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Article

Requirements of Integrated Design Teams While Evaluating Advanced Energy Retrofit Design Options in Immersive Virtual Environments

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Abstract: One of the significant ways to save energy use in buildings is to implement advanced energy retrofits in existing buildings. Improving energy performance of buildings through advanced energy retrofitting requires a clear understanding of the cost and energy implications of design alternatives from various engineering disciplines when different retrofit options are considered. The communication of retrofit design alternatives and their energy implications is essential in the decision-making process, as it affects the final retrofit selections and hence the energy efficiency of the retrofitted buildings. The objective of the research presented here was to identify a generic list of information requirements that are needed to be shared and collectively analyzed by integrated design teams during advanced energy retrofit design review meetings held in immersive settings. While identifying such requirements, the authors used an immersive environment based iterative requirements elicitation approach. The technology was used as a means to better identify the information requirements of integrated design teams to be analyzed as a group. This paper provides findings on information requirements of integrated design teams when evaluating retrofit options in immersive virtual environments. The information requirements were identified through interactions with sixteen experts in design and energy modeling domain, and validated with another group of participants consisting of six design experts who were experienced in integrated design processes. Industry practitioners can use the findings in deciding on what information to share with integrated design team members during design review meetings that utilize immersive virtual environments.

Keywords: building information modeling (BIM); immersive visualization; energy efficiency; retrofit; virtual models

1. Introduction

Residential and commercial buildings take about 40% of total energy consumption in the U.S. currently, and the number is expected to keep climbing in the next decades [1]. Practices to achieve better energy efficiency in buildings have gained acceptance in the industry, and evidence of this is the wide adoption and rapid growth of Leadership in Energy and Environmental Design (LEED) practices [2]. However, energy efficiency in new construction alone will not mitigate the growing energy demand of the building sector because more than 90% of all the U.S. buildings were constructed prior to 1990 [3]. Therefore, various retrofit options are being implemented in order to achieve a significant reduction in the energy demand.

Energy retrofitting refers to adding new systems and technologies to old facilities to improve the energy performance, and it is being performed at different levels, such as standard energy retrofits (referring to the replacement of components in systems rather than a holistic replacement) and deep energy retrofits (referring to an integrated approach to replace systems and building envelope through whole building analysis) [4]. Through such retrofits, it is possible to reduce energy use in buildings, in the order of 25% (through regular building commissioning) to more than 50% (through deep retrofits) [4].

As compared to the traditional design process, applying the integrated design process (IDP) in advanced energy retrofit projects produce larger resource savings [4]. IDP is defined as "a collaborative process-oriented set of activities for identifying shared priorities and goals in an effort to build consensus amongst all members on the retrofit team" [5]. IDP is highly collaborative and iterative in nature and involves participation of various disciplines, such as architects, engineers, contractors and project managers since the inception of projects [4]. Therefore, an advanced energy retrofit project requires effective and efficient sharing of information among members from different disciplines in an integrated design group (IDG) in order to make wise decisions about selecting the right set of energy retrofit design options.

One of the challenges in the current practice of integrated design of energy retrofit projects is the large amount of data generated from various simulation tools and overwhelming analysis of such data [6]. Various building simulation tools are available to be used for energy modeling, airflow, day lighting, thermal analysis, *etc.*, for a range of design options. As different options for building envelopes and building systems are evaluated, their implications on energy use require updated simulation models and time-intensive interpretation of their results. Integrated design teams are buried under information while they put the generated documents side by side and evaluate each alternative [7]. It is a cognitive exercise for IDG members to interpret the information about different design options and their energy implications from tabular and graphical outputs generated from energy simulation models and link them to the design information.

Immersive virtual environments are representations of virtual worlds or scenes generated by a computer in forms that people can interact with and immerse into [8]. Such environments provide opportunities to advance communication among different stakeholders [9], to convey the essentials of alternative design options [10], and to reduce the time to reach consensus among stakeholders significantly [11,12]. An essential step for developing such immersive virtual environments to support energy efficient retrofit decision-making process is the identification of the information that IDG members would need to share and analyze while evaluating retrofit design options in such settings.

This paper provides a generic list of information requirements that are needed to be shared and collectively analyzed by integrated design teams during advanced energy retrofit design review meetings. These findings are based on a study conducted with IDG of a construction project that included advanced energy retrofitting of an existing facility. The authors had access to integrated design review meetings and interacted with various energy modeling experts, architects in the Architecture Engineering and Construction (AEC) industry for validation of the findings. While identifying such requirements, the authors used an immersive environment based iterative requirements elicitation approach. The technology was used as a means to better identify the information requirements of integrated design teams to be analyzed as a group.

2. Background Research

This study builds on the previous research studies that were conducted in relation to (a) the use of immersive virtual environments in AEC decision-making processes and (b) the identification of input parameters that play critical role in energy use in buildings.

2.1. Use of Immersive Virtual Environments in AEC Decision-Making Processes

The use of immersive virtual environments has been leveraged as a key to support complex decision processes inherent to the AEC domain. Virtual environments, described as synthetic, three-dimensional worlds, are perceived from the first-person point of view and are controlled in real-time by users. Immersive virtual environments essentially surround a user in space so that he/she feels immersed in the environment [13]. Cave automatic virtual environment (CAVE) is a typical immersive virtual environment, which has stereo images and multiple screens that allow users to visualize information in immersive and 3D settings. The use of virtual environments in immersive settings has already been applied and assessed in multiple studies related to the AEC industry, such as construction planning and scheduling review [9], multi-stakeholder decision-makings for design review [10,11,14,15], on-the-job-training (OJT) in the construction industry [16], education for construction management [17], and utilization for energy retrofit projects [18–20]. In these studies, it was found that immersive virtual environment is a better tool for communication among different stakeholders [9], enable better understanding of alternative design options [10], and has the unique advantage of grasping participants' attentions on a focused task and thus significantly reduces the time to reach consensus [11].

However, previous studies on the use of immersive virtual environment for improvement of energy retrofit projects are limited. This study provides the foundational knowledge on understanding the value of immersive virtual environments in decision-making process of selecting design options. The research presented in this paper targets the needs of having an understanding of what information needs to be considered collectively by IDG members while evaluating energy retrofit options in immersive virtual environments.

2.2. Identification of Input Parameters That Play Critical Role in Energy Use in Buildings

The input parameters to energy simulation models that have significant influence on energy simulation results are among the important information items to communicate among the IDG members. This section reviews previous research studies on identification of such input parameters for energy simulation models that have high impact on the overall energy use in buildings.

Previous research studies list hundreds of internal and external building input parameters and different assumptions required by simulation tools to estimate a building's total energy consumption [21]. With so many parameters, there is also an inherent uncertainty in the industry regarding which parameters IDG members would need to collectively convey to each other during design review meetings. Several research studies approached this problem from a different angle and focused on identification of energy simulation parameters that have the greatest impact on a building's energy usage and cost; hence the parameters to which the total energy use is most sensitive. Such studies utilized sensitivity analyses and computational assessments, such as Monte Carlo simulations, to identify the parameters where the total energy use in buildings is most sensitive. Table 1 provides a synthesis of findings from such studies based on the typical information categories defined in energy simulation tools.

Table 1. Energy simulation input parameters that play key roles in total energy use in buildings.

Information Category	Sensitive BES * Parameters	References That Identified the Significance of the Parameters
Internal Gains	Occupancy (internal heat gain from people)	[22–24]
	Occupant behavior/schedules	[21,22,25–30]
	Equipment heat gains	[22,24,31]
	Lighting	[22,24,31–33]
Building Characteristics	Geometry and room size	[22]
Material Properties	Thermal resistance of exterior enclosure	[33–35]
HVAC Components	HVAC system (e.g., configuration, operational parameters, heating/cooling demand, schedule)	[29,31,32,35]
	HVAC thermal zones	[36]
	Auxiliary HVAC equipment (e.g., VAV, fan coils)	[31]
	Pump type	[33]
	Heat exchange efficiency	[26,33]
	Infiltration rate	[22]
	Ventilation and air flow	[22,26,29,33]
	Outdoor air fraction	[21]
	Setpoints	[21,22,24,28,29,33]
	Chiller parameters	[24]
Geographic Factors	Weather/climate data (Consider climate change)	[22,37–39]

Table 1. *Cont.*

Information Category	Sensitive BES * Parameters	References That Identified the Significance of the Parameters
Daylighting	Daylighting controls	[31,40]
	Illuminance, coverage, diffuse daylight, daylight autonomy, circadian stimulus, glazing area, view, and solar heat gain	[41]
Other	Embodied energy	[42]

* BES: Building energy simulation.

As shown in Table 1, the majority of the sources stressed the importance of internal gains, such as occupancy schedules, lighting schedules, occupancy rate/space, which are mainly assumptions about the spaces for which the design options are being evaluated [25,27,30]. Heating, Ventilating, Air Conditioning (HVAC) properties and components such as the airflow rate, set points, and pump type are all identified as key players in the expected energy performance of any building, whether it is a new construction or an advanced energy retrofit project. Additional factors such as geography, weather, and daylighting were also supported by numerous sensitivity studies to have a significant impact on the expected energy and cost savings of an advanced energy retrofit project. Illumination, daylight autonomy, and solar heat gain are only a few of the many daylighting parameters that are considered [41].

The synthesis of the literature review provided a point of departure for the research team to use during the initial phase of the requirements elicitation process. However, the related previous research studies have not differentiated whether all such information should be apparent to the IDG members when they utilize immersive virtual environments during design review meetings. The research presented in this paper focuses on the identification of information items that IDG members should collectively be aware of during design review meetings to finalize the selection of design options.

3. Challenges in Advanced Energy Retrofitting Process

During any retrofit projects, integrated design teams need to collect and analyze large volume of data, such as the climate, occupancy, infiltration, radiation, daylight penetration and distribution, orientation, and window count, and consider various options about possibility of reducing the plug loads, modifying the building envelopes, and upgrading/replacing existing HVAC systems [4]. Every party in the integrated design team has to propose possible solutions that meet the established goals and requirements from various perspectives (e.g., architectural, MEP systems and structural). They use various tools to analyze design options, such as energy simulation tools (e.g., EnergyPlus, eQuest, TRNSYS, DOE-2), computational fluid dynamics tools (e.g., FloVent, Autodesk Simulation CFD), day lighting analysis tools (e.g., Superlite, DOE-2, Radiance), and these tools generate a variety of documents. Table 2 shows some examples of the tasks performed by a set of IDG parties from different disciplines and the documents they usually generate. In integrated design meetings, the information contained in these voluminous documents need to be shared with parties from other disciplines, so that the team can collectively decide on the right design options. As shown in Table 2, even for a small set of tasks, there are various number of lengthy documents/reports generated and shared by the IDG members as part of the design development process.

Table 2. Examples of tasks for a set of parties involved in advanced energy retrofit projects and example set of documents they generate (a sample generated from Lee *et al.* [43]).

Party	Tasks	Documents Generated
Architect	- Generate architectural layouts based on established functional requirements - Define space interactions	- Drawings - Exterior perspective - Site development plan - Floor plans - Sections - Elevations
Mechanical Engineers	- Calculate initial loads based on collected weather, occupancy, massing data - Estimate preliminary equipment type and capacity using gross assumptions about other energy uses (lighting, *etc.*) - Defining space requirements for HVAC system and equipment types and capacities - Proposing alternative design for systems and equipment	- Plans - Layouts - Specifications - Energy simulation results
Lighting and Electrical Engineers	- Analyze form, function and activities for each space - Understand the proposed shading, glazing, fenestration, geometry and materials - Calculate sun angles and analyze effects of envelope - Define level of illumination and daylighting per space - Propose alternative lighting layouts	- Lighting layouts - Specifications - Daylighting simulation results - Solar analysis results
Structural Engineers	- Report structural system modifications and associated space changes - Develop design options for vertical and horizontal structural systems	- Structural drawings - Specifications - Engineering design simulation results

The document based nature of the shared information creates challenges for IDG members while they keep track of each design option and try to search and locate the information about energy implications of these options. These can be grouped under two.

3.1. Challenge to Keep Track of Various Design Options as Inputs to Different Simulation Tools

A design option is composed of a set of assumptions about the space, usage, occupancy, openings, material, *etc.* For instance, as a building enclosure, one design option could be steel framed walls, metal deck roof and double glazing windows, and another option could be ASHRAE-baseline insulated walls and roof, and triple glazing windows. These assumptions, such as the type of walls, roof and windows and properties of these components need to be used as inputs to energy simulation tools so that their implications on energy use can be quantified. However, there are a variety of energy simulation tools that use different assumptions of design options as inputs and it is challenging for integrated design teams to keep track of the information as it is voluminous and in the form of reports. A detailed study compared twenty different building energy simulation software in terms of their capabilities of representing eleven groups of information as inputs, such as the modeling features, zone loads, and building envelope characteristics [12]. The results showed that each software asks for a different set of information and only a small subset of these tools can represent the entire information identified as required input. Integrated design teams need to be aware of what assumptions are used as inputs while generating simulation reports, however it is quite an effort for them to go through the resulting reports, keep track of the assumptions and make a collective decision. Hence, there is a need to understand what information IDG members collectively should pay attention.

3.2. Challenge to Link the Simulation Assumptions with Space Information

There is an additional problem faced by IDG members when analyzing different simulation assumptions in relation to the physical spaces they belong to. When evaluating simulation results, it is important to know what assumptions are made in relation to building components and spaces in simulation models, how they change as spaces change and how the design options selected in each space affect overall energy consumption. Though currently there are various technologies that can be used to visualize building design options in 3D view, the challenge is that the resulting energy use information is still provided in reports, and not integrated with the visualization of design options. Simulation results are provided in tabular forms and they are linked with spaces using only space IDs. It is challenging for integrated design teams to compare the simulation results of various design options for a given retrofit project while keeping track of the building spaces and components they are associated with. Hence, there is a need for an environment where simulation results and assumptions can be linked to the corresponding space information.

4. Research and Validation Methods

The study presented in this paper utilized the design information and design review meetings held for the retrofitting of an old building, which would go a thorough energy retrofit process. The testbed building was a 30,000 ft^2 old building and was being converted to an office building with various meeting spaces, offices, research and monitoring labs. The case study project used in this research study provided examples and a real setting to conduct the requirements elicitation process in a structured way. The case project provided the data, documentation, energy simulation results, and design drawings to generate a real project setting while conducting the requirements elicitation. Regular design review meetings were held by the integrated design team during the design process. The integrated design team of the testbed project consisted of owner representatives, architects, engineers, environmental/energy/LEED experts, cost estimators, commissioning agents, and contractors.

The research methodology comprised of an iterative process of requirements elicitation [19]. The steps involved in the iterative process as shown in Figure 1 include (a) gathering information requirements, (b) creating the virtual mockup (or prototype) and displaying the mockup to elicit more requirements, and (c) conducting external validation via reaching out to a larger audience through surveys, distributing the mockup with an accompanying questionnaire, and finalizing the information requirements list.

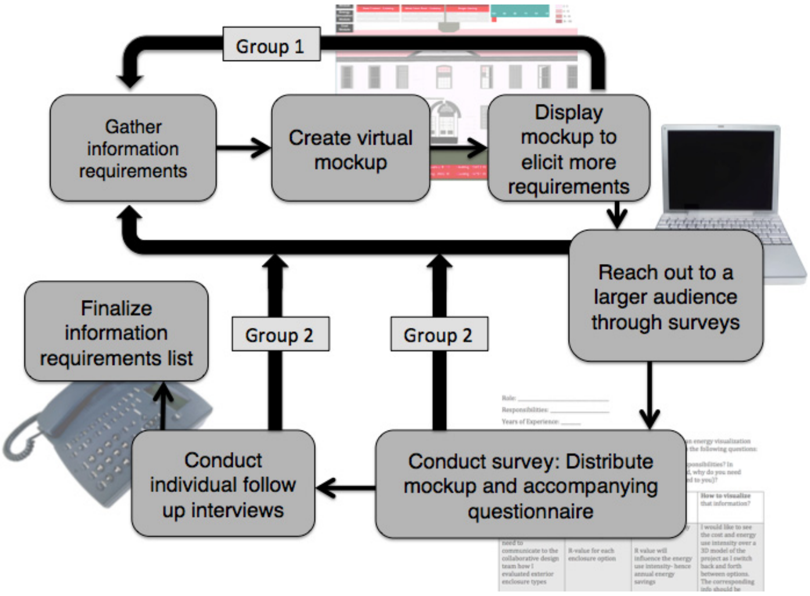

Figure 1. Steps of the iterative requirements elicitation process.

4.1. Gathering Information Requirements

In order to gather information requirements, the research team performed a detailed investigation of related literature. A literature review on identification of input parameters that play key role in overall building energy use was conducted and the findings are synthesized in Table 1. The findings of the literature review were used during the initial phases of the requirements elicitation process. This phase included an initial group of experts in the energy retrofit domain. Table 3 shows the participants of this research during the initial requirements identification phase as well as the validation phase. An overview of these participants is provided according to their profession or area of specialty as well as the range of the years of experience in their respective fields. Participants of the study in the first round of elicitation process were aptly named as Group 1.

Table 3. Participants involved in requirements elicitation and validation phases.

Title/Specialty	Group 1		Group 2	
	Number of Participants	Years of Experience	Number of Participants	Years of Experience
Architects	6	7–30	2	25
Energy Modeling Experts (EME)	4	4–32	4	4–15
Integrated Design Group (IDG) Members	6	7–32	–	–
–	**Total: 16**		**Total: 6**	

Group 1 that includes six architects, four energy modeling experts, and six IDG members working on the case building was engaged in this step in order to determine what parameters each expert considered valuable to be shared during design review meetings. The IDG team that participated in the study consisted of a representative from the architecture firm, a project manager, a construction manager, a building commissioning agent, a mechanical engineer and an electrical engineer. The research team attended design review meetings and watched previously captured videos of the team's group meetings to capture parameters that were frequently the topic of discussion and brainstormed with the group at the end of review meetings to capture requirements. The team also had face to face interviews and brainstorming sessions with additional energy modeling experts and architects to capture what information should be collectively shared in IDG meetings for effective evaluation of energy retrofit options.

In addition to this requirements elicitation phase, the research team reached out to various additional experts, who did not participate in the initial phase of the study, to generalize the findings. As shown in Table 3, the research team worked with six new participants who are experts in energy modeling and have participated in design review meetings in various other projects.

4.2. Creating the Virtual Mockup and Gathering More Requirements

Based on the feedback from the initial group of participants, a list of requirements has been identified. This list of requirements has been used to create a virtual mockup, *i.e.*, prototype of a 3D building model merged with the building energy parameters that can be visualized in immersive settings. The virtual prototype was created in a commercial virtual reality software due to its operability in 3D immersive environments, *i.e.*, the computer aided virtual environment (CAVE). The research team used CAVE equipment that was composed of three panel and three rear projections and goggles tracked by eight motion capture cameras.

To prepare the virtual mockup, first the 3D model of the baseline design of the case building was converted into a virtual model. Identified information requirements were merged into the virtual mock up through a variety of visual forms: (1)popup text: to display the thermal properties of building enclosure components; (2) color coded floor plan image: to display the layout for the thermal zones defined for the building; (3) color coded text annotation: to display assumptions such as the occupant numbers and heating/cooling loads associated with thermal zones; (4) highlighted buttons: to display design alternatives that were evaluated for building enclosure components; (5) color coded texture: to display *R*-values for the building enclosure components; and (6) animated sliding bar: to display Energy Usage Intensities, Initial Investment Costs and Annual Energy Savings for each design alternative, as detailed in [20]. The building energy information included in the mockup was derived from the actual results of a simulation performed in EnergyPlus by energy modeling experts.

The virtual mockup consisted of three modules, namely the navigation, energy simulation and the cost modules, as described below:

Navigation Module: Within the navigation module, the building owner and members of the design team could explore both the exterior and interior of the building through the 3D view. This module initially provided the information that Group 1 collectively articulated as important to see in a navigation mode in immersive settings. It also provided users the flexibility to view the assumptions of the baseline design's energy simulation model. These internal building energy parameters such as occupancy, lighting load, and infiltration were displayed in a color-coded banner at the bottom of the screen shot in Figure 2 and each space in the building was mapped with a different color. At any given point in time, the color of the banner corresponded to the color of the space that a person was in during the navigation in immersive settings. The information requirements in relation to heating, cooling and equipment loads, in addition to location, latitude and longitude, and climate were also included in each of the three modules. The color of the banner changed to match the color of the thermal zone marked on a color-coded floor plan that was visible in the bottom right corner.

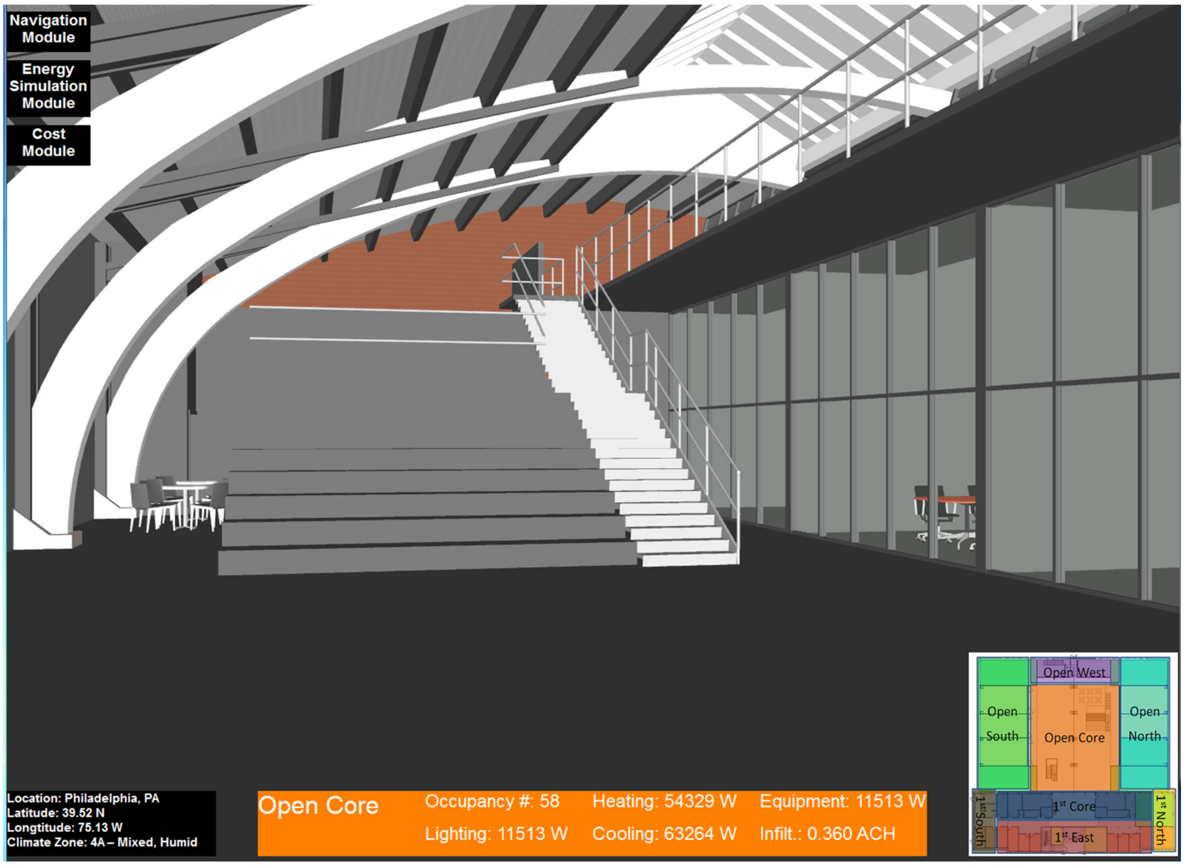

Figure 2. A snapshot of the Open Core space of the case building during a walkthrough within the building's interior space.

Energy Simulation Module: The information requirements displayed in the energy simulation module included *R*-values for each exterior enclosure option considered, as well as the energy usage intensity expected for a given design alternative. The energy simulation module allowed the IDG members to map energy simulation results to the space information as they pick and choose options for available building components using the highlighted buttons. This helped IDG members to better link the space information with the simulation results, as compared to the current practice of linking the two information through space IDs. As shown in Figure 3, the energy simulation module contains the *R*-value information of three building enclosure components, *i.e.*, the exterior walls, the roof, and the windows for which alternative design options were evaluated. The mockup contained three alternatives for each type of component, which corresponded to the options evaluated by the design team during the retrofit of that particular building and whose energy simulation models had been generated. As the participants selected from the possible alternatives, the energy usage intensity was updated and displayed on the slider scale on the view. A gradient red colored scale also updated the color of the building components as displayed on the 3D model based on the selected type of component's *R*-value. The *R*-value legend is located in the upper right-hand corner of Figure 3.

Figure 3. A snapshot from the virtual world while a user is in energy simulation module.

Cost Module: The cost module was created to meet the need for expected annual energy savings calculated for each possible design option. When the cost module was selected, the architects, engineers and project managers could simultaneously evaluate the cost implications of each design option under consideration. A second slider located underneath the energy usage intensity scale (as shown in Figure 3), conveyed the annual energy savings (in $ thousands) to the participants.

Through the use of this virtual mockup, participants both confirmed if the displayed information was among the information that should be collectively shared by IDG members during design review meetings and also articulated additional information they would like to add to the displayed set of information. The research team included such requirements in an iterative process to the mock-up.

4.3. Conducting External Validation and Finalizing the Requirements

The validation of the final set of information requirements displayed in the virtual mockup was performed through an external validation. External validation is used to determine if the information requirements deemed important by Group 1 hold true for a different group of experts, namely Group 2. During this validation phase, the generality of the information requirements that IDG members would like to convey in immersive and interactive settings were validated. The purpose was to identify a set of information requirements that are generic enough for different IDG members that are involved in advanced energy retrofitting of other buildings.

In order to conduct the validation, we reached out to a larger audience through surveys, and face to face questionnaires that were accompanied by a video of the virtual mockup. The virtual mockup that incorporates the final list of requirements obtained through 16 participants was the version distributed through email correspondence to approximately 20 architects, energy-modeling experts, and IDG members. The survey primarily was used to get feedback from external groups if the identified information items were representing what they would want to quickly get access to during design review meetings. The external validation group who responded included two architects and four energy-modeling experts.

The information requirements obtained from Group 2 were combined with the main list of requirements gathered from Group 1 to get the final list of identified requirements.

5. Research Findings and Validation

The research findings for information requirements identified by the preliminary elicitation and validation groups are presented in Table 4. The first two columns in the table list the categories and types of information that are identified as necessary to share during IDG meetings in immersive and interactive settings. Table 4 also lists the number of participants from Groups 1 and 2, out of 16 and 6, respectively, who acknowledged a piece of information as one that is necessary to share in immersive and interactive settings during elicitation and validation phases. It should be noted that if Group 1 did not identify the information requirement, column three was left blank to represent information that was only identified in a subsequent fashion by Group 2.

Table 4. Information requirements of IDG members to be conveyed in immersive settings during design review meetings.

Categories of Information	Information Requirements *	Group 1	Group 2
(a) External and gross building specific parameters	- Climate zone classification (classification code, weather classification, representative city) - e.g., 4A; mixed-humid; Baltimore Maryland	9/16	6/6
	- Annual temperature profile: average dry temperature for season/month, average daily maximum temperatures, average dew point temperatures, average solar radiation (direct, diffuse horizontal), average wind velocity with standard deviations, wind direction and heating/cooling design conditions - The number of heating/cooling degree day (HDD, CDD)	9/16	5/6
	Site information: City, state, country, latitude, longitude, time zone, elevation	9/16	6/6
	Building orientation, angle between the true north and the building's y-axis	7/16	6/6
	Building geometry and shading including surface starting position, vertex entry, coordinate system	9/16	6/6
	Building size (total square foot)	3/16	6/6

Table 4. *Cont.*

Categories of Information	Information Requirements *	Group 1	Group 2
(b) Internal and system specific parameters	Architecture/functional/spatial zones used, space usage profiles, assigned thermal zones	11/16	6/6
	Infiltration rate	2/16	6/6
	Occupancy per zone, whole building occupancy	11/16	6/6
	R-values for selected materials (exterior enclosure, windows, roof)	9/16	6/6
	Thermal energy storage capacity of systems	11/16	6/6
	Number of outdoor air intakes	0/16	3/6
	HVAC system related parameters: Hot water loop max. temperature, outside air temperature threshold (chiller on), chiller coefficient of performance, chilled water supply temperature, minimal outside air fraction, AHUs supply air temperature, AHUs supply fan efficiency, rated pump power consumption, ground surface temperature; Heating/cooling equipment by space; heat distribution, heating/cooling loads, heating cooling set points for thermal zones	9/16	6/6
	Temperature unmatched hours	9/16	0/6
	Occupant schedule	11/16	4/6
	Lighting load and schedule	10/16	4/6
	Daylighting parameters: Spatial daylight autonomy (SDA), glare indices, daylight factor values, useful daylight illuminance (UDI), number and coordinates of daylighting reference points for each zone, lighting control type and number of steps	0/16	2/6
	Air quality parameters	2/16	0/6
(c) Energy consumption parameters	Energy Usage Intensity (EUI) for each design option (kWh/m^2)	16/16	6/6
	Energy consumption—% change from baseline	16/16	6/6
	EUI for each thermal zone	0/16	1/6
	Energy consumption (breakdown by heating, cooling, lighting, equipment)	16/16	6/6
(d) Cost parameters	Cost of energy use/year; Cost of energy use/month	0/16	2/6
	Initial investment increase for each design option	16/16	6/6
	Annual energy savings for each design option	16/16	6/6

* Note: The information that marked in italics are also found in Table 1 from literature review.

As shown in Table 4, the information requirements that IDG members would need to see collectively in immersive settings are grouped in four categories: (a) external and gross building specific parameters, which define the parameters outside buildings, such as weather related (e.g., climate zone, annual temperature profile, and wind speed), site related (e.g., longitude and latitude, building orientation), and daylight related (e.g., glare indices, daylight factor values, and useful daylight illuminance); (b) internal and system specific parameters, which include the parameters inside buildings, such as space related (e.g., thermal zones, space usage profiles, occupancy per zone), building elements related (e.g., infiltration rate and *R*-value for building enclosure elements, and building systems related (e.g., outside air intake, HVAC system related parameters, lighting load and schedule; (c) energy consumption parameters, which define the simulated energy consumption related outputs generated from energy models, such as energy usage intensity (EUI), and EUI decomposed by different systems (e.g., heating, cooling, and lighting); and (d) cost parameters, which include the investment increase and energy savings associated with different design options.

Among all the information requirements listed in Table 4, 84% (21 rows in Table 4) of the total 25 rows of requirements were identified collectively by Group 1, and within these items identified collectively by Group 1, 90% of them were also identified by Group 2 (19 rows within 21 rows). This means that there was a 90% overlap between the information items articulated with the first group and the external group, who did not participate in the initial part of the study. The parameters that were not mentioned by Group 2 were air quality parameters and temperature unmatched hours. These two items have been included in the list of information that IDG members would need to collectively share using immersive settings during design review meetings. Similarly, it was observed from Table 4 that there were parameters that were identified by Group 2 only but not by Group 1, which constituted 12% of all the requirements listed in Table 4. These include daylighting parameters and the further decomposition of energy usage intensity and cost parameters that were identified with Group 1. The main reason why some parameters were not articulated in the groups (e.g., indoor air quality parameters in Group 2 or daylighting parameters in Group 1) was that there were energy modeling experts in these groups that solely focused on daylighting or indoor air quality and they articulated these needs mainly. The other two parameters included energy usage intensity, which was also identified in Group 1, being decomposed per zone, and the cost of energy use per year and month. These additional information requirements identified by Group 2, were identified either one or two of the group members, which is not the case for the remaining items that were predominantly articulated by a larger number of group members. In addition, among all identified information requirements, the ratio of the ones that were missed by Group 1 in relation to total counts (12%), and the ratio of the ones that were missed by Group 2 in relation to total counts (10%), are not high. Therefore, it is concluded that the identified information requirements that would be collectively needed by IDG members in immersive settings are generic for IDG design review meetings.

The results also reveal that there were a number of input parameters that more than 50% of the respondents believed are necessary for making appropriate AER decisions, which can be considered as critical information requirements. More than half of the experts from both groups agreed that climate zone, site location information (e.g., longitude and latitude), thermal zones and spatial usage profiles, occupancy per zone, and *R*-values for building materials were important to AER decisions and should be included in immersive settings while IDG members navigate within the space and evaluate retrofit design options. Overall, internal and external parameters such as climate, loads, and occupancy were valued more than specific building characteristics such as daylighting and indoor air quality. In fact, only energy modeling experts saw the need for an inclusion of air quality and daylighting parameters.

All 22 members participated in the study collectively viewed information requirements related to energy consumption and cost as important to AER design decisions, such as Energy Usage Intensity (EUI), initial investment increase, and annual energy saving for each design option. However, there was not a consensus about how detailed the energy and cost information should be reported. For example, one energy-modeling expert in Group 2 voiced a need to see the peak electricity demand expected on a monthly basis. In addition, one architect and one energy-modeling expert in the validation group recognized a need to view energy *vs.* cost across the year as a whole, as well as on a month-to-month basis.

In addition to this, if a quick comparison is performed between Tables 1 and 4 is done, comparison of the input parameters (information categories a and b) with Table 1 showed that among all the 20 types of sensitive inputs identified (Table 1), eleven of them were considered as required information to share with IDG members in immersive settings. These eleven sensitive input parameters embrace various items such as occupancy (internal heat gain from people), lighting schedules, geometry and space sizes, thermal resistance of exterior enclosure elements, *etc.* as detailed in Table 4 in italics. Majority of internal parameters (category b) identified in this study were covered as sensitive parameters except the thermal storage capacity and heat distribution, while all external parameters considered as important by IDG members to be conveyed in immersive settings were not covered among the sensitive parameters in the literature.

6. Conclusions

This paper provides findings of a research conducted with various energy modeling experts and integrated design team members in order to identify the information requirements of integrated design teams while evaluating design options for energy retrofit projects in immersive settings. An iterative requirements elicitation process, using an immersive virtual mockup developed by the authors, was followed in the study to identify the information required by design teams during the evaluation process of design alternatives for AER projects.

The information that was considered by experts as necessary to share during IDG meetings in immersive and interactive settings was grouped under four categories as external and gross building specific parameters; internal and system specific parameters; energy consumption parameters, and cost parameters. The findings show that more than half of participants agreed that climate zone, site location information (e.g., longitude and latitude), thermal zones and spatial usage profiles, occupancy per zone, and *R*-values for building materials were important to AER decisions and should be shown explicitly in immersive settings while IDG members navigate within the space and evaluate retrofit design options. Overall, internal and external parameters such as climate, loads, and occupancy were valued more than specific building characteristics such as daylighting and indoor air quality. All participants viewed information requirements related to energy consumption and cost as important to AER design decisions, such as Energy Usage Intensity (EUI), initial investment increase, and annual energy saving for each design option.

The findings of this research can be used by practitioners in the industry who work in integrated design teams for energy retrofit projects to create a checklist of information items that should be readily available for all design team members during design review meetings. Though the research findings provide the information requirements of IDG members who utilize interactive workspaces and immersive virtual environments to navigate within the spaces being retrofitted, the findings can be used as a summary that each IDG participating company should fill in and share with the rest of the group to expedite the decision-making process. The list can be used as a table in cases where the IDG members do not have access to immersive settings to evaluate design options for retrofit projects.

The study presented in this paper can be extended to study the impact of having the identified information readily available to the IDG members in their decision-making process and quantify the value of these requirements in the decision process in terms of time to come to a consensus among the

IDG members. It is expected that with the identified information extracted from simulation results, merged with design information and shared in immersive settings, the IDG members would make effective and efficient decisions during evaluation of design options in immersive settings. The information requirements also lay the basis for future research to study what visual forms are available and will be appropriate to display what types of information for IDG members.

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Author Contributions

Authors Katie Know, Xue Yang and Semiha Ergan contributed all the research and reporting related to this paper.

Conflicts of Interest

The authors declare no conflict of interest.

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