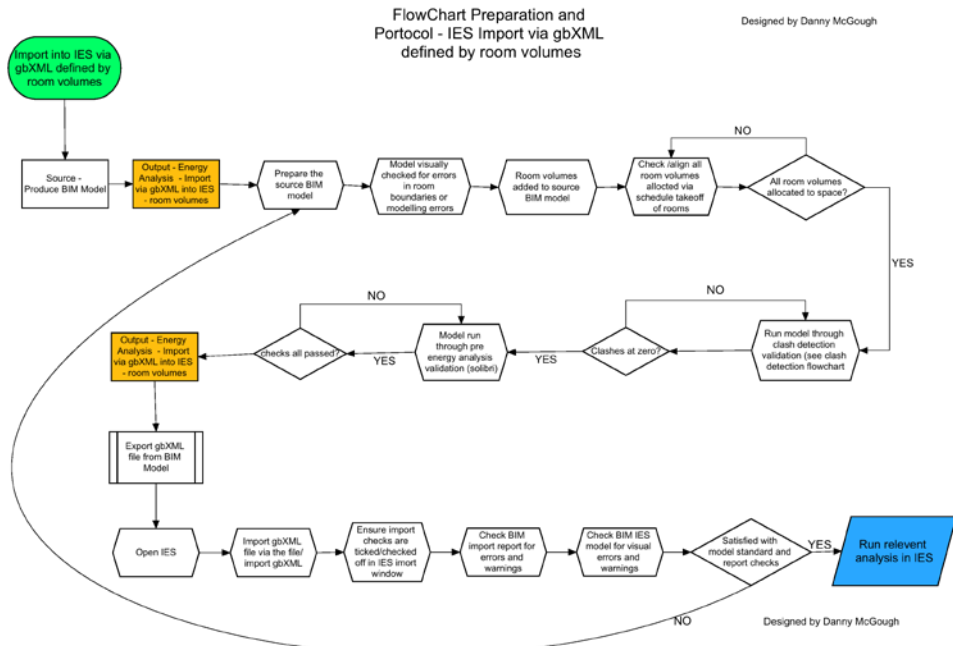
Figure 74 - Process map - Preparation and protocol - IES VE import via gbXML - Room volumes
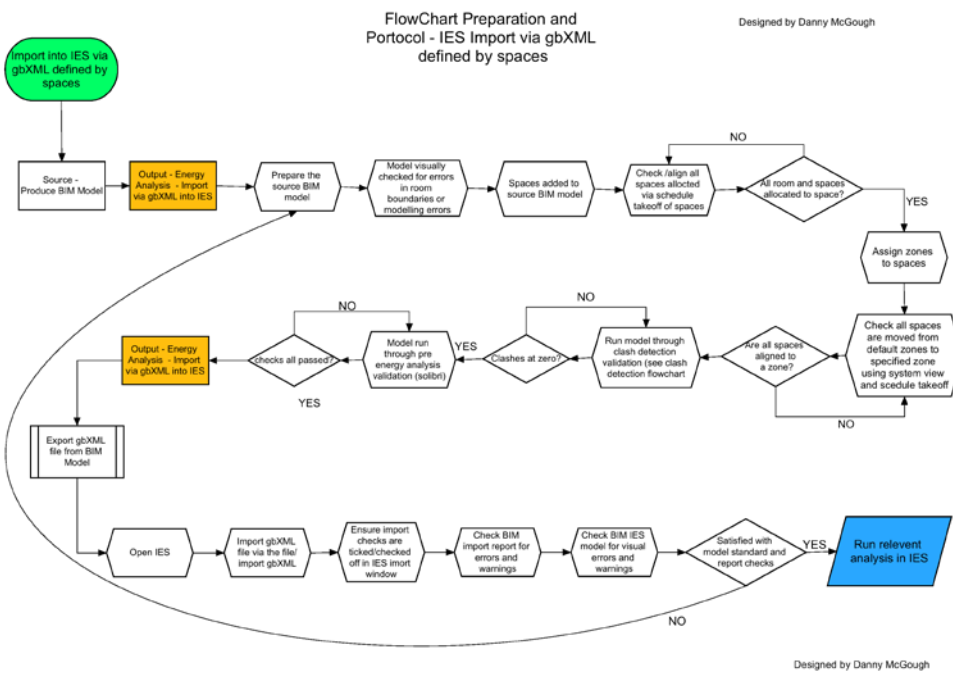
Figure 75 - Process map – BIM Model IES VE import via gbXML - Spaces

Presented in Figure 76 and 77 is the process map summary of steps to taken when attempting import to IES VE via IFC. The primary critical aspect is the requirement for the source model to be capable of export via IFC. As with the previous gbXML import processes it was critical to ensure that room volumes and spaces volumes were correctly set as per the correct procedures as discussed above either using room schedule takeoffs or checking spaces in system viewer and schedule takeoff. Again similar to previous processes the requirement for model validation is emphasised.
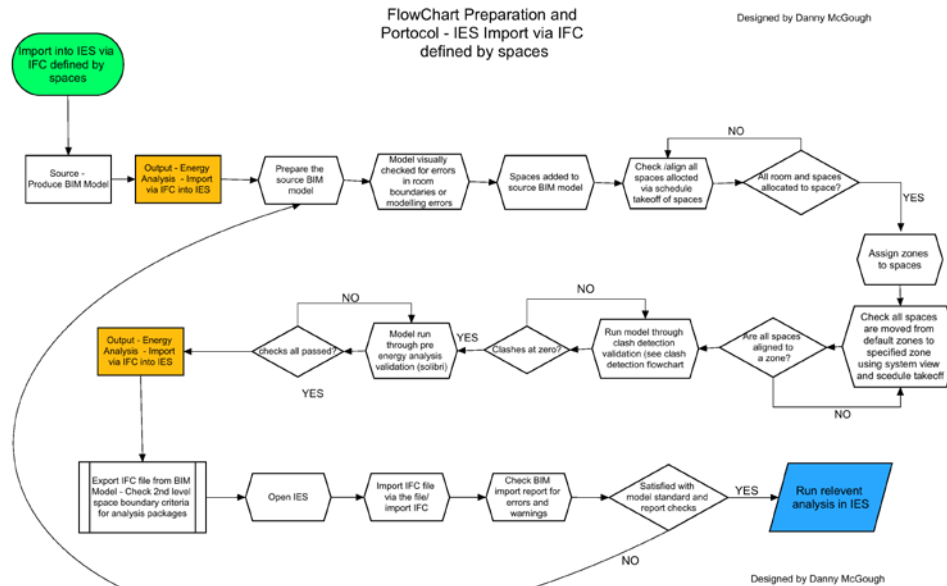
Figure 76 - Process map - BIM model import into IES VE via IFC
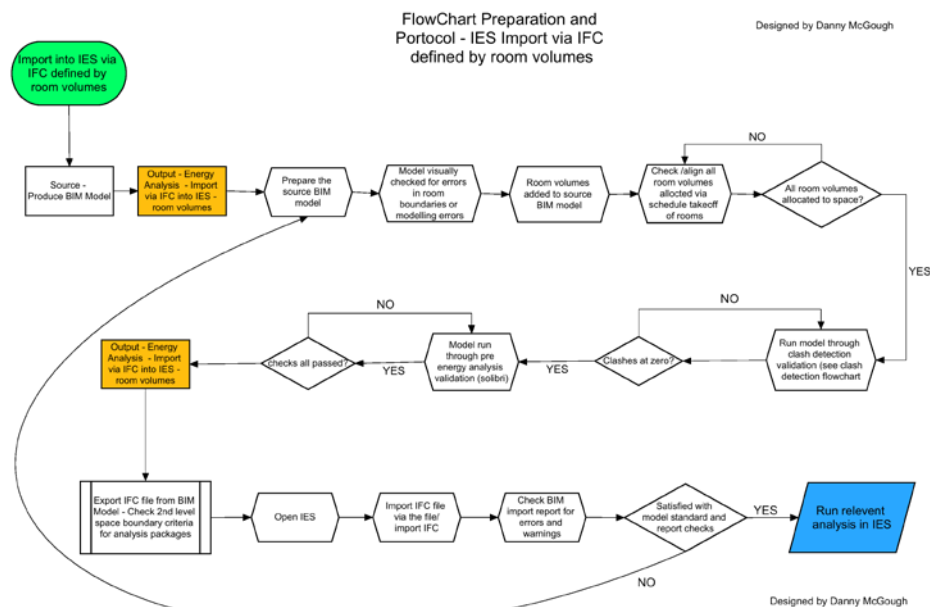
Figure 77 - Process map - BIM model import IES VE via IFC - room volume

Figure 78 shows the process map for importing into IES VE via the REVIT to IES VE plug in tool. During testing the interoperability of gbXML into IES VE using the REVIT plug in failed on basic steps. The first attempt at the process was successful in part, noting a number of errors, which replicated those when testing out the gbXML direct import into IES. This leads to the suggestion that in relation to whether importing using the REVIT plugin or directly though IES VE gbXML import the process is on par. However this statement could be misleading due to the failure of the plugin to successfully link with IES VE on a number of further occasions. It cannot be stated that the process is efficient or smooth. The REVIT IES VE plug in, despite being freshly installed and repaired repeated to fail thus leaving the experiment at a halt. Considering these facts it is reasonable to state that the direct import into IES VE via gbXML file is the most accurate and reliable method. If however the plugin worked flawlessly then it could be maintained that it would be a more an efficient process but unfortunately this statement cannot be defended from evidence within the experiments carried out. This process relied on an external plug in tool that internally transferred data. The critical step discovered in this process was the need to align all spaces with room bounding elements. Each space had to be in direct contact with the room bounding elements in contrast to being able to intentionally set space short of elements. Without the critical step aligned to import attempts would fail. Again as previous processes model validation and alignment of space zones were critical.
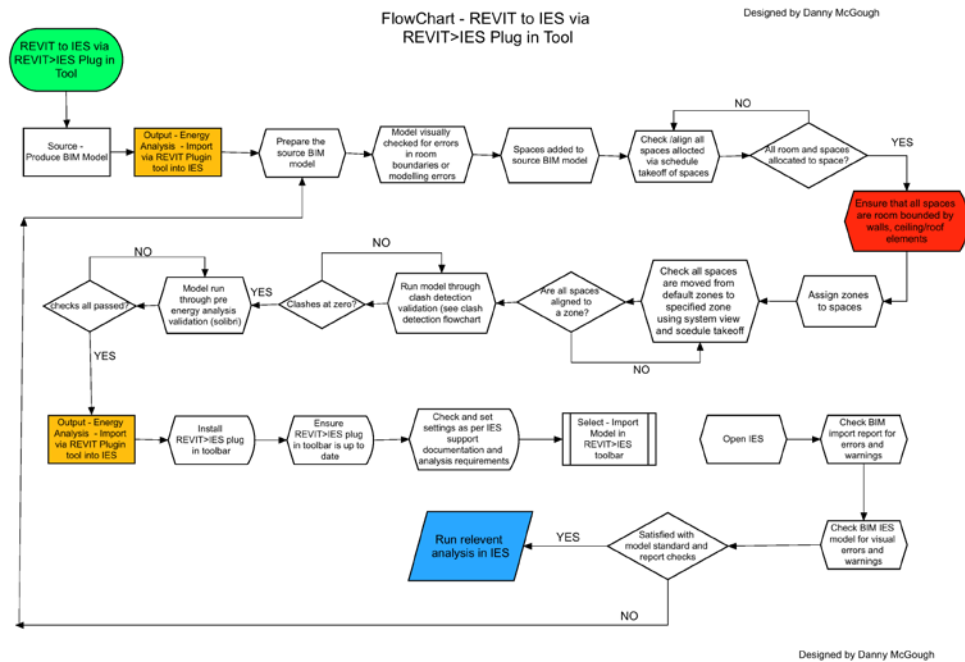
Figure 78 - REVIT to IES VE via REVIT>IES VE Plug in tool

4.10. REVIT Heating and Cooling Load (HC)

The REVIT HC process was relatively straightforward and accessible. Once the heavy workload had been completed in regards to setting up the spaces the production of the report was simple. The data allows for detailed analysis on pre-build or existing buildings to take place. This data is invaluable when evaluating predicted or current building performance. Despite the relatively simple and low workload involved in running the HC analysis in REVIT a considerable amount of time is spent in preparing a model. A number of substantial processes have to be completed prior to the analysis taking place such as the actual data collection of plans and components, basic modelling of the building, setting up of spaces for energy analysis, validation for clashes and pre-energy analysis before any tangible data can be derived which indicates a considerable workload to get a model to a robust level of detail and quality. These steps have been included within the development of the process maps.

However its important to understand that the workload put into model preparation is not specifically attached to the HC analysis process. It additionally provides a platform for multiple other strands of investigation and analysis providing a whole building platform and tool to assist in building management.

4.11. Autodesk REVIT: Rapid Energy Modelling (REM)

After the investigations into the tool using multiple varied source models there was mixed success. Using the simple low complexity models the REVIT Conceptual Design was a success with varied iterations. Intentional errors were implemented into the models to test what impact they would have such as the wall inside a wall clash and the gap in the exterior walls/facade causing a room boundary error. With both of these intentional errors the REVIT Conceptual Design simulation was still a success. The investigation then moved onto differing models with increased complexity. The JL model whilst not a particularly large building, 3000m^2, had a complex modelling structure with room boundaries set but no analytical spaces defined. The process failed. The next model to be tested was a conceptual academic model with a footprint of 4500m^2. The model structure whilst a large building was clean and relatively simple. The model had room boundaries set but not analytical spaces defined with the same settings as previous test and resulted in a success.

The differing factor between the JL model and the concept academic building was the level of complexity within the modelling detail. The JL building had a higher LOD. There are similarities between the level of detail and complexity in the JL building and that of the GE model. At this point it could be reasonably assumed that the failure of the REVIT Conceptual Design to run is down to the complex level of detail within the GE model, similar to the issues found with the test run on the JL model.

Reasoning can be made as the source of the issues. The conceptual academic model was a very clean model and robustly built in regards to the technical complexity. The JL model was initially created on a much older version of REVIT, REVIT Architecture 2011. Much of the components and families within it are embedded within each other which when assessing model integrity can result in an 'unrefined' model, which embeds issues when attempting simulations. The GE model was also fairly complex and the culmination of these modelling discrepancies as well as the level of complexity could be argued as the root of the issues with REM.

4.12. Green Building Studio

Running the experiments on GBS highlighted a number of core process steps included within the process maps to improve interoperability success between BIM models and GBS. The first test run was carried out to ascertain the interoperability of GBS when using a gbXML file defined via room volumes. The non-validated model and the validated BIM model both completed successfully, offering a number of analytical benefits. Room volumes contain a differing set of data parameters when compared to gbXML files derived from spaces. As defined by Autodesk, "Rooms and spaces are independent components used for different purposes. Rooms are architectural components used to maintain information about occupied areas. Spaces are exclusively used for the MEP disciplines to analyse volume. They contain parameters that maintain information about the areas in which they have been placed." With this observation it was important to also consider the interoperability of BIM models to GBS via gbXML files defined via spaces room boundaries.

Providing a critical comparison on the interoperability the two methods of upload with GBS were evaluated. The first being via the REVIT energy simulation tool into GBS and secondly the manual upload into GBS via gbXML import as a control. From the experiments

run it can be derived that no difference is found between the two methods and choosing either method did not have any significant impact on the process or interoperability.

The next phase was to investigate import via gbXML files defined via spaces as space-bounding definition are a crucial component of MEP analysis. The first run highlighted a significant missed step in the GBS process using spaces as the definition protocol, within the setting up of the GE BIM model prior to export of the gbXML. Zones had not been correctly allocated to the BIM model to allow for further accurate analysis to take place. Model clash detection validation had not found this issue and in reality was not intended to as the parameters are assessing different criteria for clash detection. However the preparation for energy analysis validation had also not highlighted the issue. This is an important step included within the process maps. Awareness needs to be underlined when relying on tools such as Solibri to assist in the model preparation that not all issues will be discovered or recognised by an automated checking system. It highlights the need for additional protocols during model creation and pre-energy analysis creation to proceed towards achieving a model ready for energy analysis.

An iterative process was then carried out to revisit the source GE BIM model, attempting to align spaces to zones. The process was part successful in getting the procedure past the previous error nonetheless the process did not complete successfully upon the following run. An additional error was prompted in that some zones now did not have spaces allocated to them. Again an attempt was made to revisit the source model and check that all zones were visually aligned with spaces and thus all spaces had zones attached. The following forth run was completed which again failed with the previous error, clearly the issue had not been resolved by visually trying to validate the allocation of zones to spaces and spaces to zones. This indicated a significant miss step in procedure and was a route to a notable protocol discovery within the process methodology. The resolution was to use a viewing option within REVIT found within view/system browser as discussed in the data chapter. Using the system browser inline with the schedule takeoff of the spaces and all zones and allocated spaces were identified providing a platform to evaluate the validity of allocated spaces and zones. In this latter instance the process was not solely relying on a visual interpretation of the model and thus the zone allocation. In contrary, the process was supported by specific data takeoffs and outputs, which presented the required information in a clinical and logical format, which clearly indicated missed zone allocations or errors. By using this method the spaces allocated to zones and the zone issues were all resolved.

As highlighted within the data analysis of GBS run 5 the above process did manage to solve the issue of zones having no spaces allocated to them and for the first time GBS began to attempt to run alternative runs, which was a significant step forward. Run 5 moved further into the analysis within GBS then any of the previous runs. However after a period of 4 minutes further errors were prompted highlighting issues with the message 'ERROR – Cannot simulate layers aim25649 as given. The wall is too thin'. A substantial amount of research was carried out throughout forums and help pages to try and resolves the issue. A useful explanation was found within the AutoDesk Community forum, "This error is generated due to a limitation on the DOE2 energy analysis engine used by Revit/Green Building Studio. What it actually relates to is an instability in the simulation i.e. it is not just specific to walls but any building elements that are too light (or too heavy) subjected to rapidly changing external environmental conditions and/or internal gains (like a large heat gain coming on quickly) causes the simulation to becomes unstable. All dynamic thermal simulation engines are prone to this but for different configurations" (AutoDesk Community, 2014). Taking this advice into consideration a number of attempts were made to resolve the issue but all unsuccessful. Extensive research and reattempts at the runs were carried out with no successful route through the issue found. Using the codes given with the error warnings for instance the 'aim25649' data, an attempt was made to identify the ID of the components at the

route of the issue. Error warnings highlighting component ID's described as the source of the issue could not be matched to component ID's within the source BIM model.

Multiple processes were carried out to solve the issue and identify the components preventing the analysis as discussed in the data chapter. It is reasonable to argue that an issue is present between the interoperability of the data tagging and parametric data carried between the two platforms, as it should be possible to identify ID tagging between the platforms. If this is a misstep in procedure it is reasonable to argue that the process should be made more seamless allowing for easier diagnoses of issues and a clearer link between failed runs and the cause of the failure should be implemented into the GBS system. This resulted in an insurmountable issue in regards to running the simulation, which resulted in the termination of the experiment.

As discussed throughout the study the source model used has been validated using industry standard clash detection software, thus the model is absent of any component clashes. The model had also been validated for energy analysis assessment. Visual checks were made within the model as well as the above analytical processes, therefore it is clear a number of noteworthy attempts were made to prepare the model for the energy analysis, yet none were successful. To fully evaluate if the process and protocols were the route cause as described above a critical control test was carried using a medium level of complexity model, the JL model and a far simplified model, the 'simple model'. As discussed in the data chapter the JL model failed to run within GBS. Conversely the simple model did run successfully within GBS. Under all tests the simple model completed its analysis runs successfully. This critical phase of the investigation considerably goes towards validating the protocols and processes followed within the GE and JL experiments, indicating that the correct modelling and protocols were adhered to and followed. It could be argued that GBS as a platform struggles to process greater complex gbXML files and thus complex BIM models. however this could be greater reflected as an issue with the lack of accessible interface to diagnose run terminating issues. The more complex a model the greater need there is for an accessible system to assist in diagnosing issues and discovering the route cause of errors. It is reasonable to state that the current system in place within GBS does not support this process and it was discovered within this research that the assistance through issues and errors is only often found in salient conversation within help forums and not locally within software platforms. An advice from this research would be for the reporting of run terminating issues to be communicated in a far greater accessible form, whether that be an additional plug in or an improvement of the in-system error reporting process.

4.13.   BIM Tool Selection

The tools that were selected as part of the investigation were selected to provide a reasonable spread of processes and software types. A critical tool from varying levels of BIM process was adopted. REVIT was used as the source of the data, providing an accessible platform to ensure interoperability with the recipient software platforms. As stated within the BIS BIM Strategy Report (2011) "A Building Information Model (BIM) should be the central hub for all information about the facility from its inception onward". The modelling tool used for the source data could be substituted for a multitude of industry standard BIM authoring tools as long as they met the minimum requirements in regards to export functions and interoperability as discussed in section 3.9   'BIM Authoring Tool Requirements and Selection'. The next critical process was to ensure a clean model. At first glance it may be assumed that an existing building will not need any process of clash detection, due to the fact that the Case Study building is an existing building and hypothetically the design is fixed, finished and thus clean of clashes. However just because the actual building is free of error does not mean the virtual model will be. Model validation is a critical step in insuring accuracy and quality within the data. Modelling a building is not a fool proof process and

errors can easily arise due to human or software error. The model validation process can be generalised to a multitude of validation software platform. The finite steps in the process may vary however the critical focus and requirement in model validation is transferable. IES VE was selected as a leading tool within energy simulation. The capability of accepting model import files in IFC, REVIT IES VE plug in and gbXML presented the opportunity to critically evaluate a number of techniques on one platform. The critical steps in the energy simulation processes can be generalised to further software such as the explored requirement to ensure a validated model in regards to clashes as well as the critical pre-energy validation described in section 3.16.

4.14.   Chapter Critical Appraisal

This chapter set out to discuss the topics that have been covered earlier in the thesis. The primary aim was to critically evaluate the impact of each of the topics whilst providing the first opportunity to contextualise the findings evaluating the impact of the research in relation to the wider topics of the research and the literature reviewed. The chapter begun by discussing the preparation steps prior to modelling highlighting significant issues with access to data and accuracy source plans. The chapter then went on to discuss the importance of the level of detail and complexity of models when using BIM. The fundamental finding was that careful consideration needs to be made to what the final outputs of BIM models and processes hope to achieve, as this will directly influence the design of a model and the level of detail that should be completed. A common significant issue encountered was that of interoperability and model complexity. London et al (2010) stated that due to the interoperability that is offered as part of IFC, BIM enhances the design environment creating an environment where information exchange can be synchronised using the centralised and single core model data model. This statement is contradicted by the findings within this research as a number of issues were encountered specifically indicating the need to have separate data models designed for specific outputs. An example of this is described in the discussion surrounding the IES VE interoperability, in that this work advises that a BIM model should be prepared with 'room volume' tags for architectural purposes and a separate mass or BIM model with spaces defined via 'space volume' tags should be created for IES VE energy simulation. This contradicts the statement that a single data model can be used to centralise building data indicating that the future of information management of buildings will require multiple forms of models to be utilised and accessible. The chapter later went on to discuss the challenges of a selection of BIM and performance simulation techniques and processes focusing on the successes and failures in relation to the interoperability and best practice of the platforms which informed into the process methodology produced as a result of this research.

5. Chapter 5: Conclusions and Recommendations

5.1. Chapter introduction

This chapter summarises the outcome of this project relative to the research aim and objectives. Significant findings have been discussed summarising the impact of the project, as well as reflections on recommendations for future work resulting from the research findings. The chapter highlights how the research questions have been answered and the aim and objectives of the research achieved. Finally the chapter concludes with critical evaluation of the limitations, which leads to the identification of scope for further research.

5.2. Summary of the Project

The aim of the research was to investigate the use of Building Information Modelling for information management of existing buildings. The focus is the use of Building Information Modelling software, techniques and processes in data management evaluating the challenges and hurdles. Existing and developing processes within BIM were critically evaluated using a range of experimental modelling processes to identify the critical paths in the adoption of BIM in building management. The output of the experimental methodology has been summarised into accessible framework that can be adopted/adapted in the process of BIM implementation. Whilst the focus of the study was limited to a single large complex Case Study building a number of control models were used to provide reliability to the experiments. As discussed in section 4.14 in the discussion a number of the processes could be generalised to a wider selection of models and software platforms.

The theoretical framework that underlines this work falls best under the Interpretivist paradigm, which supported the experimental and descriptive data collection and analysis focus of this thesis. The methodological design began with the use of 'Theoretical research' to construct the literature review. The thesis then progressed on to use 'Empirical research' which encompassed case studies and experimental techniques adopted. A qualitative method was adopted and progressive focus, descriptive data collection and descriptive analysis was used.

5.3. Comments on Research Objectives

This section discusses how the research objectives were met.

- Objective 1: Carry out a literature review on the role of Building Information Modelling in information management

This objective was achieved by investigating the current trends and BIM standards and practice. This provides a theoretical platform, which supported the foundation of theoretical knowledge, which underpins the experimental phase of the project. Key areas such as the drivers for BIM adoption, interoperability, collaboration and data sustainability were explored as part of the literature review to successfully achieve this objective.

- Objective 2: Objective 2: Develop Building Information Model of selected case study building:

This objective investigated the use of BIM for existing buildings. The case study model was used as the focus for the objective 3 experimental data evaluation. The processes and challenges throughout the modelling process were highlighted and critically evaluated. Aspects such as poor existing data management, lack of accurate data on assets and the

challenges with access to building data were highlighted as critical challenges when BIM modelling existing buildings.

- Objective 3: Establish experimental processes to investigate and test the application of BIM the existing buildings

This objective was achieved through experimental process, which investigated the impact of BIM techniques and simulations with retrospective application to existing buildings. Building information management protocols were developed to support the retrospective building modelling process. Case study models were validated using Solibri model validation software for technical validation. The validation process was carried out to improve the accuracy of the BIM model. Data interoperability was then tested using case study models of different levels of complexity, which were run through a number of experiments to test the success or failure of interoperability within a selection of software environments. The interpretation of the experimental results provides a platform to develop the critical paths in objective 4.

- Objective 4: Establish the critical paths when adopting Building Information Modelling tools for information management;

The data gathered in objectives 2 and 3 provides a grounding of experiments to understand and investigate the critical paths when adopting BIM processes to improve information management. A number of critical paths were identified and discussed in depth such as the accuracy of source data, critical process steps in modelling and simulation, interoperability issues and pre-modelling decisions and protocols which achieved this objective. A significant critical path was the need to validate the source model to ensure that a clean model was being transferred between the software platforms. When issues exist in the source model the accuracy of the data transfer to other software's cannot be relied open. Additionally another critical factor to consider is the level of complexity to models. When attempting to transfer a high complex model to IES VE from REVIT the import, whilst successful in some part were never exempt from clear errors. Similarly when attempting to run models through REM high complex models would fail, whereas the simple control model would succeed. This indicates an import critical concern that should be considered when exploring the potential of BIM to information management. The research indicates that a singular core model is not sufficient if a number of varying processes such as quantities or energy simulation are desired. The research has established that high complex models cannot accurately be imported into energy software. This work warns that the model design and level of complexity should be aligned with the final output. This will result in contradicting the core model ethos of BIM through the requirement to have simplified massing models for refurbishment energy assessment and detailed complex models for quantity and building data storage. The identification of critical paths then directly informed into the production of the process maps to summarise the work, which formed objective 5.

- Objective 5: Develop process maps to summarise the findings of the research in adopting Building Information Modelling processes for information management;

Objective 5 provided a clear, accessible and tangible output to summarise the research findings. The processes maps were created as an accessible point to reference the research. The critical investigations into the interoperability, accessibility and efficiency of the chosen tools as discussed in objective 4 were used to set out the proposed process maps. The process maps are to be utilised as a starting guide, which new adopters or users can adopt and adapt to suit internal bespoke requirements if BIM processes are to be utilised to enhance the information management of existing buildings.

5.4. Summary Comments on Research Questions

Research questions developed from the research objectives:

a. What is the effect of BIM processes and technology on the management of existing buildings?

The effect of BIM and what BIM has to offer to the improvement of the information management of existing buildings is significant. The UK Government has set out clear mandates forcing the use of BIM for public construction projects in 2016 for new builds. As the understanding of BIM and what benefits it has to offer became better known as a result of this mandate the benefit of the technology could surpass the restraints of new build into the realm of existing building information management and refurbishment. It can be argued that BIM processes and technology can have a positive impact on data management by providing an interoperable and sustainable data access point for building information. The effects explored as a result of this project leads to a number of processes and methods proposed to assist in the information management of existing building stock. It is argued this will be achieved through a number of ways such as the increased efficiency of data access, through digital access of data within 3D models. Likewise the sustainability of building information can be improved through the collation and storing of data in 3D models within BIM the CDE. Having data in a current and relatively future proof format improves the sustainability of the data over its 2D hardcopy or achieved CAD plan counterpart. The ability to access the data live through the CDE further enhances the accessibility.

If an OpenBIM approach is followed the interoperability can be significantly improved enhancing the transfer of data between relevant information management systems such as cloud based data storage, energy analysis and digital quantity platforms. This research argues that by improving the factors above data accessibility will be enhanced contributing in part to improve general building information management. This improvement in interoperability is intrinsically intertwined with good BIM practice as identified within the literature review of this research. With further study the results of this research have the potential to be extrapolated to wider building typologies by expanding the case study and software pool.

b. What are the challenges of retrospective application of BIM for information management of existing buildings?

The project has highlighted significant issues with access to building data and the sustainability of the data at hand. Additionally it could be argued the project has highlighted the need for building data to be fully transferred to a cloud-based environment due to the issues with gathering up to date information on assets. The cloud environment does open up the vulnerability of data security however if PAS 1192/5:2015 is adhered to then data security issues can be prepared for and hopefully circumvented. However a definitive protection against data security breakdown does not exist in the digital industry today with high-ranking networks vulnerable to being breached. In regards to data ownership the establishment of clear roles of data access and ownership for all participants through the PAS 1192 series and BIM protocol document can help to ensure that contractually and legally binding agreements are in place to ensure clarity over Intellectual property and data ownership.

This thesis has identified a key area to consider in the level of detail required in a 3D model when developing BIM models. Agreement and evaluation on the level of detail is essential to make informed decisions about what processes they will adopt and what outputs are required. For example models targeted for energy simulation software such as IES VE or Autodesk REVIT rapid energy modelling level of detail and complexity will encounter issues

if they have a high complexity. It crucial to ensure clear outputs is established when considering BIM technology adoption for information management.

The importance here is to highlight the factor of establishing a proposed use for models prior to any development of BIM processes. As discussed earlier within this thesis it was highlighted that a significant aspect of BIM was not considered fully within the early stages of the parallel RESSEEPE project. Varying partners were creating multiple models, which contradicts the core model BIM ethos. This resulted in valuable time and workload hours lost through a challenging and difficult data gathering and simulation period. A resolution discovered through this thesis to retrospectively apply BIM techniques to model the case study buildings was adopted by the RESSEEPE. The GE Case Study model produced was forwarded over to RESSEEPE to be used for energy simulation, geometric assessment and building data use. This work is on-going therefore no feedback or results have been attained at this point.

The thesis identified a clear need for more efficient processes of data storage and access, in essence having the information there, when you need it. This may appear as a widely understood viewpoint however as this research has explored not all estates management is progressing to digital data management processes such as BIM. Therefore this work identifies the potential scope for BIM adoption to improve the data access to the case Study building. The main case study building modelled was relatively old with from a time of out-dated standards of data handover at the time of construction and completion. The lack of available data however has similarities to non-BIM'd buildings of today. It could be argued that benefits that a BIM model can bring to new builds are similar to those that are on offer in retrofit or building management. The challenges however are often different as discussed throughout the thesis with lack of source data. It may be seen that in future asset processes, holding a BIM model of estates stock is common or standard, it may be argued that it's crucial.

5.5. Achievement of Research Aim and Recommendations

Considering the interoperability of software systems a particular example from this research is worth noting concerning the interoperability between the REVIT BIM model and the IES VE platform. The experiment highlighted a significant concern in regards to the level of detail and complexity of BIM models that IES VE could handle. Additionally the core model ethos proposed that all disciplines work on a core centrally model, with the release of certain parts of the building for varying teams to work on comes into question as a result of the model complexity issues identified in this project. As discussed previously critical issues were encountered in regards to what level of complexity the simulation software could accept. The reality of industry processes has evolved the practical solutions in a different direction. The issue between the IES VE and REVIT BIM model interoperability regarded the fact of IES's VE interpretation of spaces. This resulted in a duplication of recognised volumetric spaces. It leads to the argument that single model ethos will contradict the practicality of software and industry practice. Technological limitations has led the concept to move towards a federated central model concept where models can be designed and interrogated in their own space later to be federated into the central model. This allows for clearer routes of ownership, liability and risk through the federated models. The issue discussed above in regards to the duplication of space definition within IES VE supports the latter concept in that the architectural model would contain the room volume tags and the MEP model would contain the 'spaces' definition for volumetric room spaces. The model, which would be used for IES VE analysis would naturally be sourced from the MEP BIM model and would therefore only have spaces defined. The discussion does strongly reiterate the need for multiple systems and software platforms to be interoperable and the investigation of this

research justifies the move towards an OpenBIM approach within the development of best BIM practice.

This investigation explores the challenges when adopting technical BIM processes to enable for information management. BIM does not necessarily have to be envisaged as a new process, on the contrary, BIM adoption can be seen as a collation of best practice in existing design, analysis and management processes. This research has taken on a number of existing technical processes alongside a number of evolutionary BIM practices to critically evaluate what place BIM has in the existing state of information management. The result has been an experimental and enlightening window into the benefits and difficulties that can be experienced within the attempt to adopt BIM practices.

The processes trialled out within this research have been critically evaluated with an aim to move guidance beyond the theory into practical application. The result of this has led to the creation of the process maps, which aimed to provide future adopters with a quick reference guide into this research. Many processes encountered significant issues, which were not fully discussed within standard technical guidance documents. By working through these issues a platform was provided which facilitated the production of the process map outputs supported by the critical experiences within the experiments and directly informed the specific steps set out within the process maps.

It could be argued from this research that BIM tools and processes bring efficiency to building information management processes providing an accessible platform to accurate data to the contrary to the hard copy data that existed on the George Eliot case study. The existing plans were restrictive in what they could offer to information management beyond the basic drawing information. The creation of the BIM model opened up the data to be used in a umber of efficiency and informative processes such as energy simulation. The outputs attained from the experimental case study support this statement as a considerable amount of useful data and analysis was attained through adopting BIM practices. The investigation however has emphasised the importance of understanding the processes and tools when adopting new techniques. The importance of this factor should be considered crucial if efficiency, accuracy of data and analysis are signified as critical outcomes. As analysed within the key case study adopting processes, whether that be as an experienced or inexperienced user, unforeseen issues can be encountered. It could be assumed as a common understanding that having less experience and skill in the use of a platform will have a direct influence on the efficiency of use within that process. What is maybe more significant to note as a result of this research is that even when user experience is high in a software such as REVIT, information management and data transfer can often be a troublesome and complicated process when issues are encountered. Many of the issues encountered within this project did not have immediate solutions available within software support or guidance. Which supports the need for continued guidance and assistance through the processes of adoption.

The process methodologies produced are a critical result of the processes trialled within the experimental phase. The target of these process maps is not to be a one stop definitive guideline. To the contrary it is designed to be an iterative map, which can be further evaluated and evolved with future trials and testing. The process maps provide a current summarised window into the experimentation results of this research. They provide a context to assist users in making early pre-adoption decisions supplying users with the ability to foresee some of the potential pitfalls and issues, which may lie ahead. By discovering and encountering the issues within this project, proposals were made outlining steps to take in response to issues.

5.6. Limitations of the Research

The process maps would be improved with further critical evaluation and testing within a wider case study pool. This wider context application would provide a platform to improve the robustness and validity of the processes.

If comparing to the work by Fellows et al case study approach can provide a 'theoretical generalisation for the experiments, rather than empirical or statistical generalisation' (Fellows et al, 2005). Which is what this work has aimed to align to. The results of the case study investigation aimed to inform future adoption of the trialled techniques and process providing assistance and guidance. The work is not designed to provide a definitive exhaustive statement of best practice, but in contrary propose and highlight lessons learnt as a result of the work. Any findings of the work have been discovered and proposed as the result of a focused case study with limitations on the reliability when extrapolating the results to far wider context. Additionally the work could be expanded to cover different avenues of source data collection such as laser scanning or modern surveying methods if the resources were available, as it may circumvent a number of the source data issues. Exploring the limitations and benefits of laser scanning and modern surveying methods would be beneficial to establishing best practice in retrospective BIM modelling. Identifying these research limitations leads directly into the proposals for future work beyond the scope of this project.

It is also important to recognise the limitations that exist in regards to the software versions that this project used. The versions selected in this project had to be fixed to a specific snap shot of a version to ensure the project remained within a realistic scope of work. A limitation of this is that the work provides insight into a short window of time of relevance for some of the process adopted. This is not true for all aspects of the work however as some of the critical processes identified are transferable across software versions and platforms, such as the need for model validation steps prior to attempting data transfer between authoring tools and recipient platforms.

5.7. Further Research and Future Work

As discussed previously to enable for widening of the impact of the study a wider test pool of case study buildings would need to be carried out. This would provide a stronger scientific grounding for the assumptions and results. To further enhance the validity and robustness of the process maps a qualitative phase of review could take place. This peer and industry review would help to strengthen best practice guidelines outlined within the process methodologies. Additionally the process maps for each of the software specific process could be tested against a wider pool of software, which aims to perform the same tasks, such as additional energy analysis platforms.

The investigations could progress on to explore and test potential building components in suggested building refurbishments as part of an analysis phase. The investigation could be integrated further within a lab and live building demo environment attaining clear results on performance, reliability and future possibilities. Interesting future work would be to use the simulation tools investigated within this project to simulate performance predictions and critically compare the simulation, post installation and lab performance data of the interventions to evaluate the gap between predicted and actual performance.

To begin to assess the impact of the research carried out within the project a number of comparative studies could be evaluated to establish the optimum expected time for processes adopted within this study. This would provide a critical platform to quantify and establish the impact of the experiments against current optimal industry examples.

Additionally a systematic approach to the data reliability during transfer would help to establish the true performance of the interoperability between the platforms investigated.

Another suggested area for future work could be use the foundation of work in to create an app or software platform designed to utilise the best practice critical path guides. The app or platform could act as an accessible and efficient platform to assist users through the adoption of retrospective BIM processes and simulation trials.

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7. Appendix

Documents for the appendix can be found in the digital support media provided with this thesis or upon request from the author. The structure of the media is as per the Appendix contents list.

Appendix contents list

- Appendix A - Building Selections Feasibility Study
- Appendix B – GE Building Data
- Appendix C - Building Survey Outline
- Appendix D – BxP and PIP Template
- Appendix E - Model Validation
- Appendix F – IES VE
- Appendix G – Rapid Energy Modelling
- Appendix H – Heating and Cooling Loads
- Appendix I – Green Building Studio
- Appendix J - Enlarged Process Maps

Process Map for Preparation for Modelling and BIM Modelling Adoption

Process Map for Scoping Clash Detection

Process Map for General Space Check

Process Map for Pre-Check ... analysis

FlowChart Preparation for Energy Analysis and
Space Utilisation:- General Space Check
FlowChart Model Validation:
pre-check for energy analysis
(Solibri)

It is crucial to carry out the pre-energy analysis checks prior to running any other analysis to ensure the robustness of BIM models.

Model Validation pre-check for energy analysis (Solibri)

Source - Produce BIM Model

Data Export BIM Model to IFC

Process Model Validation

Data Import IFC into model validation software (Solibri)

Select pre-check for energy analysis rule set

Begin Model Validation pre-check for energy analysis (Solibri)

Resolve issues in source BIM model

Run pre-check analysis- Are there issues in the model/results?

NO

YES

View results - Can issues be accepted now and 'checked off'?

Ready for space utilisation analysis

Report issues within Solibri communication Tab

Report issues and create slides using 'add slide' option for each relevent clash

Add details and notes on the issue in 'issue detail'

Assign issue resolution to a person or role - through coordination window in 'add slide'

close of slide by clicking 'ok'

Accept issue and check off as with an accepted green tick

Validation General Space Check (GSC)

Report issues of GSC

NO

YES

Ensure that spaces are definded in BIM model if EA or GSC are a set output

Export pre-check for energy analysis (Solibri)

Export as BCF file or Excel report

Export the pre-check energy analysis report via a BCF file

Input spaces classification into source BIM model

Install BCF file interpretation tool - e.g 'BCFier' for REVIT

Use BCFier to seek each issue - then resolve

Visually check and fix issues using the excel report in the source BIM model

Using the excel export of pre-check report

As issues are fixed, check off the issue in the excel report

Manual classification into source

Fix each issue or add notes to specific resolutions or issues

Is space ... fixed?

Yes

No

Run GSC checking

Choose method to fix/align classification a or b?

a

b

Data Export fixed BIM Model to IFC

Data Import/update IFC model into validation software (Solibri)

issues in validation results

Import updated report into Solibri - BCF or Excel if required

No

... analysis or ... energy ...

Model ready to proceed toward energy analysis

Continue further validation of model in Solibri for EA

Review GSC results

... validation of model in Solibri for EA

Excel

BCF

Process Map BIM Model Import into IES VE via IFC

FlowChart Preparation and
Portocol - IES Import via IFC
defined by spaces

Designed by Danny McGough

Import into IES via IFC defined by spaces

Source - Produce BIM Model

Output - Energy Analysis - Import via IFC into IES

Prepare the source BIM model

Model visually checked for errors in room boundaries or modelling errors

Spaces added to source BIM model

Check /align all spaces allocated via schedule takeoff of spaces

All room and spaces allocated to space?

NO

YES

Assign zones to spaces

Check all spaces are moved from default zones to specified zone using system view and scedule takeoff

Are all spaces aligned to a zone?

NO

Run model through clash detection validation (see clash detection flowchart

Clashes at zero?

NO

YES

Model run through pre energy analysis validation (solibri)

Checks all passed?

NO

YES

Output - Energy Analysis - Import via IFC into IES

Export IFC file from BIM Model - Check 2nd level space boundary criteria for analysis packages

Open IES

Import IFC file via the file/ import IFC

Check BIM import report for errors and warnings

Satisfied with model standard and report checks

NO

YES

Run relevent analysis in IES

Designed by Danny McGough

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FlowChart Preparation and Portocol - IES Import via IFC defined by room volumes

Designed by Danny McGough

Process Map BIM Model Import into IES Via IFC (room volumes)

Import into IES via IFC defined by room volumes

Source - Produce BIM Model

Output - Energy Analysis - Import via IFC into IES - room volumes

Prepare the source BIM model

Model visually checked for errors in room boundaries or modelling errors

Room volumes added to source BIM model

Check /align all room volumes allocated via schedule takeoff of rooms

All room volumes allocated to space?

NO

YES

Model run through pre energy analysis validation (solibri)

Run model through clash detection validation (see clash detection flowchart)

Clashes at zero?

YES

NO

checks all passed?

YES

NO

Output - Energy Analysis - Import via IFC into IES - room volumes

Export IFC file from BIM Model - Check 2nd level space boundary criteria for analysis packages

Open IES

Import IFC file via the file/ import IFC

Check BIM import report for errors and warnings

Satisfied with model standard and report checks

YES

NO

Run relevent analysis in IES

Designed by Danny McGough

Process Map BIM Model Import into IES VE via gbXML

FlowChart Preparation and Portocol - IES Import via gbXML defined by room volumes

Designed by Danny McGough

Import into IES via gbXML defined by room volumes

Source - Produce BIM Model

Output - Energy Analysis - Import via gbXML into IES - room volumes

Prepare the source BIM model

Model visually checked for errors in room boundaries or modelling errors

Room volumes added to source BIM model

Check /align all room volumes allocated via schedule takeoff of rooms

All room volumes allocated to space?

NO

YES

Run model through clash detection validation (see clash detection flowchart)

Clashes at zero?

NO

YES

Model run through pre energy analysis validation (solibri)

checks all passed?

NO

YES

Output - Energy Analysis - Import via gbXML into IES - room volumes

Export gbXML file from BIM Model

Open IES

Import gbXML file via the file/ import gbXML

Ensure import checks are ticked/checked off in IES imort window

Check BIM import report for errors and warnings

Check BIM IES model for visual errors and warnings

Satisfied with model standard and report checks

YES

NO

Run relevent analysis in IES

Designed by Danny McGough

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FlowChart Preparation and Portocol - IES Import via gbXML defined by spaces

Designed by Danny McGough

Process Map - Model Import into IES VE via gbXML (spaces)

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Process Map Import into IES VE via REVIT>IES VE Plugin Toolbar

FlowChart - REVIT to IES via REVIT>IES Plug in Tool

REVIT to IES via REVIT>IES Plug in Tool

Source - Produce BIM Model

Output - Energy Analysis - Import via REVIT Plugin tool into IES

Prepare the source BIM model

Model visually checked for errors in room boundaries or modelling errors

Spaces added to source BIM model

Check /align all spaces allocated via schedule takeoff of spaces

All room and spaces allocated to space?

YES

NO

Ensure that all spaces are room bounded by walls, ceiling/roof elements

Assign zones to spaces

Check all spaces are moved from default zones to specified zone using system view and scedule takeoff

Are all spaces aligned to a zone?

NO

Run model through clash detection validation (see clash detection flowchart)

NO

Clashes at zero?

YES

Model run through pre energy analysis validation (solibri)

NO

Checks all passed?

YES

Output - Energy Analysis - import via REVIT Plugin tool into IES

Install REVIT>IES plug in toolbar

Ensure REVIT>IES plug in toolbar is up to date

Check and set settings as per IES support documentation and analysis requirements

Select - Import Model in REVIT>IES toolbar

Check BIM import report for errors and warnings

Open IES

Check BIM IES model for visual errors and warnings

Satisfied with model standard and report checks

YES

NO

Run relevent analysis in IES

Process Map for Green Building Studio Protocols

FlowChart Preparation and
Portocol - Green Building Studio

Energy Analysis - Green Building Studio (GBS)

Source Produce BIM Model

Output - Energy Analysis through REVIT energy simulation tool

Output - Energy Analysis through GBS - manual import

Prepare the source BIM model

Model visually checked for errors in room boundaries or modelling errors

Spaces added to source BIM model

Check /align all spaces allocated via schedule takeoff of spaces

All room and spaces allocated to space?

NO

YES

Assign zones to spaces

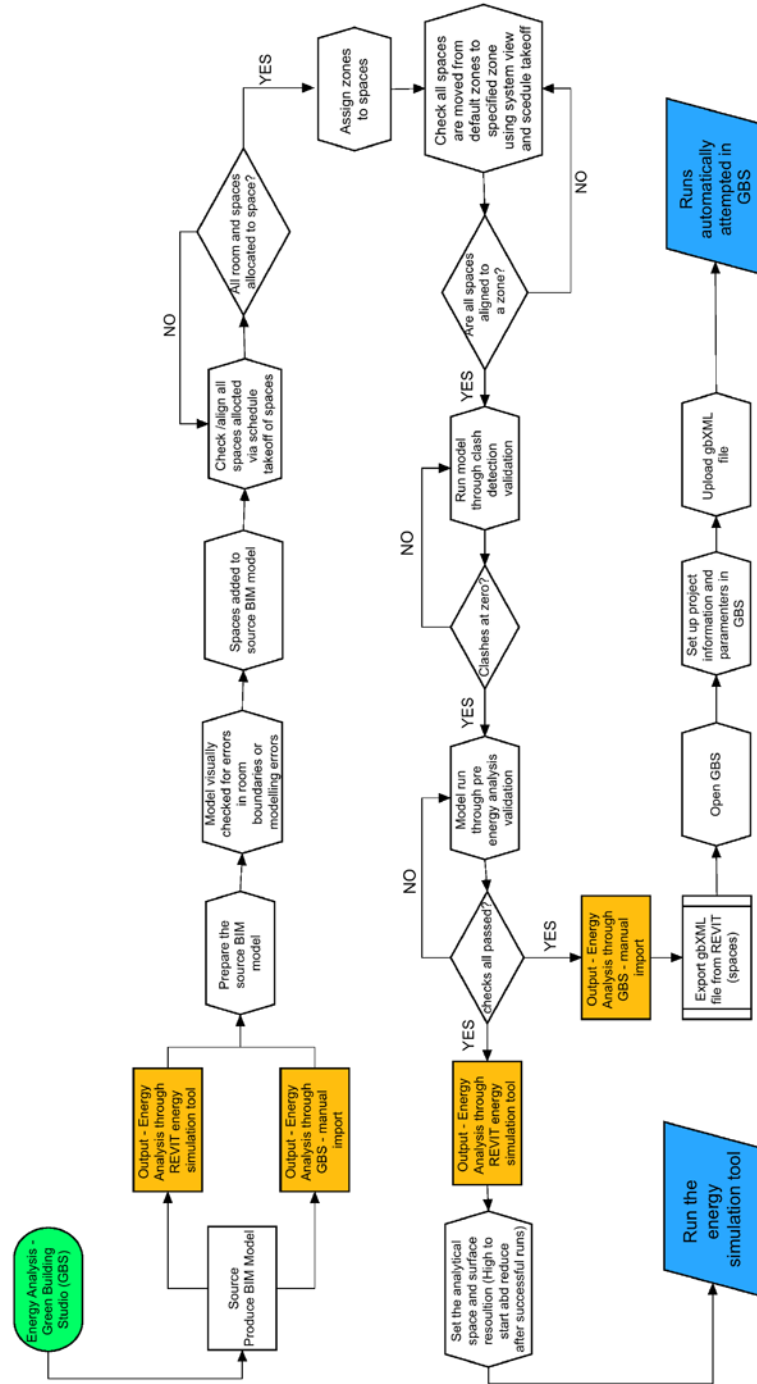Check all spaces are moved from default zones to specified zone using system view and scedule takeoff

Are all spaces aligned to a zone?

YES

NO

Run model through clash detection validation

Clashes at zero?

NO

YES

Model run through pre energy analysis validation

checks all passed?

NO

YES

YES

Output - Energy Analysis through REVIT energy simulation tool

Output - Energy Analysis through GBS - manual import

Set the analytical space and surface resoultion (High to start abd reduce after successful runs)

Run the energy simulation tool

Export gbXML file from REVIT (spaces)

Open GBS

Set up project information and paramenters in GBS

Upload gbXML file

Runs automatically attempted in GBS