DRIVERS FOR ENERGY ANALYSIS TOWARDS A BIM-ENABLED INFORMATION FLOW

ABSTRACT

Design/methodology/approach

The paper presents a set of Key Performance Indicators (KPIs) extracted from the developed Energy Analysis (EA) process maps and interviews with expert stakeholders. These KPIs stem from the literature review and link to the benefits of EA through industry expert review. The study includes; i) Development and validation of EA process maps adjusted to requirements from different stakeholders. ii) KPIs aligned with the EA process map. iii) Identification of the drivers that can facilitate lifecycle information exchange. iv) Opportunities and obstacles for EA within Building Information Modelling (BIM) enabled projects.

Purpose

EA within a BIM enables consistent data integration in central repositories and eases information exchange, reducing rework. However, data loss during information exchange from different BIM uses or disciplines is frequent. Therefore, a holistic approach for different BIM uses enables a coherent lifecycle information flow. The lifecycle information flow drives the reduction of data loss and model rework and enhances the seamless re-use of information. The latter requires a specification of the EA KPIs and integrating those in the process.

Findings

This paper depicts a viable alternative for EA process maps and KPIs in a BIM-enabled AEC design industry. The findings of this paper showcase the need for an EA within BIM with these KPIs integrated for a more effective process conforming to the current OpenBIM Alliance guidance and contributing towards sustainable lifecycle information flow.

Research limitations/implications

The limitation of the research is the challenge of generalising the developed EA process maps; however, it can be adjusted to fit defined organisational use. The findings deduced from the developed EA process map only show KPIs to have the ability to facilitate adequate information flow during EA.

Practical implications

The AEC industry will benefit from the findings of this primary research as they will be able to contrast their process maps and KPIs to those developed in the paper.

Social implications

This paper benefits the societal values in energy analysis for the built environment in the design stages. The subsequent lifecycle information flow will help achieve a consistent information set and decarbonised built environment.

Originality/value

The paper offers a practical overview of process maps and KPIs to embed EA into BIM, reducing the information loss and rework needed in the practice of this integration. The applicability of the solution is contrasted by consultation with experts and literature.

1. INTRODUCTION

Building Information Modelling (BIM) facilitates the production, management, and exchange of digital data types throughout the lifecycle of a built asset (Sacks et al., 2018; Hafeez et al., 2021). Energy Analysis (EA) is a process that aims to obtain an asset energy model from early to the detailed design stages. EA works at various project stages to forecast the energy demand and improve the building performance during the operational phase. However, traditional EA involves challenges as the error-prone manually elaborated simulation models and the complex calculations requiring up-to-date project information (Choi et al., 2016). In conjunction with BIM, EA enables a coordinated energy model with the rest of the building components and disciplines (Sattler et al., 2019).

The built environment is responsible for 20% to 40% of the global primary energy use (IEA, 2019; Perez-Lombard et al., 2008; Saidur, 2009; Shi et al., 2011). EA aims to contribute to achieving the desired energy profile for buildings in the future energy positive neighbourhoods (Crosbie et al., 2010; Ala-Juusela, M. 2016) and to follow the path towards net-zero energy buildings and green design, which is gaining momentum in Europe, Canada, and Japan (Dian et al., 2021). The choice of BIM components and parameters such as walls, windows, G-values, U-values, surface area, building orientation, and use-regime significantly impact the effectiveness of EA, which results are improved when conducted in a standardised fashion (Jin et al., 2019). For example, glazing surface and type of windows can be part of an optimization process in BIM, enhancing the performance by up to 10% of the building energy load (Sawyer, 2014). That is possible by exchanging BIM data from design authoring tools to the EA environment. Thus, the parameterization of building components becomes an invaluable design advantage that enables the integration of energy analysis within a BIM-enabled framework.

Passive design and energy-efficient systems can improve the building performance and its lifecycle costs (LCC) (Sawyer, 2014; Rodriguez-Ubinas et al., 2014). A dedicated BIM process facilitates consistency in sharing information from the design authoring tools into EA and other disciplines, informing the overall design process. The EA process analyses and ensures that performance is consistent with the client requirements and the design phase and helps make informed decisions virtually before the construction process starts (Rodriguez-Trejo et al., 2017; Choi et al., 2018).

Baldwin et al. (2010) demonstrated the positive impact of process improvement by overhauling and adding steps to advantage certain aspects of the processes in a study focused on industrial stakeholders. These changes permeate all the areas of the information flow in the Architectural, Engineering, and Construction (AEC) industry. Research and industry have argued the potential benefits of using BIM (Barlish and Sullivan, 2012; Jin et al., 2019; Zhang et al., 2018), which recently is gaining momentum in the Building Performance Assessment (BPA) and EA (Jin et al., 2019).

Kreider and Messner (2013) defined EA as "a process in the facility design phase in which one or more building energy simulation programs use a properly adjusted BIM model to conduct energy assessments for the current building design". Traditionally, architects focused on design, form, and space and did not consider EA a standard process (Shi et al., 2016). However, late trends in AEC promote integrating EA into the design, considering the lifecycle energy quantification through facility management and operation when exploring design alternatives at the conceptual design phase (Gao et al., 2019: Xu et al. 2021; Xu et al., 2021; Zhuang et al. 2021).

EA requires a comprehensive understanding of up-to-date environmental and boundary conditions, as well as the client priorities. Therefore, the definition of key performance indicators

(KPIs) and adequate scales selection is a cornerstone to EA and project success at design stages (Rodriguez-Trejo et al., 2017; Xu et al., 2021).

This study aims to indicate the gap in existing process maps. It further addresses the need for lifecycle information flow within a BIM-enabled project as depicted by Charour et al. (2021). The lifecycle information flow drivers enable seamless use of the information in other BIM Uses at the design and construction stages. Information shared across the different project stages adds meaning and value within the various BIM Uses (Lack or faulty information sharing hinders the value of BIM and increases project inconsistencies and rework. The paper presents EA KPIs from a literature review and then links to the benefits of EA through industry expert review. This paper devises a unified standard BIM process for EA used to fill the gaps found in the current literature to enable the adequate application of the process maps. A set of drivers related to the process maps are derived and then validated through a set of semi-structured interviews. As a conclusion from the paper, the main drivers to improve information exchange in the EA BIM use are depicted. The benefits and challenges for EA within BIM will be presented, classified, and analysed in the remainder of the paper. The study aims not to develop an EA process map but to identify possible lifecycle factors linked to the EA process map that would allow model re-use with minimal or no model rework. Section 2 presents the benefits and challenges of EA within the BIM process context and the gaps in the EA process and information flow found in the literature. Section 3 describes the overall methodology followed in the paper. Section 4 describes the EA process maps developed in the research, and section 5 the KPIs inferred from the maps and interviews with experts. Finally, section 6 analyses the results, and section 7 concludes the paper.

2 GAPS IN EA PROCESS AND INFORMATION FLOW

2.1 BENEFITS AND CHALLENGES

EA allows benchmarking different design options at the conceptual design stages leading to reduced LCC and optimised energy behaviour, requiring early input from the energy modeller to the architectural model. Abrishami et al. (2021) highlighted the importance of conceptual design stage automation approach for improved project outcomes. However, the energy modelling currently recommends frequent involvement and rework in the architect's software tool due to interoperability issues, complicating the iterative model improvement (Zhuang et al., 2021). A BIM-enabled process adapted to the energy consultant's needs is still not fully developed (Chang and Hsieh, 2020), lacking the proper KPI analysis and a standard process to add consistency. Gong et al. (2019) indicate a discrepancy between simulation and real-life data and the challenge of decision-making processes relating to adaptation and optimization of energy behaviour in a building project. Ying and Lee (2019) described the outcome of curved walls exported in two different EA applications; both exported models needed to be adjusted. Constraints in the process included not considering element thickness and connections between curved walls. **Table 1** illustrates the different benefits, challenges, and competencies required for the various sub-processes involved in EA.

Table 1: EA with BIM requirements, maturity competencies, benefits, and challenges

ENERGY ANALYSIS WITH BIM			
PROCESS REQUIREMENTS	**REQUIRED MATURITY COMPETENCIES**	**BENEFITS**	**CHALLENGES**
Basic knowledge of building energy systems and modelling standards. Penn State (2012)	Standards	Improved accuracy of analysis outcome through auto extraction of building information and data blending through Symbiotic Data Platform (**B1**). Eastman et al. (2011);	Personal energy use is not simulated and predicted. Eastman et al. (2011); Reddy (2012);
Knowledge of building system design.	BIM Execution Plan (BEP0	Building Energy code verification (**B2**). Eastman et al. (2011);	There is a gap between simulation results and real-live operation figures. Reddy (2012);
Navigation, handling and review capability of 3D models in energy tools.	Quality Assurance/ Quality Control (QA/ QC)	Time and cost-saving through automatic model information retrieval and multi-criteria decision analysis for energy management (**B3**). ; Gong et al. (2019)	Funding immediate cost of thermal building materials proposed for energy optimisation. Eastman et al. (2011);

Manage model LODs – received at different project stages.	Software	Optioneering and optimisation through scenario simulations (comparative analysis) (**B4**). . Eastman et al. (2011);	Technology disconnect and ability to utilise the tools. Ramaji et al. (2020); Stumpf et al. (2011); Sattler et al. (2019);
Stakeholder collaboration.	Role and Responsibility	Assist in lifecycle cost analysis and reduction (**B5**). . Eastman et al. (2011);	Lack of tool interoperability with other applications at defined project stages. Eastman et al. (2011); Ramaji et al. (2020); Sattler et al. (2019); Lin et al. (2010);
Certification requirements.	Software	Modelling documentation for building rating certification (**B6**).	Lack of direct feedback loop between EA tools and design native tools. Eastman et al. (2011); Lin et al (2010);
EA Modelling .	Knowledge of EA input	Predictive analysis of outcome capability and blending BIM data with real-time Information (**B7**). Birgonul (2021)	Input assumptions are variable. (Author)

2.2 INFORMATION SHARING AND LOSS

Laine and Karola (2007) consider that BIM methodologies enable re-using information across the whole building lifecycle. This paper considers this information flow a set of rules, represented as non-graphical or graphical data objects within process maps. Dawood and Vukovic (2015)explain that lifecycle information flow needs the adoption of the "project DNA "and advocate the four pillars of BIM as People, process, policy, and technology, highly interdependent. Design practitioners who do not consider energy analysis may lose the opportunity to make informed decisions on developed improved designs that can provide better energy savings over the lifecycle of a building. However, one of the challenges of the EA concerning architectural design models is the transfer of information from architectural design models to energy modelling tools. For example, parametric properties embedded in design authoring tools are often not readable in some EA tools. The different sets of information required for the EA include general information such as building form, orientation, window size, construction materials, weather data (location set), energy and thermal systems, set-points, and use patterns (internal loads). Despite the efforts to make data available in a common data environment, there is a need to produce information in formats that value the succeeding building design and construction stagesandother BIM Uses within the project lifecycle prone to information loss (Figure 1Dawood and Vukovic, 2015); this also occurs within a single stage due to exchanging information from different software applications to others, as described in table 2.

Table 2: Energy Modelling Details and LOD

Design Phase	**LOD (CIC, 2013)**	**AIA (2013)**	**DETAIL INCREASE**	**ENERGY MODELLING DETAILS**	**ME**	**ID**
Preparation and Brief	Brief (1)	LOD 100		Site location, preliminary positioning, preliminary massing, layout (locate rooms & volumes), special requirements, performance standards (natural ventilation, temperature range), schedules, statutory requirements, user profiles. Gerrish et al. (2019); Osello, et al. (2011); Capper et al. (2012)		
Concept Design	Concept (2)	LOD 200	Building type e.g School	Geometry, dimensions, elevations, massing, size, form, volumes, orientation, master plan, preliminary material specification, target U-Values, glazing ratio for facades, shading depth & height, thermal mass, preliminary services specification. Lin et al. (2010); Gerrish et al. (2019); Osello, et al. (2011); Capper et al. (2012)	x	x
Developed Design	Developed Design (3)	LOD 300	Systems, e.g. External walling	Definite window size/shape/location, materials, accurate location on-site & orientation, correct building envelopes, compact surface areas, accurate building services, the numbering of elements, ceiling, voids, plant location &size, duct size. Capper et al. (2012); Gerrish et al. (2019),	x	x
Developed Design	Developed Design (3)	LOD 350		Detailed model. Gerrish et al. (2019),	x	x
Technical Design	Production (4)	LOD 400	Element, e.g. Cavity wall	Construction details, daylighting & artificial lighting strategies & controls, date, specification of products, definite contract, maintenance strategy. Gerrish et al. (2019)	x	x
Construction Handover	Installation/as constructed (5)	LOD 500	Materials, e.g., Brick	As-built validated model. Gerrish et al. (2019)	x	x
	ID: Information Drop; **ME**: Model Exchange					

2.3 MODEL INFORMATION DEVELOPMENT

There are different file formats for data transfer and exchange within a BIM environment and EA tools, as IFC, OSM, HTML, XHTML, bcXML, gbXML and ifcXML (Ramaji et al., 2020; Volk et al., 2014; BuildingSmart, 2010). These include whole building, space/zone, and building elements and materials; data interoperability is fundamental to inform the design, and this exchange needs to continue along the building life span (Bort et al., 2013), and the simplification of the number of formats to be used allow a seamless process (Ramaji et al., 2020). Chang and Hsieh (2020) describe how interoperability within a BIM platform remains a substantiated limitation towards achieving an optimised BPA. Lewis, Valdes-Vasquez, and Clevenger (2019), in their e-survey, found no correlation between the green building stakeholders' perception of the value of Information from BIM into energy simulation and their engagement level towards BIM and energy simulation, which shows a lack of stakeholders' involvement. Sattler et al. (2019) highlighted the importance of interoperability needs. These include accessing, re-using, checking, retrieving, linking, and combining data and data hubs. Maile et al. (2013) described some challenges while exporting data into the IFC data model. These include the missing space boundaries; missing spaces; incorrect space volume; duplicate objects; missing exterior walls; misalignment of space and building element; incorrect second level of space boundaries; column dislocation; incorrect normal vector direction; and so on, impacting the accuracy and reliability of the information that needs to be checked and fixed.

Process mapping and business process modelling are a range of techniques to study the as-is state of an industrial process and to analyse the improvements or adaptations needed to implement new technology (Van der Aalst, 2013). Business Process Model and Notation (BPMN) is a widely adopted mapping process used to define and conceptualise the construction industry's processes and reflect on the technology and methodology changes required by the BIM adoption (Penn State, 2012).

Missing data from BIM when dealing with EA includes weather conditions and characteristics, occupancy and activity schedule, specific material properties for energy and simulation, etc (Katranuschkov et al., 2014). **Error! Reference source not found.** provides some existing details for energy modelling with BIM. However, these are rarely available in one document, and correlation among energy modelling detail and LOD or LOI is seldom found.

2.4 REQUIREMENTS FOR EA INFORMATION EXCHANGE

interoperability issues in the process of information exchange lead to information loss and inconsistencies (Kamel and Memari, 2019). Lin et al. (2010) noted four solutions towards the challenge of information exchange during EA within a BIM-enabled project. These are: 1) the use of Industry Foundation Class (IFC) format files that allows information exchange between different applications, but there are limitations related to the maturity of the information exchanged for EA; 2) The application of standalone EA tools. These require more man-hours time towards modelling becoming more expensive; 3) embedded EA tools require native file applications to have EA capability or ability to exchange information to other applications they own. This solution could remove interoperability challenges, but there is a need for the applications to provide more detailed EA; 4) Green Building XML schema (gbXML) allows information transfer across building models. It also contains heating and cooling data within the gbXML file structure, which is important for Heating Ventilation, and Air Conditioning (HVAC). Some limitations are present as, after the information exchange through gbXML, some information is lost or modified. For example, a wall assembly information set in the defined BIM model is exchanged with default data adjusted manually when required. After simulation through gbXML, any parameters edited cannot be exported back into the native BIM model. Zanni et al. (2014) identified three important EA lifecycle drivers to consider for effective model sharing. These are 1) Level of Detail required for sharing information; 2) interaction with the client at each stage, and; 3) format of input and output. Table 3 show various requirements from various sources that call for the need for standardised requirements readily available.

Table 3: Modelling Requirements for EA

BIM USE CASE	FOCUS	SOURCE	CONSIDERATIONS DURING DESIGN AUTHORING FOR EA PURPOSES
Energy Analysis Modelling	Coordination View	CoBIM (2012)	Remodelling is required if the requirements of the energy analysis modelling are not met. Requirements include: The IFC exchanged files should have the coordination view (between the architect, structural, and MEP designer).
	Surface and Opening Definition	BuildingSmart (2010) Yin and Lee (2019)	SB add-on view (defines space surfaces and their connection to structures, openings, etc.). Challenge of exporting curved walls and lacking wall thickness.
	Energy Flow Estimation	Statsbygg (2013)	SB is used to estimate energy flow between spaces
	Coordination	Berlo and Papadonikolaki (2016)	There should be only one IfcProject object per file (no more, no less); There should be only one IfcSite object per file; All objects should be linked to an IfcBuildingStorey object; There should be at least one IfcBuildingStorey in the dataset; The naming of the building storeys should be consistent and in order, i.e. floor-numbers; and so on
	Linking Light to Spaces	BuildingSmart (2010)	Space Boundary Levels (SBL) are required to be defined, there are different SBL for different BIM Use case
	Linking Services to Spaces	Statsbygg (2013)	Structured modelling with the alignment of space and its services
	Generic Recommendation	Maile et al. (2013).	Building elements with proper geometry, Model-checking for quality purposes, Building elements need proper material definitions Adaption of IFC2x4 Spaces must be completed enclosed Avoid spatial overlapping, duplication of building elements.
	Object Library	Choi and Kim (2015)	The use of object library to increase accuracy
	Multi level LOD	Singh and Geyer (2020)	Parametric uncertainty in a multi-LOD approach. Define LOD should be adopted.

Soust-Verdaguer et al. (2017) described the challenge of material properties and data exchange. There is insufficient data on material properties that the energy modeller might have to conduct manually at the initial project stages. Gerrish et al. (2017) described storage of (HVAC) systems details or spatial geometries in both EA and BIM tools as possible; however, the method of information storage is not standardised, causing incompatible transfer of data. They found explored the application of LOD's during EA. Andriamamonjy et al. (2019) stated that assumptions during EA are not communicated or documented.

GSA (2015) stated that consistent creation or editing of models is difficult; it needs to be simplified to accommodate the modeller's understanding, knowledge, and resources; this brings subjectivity to the process. However, several literature sources and organisations such as BuildingSmart provide modelling requirements for EA to enable better lifecycle information flow. For example, some considerations and recommendations are illustrated in Table 3, such as using IFC exchange files that could facilitate information re-use throughout the building lifecycle. In addition, the literature suggests that a technology change requires a change in methodologies and processes. The BIM use related to Energy modelling involves a set of particular problems that have been enunciated. These make necessary the development of standard process maps adapted to the topic (BuildingSmart, 2010). In this paper, the new process maps for Energy modelling BIM use are developed to sort the disruptions and information loss that happens within and with other BIM uses across the building lifecycle information flow.

2.5 GAPS WITHIN EA PROCESS MAPS

Over the years, several process maps have been developed. However, Table 4 illustrates some limitations in existing process maps, such as linking EA requirements to EIR. These will allow the energy modeller and the architectural design team to make informed decisions before developing the models and perhaps reduce the need for model rework during the EA process. Various research (Penn State (2010); Zanni et al. (2014); Asmi et al. (2015); Laine and Karola (2007)) which developed EA Process maps required the model to be modified before EA, due to the interoperability challenges. Furthermore, the required level of LOD can be clearly stated. However, a lower level of LOD is required for EA. Ramaji et al. (2020) described imported IFC models as planar query elements, aggregation of spaces and voids (possible openings) in applications such as open studios.

Table 4: Gaps in existing EA process maps

Reference	Model Adjustment Required	LOD during Model Exchange	Linking EA Requirements to EIR	Client Team Review
Penn State (2010)	X	NA	X	NA
Liebich, et al. (2011)	X	NA	NA	NA
2011	X	NA	X	X
Zanni et al. (2014)	X	X	X	NA
Asmi et al. (2015)	X	NA	NA	X
Laine and Karola (2007)	NA	NA	NA	NA
Jalaei and Jrade (2014)	X	NA	NA	NA
Gerrish et al. (2017)	X	X	NA	X
Pinheiro et al. (2018)	X	NA	NA	NA
Ying and Lee (2019)	X	NA	NA	NA
Ramaji et al. (2020)	NA	NA	NA	NA
Authors developed EA Process map	X	X	X	X
Note: It is noteworthy to highlight that the existing EA process maps above do not focus on the entire stages. However, they are limited to a defined context study focus.				

3. METHODOLOGY

This research grounds on existing processes for EA and BIM in the AEC industry. The paper aims to identify drivers that facilitate information flow within the developed EA process maps. This methodology is described in Figure 1 and focuses on developing an EA process map through the workshop involving multiple tasks (literature review, brainstorming exercise, and input from industry expert review). The same experts participated in the workshop activities. The existing EA Process maps, such as Penn State maps, were explored during the study. In addition, the Business Process Model Notation (BPMN) method was adopted. Several process models for the building construction industry were developed using the BPMN, which captures the exchange of information between actors in a business process (Underwood & Isikdag, 2010).

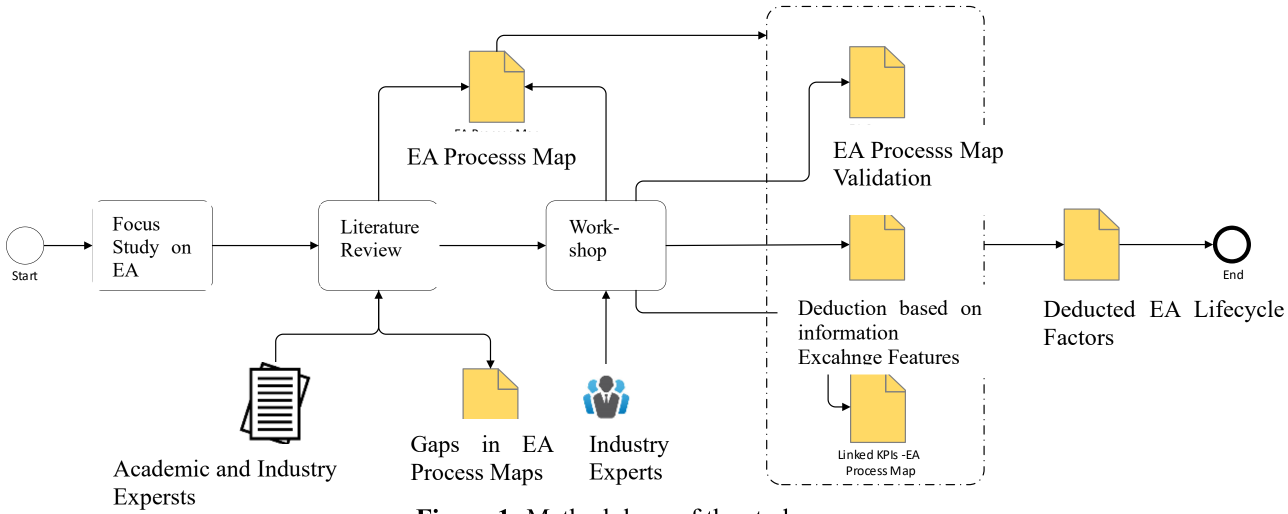


Figure 1: Methodology of the study

2- A workshop with six industry experts was conducted (see table 5). The workshop included the EA Process map validation process, the deduction of KPIs, and the linking of KPIs to develop the process maps. The workshop participants included a sustainability consulting organisation; a leading virtual construction organisation, and an energy software vendor. There were two participants from each organisation, with a minimum of ten years of BIM working experience. Each review lasted for about 45-60 minutes in each of the three sessions. The process consisted of collecting primary data (qualitative analysis); presenting and reviewing the process maps, and final reviewing the process maps.

Table 5: Workshop participants

ORGANISATION TYPE	JOB TILE	YEARS OF EXPERIENCE	WORKSHOP
Energy Software Vendor-	Regional Manager	10	3 sessions
Energy Software Vendor-	Project Manager	10	3 sessions
Sustainability Council	Head of Sustainability	30	3 sessions
Sustainability Council	Research Assistant	20	3 sessions
Design Consultancy	Head of Operations	20	3 sessions
Design Consultancy	BIM Manager	10	3 sessions

The chosen validation method for the EA process map adopted a collaborative process mapping and modelling through the workshop. For example, the Kit process was adopted with three steps and allowed a feedback loop between industry experts and researchers, as described in Figure 2. First, the research collects information from the industry experts and processes it. Later, the researchers provided the industry expert with the inference from the previous meeting, and further adjustments were made in a feedback loop until the adequate output was achieved. Three KPIs were deducted from the identified from the literature review and the industry experts. 4- A Focus review with industry experts was conducted to align the KPIs with relevant benefits that could lead to relevant lifecycle information. Kerzner (2015) defined the KPIs characteristics as Specific, Measurable, Attainable, Realistic, and Time-based (SMART) were adopted. 5- The KPIs were aligned with information flow features; Demian and Walters (2013) described five KPI's features for information flow studied by Tribelsky and Sacks (2010). These are:

Information Object- components of a building such as walls; information attribute-technical and management features such as colour, dimensions, and materials;

Information Package- a document used for the communication and transfer of information such as 2D drawings, spreadsheet, and email exchanges.

Information batch - A collection of information packages transferred by a project participant simultaneously.

Project Action – a project participant acts to share information with one or more stakeholders.

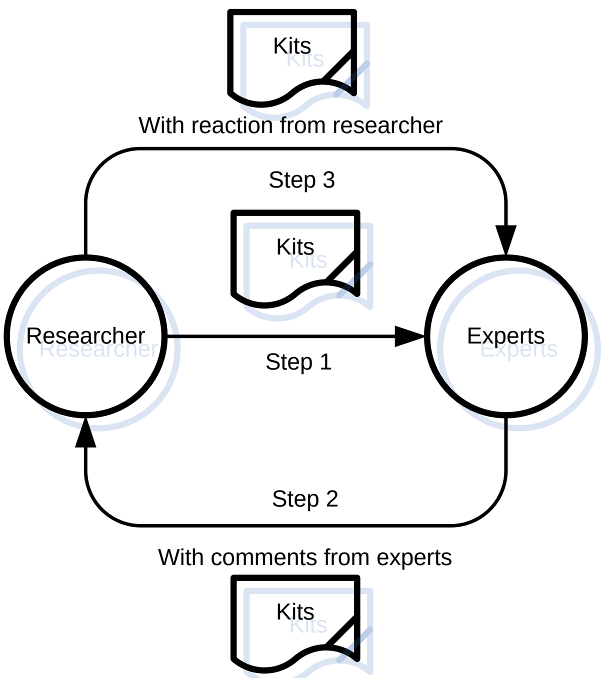


Figure 2: KITS Process for developing EA process map

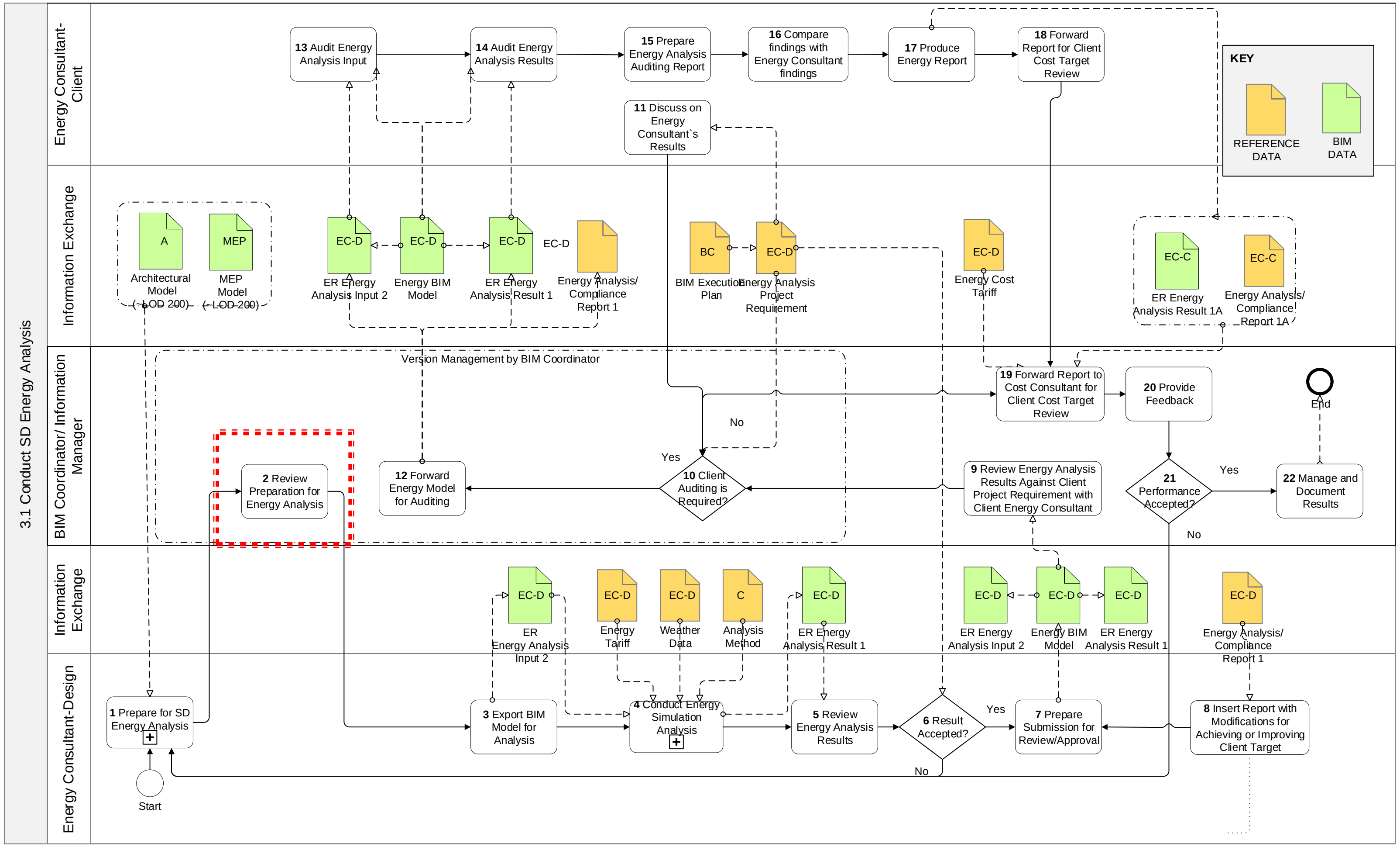
The validations of the EA process map are achieved using three-floor institutional buildings using VE IES software application (IES); afterwards, the KPI'S and determinants were deducted from the generated maps. The KPIs with lifecycle information flow capability is considered as lifecycle drivers for this study. These were identified through industry expert reviews. The workshop in this study allows the achievement of 1- EA process map; 2- EA process map validation; 3- deducted KPI's based on information exchange features; 4- Linked KPI's to EA process map; and 5- Deduction of EA lifecycle factors.

4. THE DEVELOPED PROCESS MAPS

The development of the EA process map was based on existing process maps developed by Penn State (2012). In addition, the study conducted reviews and revisions based on the industry experts' input. The developed EA process map has 22 tasks, as illustrated in Figure 3; it was designed to identify relevant KPIs that would facilitate lifecycle information flow to allow other BIM Uses to be conducted without Information and model rework while promoting EA. The map is focused on Schematic Design Stage but would accommodate slight changes as the project stages progress for a range of construction and infrastructure projects after adaptation. In addition, the tasks within the EA process map in Figure 3 would slightly vary at the different project stages as building Information and LOD increase. **Error! Reference source not found.** shows how information detail used for EA increases as the project stages evolve from the schematic to the construction stage; this indicates that the process map could vary in different projects and between different phases. EA is conducted after the Concept Design (CD) stage, at the Schematic Design (SD) stage, and later project stages. The main differences between stages relate to the LOD, i.e., LOD 200 is adopted for the SD stage, while LOD 300 is adopted for the Detailed Design (DD) stage. Therefore, a lower LOD is preferable for EA. An energy consultant from the design team can conduct the EA. However, when required, the energy consultant from the client side can achieve a further review of the EA. The map allows the client energy consultant to review and audit the project energy consultant input and results. The BIM coordinator acts as merely as an administrator in this case. However, the client energy target set in the EIR and BEP can be reviewed against the energy consultant results.

Two steps are elaborated in the high-level EA process map, as shown in Figure 3. First, prepare for energy analysis (Energy Consultant); and conduct energy simulation analysis (Energy Consultant). This process starts with adjusting the energy consultant's energy analysis model and is reviewed by the BIM coordinator to document what was done. Then, the BIM model is adjusted and exported. *Exchange Requirement (ER) Energy Analysis Input 1* is added when preparing for energy analysis. While ER Energy Analysis Input 2 is achieved when adjustments are made after *ER Energy Analysis Input 1*. The energy simulation is conducted using Energy Tariff, Weather Data, and Analysis Method. The *ER Energy Analysis Results* are produced and reviewed against the EA *Project Requirement*. If results are acceptable, the energy consultant prepares to submit Energy BIM Model that contains performance and modification for improvements are suggested in the *Energy Analysis Report*. The BIM coordinator discusses the energy consultant's ER Energy Analysis Result with the client's energy consultant to decide if the client's energy analysis is required. If no, then ER *Energy Analysis Result* and Report are provided to the cost consultant. If yes, the BIM coordinator forwards the *ER Energy input 2* and *ER Energy Analysis Result* to the client's energy consultant, who conducts an audit and compares their results with the energy consultant's findings. The client's energy consultant provides a report to the cost consultant, who provides feedback to approve or disapprove analysis of the energy consultant based on cost implications. Figure 4 has 15 tasks; it starts with adjusting the model for energy analysis by aligning work structure to Client energy aspiration defined in the EIR.

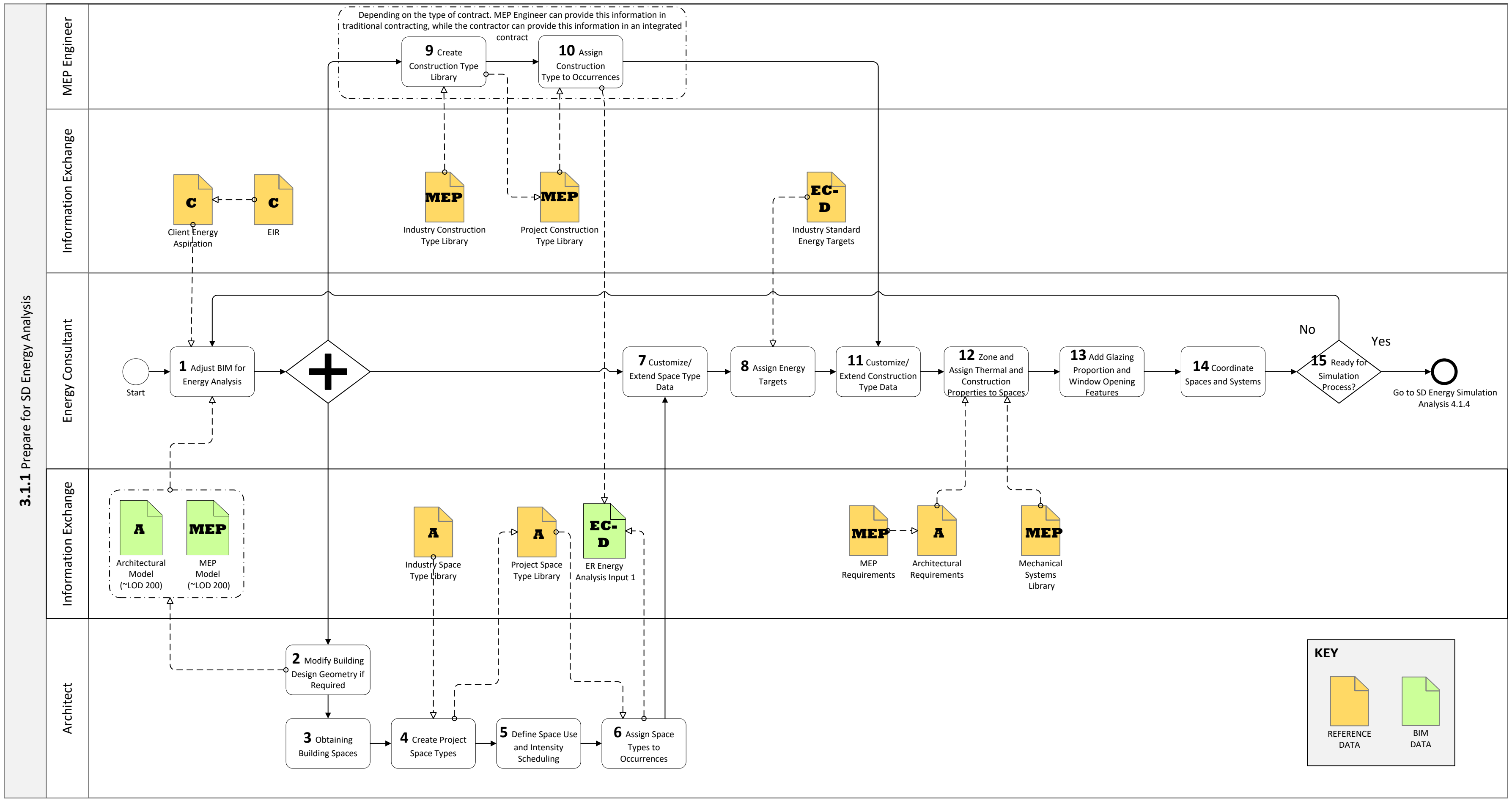
The architect obtains building spaces, and a Project Space Type Library is created using the Industry Space Type Library. In the meantime, the MEP consultant/ contractor creates the Project Construction Type Library using the Industry Construction Type Library. These combined define the ER Energy Analysis Input 1. Next, the energy consultant customises the Construction Type Library and the Space Type Data. Further inputs before achieving ER Energy Analysis Input 2 include assigning energy targets, window glazing and opening, space use intensity, and coordinating spaces and systems. The process described in Figure 5 has 20 tasks; it starts with loading design with Weather Data and Energy supply and demand features. Then, optimisation between supply and demand is conducted to achieve optimum performance. Before working, the Simulation Analysis Method, as described in the BIM Execution Plan, is adopted. The Energy Tariff is added, and simulation output is recorded as ER Energy Analysis Results.



LEGEND:
A: Architect; MEP: Mechanical, Electrical and Plumbing; O: Others; BC: BIM Coordinator; EC-D: Energy Consultant Design; EC-C: Energy Consultant Client; C: Client

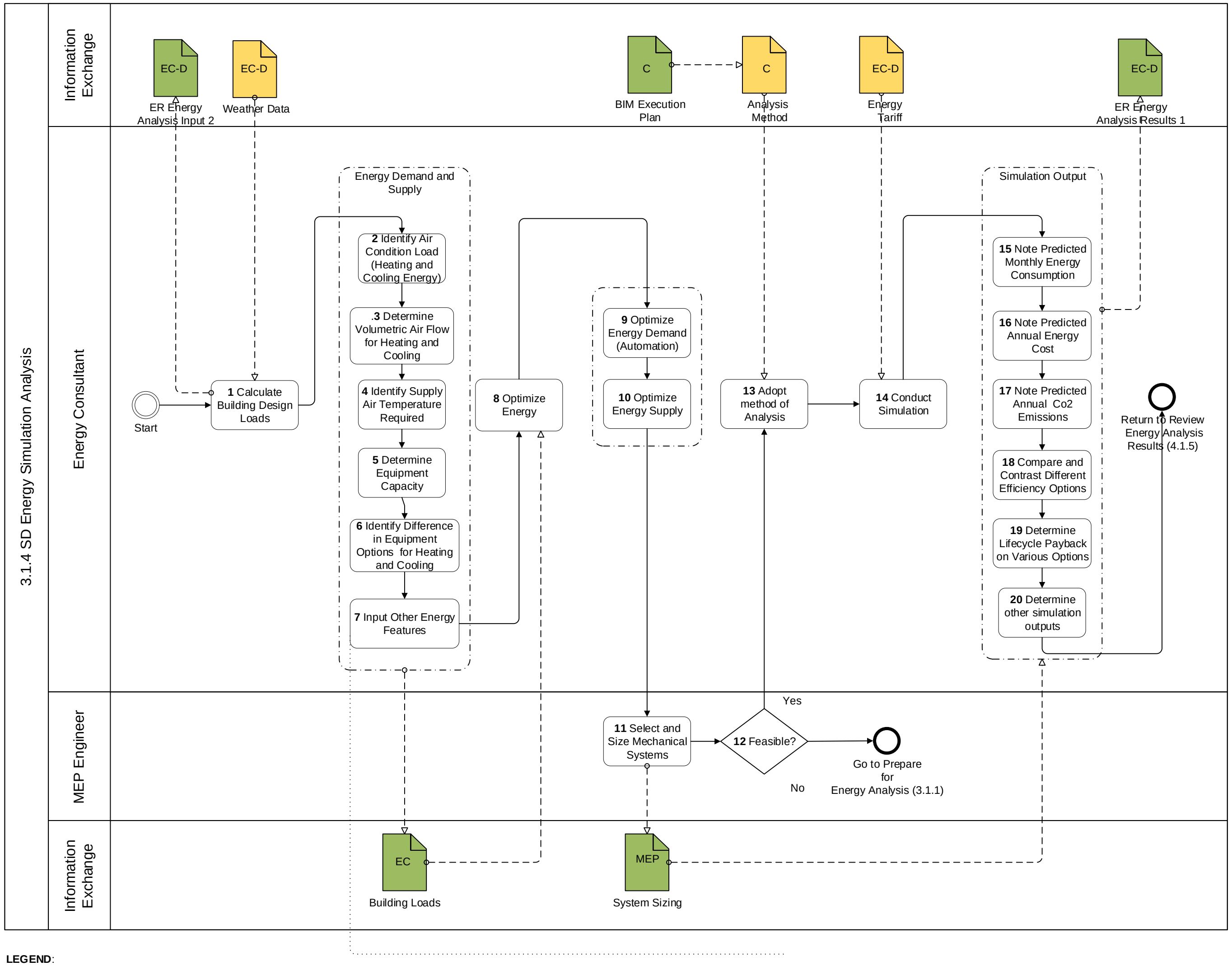
ENERGY REPORT
Energy Report has Two Documents:
1. Performance reached and
2. Modification for improvements

Figure 3: EA Process at Schematic Design Stage



LEGEND:
A: Architect; **MEP**: Mechanical, Electrical and Plumbing; **BC**: BIM Coordinator; **EC-D**: Energy Consultant Design; **C**: Client

Figure 4: Preparing for Schematic Design EA process



LEGEND:
MEP: Mechanical, Electrical and Plumbing; BC: BIM Coordinator; EC-D: Energy Consultant Design; C: Client

OTHER ENERGY FEATURES INPUT
These may include indoor air quality, humidity, noise filtering, material emissions, pollutant concentrations and so on

Figure 5: Schematic Design Energy Simulation Analysis

4.1 EA Process map Validation

The process maps were developed based on a reference template (Penn State, 2012) with additional complexity and definition. It was validated based on a case study project (two storeys institutional building); different software vendors validated the maps. However, IES software was used for the validation process due to availability.

Description of Task: Map 3.1.1; Task 1

Task 1: Adjust BIM model for Energy Analysis

Model requirements of the EA are considered during the Design Authoring stage; the EA modeller adds all requirements that cannot be met. The BIM model is adjusted to suit the Energy Analysis software solutions selected for the project. IES was chosen for the energy analysis. Figure 6 illustrates Task 1- the BIM model adjusted in Revit before exporting it to IES. The architect can configure the features, such as location, weather, and site for daylight and other analysis in Revit. However, weather information is added when the model is exported. Architectural building spaces are categorised as *Rooms* in Revit; they are analysed for clashes through *analytical surfaces.* Rooms that need to be revised are identified; this shows that the architect can adjust the model in a design authoring tool (Revit) before forwarding the model to the energy consultant. BIM use and requirements should be stated in the EIR for early decision-making towards reduced model rework.

Description of Task: Map 3.3.4; Task 14

Task 14: Note predicted monthly energy consumption

There are several factors to consider towards forecasting the energy consumption of a building. These include weather information. Figure 7 describes Task 14. Weather data information within the gulf region shows cooling is required almost throughout the year. As the weather readings show, May, June, July, and August are the hottest periods, which require a large amount of energy for cooling. In addition, the readings show no energy use between 01.30 to 07:30; and 17:30 to 23:30 as the building is out of service.

Description of Task: Map 3.3.1; Task 11

Task 11: Customise/extend construction type data

The EIR can provide the necessary construction type data to be adopted at the early stages. However, individual constructions that are not fully defined within the project construction type library may be updated. These could be created by editing/updating/ customising existing elements in the library. Elements created are then saved in the project construction type library. Figure 8 describes Task 11. Construction type data can be edited using the *edit construction* option as shown. In addition, the construction type for each room can be edited for each building element.

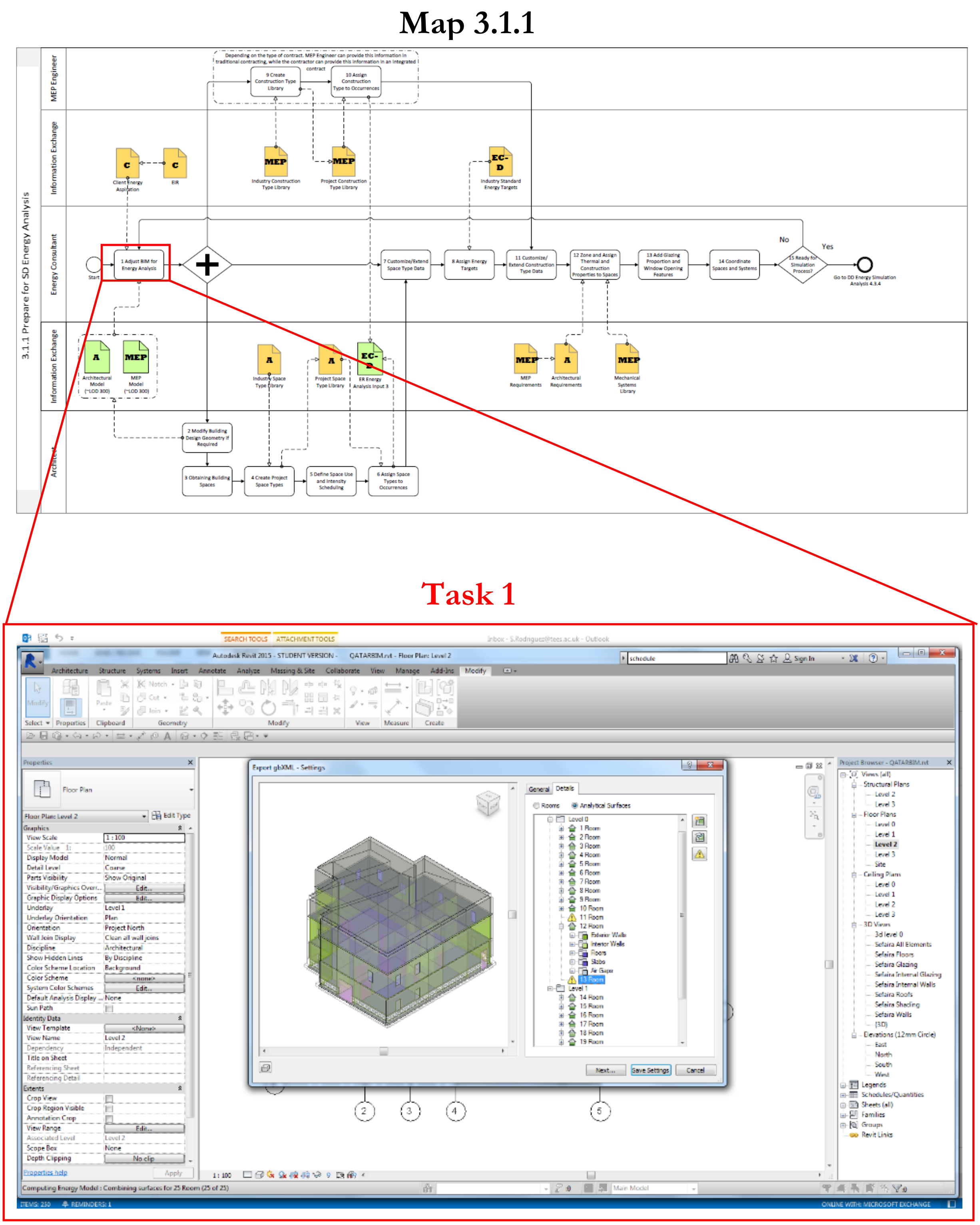


Figure 6: Validation adjusting of the BIM models during preparation

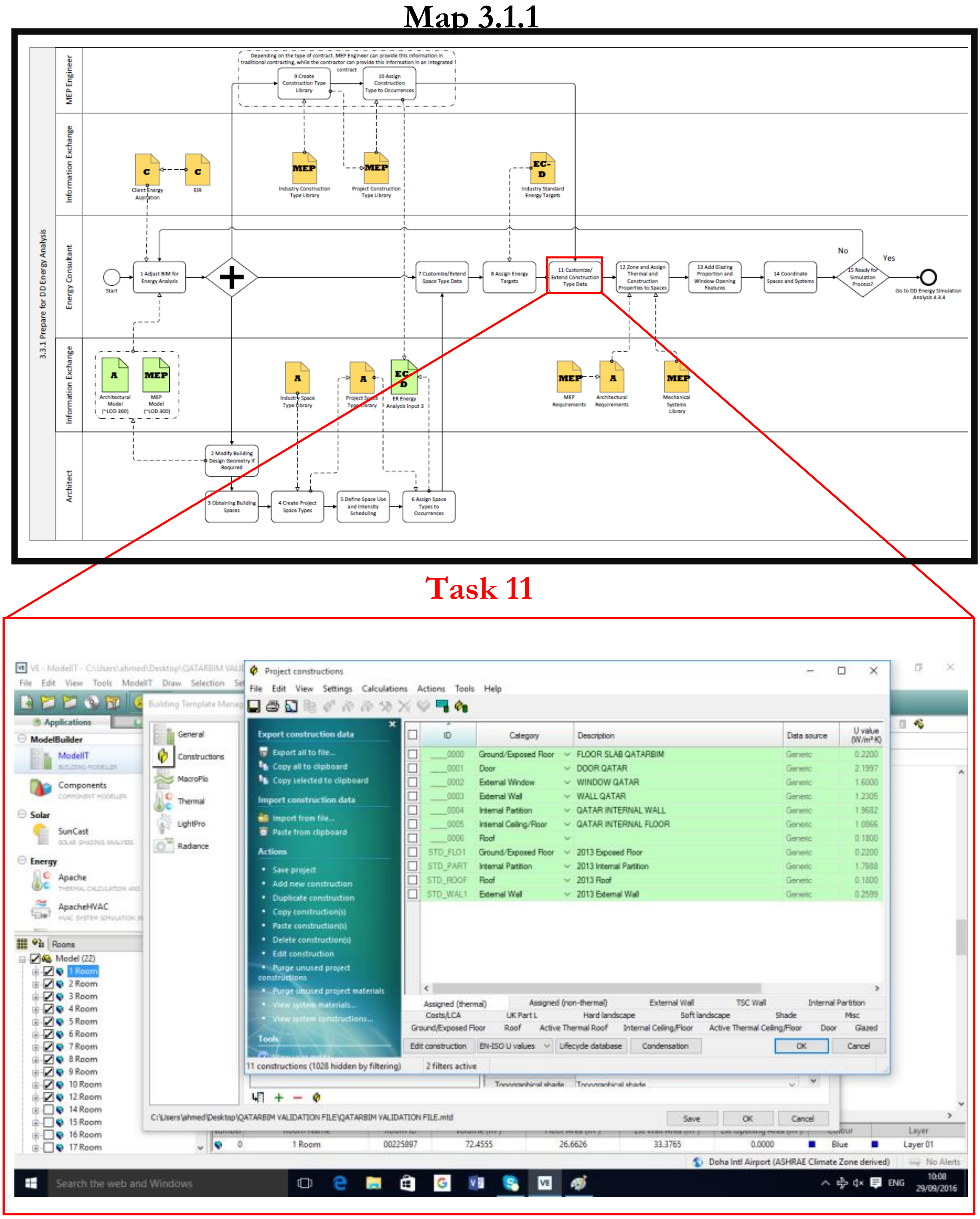


Figure 7: Validation- Construction type data

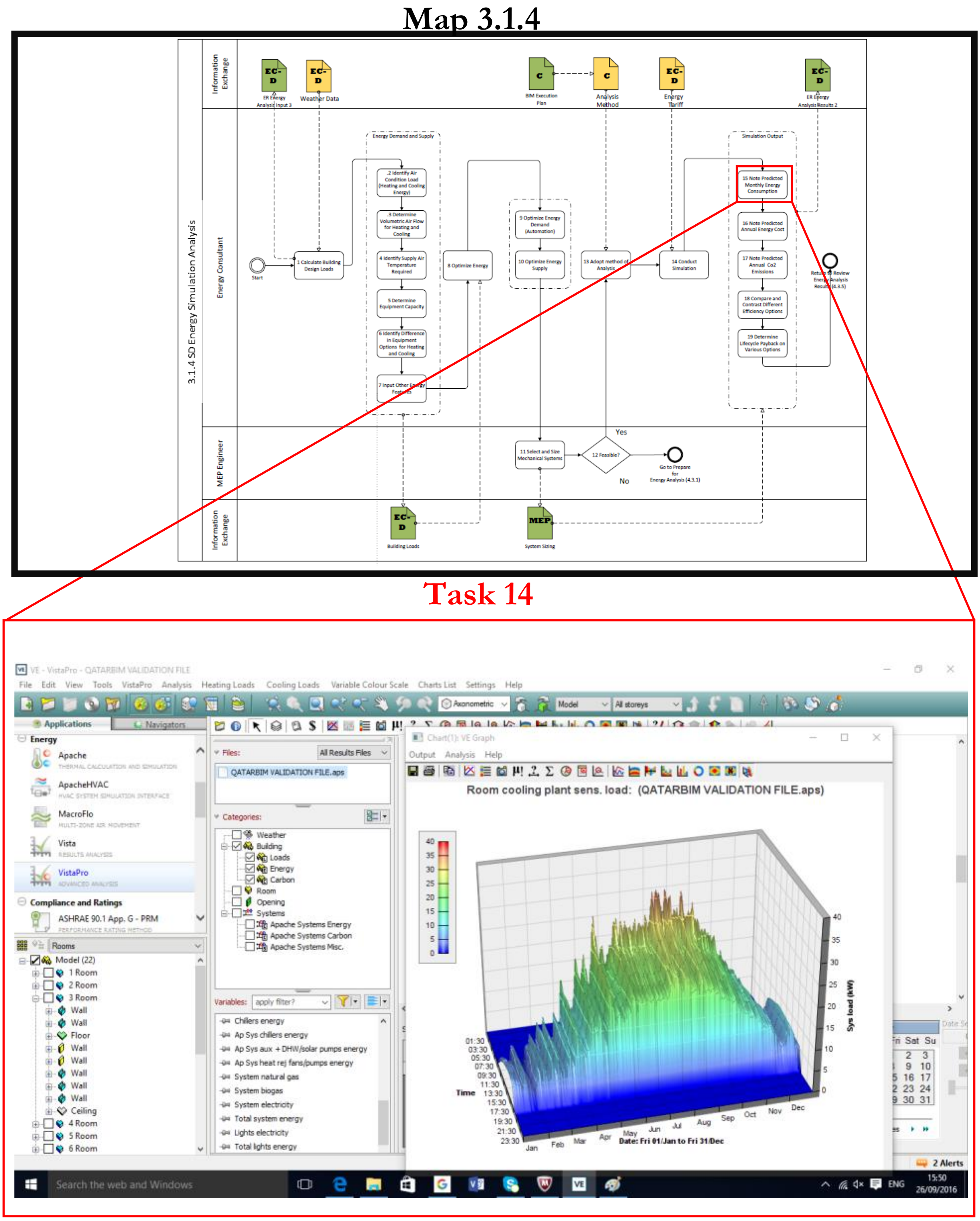


Figure 8: Validation- Predict Monthly Energy Consumption

4.2 CONSIDERATION FOR THE EA PROCESS MAPS

The introduction of the client's energy consultant allows the work of the design energy consultant to be reviewed. A cost consultant is introduced for client target review. The BIM coordinator manages the versioning of information within the process. The Energy Report has two documents: Performance reached and modification for improvement. When loading the design before conducting energy simulations, it is noteworthy to note that there are other inputs (energy features) apart from energy and supply. These include indoor air quality, humidity, noise filtering, material emissions, pollutant concentrations, etc. Energy consultants should be introduced early in the building stages; otherwise, valuable input would be lost to save costs and improve facility performance during facility management and operation. Findings show that adjusting the model for EA is the most challenging feature of the EA process. Assumptions and frequent design changes updated centrally are automatically updated and can be shared, thus reducing rework.

The items added to the developed EA process map include:

- The cost of EA proposals is reviewed against the client requirement, as shown in Figure 3 step 19.
- The appropriate steps within the process maps that would allow performance management and assessment of EA.
- The EIR should contain all the EA requirements that allow lifecycle information flow, as shown in Figure 4, step 1.
- The Client Team is introduced to cross-check to ensure that EA requirements are adopted in Figure 3 (map 3.1, step 2).
- Depending on the type of contract (traditional/ integrated), the MEP engineer provides information on construction type library, as shown in Figure 4 step- eleven
- The identified activities are organised and managed by the information manager.

5 DEDUCTION OF KPI's BASED ON INFORMATION FLOW

The relevance of the identified KPI's was indicated through the application of information flow features. **Table 6** proposes the alignment of information flow features described by Demian and Walters (2013) with proposed EA KPIs. The frequency of occurrences of the different KPIs would vary from project to project. These could be tabulated within a defined time scale or project stage. The KPIs can facilitate the outcomes that would enable effective and efficient EA. The benefits of Energy Analysis are described in Table 1. The KPIs have been categorised as local and determinates. The *local KPIs* are considered factors directly linked to the process maps, while determinates are considered factors that can indirectly enhance the data flow from the process maps. For example, the KPI: *Time required to adjust the imported model for Energy Analysis* is not directly lifted from the process map. However, the task is stated as an adjusted Model for EA. If it takes a long time to adjust, the model is problematic in its native file. As a result, adjusting time is considered a measure of adequate information sharing between the Design Authoring team and the EA modeller. **Table 6** show KPIs and their relevant output nature and information flow feature to better understand the KPIs.

Table 6*:* EA Process Map KPIs and Information Flow features

INFORMATION FLOW FEATURES	INPUT/ OUTPUT	ENERGY ANALYSIS (EA) PROCESS MAP KPIs	KPI OUTCOME
Information Object	Input	No. LOD model adjustment required per model exchange (Reducing unnecessary detailing) (Expert review)	Model Adjustment
Information Attributes	Input	Raised Revisions Rate during EA	Information Iterations
	Output	Revision Rate during EA	
Information Packages	Input	No. Available but unused information files	Information Redundancy
	Output	% Information shared on a Centralised platform	Stakeholder collaboration
	Output	% Annual Energy Emission Reduction towards Client Target	Simulation Projections
	Output	% Annual Energy Cost Savings towards Client Target	Simulation Projections
Information Batch	Output	No. Prepared Energy Reports (performance and modification report)	Energy Reporting
Project Action	Input	The time required to adjust the imported model for Energy Analysis	Model Adjustment
	Output	% Stakeholders using compatible applications	Information Exchange

5.1 LINKED KPI's WITH EA PROCESS MAPS

The identified KPI's were filtered based on information flow features; however, there is a need to sift through other criteria further. **Table 7** shows a possible alignment of identified KPIs with proposed EA process maps. All the KPIs identified met the KPI SMART criteria based on the workshop participants.

Table 7: Linking Energy Analysis Process Map with identified\ KPIs. ((

ENERGY ANALYSIS MAP ALIGNED WITH KPIs								
	MAP REFERENCE	**TASKS**	**LOCAL KPIS/ DETERMINANTS**	**S**	**M**	**A**	**R**	**T**
Energy Analysis Process Map	**3.1**	**4**	% Stakeholders using compatible applications Adapted from Won et al. (2013)	**x**	**x**	**x**	**x**	**x**
	3.1	**3**	% EA information shared on a centralised platform (CIC, 2012)	**x**	**x**	**x**	**x**	**x**
	3.1.1	**1**	Time required to adjust the imported model for Energy Analysis (CIC, 2012)	**x**	**x**	**x**	**x**	**x**
	3.1.1	**1**	No. LOD model adjustment required per model exchange (Reducing unnecessary detailing) (Expert review)	**x**	**x**	**x**	**x**	**x**
	3.1.4	**17**	% Annual energy emission against client target (Expert review)	**x**	**x**	**x**	**x**	**x**
	3.1.4	**16**	% Annual energy cost saving against client target (Expert review)	**x**	**x**	**x**	**x**	**x**
	3.1	**20**	Raised Revisions Rate during EA. Adopted from Demian and Walters (2013)	**x**	**x**	**x**	**x**	**x**
	3.1	**20**	Revision Rate during EA. Adopted from Demian and Walters (2013)	**x**	**x**	**x**	**x**	**x**
	3.1	**22**	No. Available but unused information files. Adopted from Demian and Walters (2013)	**x**	**x**	**x**	**x**	**x**
	3.1	**22**	No. Prepared Energy Reports (performance and modification report). Adopted from Demian and Walters (2013)	**x**	**x**	**x**	**x**	**x**
S: Specific M: Measurable **A:** Attainable **R:** Realistic/ Relevant **T:** Time-based								

5.2 OBSTACLES CONCERNING INFORMATION FLOW

Table 8 shows possible obstacles related to the adoption of the process maps. These could be considered by EA consultants to make better and informed decisions during the process. The five obstacles have been identified from the EA process maps through the expert review. The primary industry challenge highlighted is exchanging information from design teams to EA teams without modelling further rework modeling. Lin et al. (2010) observed two possible options towards model management. These are traditional and BIM-enabled. Traditionally the design and energy team have separate models that are expected to be identical. However, the energy model was developed after the design team had exchanged their model with the energy team (non-synchronised model). EA in a BIM-enabled project allows developing a synchronised model that can be exchanged between the design and energy team. However, it may require certain model adjustments to be compatible with EA. Model changes proposed by the energy modeller are provided to the design team as feedback. These have to be manually adjusted to the design models in their native file formats. Some development is taking place within commercial vendors where native files are integrated with EA capability. For example, AutoDesk Revit and Nemetschek ArchiCad can be used for both Design Authoring and EA simulation.

Table 8: EA Process Map with Information Flow Obstacles

THEME	Input/ Output	DESCRIPTION OF EA PROCESS MAP INFORMATION FLOW OBSTACLES
MODEL GUIDELINES	Input	Non-availability of widely accessible energy modelling guidelines during Design Authoring
MODEL ADJUSTMENT	Input	The energy modeller would waste critical time on adjusting the model
MODEL BI-EXCHANGE	Output	The model used for EA is challenging to export back to the native files to communicate (feedback) directly with the design team. Manual updating required
MODEL LOD	Input	Higher LODs are not recommended for EA
MODEL COORDINATION	Output	The stakeholders involved need to coordinate their models to reduce rework

5.3 EA LIFECYCLE DRIVERS

The lifecycle drivers are deducted from the KPI/ Determinants relevant to the developed process map. The six industry experts in the workshop facilitated the deduction of the KPIs with aligned EA benefits and possible lifecycle information flow capability. The relevant KPIs identified in **Table 9** to facilitate lifecycle information flow are managing large model file handling (scalability). The percentage of information shared on a centralised platform could indirectly facilitate lifecycle information flow.

The percentage of stakeholders using compatible applications can simplify lifecycle information flow directly. Other factors are related to the interoperability of software adopted. XML allows for interoperability, but there are limitations due to its *flat-file* format that cannot account for data generated during operational building management (Gerrish et al., 2015). Another challenge is the one-way information exchange between the design authoring team and Energy consultant due to interoperability. There is a need for IFC BIM models ready for energy simulations.

Table 9: Relationship between KPIs, EA benefits and LC

BIM Use	**Local KPI/ Determinant**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**LC**
Energy Analysis	% EA models files shared within the defined file size (scalability)	x	x	x	x	x	xx	x	x
	% Stakeholders using compatible applications	xx		x	x	x	x		xx
	% Information shared on a centralised platform				xx	xx	x		x
	The time required to adjust the imported model for Energy Analysis			xx	x	x			
	No. LOD model adjustment required per model exchange (unnecessary detailing)	x	x	xx	x	x			
	% Annual energy emission against client target				x	xx	xx	xx	
	% Annual energy cost saving against client target				x	xx	xx	xx	
	No. Prepared Energy Reports (performance and modification report)				xx	xx	xx	x	
	No. Available but unused information files								
	Raised Revisions Rate during EA	x		x	x				
	Revision Rate during EA	x		x	xx				
Indirect Benefits: **X**; Direct Benefits: **XX**; Benefits (Design Authoring): **B**; KPIs towards Life Cycle information flow drivers: **LC**									

6. FINDINGS AND DISCUSSION

The study focuses on analysing EA tools for lifecycle information flow used for facility management and facility operation. Six industry experts participated in the study, including two participants from a defined energy software Vendor, a digital construction management consultant, and a sustainability organisation. They participated in developing and validating the generated process maps. Furthermore, supported the process of deduction of the KPIs from the process maps and alignment with possible lifecycle features was achieved in the workshop. However, due to the gaps identified in Table 4, existing process maps could not be adopted without adjustments. These include the need for client review, LOD adjustment, and linking EA requirements to the EIR.

However, it is essential to highlight that the developed process maps do not fit all but can be adjusted to meet individual organisation setups. Furthermore, the quality of information input into the process will yield a similar output. Designers with limited EA understanding can benefit from the project's outcome. The developed KPIs used to assess its applicability towards information exchange would facilitate performance design and operation tasks for energy and cost savings.

The EA process map was developed to indicate KPIs that could facilitate lifecycle information flow within the tasks of the developed process maps. The KPIs meet the SMART criteria (Kerzner, 2015) and are linked to the developed process maps. The nature of the KPIs is described in terms of information flow, as illustrated by Demain and Walters (2013). At the same time, the KPI outcome shows related feature categories such as model adjustment, simulation, information exchange, etc. This information would enable a better understanding of EA and help improve information flow to reduce the possible loss of information during information exchange between architectural designers and energy modellers.

Within the eleven KPIs identified, only three had lifecycle information flow capability. The percentage of EA models files shared within the defined file size (scalability) - *indirect benefit*; the percentage of stakeholders using compatible applications- *direct benefit*; and the percentage of information shared on a centralised platform – *indirect benefit*.

In addition, some obstacles to the EA process have been identified; they are categorised under Model Guidelines- lack of universal standards; Model Adjustment- EA model conduct model rework before model use; Model Bi-Exchange- EA modeller changes have to be manually applied to architectural design models; Model Lod- high level of LoD makes the model more complex for EA; Model Coordination- stakeholders need to coordinate and manage their models to reduce rework. Hitchcock and Wong (2011) indicated that dominant vendors perceive better business cases for developing embedded energy analysis tools within their native products format rather than participating towards the adoption of robust data exchange with third-party tools and stakeholders. In addition, the main challenge is the robust transformation of thermal view space boundary geometry.

Assumptions are made to improve the lifecycle information flow; they should be automatically updated and shared centrally. Furthermore, frequent design changes should be updated centrally to reduce rework. Model changes proposed by the energy modeller are provided to the architectural design team as feedback. These must be manually adjusted to the architectural design models in their native file formats, as EA tools are incompatible with native authoring tools.

7. CONCLUSION

EA is vital for facility management and operations (lifecycle) cost and emission management. Information is essential for effective stakeholder decision-making, adhering to project cost, time, quality, and client satisfaction. The EA process map developed has taken into account the practical implications of industry best practices. The proposed EA maps are founded on existing EA processes available in the literature. The maps indicate the introduction of the information manager/ BIM coordinator to manage information shared within the process; when input and output formats are standardised and managed, information can be shared with other BIM Use consultants within a construction project. The study proposed eleven KPIs for assessing the quality of the EA process maps. The KPIs have met the SMART criteria and are aligned to the developed EA maps, as shown in **Table 7**. The proposed KPIs are categorised under defined information flow categories, as shown in **Table 6**. The proposed KPIs are also expected to help achieve the defined benefits of EA and lifecycle information flow. As illustrated in Table 9, three are expected to simplify lifecycle information flow within the eleven KPIs identified. These are handling large-size models (scalability), centralizing shared information, and using compatible applications to enable users to access or re-use information without recreating existing data, which could lead to loss of information. Furthermore, the use of standardised object and material libraries can further simplify information exchange during EA.

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