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Evaluating Social Housing Retrofit Options to Support Clients' Decision Making—SIMPLER BIM Protocol

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Received: 22 March 2019; Accepted: 24 April 2019; Published: 30 April 2019

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Abstract: The UK government made significant commitments to upgrading the energy efficiency of seven million British homes by 2020, aiming at reducing carbon emissions and addressing fuel poverty. One alternative to achieve better energy performance in existing houses is retrofit. However, there are difficulties associated with retrofitting social housing. It is currently challenging to compare scenarios (retrofit options) considering costs, potential energy efficiency gains, and at the same time minimising disruption to users. This paper presents a Building Information Modelling (BIM) protocol aimed to support decision making by social housing owners. It adopts BIM to simulate alternative retrofit options, considering: (a) potential reductions in energy consumption, (b) 4D BIM for retrofit planning and reduction of users' disruption and (c) simulation of costs. A what-if scenario matrix is proposed to support decision making in the selection of social housing retrofit solutions, according to client and users' needs. A case study of the retrofit of a mid-terrace house is presented to demonstrate the workflow. The main output of the work is the BIM protocol, which can support client decision making in diverse social housing retrofit projects, considering all three elements (energy simulation, planning for reduced disruption and cost estimation) in an integrated fashion. Such an integrated approach enables clients to make better informed decisions considering diverse social housing retrofit options through a simple process using readily available BIM technology.

Keywords: retrofit; building information modelling; social housing; energy simulation; cost estimate; 4D simulation; construction disruption

1. Introduction

Fuel poverty occurs when a household needs to spend more than ten per cent of its income on heating, hot water, lighting and cooking. Li and Yao [1] point that heating is a direct energy cost of a building, and its impact should be properly considered during the design of social housing. According to the annual fuel poverty statistics report [2], 42% of the total households in Northern Ireland were in fuel poverty in 2011. A similar situation is observed across the UK: 30% in Wales in 2012; 35% in Scotland in 2014; and 11.6% in England in 2014. Thus, because of the considerable percentages of fuel poverty, a large number of UK homes require sustainable retrofit to improve their energy efficiency. Also, retrofitting the existing housing stock is a key factor to reduce the UK's carbon emissions, and as such it has been supported by several government schemes, e.g., the Energy Company Obligation [3] and Green Deal [4].

There are around 4.95 million dwellings in the UK's social housing stock. Solid wall 'no fines' housing represents 25% of that stock—1.238 million dwellings [5]. The 'no fines' cast in-situ concrete panels, which is a type of concrete obtained by eliminating the fine material sand from the mix, is not appropriately insulated, and therefore, usually do not meet the minimum requirements of energy conservation during use. Kristjansdottir et al. [6] point out that energy-related factors depend on which materials are initially used in a building, as well as on its general design, and not only on the extra insulation or technical components added to the building systems. Thus, retrofit is needed to improve the thermal comfort and to replace building components which are at the end of their useful life, promoting a better performing building, which can provide a suitable environment for its users.

A well-structured retrofit requires surveying, purchasing, design, contracting and installing measurement tools, such as energy consumption monitoring devices. This process tends to be expensive, and the building's end performance is not guaranteed [7]. Goh and Sun [8] argue that any retrofit decision-making should be taken considering a long-term, building in-use view. It is therefore essential to offer means for clients to evaluate diverse retrofit technical solutions that could achieve energy savings. Also, the housing occupiers should remain as much as possible using the building over the period when the retrofit is being carried out. Hence, minimising the disruption to users (or housing tenants) becomes essential [9]. Finally, sustainable retrofit has a relatively long payback period. Consequently, a comparison of the retrofit cost and potential energy efficiency gains is needed. In summary, the evaluation of a retrofit solution should consider three aspects: (i) the potential energy efficiency gains; (ii) the disruption caused to the housing occupants; and (iii) the costs involved in the process. These aspects should be evaluated in an integrated way, to support the definition of which retrofit solution may be better suited to the specific housing owners and occupier's needs.

Prior research discusses the potential of BIM in retrofit due to its capabilities for design reviews, energy modelling to maximise the potential energy efficiency gains, and other aspects of performance analysis, such as using alternative materials [10–12]. This research exploits the use and benefits of BIM in social housing retrofit. The research presented here is part of a broader project entitled Solid Wall Innovative Insulation and Monitoring Processes using Lean Energy Efficient Retrofit (SIMPLER) (http://www.s-impler.com). The scope of S-IMPLER includes the retrofit of solid wall social housing, with the aim of achieving a significant reduction in monitored energy costs, with less disruption, at least 10% faster production, without reductions in quality and safety. The research was a joint initiative between a housing association, two small and medium enterprises, a contractor, academic institutions, a lean consultant, and a construction organisation. One outcome of the overall project, presented in this paper, is a BIM protocol enabling 'what-if' scenarios for retrofit solutions. The protocol delivers an evaluation of retrofit technical options—what-if scenarios—to support clients' decision making, focusing on: (i) potential reduction in energy consumption; (ii) disruptions to the housing occupier and (iii) estimated costs. This paper describes the BIM protocol and discusses its development.

The following section reviews research in BIM for energy analysis, construction scheduling and cost estimate. Following, the research method adopted in this work is presented. The SIMPLER BIM protocol is described, followed by a case study presenting its practical application. Finally, conclusions are drawn.

2. Related Research

This section presents applications of BIM in energy analysis, construction scheduling, and cost estimation. Additionally, research attempts on adopting such BIM-based functionalities in housing retrofit projects are discussed.

2.1. BIM in Energy Performance Analysis

BIM has been used for building energy performance analysis [13], such as for energy simulation and support for building performance modelling. The primary issue identified is how to integrate geometric models of the buildings and the calculation models for simulation. To deliver design through fast iterations, an architect should be able to quickly perform building performance simulation on geometric models [14]. To perform energy analysis on geometrical models, they must be developed by using modularisation of objects and by creating connection rules among them which reflect the way they are connected in the real building, by using parametric modelling [15]. In this sense, within building geometric models, users should incorporate in the parametric objects all relevant properties associated with their energy consumption and behaviour [16]. Whyte and Hartmann [17] point out that using digitalised building information can contribute towards supporting energy monitoring through the building life cycle. Additionally, Symonds et al. [18] argue that when modelling energy information for a group of buildings which belong to the same geographic region, predictions become more accurate.

Currently, various BIM tools allow the generation of energy calculation models based on geometric and parametric models, which facilitates energy simulation. By using BIM-based Building Energy Simulation (BES) tools, Kim and Woo [19] compared several design alternatives based on their energy consumption. Guo and Wei [20] also investigated the energy-savings of a building with an alternative building envelope by using these tools. Some other BES tools can use BIM models as input by importing them under specific data formats. Open data schemas, e.g., Industry Foundation Classes (IFC) and Green Building XML schema (gbXML), facilitate the exchange of semantic information among various BIM-based software and BES tools [21,22]. For instance, Welle et al. [23] developed an IFC-based middleware to integrate a parametric BIM model to an energy simulation engine (EnergyPlus) and a daylighting simulation engine (Radiance) for building performance analysis. Naturally, the reliability of the BES result corresponds to the quality and depth of information in the model [24]. The work developed so far on using BIM in the energy performance analysis have demonstrated the capability of BIM-enabled BES in the design phase.

2.2. BIM in Construction Scheduling

BIM 4D provides a better understanding of construction components and schedule, by aligning 3D models with the associated construction schedule, which can support the development of better construction plans [25]. Recent research has shown the benefits of using 4D BIM simulation in scheduling, regarding plan visualisation [26], comparing the 'as-planned' and the 'as-built' [27], construction schedule compression [28], and supporting the production planning and control [29]. The critical element of BIM-enabled construction scheduling is to generate the task breakdown and schedules, connecting them to a 3D model so that the construction process can be virtually simulated [30]. BIM 4D allows visualising critical components and flows of building construction, usually hidden when using traditional planning and scheduling methods, and contributes to a better understanding of the overall production process [29]. Using BIM 4D allows for effectively communicating essential aspects of the production plan, such as a sequence of construction, the precise location of work and the associated impacts of moving resources on the construction site [31]. Furthermore, 4D methods can support exploring alternative scenarios for production before actual construction [32], which can provide evidence to help decision-making during production planning processes.

In summary, the use of BIM 4D and other related tools support a better understanding of the production phase, and allow for the development of multiple production scenarios. Furthermore, connecting geometric models to scheduling data can provide more reliable plans. These are important, especially in retrofit situations, in which users might stay at their homes during construction.

2.3. BIM in Cost Estimation

Zheng and Cao [33] discussed BIM-enabled cost estimation by comparing it to the traditional methods. The most significant advantage described is that BIM can automate the quantity take-offs [34,35], which takes significant time if done through a manual process [36]. In addition to extracting the quantity data, Ma and Liu [37] developed an approach to effectively retrieve the construction information in a BIM model for automating the cost estimation. Lee, Kim and Yu [38] proposed an ontological inference process to retrieve work items information automatically and to match among the work items for accurate calculation. Labour cost is also a significant portion of the construction costs. Consequently, construction companies require extensive experience to interpret construction practices into credible cost estimations. Mohsenijam and Lu [39] used historical construction cost records together with corresponding BIM models to estimate the labour cost for future projects.

2.4. BIM and Lean in Retrofit Projects

Analysing the behaviour of a building by using simulation can contribute positively towards increasing its efficiency with fewer costs, anticipating potential issues and satisfying the users' needs [40]. Ilter and Ergen [12] presented a comprehensive review of BIM usage for sustainable retrofit. Building surveying, building performance simulation and information interoperability were the key subjects discussed. Similar areas were included in a multi-criteria decision-making framework for retrofit solution selection, developed by Woo and Menassa [41]. Their solution includes several technical components, such as rapid survey using laser scanning, BIM, energy sensing network and occupancy survey. The research focused on improving the Heating, Ventilation and Air Conditioning (HVAC) system in commercial buildings. Evaluation criteria were related to reducing energy costs, improving occupants' comfort and minimising environmental impacts. Lützkendorf [42] points out that each design variant must be considered and evaluated based on its environmental performance and functional and technical criteria, meaning that it should also embody cost and feasibility aspects.

BIM can greatly facilitate the building energy consumption assessment specifically for retrofit projects, as a process of managing the project lifecycle data [43]. Another benefit is that BIM allows enhanced graphical and informative communication regarding the building defects among the stakeholders in the retrofit process. Also, the prices of the building elements can be linked to the models, and the quantities of the elements can be easily derived.

BIM-enabled 4D construction simulation can facilitate minimising disruption caused by the retrofit work [44]. The integration of BIM and Lean Construction can greatly improve production management in retrofit projects [45]. These previous works [44,45] have explored the applicability of lean principles in retrofit, with the aim of mitigating some of the issues inherently associated with this type of construction project. Such benefits relate to the formalisation of activities, improving visual management, a better understanding of the plans and the assessment of disruptions itself.

In summary, a BIM-based process enables the exploration of different alternatives and supports the adoption of Lean principles [44]. Building energy performance analysis, construction scheduling, and cost estimate are key elements of the evaluation of a building retrofit plan. The feasibility and benefit of using BIM in each of these three aspects has been discussed in the literature. However, past research tends to focus on the analysis of one of these aspects at a time. In this research, all three elements are considered in an integrated fashion to support decision making in the selection of social housing retrofit solutions.

3. Research Method

This research adopted Design Science Research (DSR). DSR aims at developing a solution that solves a practical problem and provides contributions to the associated theoretical knowledge [46]. The innovative solution, called artefact, is usually developed in cycles of evaluation and redesign [47]. The artefact may include constructs, models, methods and instantiations [48]. The practical nature of this research is in the use of BIM for housing retrofit; The artefact produced is a BIM protocol, which presents a method for the use of existing BIM-based tools in social housing retrofit projects. The aim of the research is to devise a protocol that is applicable to similar retrofit projects and can benefit the retrofit of a number of existing single walled homes in the UK and elsewhere. The protocol enables the evaluation of what-if scenarios (technical options) for retrofit works to support client decision making on the most suitable retrofit option.

In the overall SIMPLER project, described in the introduction, seven 'no-fines' social houses were used as a test base for developing and analysing retrofit solutions. The seven houses were 1950 Wimpey

No-fines' homes, located in Antrim (NI), property of the housing association which collaborated with this research project. There are approximately 5000 such houses in Northern Ireland, many in need of retrofit. These are social houses which are considered to be representative of the UK's 1.3 million solid walled homes [5] in need of improvement for energy efficiency. The houses were made available for retrofit (which included the installation of external insulation panels, changing windows, between others) as part of this research. The houses are shown in Figure 1.

Figure 1. The 'no-fines' social houses.

The proposed approach for BIM adoption includes three aspects: (i) potential reduction in energy consumption; (ii) disruptions to the housing occupier and (iii) estimated costs. As a result, the solution addresses four questions:

- How to compare energy efficiency gains of different retrofit options using BIM?
- How to evaluate the disruption to the occupants caused by different retrofit options using BIM?
- How to compare the cost of different retrofit options using BIM?
- How provide simple and clear information for clients to select the most appropriate retrofit option based on the synthesis of the three aspects above?

The research was divided into four stages, following the steps suggested for DSR [47]: (a) define the problem; (b) plan the intervention; (c) implement the intervention and (d) evaluate it. As shown in Figure 2, the development of the BIM protocol was highly iterative, as is typical of DSR projects.

The retrofit project was carried out in four phases to enable analysis, learning and improvement between phases: Phase 1-A (House 6), Phase 1-B (houses 44 and 45), Phase 2 (houses 46 and 47), Phase 3 (houses 49 and 50), and Phase 4 (house 48). This paper reports on the final version of the BIM protocol, and presents data from house 6 as a case study. Activities developed at each phase (Figure 2) included:

- Phase 1A: involved a deep understanding of the research problem, and the development of simulations for 1 retrofit scenario. Data was collected via a set of visits to the houses, participation on project meetings and two interviews with tenants. These provided the information needed to develop 3D models and it helped in identifying expectations by tenants. The team also selected the software to support the energy, costs and 4D simulations in this phase. The outcome was an initial version of the protocol, which was presented to the project team for a preliminary validation.
- Phase 1B: focused on the 4D for identifying disruptive activities as part of the retrofit plan. Disruption types were identified according to the literature, the 4D modelling process was simulated for 2 further scenarios, and potential links between the 4D and the last planner system of production planning and control were investigated—please see results of this specific element of the research in Chaves et al. [44]. Data was collected through participant observation in three planning meetings, two structured interviews, two semi-structured interviews and document analysis. At the end of this phase, the second version of the BIM Protocol was produced.

- Phase 2: the phase started with adjustments to the level of detail of modelling for simulations. Three scenarios were modelled and an interactive cycle of data collection, analysis and presentation of results to the project team took place. The first version of the what-if scenario matrix was developed. The main sources of evidence were participant observation in three planning meetings, and direct observation in three site visits. By the end of phase 2, the third version of the BIM Protocol was delivered.
- Phase 3–4: this involved a full revision of the BIM protocol and the refinement of the simulations developed. Further data was collected through 2 semi-structured interviews, in which the protocol was presented and feedback gathered. The final BIM protocol was presented in two workshops, one to the project team, and the second involved members from 6 other housing associations from the UK.

The final BIM protocol is presented as follows, and the results of the simulations performed for one case study (house 6) are presented in Section 5.

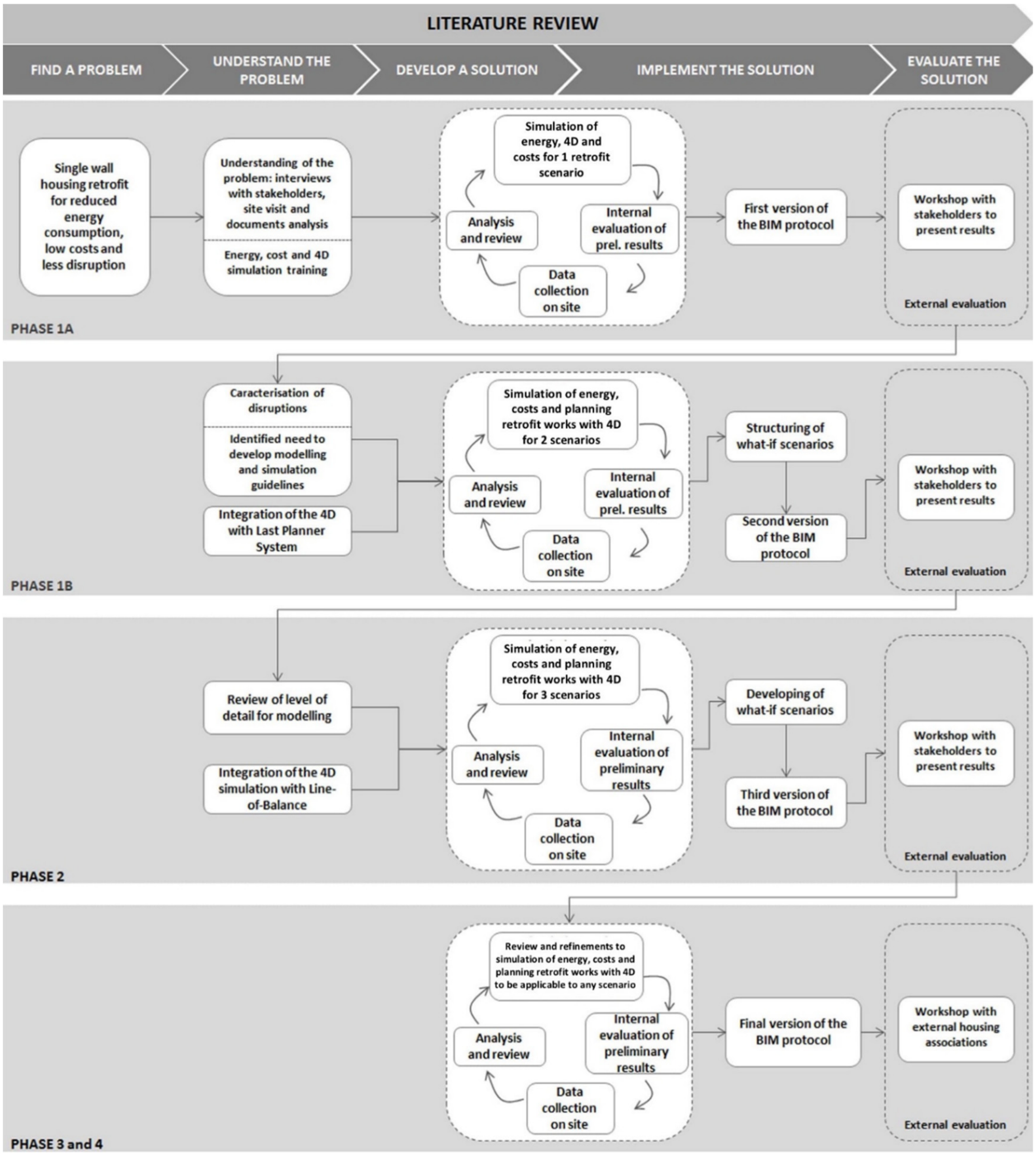


Figure 2. Overview of the research design.

4. BIM Protocol

The protocol starts with a housing stock and the definition of the intended performance specification for the retrofit. Following, there is a need to produce a 3D model for the existing housing, and a number of sources of information can be used for this, e.g., existing drawings or measurements of the houses, existing energy performance if available, existing energy costs, between others. The developed model then goes through a quality assurance test. The next step involves the definition of the scenarios, or retrofit options, for simulation. Following, simulations for energy consumption, disruption and costs are performed for each scenario, as follows:

1. based on the house survey and interviews or discussions with clients, retrofit options are proposed, and the energy consumptions are estimated through energy simulations
2. based on the retrofit options, construction plans are proposed. Possible disruptions to the occupiers can then be identified and quantified
3. based on the retrofit options and the construction plans, the construction cost is estimated for each proposed scenario
4. finally, the energy consumption, the disruption to users, and the cost are incorporated in a multi-criteria decision making matrix which enables the client to select the most appropriate retrofit option, considering the effectiveness of each option as per BIM simulation results.

Each of these elements are further described as follows. The final BIM protocol (Figure 3) also contains activities to be developed during construction, which are not detailed in this paper, and include the potential for monitoring real energy consumption after retrofit. All simulations can be produced using readily available software, which makes the practical application of the protocol easier to be achieved.

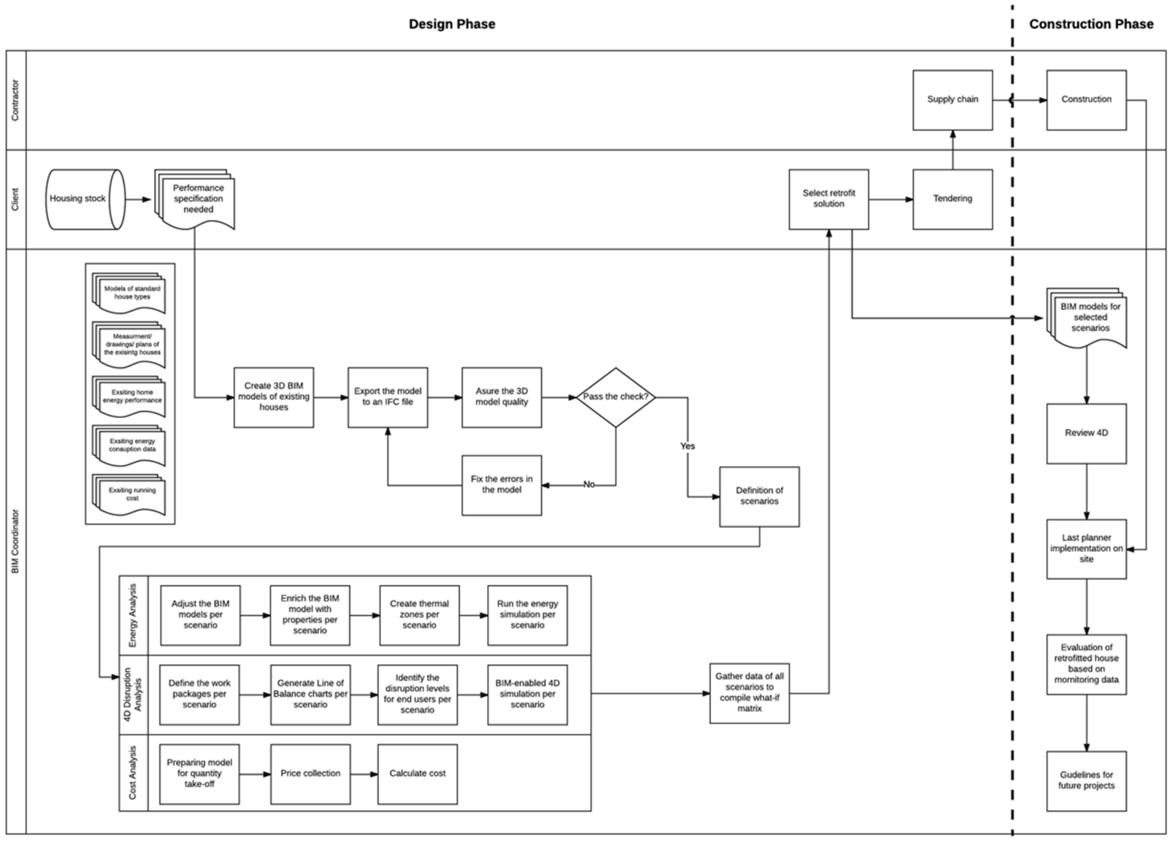


Figure 3. The BIM protocol.

4.1. BIM-Enabled Energy Analysis of Retrofit Options

The development of housing retrofit options requires spatial and dimensional measurement of the building and diagnosis of its existing energy performance. Clients usually request a house survey to collect the spatial and dimensional data. If available, 2D CAD drawings can be used to generate 3D geometrical models of the existing houses [49]; 3D laser scanning is another way to capture the 'as-is' state of a building rapidly and can be used to reconstruct the 3D model of the building [50]; manual measurements are required if none of these can be done.

The process of determining the energy performance of a house can be supported by estimating the houses' monthly and annual purchased energy and gas consumption or gas bills. The energy performance of a house is related to the installed types of boilers, heaters, window glazing, etc. The thermal condition of the building can also be assessed by infrared thermal imaging [51], if available.

Based on the 3D model and the existing energy performance, technical retrofit options can be proposed, considering various alternatives, e.g., different external insulation options, changing windows to double or triple glazing, etc. Each retrofit option should be encapsulated in a BIM model, which defines the location of the house (latitude, longitude, altitude, and project north angle), local climate information (weather, wind protection and surface heat transfer), building envelope components, lighting system, cooling and heating systems (nominal capacity). Energy consumption of a building is usually simulated based on its thermal blocks, which consist of spatial zones. These zones need to be defined by modelling the space object typology, to be further used in energy evaluations. The type, material and thickness of layers of the building elements contained in the model also should be specified during the architectural phase. The model should also be enriched by adding energy-related properties to the objects, such as heat transfer coefficients, i.e., Heat Transfer Coefficient (U)-values, which measure how effective elements of a building's fabric are as insulators. This type of properties should be specified for materials, components and products, of which different solutions consist.

In the UK, the Standard Assessment Procedure (SAP) is a method used by the Government to assess and compare the energy and environmental performance of dwellings [52]. It includes generic U-values. While design calculations in SAP are theoretical; on-site measurements can be undertaken. Thermal transmittance calculations can be carried out using a heat flux meter. This consists of a thermopile sensor that is firmly fixed to the test area, to monitor the heat flow from inside to outside [53]. Thermal transmittance is derived from dividing average heat flux (flow) by average temperature difference (between inside and outside) over a continuous period of about two weeks (or over a year in the case of a ground floor slab, due to heat storage in the ground). The measured U-Values of the houses may vary remarkably, even for houses on the same estate and built under very similar conditions [54]. This directly influences the accuracy of the energy simulation results, so it would be essential to identify a U-Value which would be representative of the houses under retrofit, whenever possible. Finally, the housing energy sources, the associated costs and their influence on the environment need to be considered for the energy consumption calculation, so that retrofit options can be analysed.

4.2. BIM-Enabled Disruption Analysis of Retrofit Plans

Retrofit tasks vary from project to project, and can involve: (a) replacing the existing windows and doors; (b) strengthening the existing loft insulation layer; (c) insulating the external walls and (d) replacing the heating system to improve energy efficiency, between others.

Initially, a master plan should be defined including the retrofit work packages and dependencies. The traditional retrofit planning process is based on the Critical Path Method, which includes master planning and work breakdown definitions. The master plan can be used to develop a 4D BIM simulation. Temporary elements of the construction site, such as scaffoldings, will be incorporated in the virtual model, as is shown in Figure 4. The 4D BIM simulation of the retrofit work is different from a simulation of new construction, as some building elements need to be removed, such as windows and doors, and be replaced by new ones. Other new elements such as external wall insulation, gutters, eaves, downspout, and ventilation systems will vary according to the technical scenario under investigation.

Figure 4. Modelling the scaffolding.

To have a better visualisation of the 4D simulation, special visualisation adjustments of the BIM elements are needed. For example:

- Scaffolding: to ensure the visibility of the external wall, scaffolding should be transparent after installation on site;
- Roof: to ensure the visibility of the internal activities, roof or any other objects that may cause occlusion should be transparent;
- General objects: objects can be highlighted using a different colour if the associated activities require attention during the execution.

A very detailed model makes visualisation of the sequence of activities difficult. There is a risk of having too much detail, which makes the information overwhelming. For example, the work packages defined include several steps of fitting parts of one heating system in sequence. However, it is not necessary to divide one object into parts and model each part separately to match the work packages. It is suggested that the level of development (LOD) of the 3D BIM models to support planning should be LOD 200 [55]. A detailed description of the use of 4D BIM modelling in retrofit work can be found in another research paper [56].

A list of disruptions that may be caused by the retrofit work has been developed by the information gathered from the literature [56] as well as results from interviews and questionnaires. The retrofit work may affect the continuity of gas supply, electricity supply, and water supply when the workers upgrade the building systems, such as heating and ventilation. It may block or limit the access of residents when the workers replace the external doors and renovate the lobby. It may affect the daily life of the residents such as studying, cooking, and taking a nap when the workers change the windows and other internal works, which requires that the residents and the workers share the space. It may generate different levels of noise pollution when the workers remove the façade using tools like hammers and mallets; it may generate different kinds of waste such as dust and debris when the workers perform the internal work and rendering.

The disruption types were further classified into different levels, which are shown in three different colours in Figure 5. The figure provides a simple visual representation of the disruptions. (a) High-level disruption activities are shown in red. They tend to be executed inside the houses or cause interruptions in everyday life or building services provision. (b) Medium level disruption activities are shown in orange. They usually have a long duration, potential to block access temporarily to part of the house and services or can cause excessive dust. (c) Low-level disruption activities are shown in yellow. They usually take place outside the houses.

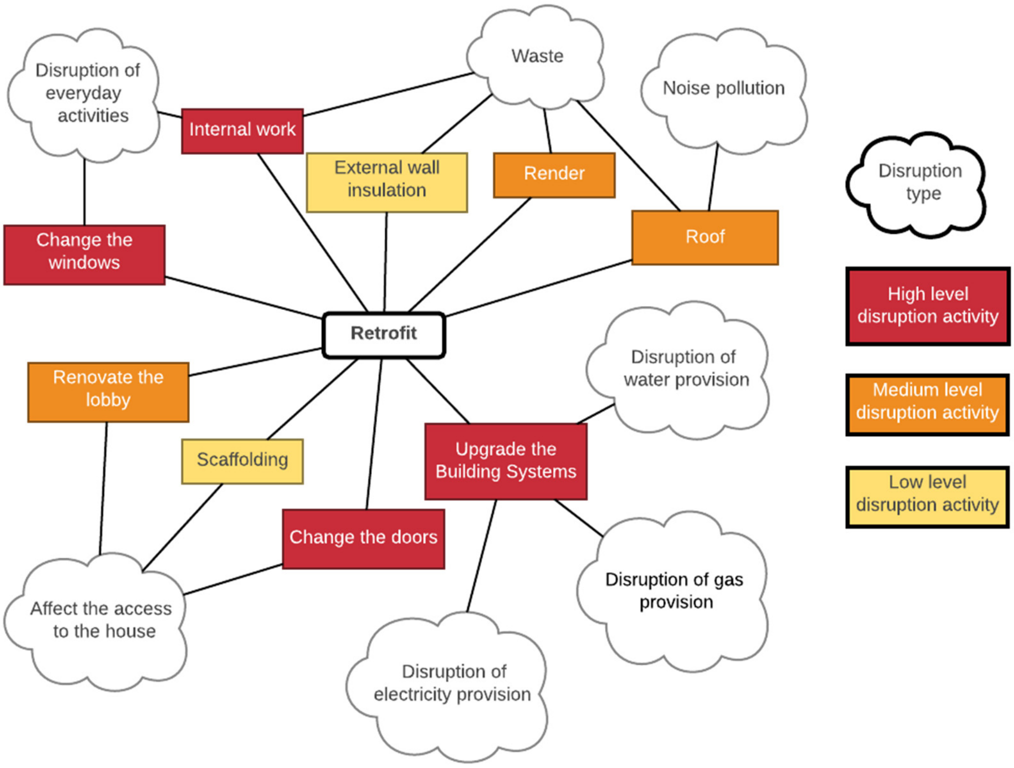


Figure 5. Retrofit activities that cause disruptions.

To associate the disruption to the retrofit work packages, the Line of Balance (LoB) was adopted. LoB is used to assign the disruption levels to the activities according to their duration, resource needs as well as location. As such, it provides an easy way to calculate the total number of disruption days for a determined retrofit scenario. Furthermore, replacement/installation in these work packages results in the trades' occupancy of a specific work area in the houses. LoB is a powerful way to represent such occupancy, so it facilitates the identification of disruptions to the house occupants. Figure 4 presents disruptions identified in this research, classified according to its level of severity (for further details, see Chaves et al. [56]).

4.3. BIM-Enabled Cost Estimate of Retrofit Work

One of the advantages of using BIM in cost estimation is that it can automate the quantity take-off, which requires much more effort if performed by a manual process. Many quantity extraction algorithms can be used to analyse the model geometry and to extract the appropriate element quantities, which results in a set of take-off quantities per take-off item.

The building blocks of a cost estimate are the components and assemblies which make up the bill of materials. The hierarchical structure of the cost estimate can be derived from a BIM model. Every line item (Assembly) can be further refined with additional Components, providing flexibility, and enabling the estimator to gradually develop the cost plan from a basic abstract level to a highly-detailed cost estimate.

Alternatively, the line items can be organised in an Excel spreadsheet. Source quantity, consumption, waste/factor and unit cost can be added to the spreadsheet. Any existing government incentives or subsidies available do need to be considered as part of the cost estimations.

4.4. What-If Analysis

The selection of the best retrofit plan should consider the energy efficiency gains, construction disruptions, and costs. What-if analysis is used to support a multi-criteria decision-making process. It compares multiple scenarios using different criteria from the analysis carried out. A What-if matrix is created based on the results of the simulations of multiple retrofitting options. The results are aggregated into a single matrix to simplify comparison by the client, and to aid decision-making. The matrix aims to present a summary of all simulation results (scenarios for energy consumption, costs and disruption for users) as to facilitate clients (e.g., housing associations) to choose the most suitable option for the retrofit.

The following section presents a case study, which was used to support the development of the BIM protocol as an application for testing. The case study also supported the evaluation and refinement of the BIM protocol developed.

5. Case Study

A mid-terraced building (Figure 6) was selected to support the development of the BIM protocol. The house is located in Antrim, Northern Ireland. There were 2D plan drawings of the house available. Also, a site survey was performed to collect information about services, defects, and geometrical properties of the house. Some information is shown below. The outdoor temperature is usually between −6 °C and 26 °C.

Figure 6. 3D visualisation of the virtual building model, developed in Revit.

- The total floor area is 107 m^2.
- The annual energy consumption is 33,677 kWh.

The house included 16 closed spaces, each of which were considered as a thermal zone for the energy efficiency simulation. The U-values of the building elements were estimated, as is shown in Table 1.

Table 1. Building elements in the mid-terraced house.

Type	Description	Quantity	Heat Transfer Coefficient (U)
External Door	Solid core wood, wood storm 730 × 2135	1	1.6466 W/(m^2·K)
Door	Wood panel 730 × 2135	2	3.8042 W/(m^2·K)
Door	Hollow core wood 680 × 2135	6	3.1796 W/(m^2·K)
Door	Hollow core wood 730 × 2135	5	3.1796 W/(m^2·K)
Floor	Wood joists + Oak Flooring	142 m^2	0.1228 W/(m^2·K)
Floor	Concrete cast-in-place Oak Flooring	62 m^2	3.3589 W/(m^2·K)
Roof	Wood tile	72 m^2	6.9000 W/(m^2·K)
Roof	Wood asphalt	5 m^2	25.0000 W/(m^2·K)
Wall	Brick + 10 mm gypsum plaster	94 m^2	6.1150 W/(m^2·K)
Wall	Brick + 30 mm gypsum plaster	7 m^2	4.6988 W/(m^2·K)
Wall	No-fines cast-in-place	168 m^2	3.7391 W/(m^2·K)
Window	6 mm single glazing 915 × 1220	6	3.6886 W/(m^2·K)
Window	6 mm single glazing 610 × 610	1	6.7018 W/(m^2·K)

According to the energy simulation, the Energy Use Intensity (EUI) of this house was 1464 MJ/m^2/year, and the annual energy cost is about £1475.

Each simulation involved a specific modelling activity, as described in the protocol presented on Figure 3. The generic BIM model of the existing building had to be adapted to the needs of each specific simulation, e.g., thermal zones were determined to enable the energy simulation to take place and construction activities were modelled to enable the 4D to be produced. The simulations were developed considering the retrofit materials and construction activities needed for each one of the scenarios proposed. Hence, diverse information had to be included on the models, to enable appropriate simulation of each scenario to take place.

5.1. Energy Simulations of Three Retrofit Options

Three retrofit scenarios were proposed in discussions with the housing association, as well as with the support of industrial partners involved in the research. Such industrial partners provided information regarding alternative insulation materials, which were used to determine alternative retrofit scenarios. These are described below.

5.1.1. Scenario 1

The first scenario consisted of using a new heating system and changing building elements, as follows:

- Use of a Dynamic External Wall Insulation, the U-value of which is 0.13 (as proposed by one supplier/industrial partner)
- Windows would be changed from the existing single glazing to double glazing.
- Roof insulation would be changed to use Wood Rafter 184 mm—Asphalt Shingles
- Internal doors would be changed from hollow core wood ones to wood storm ones
- The boiler uses the Ideal Logic system which has a seasonal efficiency of 89.6%, i.e., 11.4% of fuel used does not contribute to heating demand.

The specification of these changes is shown in Table 2.

Table 2. Material specification of changes in scenario 1.

Type	Description	Quantity	Heat Transfer Coefficient (U)
Door	Door-wood-hollow core-wood storm	6	1.8737 W/(m^2·K)
Door	Door-wood-hollow core-wood storm	5	1.8737 W/(m^2·K)
Roof	Wood Rafter 184 mm-Asphalt Shingles	72 m^2	0.1016 W/(m^2·K)
Wall	Dynamic External Wall Insulation	168 m^2	0.1311 W/(m^2·K)
Wall	Interior-79 mm Partition (1 h)	94 m^2	0.5752 W/(m^2·K)
Window	6 mm double glazing	6	1.9873 W/(m^2·K)

The energy consumption simulation showed that the EUI of scenario 1 was 742.1 MJ/m^2/year, and the annual energy cost was predicted to be £710.

5.1.2. Scenario 2

The second scenario defined consisted the following changes:

- Roof insulation uses Wood Rafter 184 mm—Asphalt Shingles (same as scenario 1);
- Windows use Low-E double glazing glass;
- Same Boiler as used in Scenario 1: Ideal Logic system 89.6% efficient;
- Internal doors changed to solid core wood ones.
- Use of a multiple block layer on the external walls.

The detailed specification of the changes is shown in Table 3.

Table 3. Material specification of changes in scenario 2.

Type	Description	Quantity	Heat Transfer Coefficient (U)
Door	Solid core wood, wood storm	6	1.6466 W/(m^2·K)
Door	Solid core wood, wood storm	5	1.6466 W/(m^2·K)
Roof	Wood Rafter 184 mm	72 m^2	0.1016 W/(m^2·K)
Wall	Exterior-Block on Metal Stud partition (Mtl. Stud)	168 m^2	0.1106 W/(m^2·K)
Wall	Interior-79 mm Partition (1 h)	94 m^2	0.5752 W/(m^2·K)
Window	Low-E double glazing-domestic	6	2.2147 W/(m^2·K)

The energy consumption simulation showed that the EUI of scenario 2 was 796.0 MJ/m^2/year, and the annual energy cost was predicted to be £767.

5.1.3. Scenario 3

The third scenario defined consisted the following changes:

- Windows were changed to triple glazing (6 mm thick-clear/clear/low-E (e = 0.2) glass). The U-value was 1.5330 W/(m^2·K).
- The doors were the same as the ones in scenario 1.
- The boiler was the same as the one in scenario 1: Ideal Logic system 89.6% efficient
- Exterior insulation system for exterior walls, with a 75 mm layer.

The detailed specification of the changes is shown in Table 4.

Table 4. Material specification of changes in scenario 3.

Type	Description	Quantity	Heat Transfer Coefficient (U)
Door	Door-wood-hollow core-wood storm	6	1.8737 W/(m^2·K)
Door	Door-wood-hollow core-wood storm	5	1.8737 W/(m^2·K)
Roof	Wood Rafter 184 mm-Asphalt Shingles	72 m^2	0.1016 W/(m^2·K)
Wall	Exterior-EIFS on Mtl. Stud	168 m^2	0.0876 W/(m^2·K)
Wall	Interior-79 mm Partition (1-h)	94 m^2	0.5752 W/(m^2·K)
Window	Double glazing-6 mm-clear/low-E	1	1.9873 W/(m^2·K)
Window	Triple glazing-6 mm thick	6	1.5330 W/(m^2·K)

The energy consumption simulation showed that the EUI of scenario 3 was 779.3 MJ/m^2/year, and the annual energy cost was predicted to be £750.

The three simulation results are compared in Table 5. Scenario 1 has the least energy consumption.

Table 5. Energy simulation results of the three scenarios.

Scenario	Energy Use Intensity (MJ/m^2/Year)	Annual Energy Cost (£)
1	742.1	710
2	796.0	767
3	779.3	750

5.2. Disruption Analysis of the Retrofit Plans

The proposed three retrofit scenarios required different construction activities. These were defined on plans devised using MS project, simulated in 4D BIM, and also evaluated through the use of the LoB. Different disruptions have been identified and classified, as shown in Figure 7.

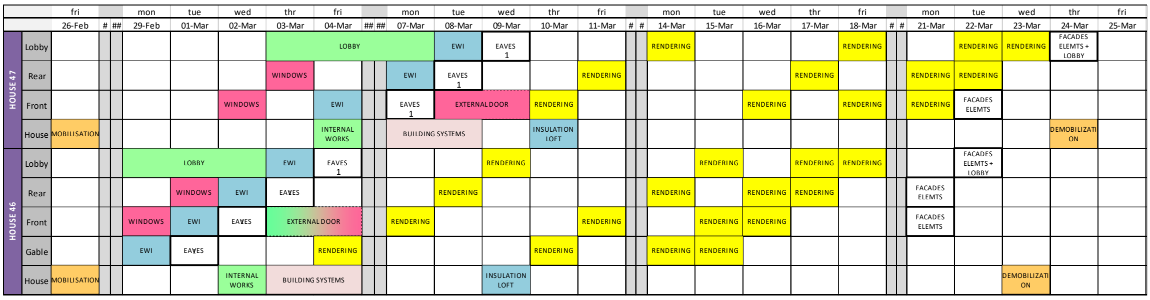
Disruption Level	Work Packages
	Windows, external door, internal works, loft insulation, building services
	Lobby, render, facade element
	Mobilisation, external wall insulation, eaves, demobilisation
	WIP (no activities developed in the production batch)

Figure 7. Levels of disruption of work packages (see Chaves et al. [56] for further details).

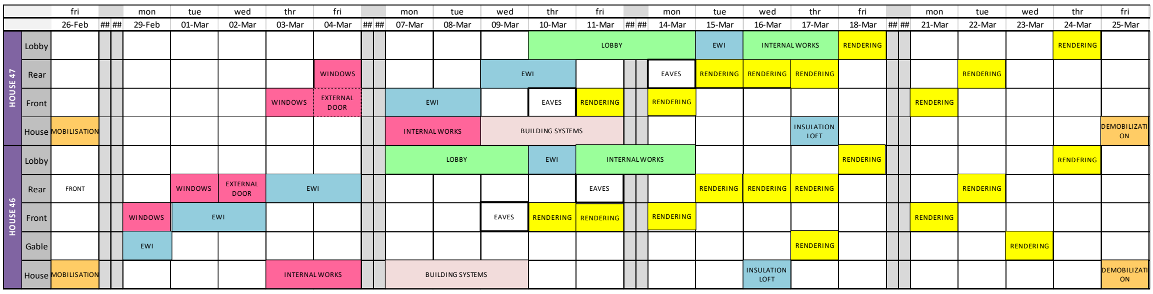
The traffic light model provides a simple visual representation of disruption:

a. red level activities are the most disruptive ones for the users, and tend to be executed inside the houses or cause interruptions in everyday life or building services provision
b. orange level activities have a medium level of disruption, e.g., activities that have a long duration, potential to block access temporarily to part of the house and/or services or can cause excessive dust
c. yellow level activities have a low level of disruption, such as activities that take place outside the houses
d. light green activities are work in progress (WIP). WIP was considered as a disruption to users, as they perceive it as a waste of time—for example, days in which no activity is being carried out. The activities defined in the LOB will be assigned with different disruption levels.

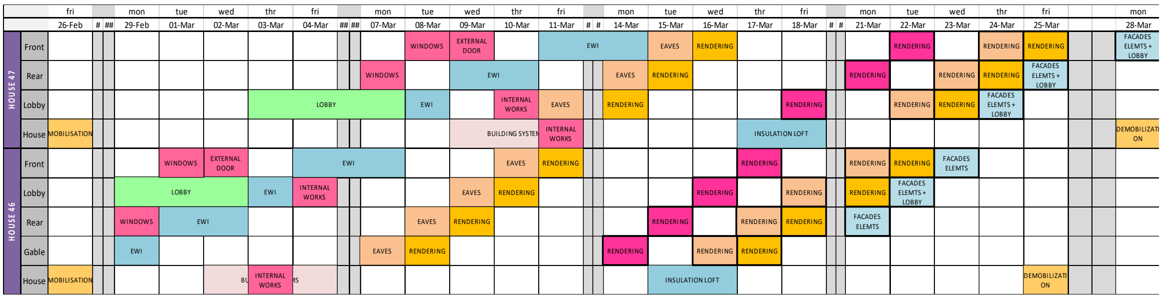
Figure 8 shows the three line of balance (LoB) charts that were compiled based on the work packages defined for the different scenarios, while in Figure 9 the work packages defined for each scenario are presented. Information provided in LoB includes: (a) the disruption levels of the activities that are coloured according to Figure 6; (b) duration and rhythm of activities; (c) the daily crew locations (inner, rear, front and top of the houses); (d) interferences between crews; (e) overlapping days of disruptive activities inside the house and (f) the total duration of the retrofit project.



(**a**) Scenario 1

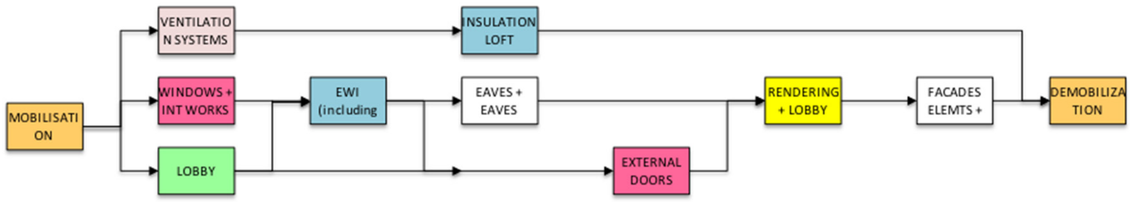


(**b**) Scenario 2

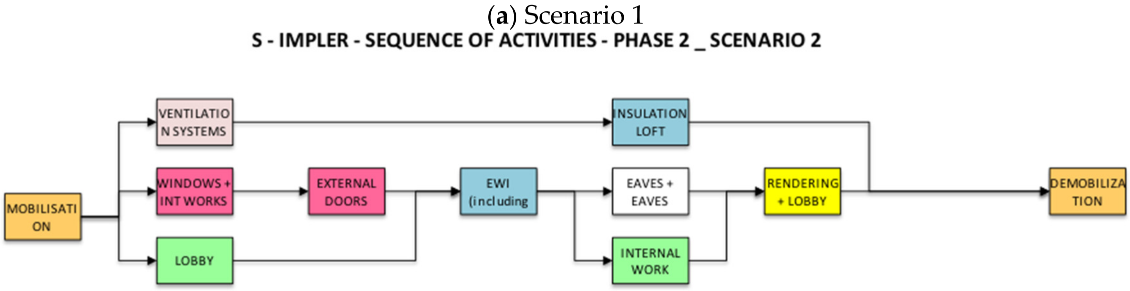


(**c**) Scenario 3

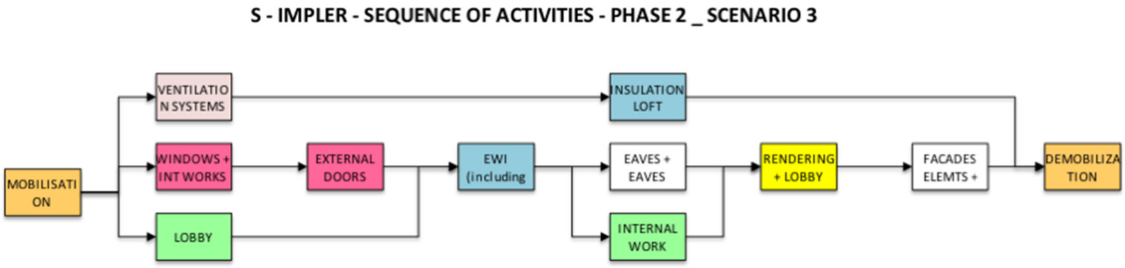
Figure 8. Line of balance charts of the three scenarios.



(**a**) Scenario 1



(**b**) Scenario 2



(**c**) Scenario 3

Figure 9. Work packages defined for each scenario.

If activities with different disruption levels are performed on the same day, the level of disruption of that day is considered as the highest one among the disruption levels of all activities. Table 6 shows a summary of the result: (a) the total duration of the project; (b) the number of days that have high disrupting activities; (c) the number of days that have medium disrupting activities but no high-level disruption activity and (d) the number of days that only have low disruption activities.

Table 6. Summary of the three scenarios for house 6.

Disruption Scenarios Comparison			
	Scenario 1	Scenario 2	Scenario 3
Total duration	20 days	21 days	22 days
User's disruption–internal works (Red) (External door, internal works, building systems, and loft insulation)	7 days	9 days	7 days
Number of work packages in simulation	12	11	12
Number of tasks	75	60	77
Days of work in progress	47	56	53

In this context, scenario 2 has the worse disruption to the occupant, while scenario 1 was considered to be the most effective, as it results in the smaller number of disruptive days. Further details on the 4D and disruption elements of this research can be found on Chaves et al. [56].

5.3. Cost Estimate

The unit price of the retrofit work packages was proposed by the contractor. The quantity of the model changes was derived, and the total costs of the retrofitting work were aggregated, as shown in Tables 7–9. Each scenario has a diverse cost due to specific costs of each of the materials (e.g., external insulation panels, windows, etc.) used on each scenario.

Table 7. Retrofit cost in scenario 1.

Component	Description	Quantity	Price per Unit
Door	Door wood-hollow core-wood storm	6	£530
Door	Door-wood-hollow core-wood storm	5	£490
Roof	Wood Rafter 184 mm-Asphalt Shingles	72 m^2	£15/m^2
Wall	Exterior-EIFS on Mtl. Stud	168 m^2	£15/m^2
Wall	Interior-79 mm Partition (1 h)	94 m^2	£9/m^2
Window	Double glazing-6 mm-blue-green/low-E (e = 0.05)	6	£380
	Total Cost for Scenario 1		**£12,356**

Table 8. Retrofit cost in scenario 2.

Component	Description	Quantity	Price per Unit
Door	Solid core wood, wood storm	6	£570
Door	Solid core wood, wood storm	5	£520
Roof	Wood Rafter 184 mm-Asphalt Shingles	72 m^2	£15/m^2
Wall	Exterior-Block on Mtl. Stud	168 m^2	£12/m^2
Wall	Interior–79 mm Partition (1 h)	94 m^2	£9/m^2
Window	Low-E double glazing-domestic	6	£360
	Total Cost for Scenario 2		**£12,122**

Table 9. Retrofit cost in scenario 3.

Component	Description	Quantity	Price per Unit
Door	Door-wood-hollow core-wood storm	6	£530
Door	Door-wood-hollow core-wood storm	5	£490
Roof	Wood Rafter 184 mm-Asphalt Shingles	72 m^2	£15/m^2
Wall	Exterior-EIFS on Mtl. Stud	168 m^2	£15/m^2
Wall	Interior-79 mm Partition (1 h)	94 m^2	£9/m^2
Window	Double glazing-6 mm thick-clear/low-E (e = 0.1)	1	£380
Window	Triple glazing-6 mm thick-clear/clear/low-E	6	£430
	Total Cost for Scenario 3		**£13,036**

5.4. What-If Analysis

A What-if matrix was created based on the results of the simulations of the retrofitting options. Energy consumption simulation, 4D disruption simulation and cost analysis provided three different angles to evaluate each retrofitting solution. The results were aggregated into a single matrix to simplify comparison by the client, and to aid decision making.

The what-if matrix of this case study is shown in Table 10. In its use, for instance, a housing association who wants to achieve the most energy consumption improvement may be willing to pay more and to let housing users/occupiers suffer a higher level of disruption during the construction works. The solution that is highlighted in Table 10 presents the best balance in all the three aspects. It has the most energy efficiency gain, it is not the cheapest option, but it has almost the minimum disruption to the occupants.

Table 10. What-if analysis in S-IMPLER.

		Energy Consumption								
		Scenario 1			**Scenario 2**			**Scenario 3**		
		Energy Savings	**4D Disruption**	**Cost Estimation**	**Energy Savings**	**4D Disruption**	**Cost Estimation**	**Energy Savings**	**4D Disruption**	**Cost Estimation**
4D Disruptions	Scenario 1	49.3%	20 days	£12,356	45.6%	20 days	£12,122	46.8%	20 days	£13,036
	Scenario 2	49.3%	21 days	£12,356	45.6%	21 days	£12,122	46.8%	21 days	£13,036
	Scenario 3	49.3%	22 days	£12,356	45.6%	22 days	£12,122	46.8%	22 days	£13,036
		Scenario 1			Scenario 2			Scenario 3		
		5D Costs Estimation								

6. Conclusions

The main contribution of this research is the development of recommendations describing the steps to be undertaken by decision makers in evaluating retrofit scenarios for social housing. The BIM Protocol describes these recommendations, and provides the means and tools to use simulation to support the decision-making when choosing the most appropriate social housing retrofit solution, delivering energy improvements at reduced levels of disruption to users and enabling cost reductions. The BIM protocol was developed and evaluated through a case study of a no-fine social house, with the direct involvement of the research team, the construction team, tenants and the client i.e., housing association. The use of readily available BIM tools as part of the protocol aims to ensure it can be easily adopted in practice.

During design, the protocol enables the evaluation of the most effective retrofit solution for energy efficiency considering costs and potential levels of disruption of alternative technical retrofit solutions. During the construction process, it enables the identification and evaluation of different project execution plans and aligns the use of 4D BIM with the Last Planner System and the Line of Balance to support production planning and control. A what-if analysis matrix has been proposed to enable an easy evaluation of the performance of retrofit options, supporting clients' decision making.

A contribution of the research is that all three elements (energy, disruption and costs) are considered in an integrated fashion. Further benefits relate to the capabilities provided to clients through the BIM protocol: (a) evaluation of alternative technical solutions with regards to their energy efficiency gains. This involves the use of readily available BIM software to deliver simulations for each alternative solution; (b) evaluation of alternative technical solutions with regards to their costs. One of the aims of the project was the identification of cost-effective retrofit alternatives and the BIM protocol enables the evaluation of costs of alternative solutions and (c) evaluation of alternative technical solutions with regards to the construction process on site and the potential disruption caused to house users/occupiers during construction. 4D modelling and line of balance are used to identify how disruptive each alternative is from the housing users' perspective (presented as disruption-days). The identification and characterisation of disruption is a theoretical contribution of the work, which can result in higher satisfaction with the retrofit process by housing occupiers. The three elements can be evaluated side by side by social housing providers, and as such enable a better-informed decision-making process.

One area for further work is the extended consideration of the impact of energy savings over the remaining life cycle of the houses, which was also identified by [57,58]. It is further suggested that the proposed protocol should be explored in different project contexts to further verify its broader applicability.

The simulations provide a good overview of the potential savings in energy consumption and costs of diverse retrofit technical solutions for solid walled social homes. Results also demonstrate that the development of 4D models supports a better understanding of the retrofitting process alternatives as well as the construction process on site. The 4D models are helpful for communicating the construction programme to clients and valuable to enable the visualisation of aspects related to site logistics such as material storage, scaffolding position, and users' access. It is an important tool to identify disruptions related to the existing site conditions, and used in conjunction with the LoB it provides a clear way to measure disruption/days of alternative technical solutions.

Author Contributions: Conceptualization, P.T. and L.K.; methodology, P.T. and L.K.; modelling and first manuscript draft L.M. and J.S.J.; writing—original draft preparation, all authors; writing—review and editing, P.T. and J.S.J.; project administration, P.T.; funding acquisition, P.T. and L.K.

Funding: This research was funded by Innovate UK grant number 101615aAnd The APC was funded by the University of Huddersfield.

Acknowledgments: The authors would like thank Innovate UK, Coordination for the Improvement of Higher Education Personnel (CAPES), Brazil, and National Council for Scientific and Technological Development (CNPq), Brazil, for the financial support received. In addition, we would like to thank the wider S-impler project team for their direct contributions to this investigation. We would also like to thank Arto Kiviniemi, Carlos Formoso, Julie Comlay, Sérgio Kemmer, Fernanda Chaves and Clarissa Biotto, who provided diverse insights, inputs and contributions to the research.

Conflicts of Interest: The authors declare no conflict of interest.

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