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A FRAMEWORK AND DECISION SUPPORT SYSTEM TO INCREASE BUILDING LIFE CYCLE ENERGY PERFORMANCE

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SUMMARY: *The main aim of the research presented in this paper is to contribute to a reduction in carbon emissions from buildings. Carbon reduction is a global goal and in line with this UK government policy seeks to reduce carbon emissions 60% by 2050, and 80% by 2100, compared to 1990 levels. To meet these targets it will be necessary to greatly improve the energy performance of the built environment. Current green building guidelines and frameworks provide information about which design standards should be achieved but they lack practical information about how to meet those standards. One of the main objectives of this research is to ameliorate this problem. To do so a process framework for building design and an ICT system to support multi stakeholder decision making that facilitates the inclusion of energy issues in the early design phase of buildings has been developed. The framework developed is an extension of the Royal Institute of British Architect (RIBA) plan of work stages, and as such can be described as a RIBA sub-process. The ICT system 'dubbed' Environmental Assessment trade-off tool (EATT) is designed to support multi stakeholder decision making in the design process. The main aims of this paper are to identify gaps in the RIBA process and current green construction guidelines with regard to supporting the design of new energy efficient buildings and building refurbishments, outline the RIBA sub-process and the EATT and demonstrate the application of the trade off tool in a case study.*

KEYWORDS: *energy efficiency, building design, material procurement, trade-off, Analytical Hierarchy Process.*

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1. INTRODUCTION

The UK Government committed to making ambitious reductions in CO2 emissions in the 2008 Climate Change Act (HMG 2008). The Act promises to reduce CO2 emissions in the UK by 60% by 2050 and 80% by 2100 compared to the 1990 level (HMG 2008). In doing so it provides the legislative framework necessary for legally binding interventions to "*improve carbon management and help the transition towards a low carbon economy*" (DEFRA 2009). Buildings account for approximately 40% of CO2 emissions in the UK and across the EU (Carbon Trust 2010). Therefore it is unsurprising that tackling energy use through the design and development of low carbon buildings is a policy priority for the UK government and forms part of wider policies promoted by the European commitment to reduce energy consumption (European Commission 2005, Crosbie et al 2010). In the light of recent EU and UK policy commitments the aim of the research presented in this paper to contribute to a reduction in CO2 emissions from buildings is very timely. To meet this aim the main objectives of the research presented are the development of a building design framework and an ICT system to support multi-stakeholder decision making in the design process which enable the inclusion of energy issues in the early design phase of buildings.

The building design framework, developed in the research presented, is an extension of the Royal Institute of British Architects (RIBA) plan of work stages, and as such can be described as a RIBA sub-process. The ICT system, developed in this research is 'dubbed' Environmental Assessment Trade-off Tool (EATT). It is designed to enable the multiple stakeholders involved in the design, development and refurbishment of buildings to assess the effectiveness of different design options with regard to energy performance, financial costs and personal taste at the early stages of building design. The EATT uses building simulations to form the basis of a lifecycle cost assessment (LCCA) to assess running, build and maintenance costs. Lifecycle assessment (LCA) to address the issue of embodied energy in the materials used to construct buildings is also considered via integration of the database underpinning the EATT with the BRE Green Guide to specification (BRE 2010). Multi-criteria decision analysis (MCDA) theory, also known as multi-criteria decision making (MCDM), is used to explore trade-offs between different design variables and to address their impact on the overall design of the building with regard to costs, energy performance and personal aesthetic tastes and priorities. Here it is important to note that although some consumers understand the benefits of green building, including the possibilities provided for increased revenue, capital cost is a major barrier to the uptake of green building and green refurbishment practices (Loh, et al. 2009, Green Building Council of Australia 2008). Hence, it is crucial to find cost effective methods of encouraging green building design (Crosbie et al 2010).

The aims, objectives and approach of the research presented in this paper are justified by the findings of numerous national and international research projects, including an EU funded project called EIPRO (Environmental Impact of Products), which analysed life cycle environmental impacts related to final consumption. This work found that building occupancy and structure make up 20 to 35% of the environmental impacts of all products (EIPRO 2006). Following on the findings of the EIPRO project a subsequent EU funded project explored the environmental improvement potential of buildings (IMPRO-Building 2008). This work found that the condition of the EU building stock in terms of environmental performance is far from the currently discussed low-energy standards and as such there is a tremendous potential for improvement (IMPRO-Building 2008). The IMPRO project concluded that the promotion of strong actions from all stakeholders are necessary if the environmental improvement potential of buildings is to be realised (IMPRO-Building 2008). However, a critical aspect of the decision making process is to enable stakeholders not only to interpret and make decisions based on expert judgments but, also to appropriately involve the relevant parties in the decision making process (Loh et al 2009, INPRO 2010). To do so some form of IT supported decision making environment is necessary to simplify and inform the decision making process (Loh et al 2010, INPRO 2010). Previous research has also illustrated that the greatest opportunity for cost-effective energy measures occurs at the early stages of the design process in the case of both new builds and building refurbishments (Schlueter and Thesseling 2009, INPRO 2010).

The approach developed in this research also builds on earlier work which argues that CO2 reduction in the built environment demands more informed early design planning to support improvements in the selection of the materials used in the construction of buildings in terms of their impact on energy performance and embodied energy (Crosbie et al 2010, Arup 2008, Roberts 2008 and Halliday 2007). In line with this the EATT focuses on the selection of the materials used in building construction. This is because construction materials have a significant impact on building life cycle performance but research has not given consideration of energy issues within their selection a large amount of attention in the past (Haapio and Viitaniemi 2008, Gonzalez and Navarro 2006). Hence, the EATT presented in this paper contributes to closing a gap in earlier research. The remainder of this paper identifies the gaps in the RIBA process and current green construction guidelines with regard to supporting the design of energy efficient buildings and building refurbishments, outlines the RIBA sub-process and the EATT tool as well as demonstrating the application of the EATT in a case study.

2. GAPS IN CURRENT DESIGN APPROACHES

In recent years a number of researchers have developed general lifecycle design frameworks for buildings to support energy efficient building design (see for example INPRO 2010). However the approach adopted often demands that architects and building contractors completely transform current building design practice (Dunsdon et al. 2006), which may be desirable but is not feasible. The approach adopted in the research presented here is somewhat different. In that the framework developed to support the design process seeks to provide practical guidance on when and how to use IT tools and green guidelines to support multi-stakeholder environmentally sound design practices within current business processes. To do so, the framework developed in this research is integrated within the Royal Institute of British Architects (RIBA) 'Plan of Work Stages' (RIBA 2008), which is the most widely used framework by the Architecture, Engineering and Construction industries for the delivery of construction projects within in the UK and elsewhere (McElroy 2009).

The 'RIBA Plan of Work Stages' describes activities involved in the design and construction process from appraising the client's requirements through to post construction (RIBA 2008). It divides the design and construction process into eight stages from A to M (RIBA 2008). In general, stages A and B focus on project feasibility, stages C to H are mainly concerned with the pre-construction process whilst stages J to M are concerned with the site construction process. There are a number of IT applications designed to support the building design process outlined in the 'RIBA Plan of Work' (Crosbie et al 2010) the different types of applications available and their function are illustrated in table 1. These IT applications offer the opportunity to support a reduction in the environmental impact of buildings throughout their lifecycle (Crosbie et al 2010). For example, Life Cycle Assessment (LCA) tools provide improved decision support when optimising environmentally favourable design solutions that consider the impacts caused during the entire lifetime of the building (Malmqvist, et al 2010). However current design practice marginalises these opportunities (Crosbie 2010, INPRO 2010, Malmqvist, et al 2010). This is reflected in the RIBA 'Plan of Work' (2008), a major weakness of which is that it overlooks the environmental responsibility of Architecture, Engineering and Construction professionals (McElroy 2009).

TABLE 1: Overview of the tools avaiable to support the design process

Software category	Function	Examples
Building Information modelling software (BIM)	Modelling and visualisation	Autodesk Revit, ArchiCAD, Microstation
Energy simulation tools	Assessment of energy performance and visualisation of results to support decision making	IES, Ecotect, DesignBuilder, Esp-r, Energy Plus
Building Environmental Assessment tool (BEA)	Assessment of building environmental impact and visualisation of results to support decision making	Envest II
Life cycle assessment tool (LCA)	Assessment of material life cycle performance and visualisation of results to support decision making	SimaPro, BEES, ATHENA Environmental Impact Estimator
Life cycle cost assessment tool(LCCA)	Assessment of building life cycle cost performance and visualisation of results to support decision making	IES, Envest II, Building Life Cycle Cost (BLCC)

There are attempts to incorporate current green building guidelines within the RIBA plan of work. The most prominent of these are the 'Environmental Code of Practice[1]' (BSRIA 1999), the 'Environmental Handbook' (CIRIA 1997) and the 'Green Guide to the Architect's Job Book' (Halliday 2007). However, while the incorporation of these types of guidelines into the design process can have positive impacts with regards to the environmental performance of buildings, they are limited in terms of practical guidance for stakeholders in the building design and refurbishment process. For example while the 'Environmental Code of Practice'[2] recommends consideration of embodied energy in construction materials at the design stage of buildings it does not give guidance on how this might be achieved (Guthrie et al 1999). The 'Green Guide to the Architect's Job

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[1] Developed by the 'Building Services Research and Information Association' (BSRIA): a not-for-profit, member based UK test, instrumentation, research and consultancy organisation, providing specialist services in construction and building services.

[2] Also developed by BSRIA

Book', as the name suggests, is aimed at architects rather than all stakeholders in the design process, but it is designed to inform good practice during the whole life cycle of buildings. However, it's focus on architects' means that it provides little support for other stakeholders in the design process. Unlike the 'Green Guide to the Architects Job Book', the 'Environmental Handbook'[3] aims to "*inform anyone involved in a project about their obligations and the opportunities open to them to improve the industry's environmental performance"* (CIRIA 1997). It contains "*information and practical guidance on the environmental issues likely to be encountered at each stage in the design and specification of a building or civil engineering project"* (CIRIA 1997). However, due to the level of detail required it is not user friendly and it does not map well with good practice legislation.

Table 2 summarises the advantages and disadvantages of the green guides to construction discussed in this paper. It illustrates that one of the main problems with these approaches is that they provide little practical guidance on the inclusion of the IT tools available to support good design practice during the building design process. To put it succinctly, current green building guidelines provide information about which design standards should be achieved but they lack practical information about how those standards should be met. In order to contribute toward closing this gap a building design process framework was developed to support an understanding of the methods and tools available to support good environmental design practice in the early stages of the design process. It is important to emphasise this building design process framework is a 'RIBA sub-process' and is not intended to replace the existing green guidelines; rather its' role is to support the incorporation of existing guidelines into the work stages outlined by RIBA to inform the use of the ICT tools and methods to achieve/exceed the guideline's requirements.

TABLE 2: Comparison of green construction guidelines highlighting the features and gaps

Green Guide Attributes	**Environmental Code of Practice** (Halliday 1994)	**Environmental Handbook** (CIRIA 1997)	**Green guide to the Architect's Job Book** (Halliday 2007)
Based on RIBA work stage?	Y	Y	Y
Incorporates actions for all stages of the design process?	Y	Y	Y
Supplies guidance on the use of supporting tools?	N	N	N
Supplies guidance on good design practice?	N	Y	N
Highlights the potential pitfalls of each design stage?	Y	N	Y
Provides guidance on the legislation to be considered at each stage?	Y	Y	N
Identifies stakeholders at each stage?	Y	N	Y
Accessible (easy to read/understand?)	Y	N	Y
Accessible at any stage?	Y	Y	Y
Accessible by all stakeholders?	Y	Y	N

3. INFORMING THE BUILDING DESIGN PROCESS

The RIBA sub-process proposed in this paper is an extension of RIBA work stage C its role is to provide practical guidance on when and how to use IT tools to support good design practice during the building design process. The design and build project procurement route proposed in the RIBA Plan of Work (see Fig. 1) is used to demonstrate the RIBA sub-process in this paper. This is because it is one of the most common routes used in the UK construction industry. However the proposed RIBA sub-process could also be used to support different procurement routes.

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[3] Developed by the Construction Industry Research and Information Association (CIRIA): a not-for-profit UK association that delivers enterprise programmes and research in the construction industry

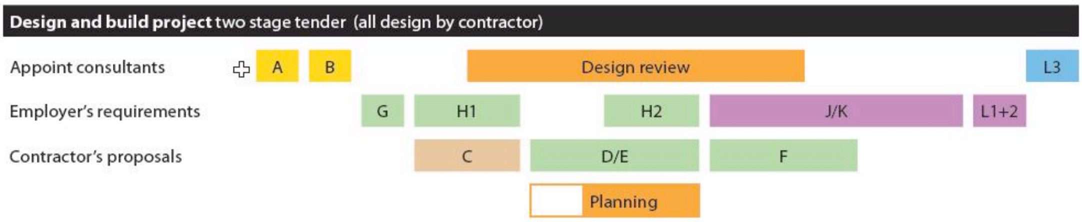

FIG. 1: Processes for design and build projects (adopted by RIBA plan of work 2007)

At the outset of a project, during stages A to B of the 'RIBA Work Stages', an initial appraisal is carried out to begin to identify project constraints, procurement route, stakeholders and develop an idea of the building design. During this process all relevant regulations and legislation are referred to, ensuring the project meets all legal requirements, and the strategic brief prepared by the client containing their initial requirements is sent to the architect. Stage C of the 'RIBA Work Stages' involves the further development of the conceptual/outline design proposals developed in stages A and B. It is at this stage of the design process that outline/conceptual designs of a building are detailed to the extent that an approximation of construction costs and information for cost planning are provided. This enables client approval to be sought for a building design and its associated costs. Therefore stage C of the design process provides an ideal opportunity to demonstrate different design options with regard to energy performance and financial costs. Fig. 2 presents an overview of the processes involved stage C of the RIBA Work Stages and points to the stages at which IT tools can be used most effectively.

As outlined in Fig. 2, during stage C of the 'RIBA Work Stages' a full set of tendering documentation including design brief, site data, project schedule, project budget and client requirements are prepared and given to tendering contractors/architects to prepare the full design proposal. If a single stage tender process is adopted in a project, a contractor will be appointed at stage C, or, a client will shortlist candidates and decide on the winning contractor after reviewing all the final design proposals submitted. Following stage C, as outlined in stage D of the 'RIBA Work Stages', investment decisions are finalised and applications for planning permission are made.

During stage C of the RIBA process the building design is further developed in order to detail the internal layout of the building and to provide details about construction materials to inform the initial costing of the building etc. As outlined in Fig. 2 and further detailed in Fig. 3, 4 and 5 it is during this process that the output from LCCA, LCA and energy simulations can be used to inform stakeholders of the energy and cost implications of different design options. To appropriately involve all relevant stakeholders in the decision making process some form of IT supported environment is necessary to simplify and inform the decision making process (Loh et al 2010). The way in which an IT tool can be incorporated into the process, to support trade-offs within the material selection process is presented in Fig. 4.

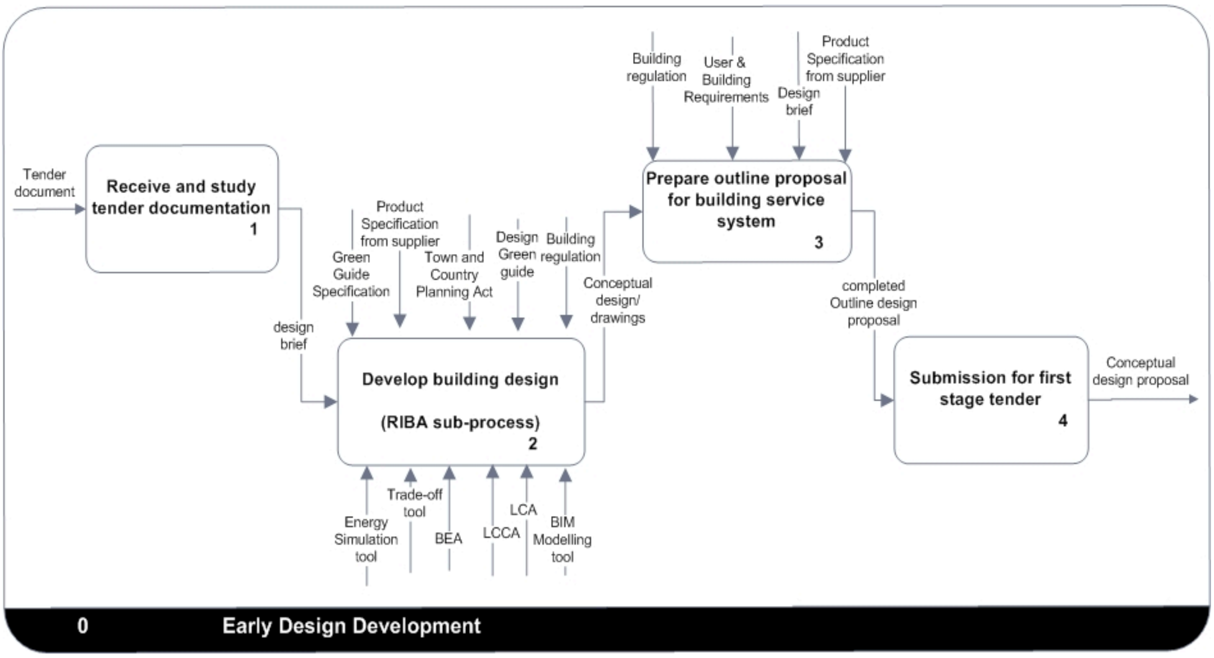

FIG. 2: Overview of early design development

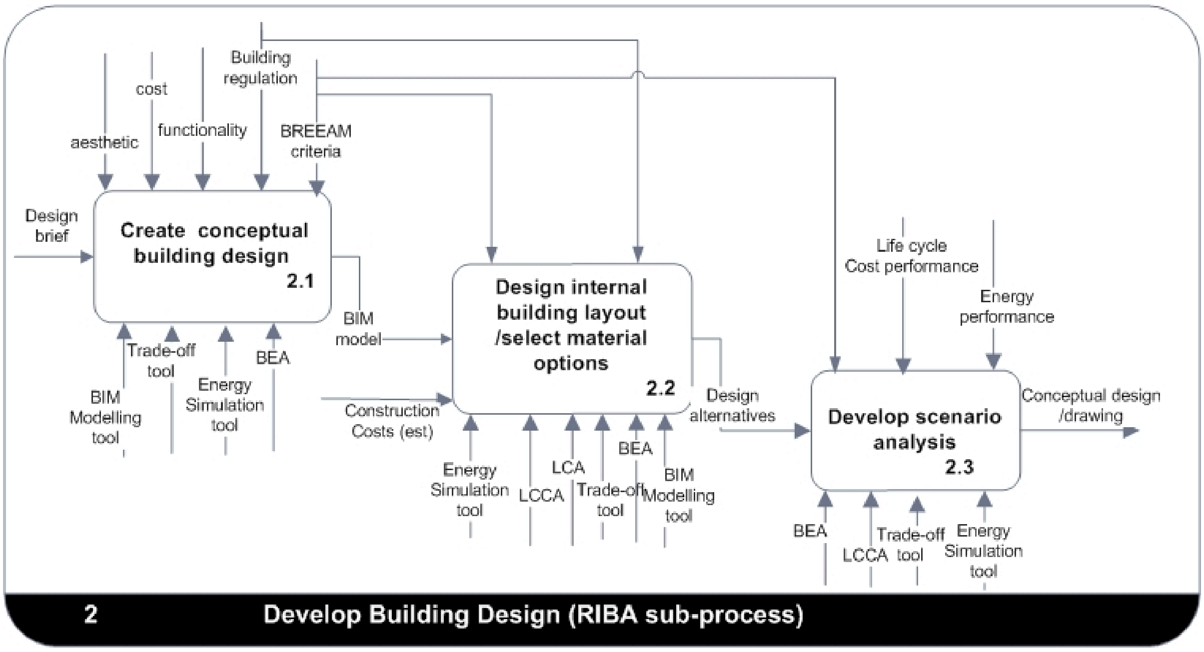

FIG. 3: Building design development

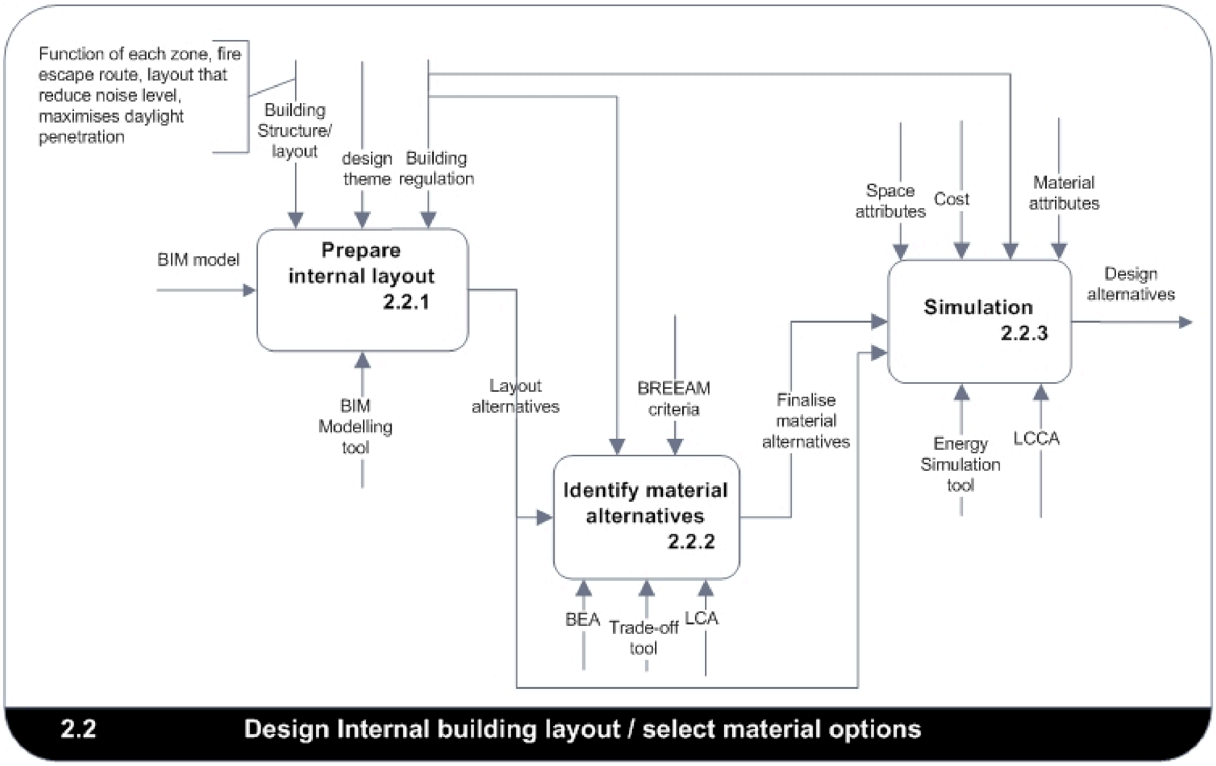

FIG. 4: Internal building configuration and material selection process

The design elements usually considered during the design of the internal layout of a building include the function of the building, fire escape strategy, and noise insulation, intake of indoor natural light, the design theme and building regulations. It is suggested here that during the design of the internal layout of a building a facilitated *charrette*[4] is conducted to identify, options for the internal layout of the building and the preferred construction materials of each stakeholder. The output of this process can then be used to conduct a materials trade off to ascertain which combination of construction materials meet the most of all the different stakeholders requirements. The different options for the internal layout of the building combined with the different building material combinations identified during the trade-off are then used to run energy simulations and LCCA to help stakeholders identify the energy and cost implications of each of the design options. This process is further elaborated in the following sections. The first of which outlines the design of the EATT tool developed in this research to support the processes illustrated in Fig. 4.

4. INFORMING DESIGN DECISIONS

The EATT was developed using MsExcel. It is intended that the EATT is used as an integral part of a computer-supported environment that facilitates access to data describing a buildings' design and evaluating its energy performance using simulation tools to integrate energy issues in the early design phase of buildings. It is specifically designed to enable stakeholders involved in the design, development and refurbishment of buildings to assess the effectiveness and trade off different construction materials and building internal layout options with regard to energy performance, financial costs and personal aesthetic considerations. It should be noted that the EATT could also be used by architects alone, or in other words it could be used to assist single user decision making, but part of its strength lies in its ability to support multi-user decision making (Loh et al 2009).

It is also important to stress that the solution provided by the EATT is not necessarily the most sustainable design approach or the cheapest solution. What it provides is a solution that meets the most of the stakeholders' requirements. This means that energy efficiency could be compromised in the selection of criteria as the selections made depend on stakeholders' priorities.

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[4] A charrette is an inclusive consultation technique, used within urban planning and building design.

4.1 System Functionalities

As detailed in the previous sections the EATT supports tradeoffs between different options for construction materials and internal building layout. To do so it has the following two main functions:

i) Material assessment

There are five material attributes in the system. These are external wall, internal wall, external window, roof and ceiling. Each stakeholder selects a particular material for each attribute and inputs the weighting factors for each according to their preferences and priorities. The system analyses the cost and benefit of the different material options in order to generate the best material combination that meets stakeholders' requirements.

ii) Project assessment

The output of the materials assessment is then used to run energy simulations which are input into the EATT system along with the necessary benchmark data and the system analyses the material and internal configuration alternatives. This stage of the trade off process is also conducted in terms of costs and benefits. The system uses the same weighting method for the project assessment as is used for material assessment.

4.2 Trade-off technique

Analytical Hierarchy Process (AHP) is the MCDA trade-off approach which lies at the heart of EATT decision support system. The reason AHP is used rather than multi-objective optimisation techniques, such as evolutionary algorithms, is because these techniques usually require significant numerical data input (Reeves and Rowe 2002). The numerical data in EATT is not significant and thus AHP has the advantage over multi-objective optimisation techniques which are not suitable to support the trade-off functionality of the EATT. One of the reasons for this is that "*multiple objective programming techniques face the problem of a large (if not infinite) number of alternatives*" (Olson 1998). Another reason for using AHP is that it supports trade-offs with and without tangible values. Or in other words, this approach enables aesthetic issues as well as environmental impacts to be considered. This feature is important as decision making in reality engages with solid, verbal and subjective elements (Saaty 1994). However, the EATT does support the use of tangible data on its own in the selection of construction materials. This is achieved by inputting a weighting factor into the global priorities embedded within the system and setting the weighting factor of subjective criterion to neutral.

Fig. 5 illustrates the AHP hierarchy for the material assessment using the example of roofing. The primary criteria are material cost and material benefit. Each of these primary criteria has a related set of sub-criteria and as an optional step the user is able to assign weighting factors to each of the sub-criteria (see table 3 for the relation between the primary criteria and the sub-criteria). Users input the weighting factor for material cost versus material benefit (see Fig. 6 for an example of the user interface). The weighting method is based on the AHP where a value of 1-9 represents a criterions' priority with 1 representing neutral/ or of no importance and 9 representing vital or of critical importance. This same trade-off procedure is carried out for all material attributes. The five major material attributes included in the EATT are those which have the largest impact on the energy performance of a building design. In a nutshell, as users select any material, the material objective data, such as material rating, capital cost, life cycle performance, etc will be retrieved from the database and the logic within EATT will generate a result based on these objective criteria. The EATT material database was created based on the Green Guide to Specifications published by BRE[5] (BRE 2010). The material output from EATT supports a more effective material input process in energy simulation software such as IES.

After the trade-off procedures are completed, a material assessment report is generated for stakeholders to review (see case study for further details). The same principle of AHP hierarchy structure is also applied to the project assessment. Table 4 illustrates the criteria used in project assessments (see the case study presented in the next section for further details of project assessment output).

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[5] The environmental rankings of the materials in this specification are based on Life Cycle Assessments using BRE's Environmental Profiles Methodology 2008

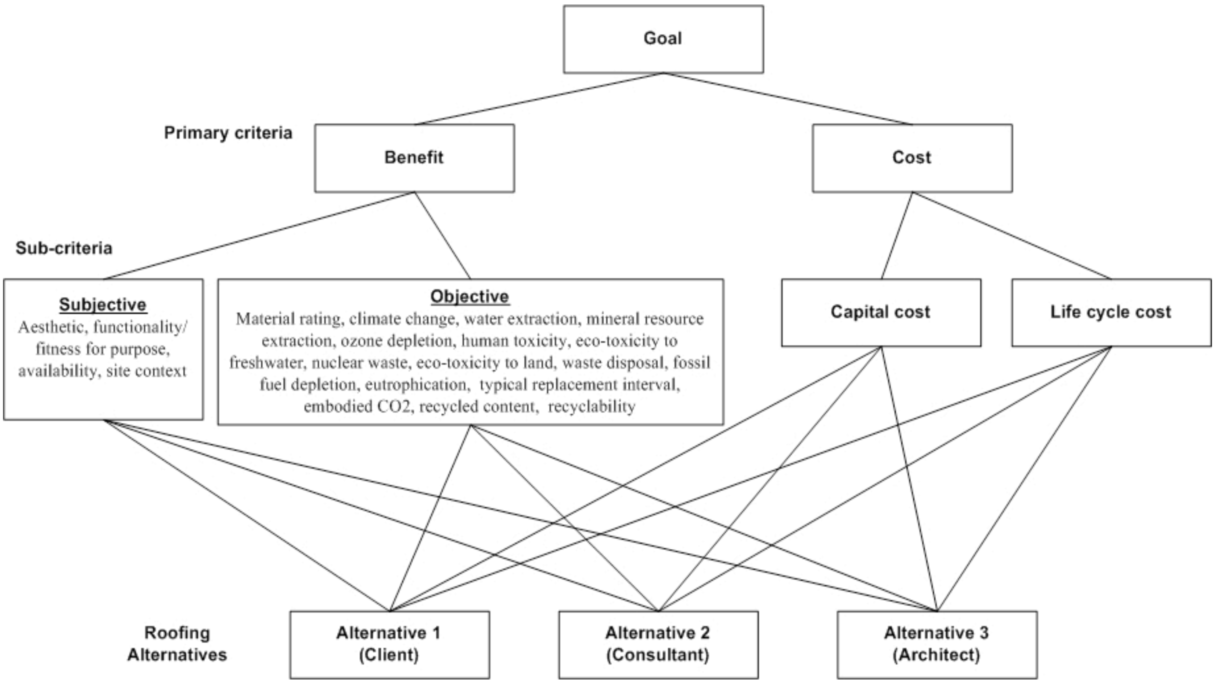
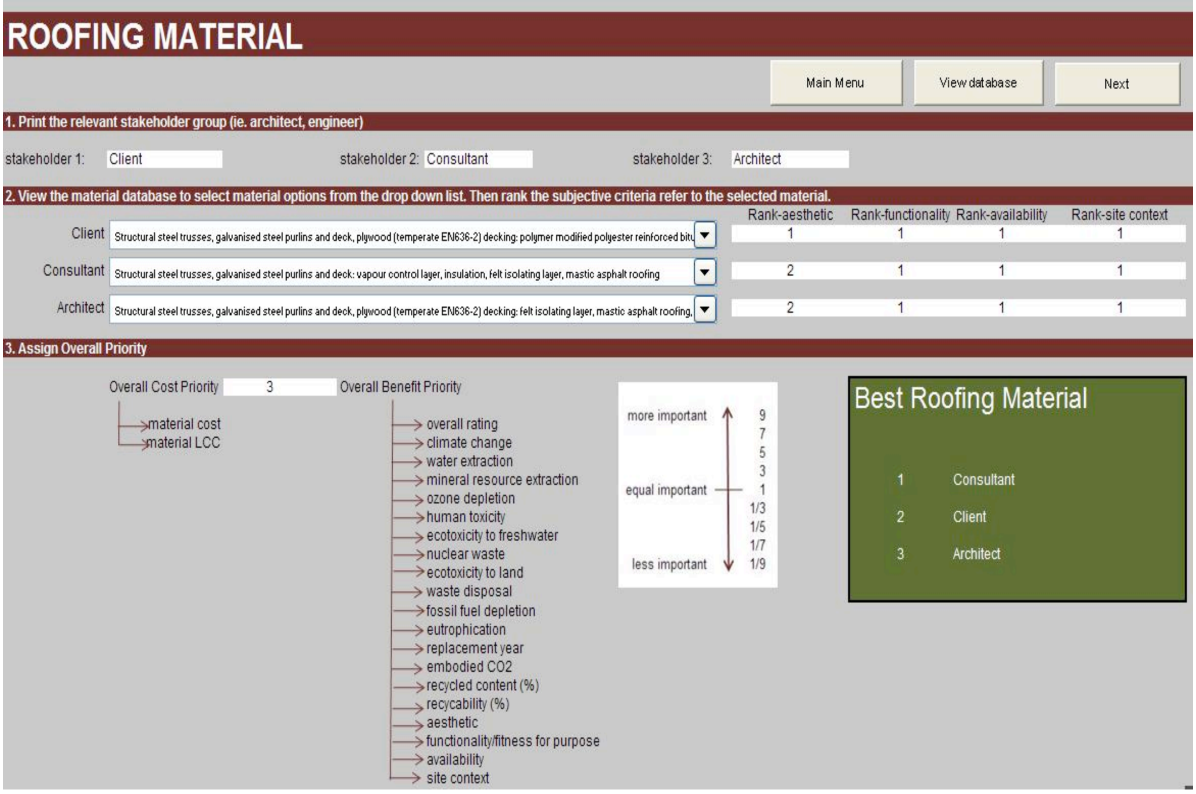


FIG. 5: AHP hierarchy for the roofing material



ROOFING MATERIAL

1. Print the relevant stakeholder group (ie. architect, engineer)

stakeholder 1: Client
stakeholder 2: Consultant
stakeholder 3: Architect

2. View the material database to select material options from the drop down list. Then rank the subjective criteria refer to the selected material.

		Rank-aesthetic	Rank-functionality	Rank-availability	Rank-site context
Client	Structural steel trusses, galvanised steel purlins and deck, plywood (temperate EN636-2) decking: polymer modified polyester reinforced bitu	1	1	1	1
Consultant	Structural steel trusses, galvanised steel purlins and deck: vapour control layer, insulation, felt isolating layer, mastic asphalt roofing	2	1	1	1
Architect	Structural steel trusses, galvanised steel purlins and deck, plywood (temperate EN636-2) decking: felt isolating layer, mastic asphalt roofing,	2	1	1	1

3. Assign Overall Priority

Overall Cost Priority 3

Best Roofing Material

1 Consultant
2 Client
3 Architect

FIG. 6: User interface for Materials selection in EATT

TABLE 3: Criteria for material alternatives

Source of Information	Criteria Type	Primary Criteria	Sub-Criteria	Material Attributes
Green Guide to Specification	Objective	Material Cost	Capital Cost	Roofing External walls Internal walls Ceiling External windows
LCCA [IES]	Objective		Life Cycle Cost	
Green Guide to Specification	Objective	Material Benefit	Material rating, climate change, water extraction, mineral resource extraction, ozone depletion, human toxicity, eco-toxicity to freshwater, nuclear waste, eco-toxicity to land, waste disposal, fossil fuel depletion, eutrophication, typical replacement interval, embodied CO2, recycled content, recyclability	
Stakeholders	Subjective		Aesthetic, functionality/fitness for purpose, availability, site context	

TABLE 4: Criteria for design alternatives

Source of information	Type of criteria	Primary criteria	Sub-criteria
IES (simulation result from the material assessment)	Objective	Project cost	CO2 emission, energy consumption, capital cost, energy cost, material replacement cost, total life cycle cost
Stakeholders	Subjective	Project benefit	Space function (fit for purpose), site context (aesthetic qualities, topography)

4.3 System Architecture

The main menu of the EATT system consists of three buttons including options for material assessment, project assessment and the user guide. As mentioned earlier, the EATT is flexible and can be used by single or multi users. Fig. 7 shows a class diagram created using the Unified Modelling Language (UML), which describes the attributes and the operations between different system classes. In the expression of UML each material is presented in the form of 'material classes' that are inclusive of the materials attributes and operations. There is a composition between the material database and every material class. In other words, the material classes have a relationship with or a life cycle dependency on the material database. When a user selects a material, from the dropdown list in the user interface, the objective data of the selected material is retrieved from the database and the logic trades-off the criteria.

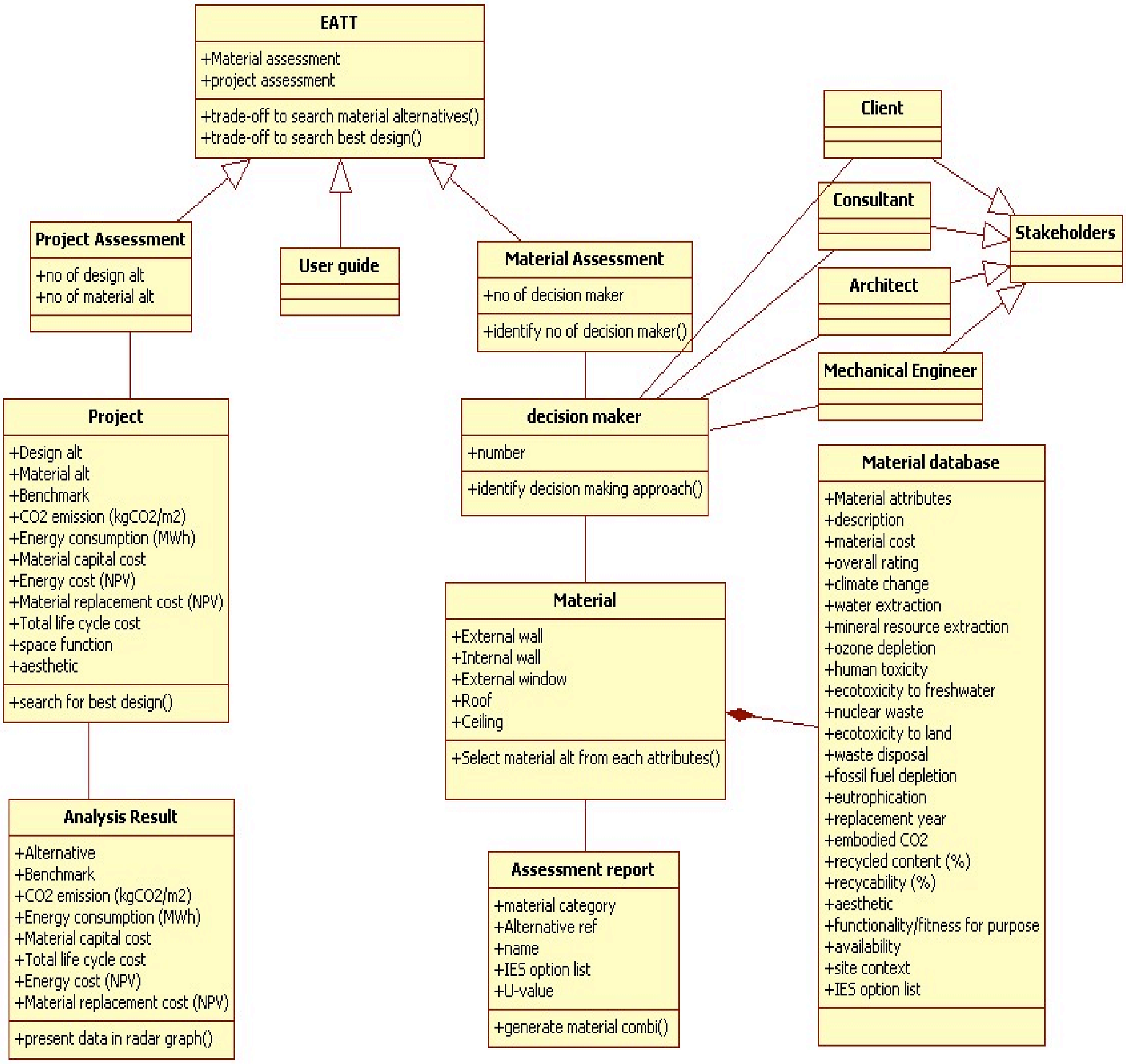


FIG. 7: Class diagram for the EATT system application layer

5. VALIDATION

Observational studies at architectural practices in the UK were used to inform the development of the EATT. The EATT interface was tested by an architectural technician and the development of the tool was further informed by data collected during semi-structured interviews with architectural practitioners. Most of the interviews were conducted face to face but one was conducted over the telephone. One of the authors spent time at an architectural practice observing the way in which work was conducted during the early design of buildings to inform the initial development of the EATT. Following this the tool was piloted by an architectural technician mainly to test the 'user friendliness' of the interface.

A short presentation about the functionality and material input procedure of EATT was given to the architectural technician and then he was asked to test the tool. The test began with the selection of material alternatives from the EATT database. During this process, the technician only considered the performance and structural qualities of the materials. He said this was because an architectural technician usually focuses on structural suitability when selecting a material. To further validate the EATT system two interviews were conducted with senior architectural practitioners from two different architectural companies. Those taking part the interviews agreed that it is usual to rely on the BRE Green Guide to Specification and architects experience when making decisions about which materials to use in a construction project. However interviewees also mentioned that as there are more than 1500 products in the BRE Green Guide to Specification, decision making can be difficult, especially when there are more than two sustainable materials in a similar price range. The interviewees were given the same short demonstration of the EATT tool as the architectural technician and they along with the technician said that they think the tool is user friendly and also commented that it takes a surprisingly short time to generate results. The interviewees recommend the development of a 'light' version of the EATT which could be used to support material selection even earlier in the design process during the initial or conceptual stages.

The discussions of the value of a 'light' version of the EATT tool for the conceptual stage of building design with interviewees highlighted the way in which the use of BIM is developing within architectural practice. The approach adopted within the development of the EATT necessitates the development of a BIM during the early stages of building design. The observational study and the interviews revealed that a BIM massing model is usually developed at the conceptual design stage, the detail of this massing model is then built up during the design process into a full BIM. However the interviewee from the smaller architectural practice indicated that BIM models are not always developed before the detailed design stage once planning permission has been obtained. The reason given for this is that in some cases it is not cost effective to develop a BIM model before the early design stage, as the design is yet to be finalised and there are usually changes to be made later in the design process.

It would seem that the timing of BIM implementation depends on the scale of the architecture practice and the size and skills of the design team. However the interviews also indicated that BIM technology can and is used at the early design stage and it is cost effective, if the design team has a common understanding of the purpose of the BIM model. This demands that a BIM modelling quality document is drafted by the BIM manager so that the BIM model is adequate for use throughout the building design process. It must be noted that the major part of the building design is finalised at the early design stage and only the interior layout is likely to change. In fact, larger scale projects tend to require that the design is firmed up as early as possible within the design process to prevent extra costs and delays in the construction process. This suggests that it will be most effective to use BIM in the early design phase when working on larger projects. It must also be noted that there is a move within sustainable design towards performance based assessments of building designs and this will necessitate the use of BIM throughout a buildings lifecycle (Crosbie et al 2010).

The overall findings from this initial validation indicate that the use of BIM technology and EATT at the early design stage to support the material procurement and ensure the quality of a buildings' lifecycle energy performance is considered by architectural practitioners to be advantageous. In the next section a case study is used to illustrate how this may be achieved.

5.1 Case Study

A primary school development undertaken by Durham County Council in the UK (see Fig. 8) is used in this paper to demonstrate the EATT. In this case study Autodesk Revit MEP was selected to support visualisation, and IES is used to conduct the energy simulations and the LCCA. The approach adopted utilises the design data from the primary school project in conjunction with the output of a focus group which is used to simulate stakeholder involvement in the design process. The focus group participants were selected with regard to their ability to represent actual stakeholders within the building design process. Therefore a teacher was used to represent the client, an architect was used to represent the architect of the school and a post graduate student studying environmental management was used to represent the projects' environmental consultant.

FIG. 8: Primary school main enterance

During the focus group participants examined and discussed the design proposal for the school (see Fig. 9). The output of this process was an alternative design in which the size of the class rooms in the south wing is slightly increased to provide a larger teaching environment (see Fig. 10).

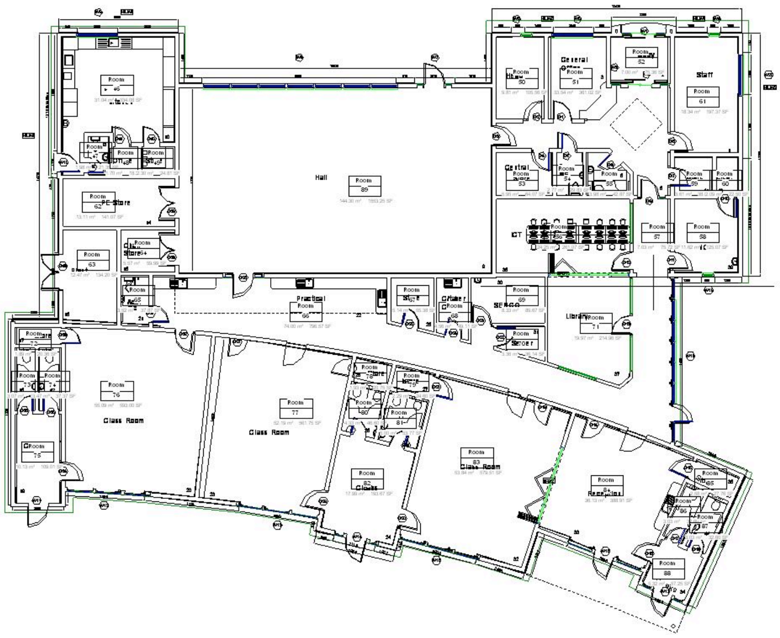
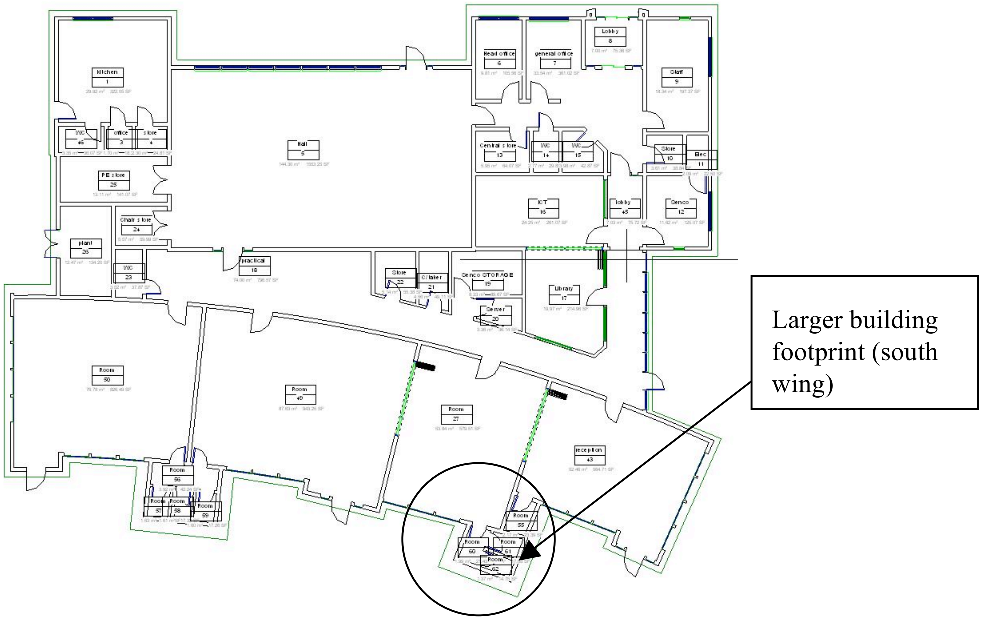


FIG. 9: First design proposed by the architect (Alternative 1)



Larger building footprint (south wing)

FIG. 10: Alternative design generated at stakeholders' meeting (Alternative 2)

Focus group participants were then asked to select the construction materials they prefer for the external wall, internal wall, external window, roof and ceiling using the EATT (see table 5 for participants' materials selections). Following this, focus group participants ranked the subjective criteria in the EATT, these include aesthetic qualities, functionality and availability (see table 6). The focus group participants did not consider site condition and therefore only three subjective criteria are demonstrated. During the material selection process focus group participants were able to agree on the ranking of the subjective criteria, however, if agreement on the ranking of subjective criteria cannot be reached and materials are considered to have equal importance the best solution is to rank these criteria as neutral. The next stage of the process involved the selection of the cost benefit criteria priorities for the design options at this point sub –criteria can also be selected if necessary. The output of the material trade off consists of three materials combinations ranked according to the priorities of the stakeholders i.e. the best, the second best and the third best material combinations (see table 7).

TABLE 5: Materials selected by focus group participants

Materials attributes	**Stakeholders**		
	Client	Consultant	Architect
Roofing	plaster board, vapour control layer, insulation, plywood decking, timber joists, polyester reinforced bitumen felt, chipping	plaster board, timber joists, plywood, asphalt, insulation, chipping	plaster board, timber joists, plywood decking, vapour control layer, insulation, felt isolating layer, asphalt, chippings
External wall	brickwork outer left, insulation, aerated block-work inner left, plasterboard/plaster	brickwork, timber frame with insulation, plasterboard	western red cedar cladding on timber framework, insulation, dense block-work, plasterboard/plaster
External window	hardwood timber frame window	aluminium frame window	aluminium composite window
Internal wall	steel jumbo stud, 2 sheets plasterboard each face, glass wool insulation (90mins fire protection), paint	timber stud, plasterboard and skim, glass-wool insulation, paint	timber stud, plywood, glass-wool insulation
Ceiling	direct finish-plasterboard on timber battens	Joint-less suspended ceiling-plasterboard	suspended ceiling, exposed grid: vinyl faced gypsum based tile

TABLE 6: Ranking for subjective criteria

Materials attributes	**Aesthetic**			**Availability**			**Functionality**		
	Client	Consultant	Architect	Client	Consultant	Architect	Client	Consultant	Architect
Roofing	1	1	1	1	1	1	1	1	1
External wall	3	2	1	1	1	2	1	1	1
External window	1	2	2	1	1	1	2	1	1
Internal wall	1	1	1	1	1	1	1	1	1
Ceiling	1	1	3	2	1	1	3	2	1

TABLE 7: Accumulation of material combination based on the criterion priority

	Best material combination	**2nd material combination**	**3rd material combination**
Roofing	Consultant	Architect	Client
External wall	Consultant	Client	Architect
External window	Consultant	Architect	Client
Internal wall	Client	Architect	Consultant
Ceiling	Client	Architect	Client

IES was then used to conduct energy simulations and LCCA for each of the six different material-design combinations and benchmark data was generated using the existing building design. The outputs of these simulations and LCCAs are presented in table 8. As illustrated in table 8 the existing building has the lowest capital cost. However, the material life cycle cost of the existing building is the third highest of all the alternative building designs. The figures in table 8 also illustrate that by investing an extra capital cost of £51,828, the building life cycle cost is reduced by £488,726 or 60% over a lifecycle of 60 years. These findings support the assertion that the selection of construction materials should be given careful consideration during project design as they have a large impact on the sustainability of buildings in terms of energy consumption and running cost. In addition the case study presented illustrates that the EATT can indeed assist multi-stakeholder assessments of the cost and benefits of different construction materials and internal design layouts

TABLE 8: Simulation results for design alternatives and existing building

	Design alternative	**Material alternative**	**CO2 emission**	**Annual energy consumption**	**Capital cost (materials)**	**Total LCC(60)**
Alt			kgCO2/m2	MWh	£	£
1	1	1	7920	38.78	329,671	775,919
2		2	7640	37.43	284,157	1,035,514
3		3	7390	36.20	284,889	1,299,673
4	2	1	8400	41.14	332,454	796,088
5		2	8230	40.31	294,456	1,037,258
6		3	7960	38.97	294,714	1,313,520
	existing		7380	36.13	277,843	1,264,645

6. CONCLUSIONS

The research presented in this paper illustrates that careful selection of construction materials and building layout could form a crucial step on the road to reducing CO2 emissions from the built environment. This work acknowledges current building design practice by illustrating how a ‘sub-process’ maybe used to detail the work necessary to stage C of the RIBA design process. In this way how existing green guidelines can be incorporated into the work stages outlined by RIBA to inform the use of the ICT tools and methods to achieve/exceed the requirements of green guidelines was illustrated. Furthermore this paper has demonstrated how the EATT can be used to support multi –stakeholder involvement in the selection of construction materials and building layouts in ways which enable building energy performance to be considered at the early stage of building design. However further work is required to fully validate the EATT and the methodology presented. To do so it will be necessary to run further case studies ideally using ‘live’ building design projects. Further research is also required to overcome the limitation caused by basing the EATT on BRE’s Green Guide to Specifications, as this means that unusual materials or tailor made materials cannot be included within the tradeoffs conducted using the tool. Therefore future development of the EATT is required to support user's manual input of objective data for the materials trade off. The development of a 'light' version of the EATT for use at the very initial stages of building design also deserves some further exploration, as research has shown that the earlier environmental issues are considered within the design process the more cost effective they become (Schlueter and Thesseling 2009).

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