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Integration in building physics simulation

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Abstract

For more than a quarter of a century, building simulation programs have been developed to undertake non-trivial performance appraisals. In general these programs deal only with a small sub-set of the overall problem. However, advanced architectural developments require an integrated approach to design. The domains of heating, lighting, ventilation and acoustics, for example, are often closely related and it is only by taking into account their interactions that a complete understanding of building behaviour can be obtained. This paper describes some recent work to further the development of a multiple-domain approach. © 2001 Elsevier Science B.V. All rights reserved.

Résumé

Depuis plus d'un quart de siècle, des programmes de simulation en physique du bâtiment ont été développés pour simplifier la résolution de calculs fastidieux et complexes. Mais quel que soit le type de programmes, ils ne traitent que d'un nombre limité de domaine de la physique du bâtiment. Néanmoins, les développements récents en architecture requiert de plus en plus une approche intégrée des différents domaines découlant du concept et des matériaux utilisés. Chaleur, lumière, ventilation ou acoustique sont étroitement liés et ce n'est qu'en tenant compte des ces interactions, qu'il est possible de connaître le comportement global du bâtiment. Ce papier décrit une approche possible pour une méthodologie intégrée de la simulation en physique du bâtiment. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Building simulation program; Holistic building simulation; Multiple-domain simulation; ESP; Energy; Envelope

1. Introduction

Many historical precedents exist of buildings that have managed to maintain comfort conditions while striking a balance with the environment. The moucharabieh, which is a balcony closed by worked timber, was developed hundreds of years ago by the Arabs. At that time transportation was limited, therefore, the use of imported raw materials was reduced. As timber is generally rare in hot climates, the system was made of a precise assembly of small timber waste.

By using different locations and sizes of aperture, the moucharabieh provides, in a simple way, the possibility to control natural ventilation, harness solar energy and daylight, cool water, and provide privacy without isolating occupants from the external environment, as shown in the left part of Fig. 1.

This ingenious solution leads to a constructive balance between occupant requirements and environmental impact using local materials and techniques. The advantages of the concept have led to its widespread use around the world in hot and dry climates. The development of the moucharabieh took several decades of development [1], but is an example of vernacular architecture that solves multiple-domain constraints with just one building component. Recently, architectural developments tried to adapt the moucharabieh concept to fully glazed facades (Institute of Arabic World, Paris) as shown in the right part of Fig. 1. Unfortunately, the efficiency of the new system was not as outstanding as the traditional concept.

Technical developments during the second half of the 20th century have given architects the ability to develop almost any imaginable concept and to use a vast range of materials within the construction process. These developments have rolled back the limits of the architect's imagination. For instance, lightweight office buildings with transparent facades are now common in any climate. This constructional type, in contrast to traditional heavyweight constructions, requires an integrated approach to the design of the different domains in order to provide acceptable indoor environment quality (IEQ). Otherwise, overheating, poor visual comfort and acoustic problems will result.

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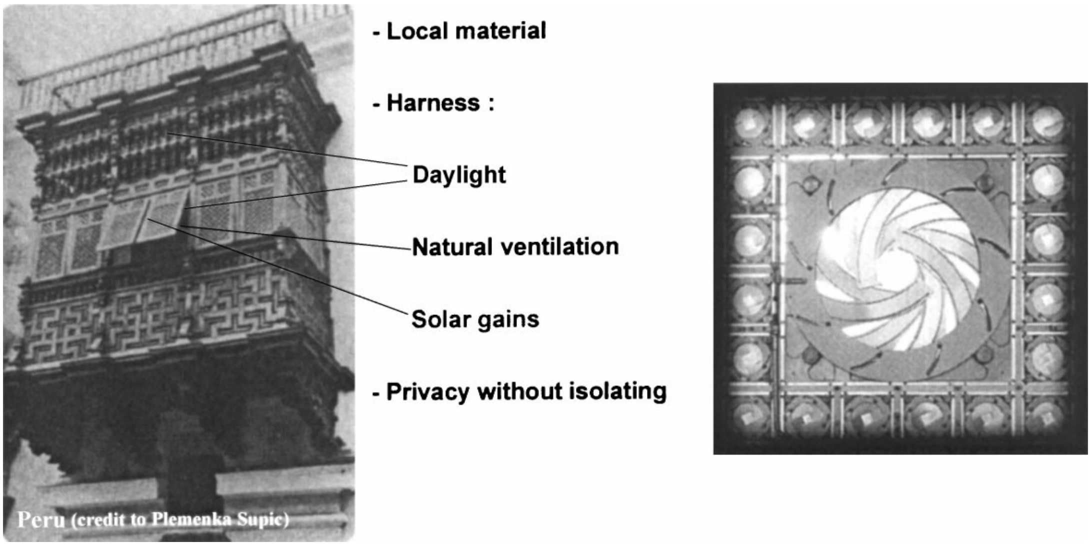


Fig. 1. Traditional moucharabieh (left) and a modern adaptation (right).

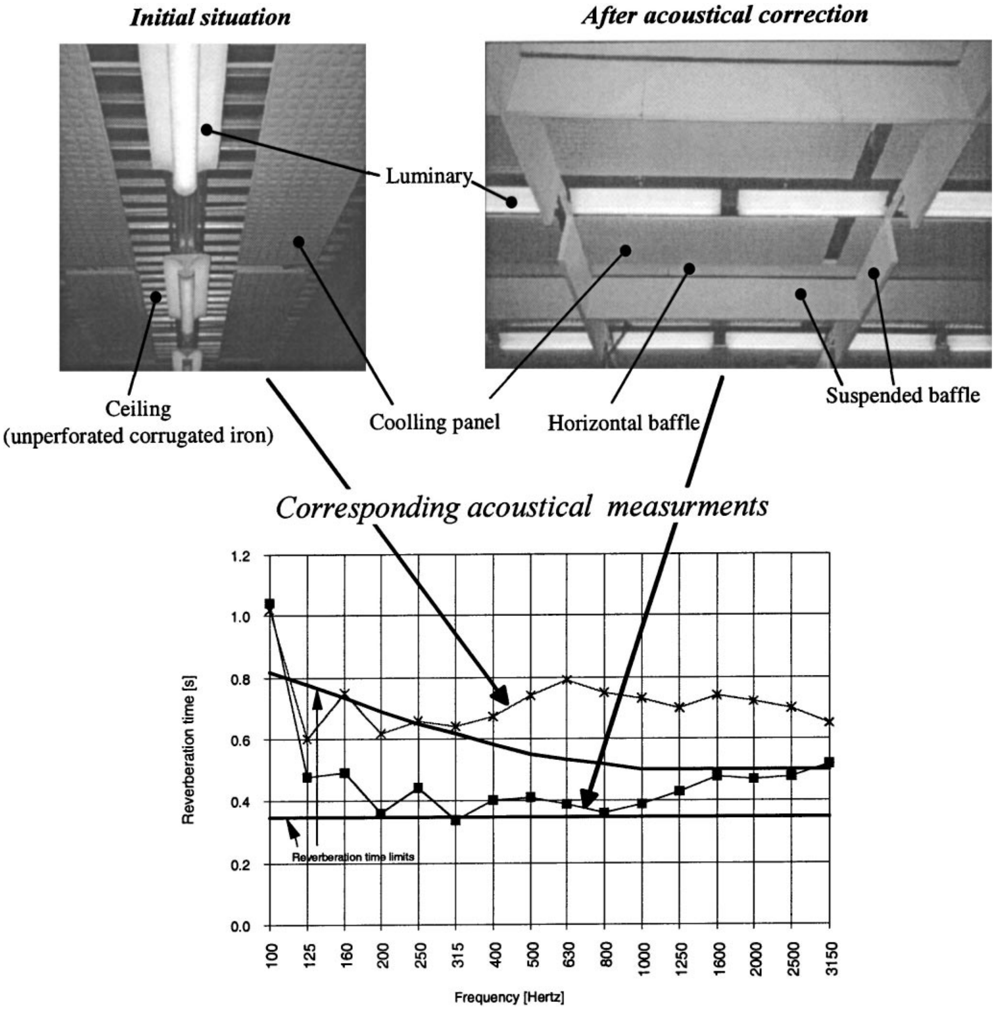


Fig. 2. Example where an acoustic problem has occurred due to a lack of a holistic approach during the design stage.

Table 1
Comparison of building physics simulation approaches

Approach	Type	Advantage	Disadvantage
Experimental	Small scale	Reproductive experiment	Scale effects
		Low cost	Model approximation/error
		Compare variants	Measurement errors
	Full scale	Complex phenomenon	Time consuming
		Global analysis	Expensive
Mathematical	Analytical	Ease to use	Measurement errors
	Numerical (computer)	Complex model	Simplified model
		Fast calculation	Validation
		Compare variants	Model might be complex
			Model approximation/error

Fig. 2, for example, shows the case of an open-plan office room with a cooling ceiling where the thermal, ventilation and lighting systems were correctly analysed, but the absence of a holistic approach has necessitated a post occupancy acoustic correction.

It is interesting to note that a similar problematic was studied by Newman [2] in the fifties when unacceptable room acoustic performance was shown to be due to the massive use of translucent acrylic ceilings used for artificial lighting.

These two examples illustrate the importance of simultaneously assessing the building's performance from different viewpoints. Not adopting such an integrated view can result in an unacceptable IEQ, which is generally difficult to resolve once the building is occupied, can be expensive in time and money and lead to solutions that are not ideal.

2. Holistic building simulation

A holistic approach to building design requires a method to estimate the performance that will result from the interactions between the different technical domains. As shown in Table 1, real scale experimentation and numerical simulation are suitable methods because they each can integrate the complex physical processes.

Because the experimental approach is time consuming and expensive, it can be argued that computer simulation is the preferred option for the holistic appraisal of design options.

3. Multiple-domain simulation approaches

A performance assessment method for computer simulation can work in three stages as shown in Fig. 3.

Stage 2 can be more or less complex depending on the solution employed to perform the multiple-domain simulation. From the point of view of simulation capability, four program categories can be identified, ranging from fastidious to easy to use.

1. **Stand alone programs**: These are the most basic solution for multiple-domain simulation. In this approach several *unrelated* applications are used. This obliges the user to create one project model per application as shown in Fig. 4.

   Creating different models of the same project has several disadvantages. Firstly, it is time consuming. Secondly, any modification in the project has to be translated between models. In practice, a design change must be communicated to each member of the design team, who then must adapt their portion of the model in order to assess the impact on their performance domain.

   Furthermore, some aspects of different domains can require the same input. For example, to support an advanced room acoustic and daylight analysis of a room, a 3D model of the project geometry will be required. If inter-application data transfer is not supported then two distinct geometry models must be created. The stand alone approach will then give rise to data redundancy and the potential for inconsistency between models. An other limitation of this approach is that the user is required to master each program's interface.
2. **Interoperable programs**: These programs provide a procedure whereby different computer tools can share information. The model transfer is only possible at the application invocation level of the model, which does not allow an interactive data exchange during the simulation process itself. As with the standalone approach the user is required to master each program's

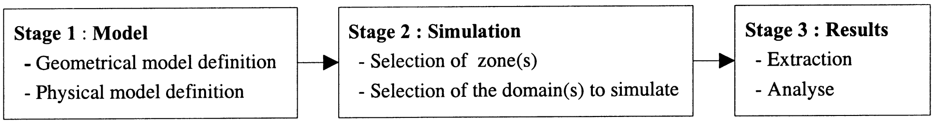


Fig. 3. Performances assessment method for holistic computer simulation.

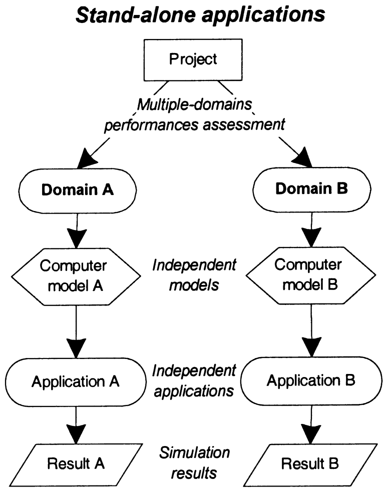


Fig. 4. Stand-alone approach in multiple-domains simulation.

interface. For interoperable applications, data model management is an important issue, which proposes to resolve redundancy. The two following approaches are possible:

2.1. *Model exchange*: The applications exchange a model, in whole or part, by using a data exchange facility generally based on a standardised file format as shown in Fig. 5.

The model can be created using an appropriate CAD tool and then exported to each application using a neutral file format. While IGES or DXF formats only describe the geometrical part of the model, the international foundation classes (IFC) [3] include both the geometrical and the physical parts. This simplifies model construction, but, as there is still one model per application, may not solve the problems of inconsistency (model maintenance).

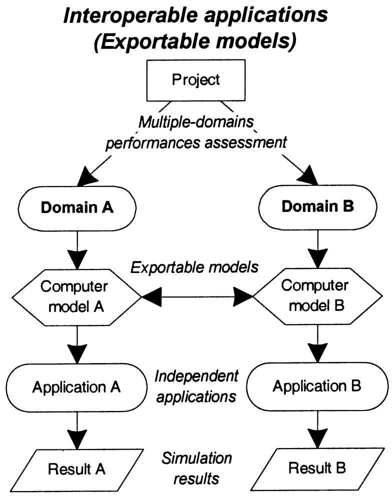


Fig. 5. Model exchange approach in multiple-domains simulation.

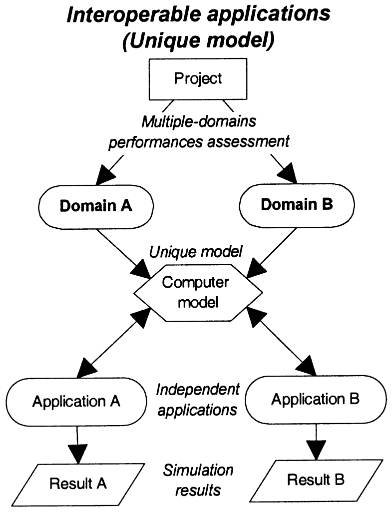


Fig. 6. Model sharing approach in multiple-domain simulation.

2.2. *Model sharing*: Model sharing allows the domain-specific applications to extract the data required for their own purpose from a single data management system that holds both the geometrical and physical parts of the model as shown in Fig. 6.

A typical example is the COMBINE project [4]. This approach avoids redundancy of data, but does not entirely prevent inconsistency and still requires an important data management system. When the model is modified, all the other parties have to be informed so that they may download it.

The interoperable approach is a computer representation of the real interaction between the partners involved in a project. Even then, within a real project practitioners would probably recognise that much time and effort is still required to locate, translate, enter, exchange and update data between the parties. Hopefully, future computational advances will simplify this work as depicted in the two following categories.

3. **Coupled (or linked) programs**: These programs provide the facility to link applications at run-time in order to co-operatively exchange information as shown in Fig. 7.

Generally, one application controls the simulation and calls the other application(s) when necessary. In this case, only the simulation engine of the coupled program(s) is required and the front-end interface corresponds to the driving application. The main advantage of the coupled approach is that it supports the exchange of information during a simulation contrary to the previous approaches. For example, Janak [5] has enabled a run-time coupling between the thermal/ventilation application ESP-r [6] and the lighting application Radiance [7].

The inconvenient of the coupled approach is the maintenance of data and link consistency which dependent on the separate evolution of each coupled application and making difficult any change or improvement.

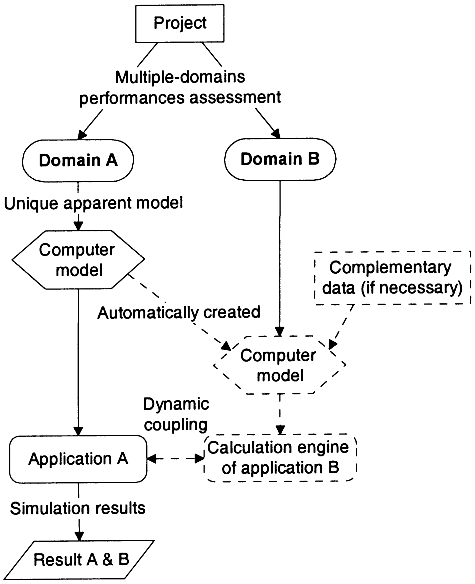


Fig. 7. Coupled approach in multiple-domains simulation.

4. **Integrated programs**: These programs provide a facility to simulate different domains within the same program as shown in Fig. 8.

As with the coupled case, an integrated program supports information exchange throughout a simulation. Some simulation programs already integrate thermal, ventilation, air quality, electrical power and lighting calculations [8]. Integration can also be achieved by merging existing application such has been done in the case of EnergyPlus [9].

Even where domains are not directly coupled, the integrated approach has several advantages. Firstly, the evolution of the application is made easier because it does not depend on external applications. As only one model is needed to run multiple-domain simulations, data management is simplified. No exchange file format is required and any modifications need only be implemented once.

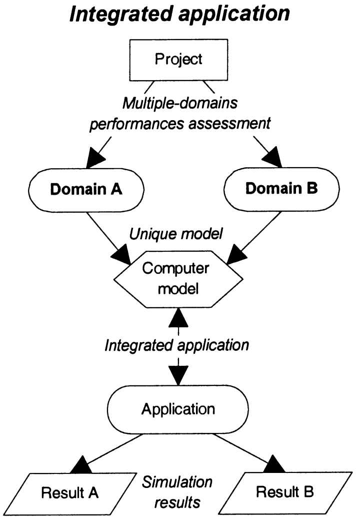


Fig. 8. Integrated approach in multiple-domains simulation.

Another advantage is the possibility of an adaptive user interface. The more detailed data model allows the input to be adapted to the design stage. At an early design stage, limited knowledge is available and various defaults may be relied upon. As the design evolves, these defaults may be replaced by specific data as and when they become available. Significantly, there is no need to change the application during the evolution of the design.

The main difficulty in such an approach relates to the creation of the physical model. During the design stage only a few people know the exact composition of the different building elements. But once the physical model has been created, the integrated approach allows a flexible, simple and concurrent multiple-domain simulation. The advantage of the integrated approach stems from its closer mapping to the real world.

In the authors' opinion only the coupled and integrated approaches can take into account the dynamic behaviour of a building to enable the assessment of concurrent and transient physical processes. These approaches also simplify model creation due to the fact that there is only one model. Finally, the integrated approach simplifies the application development. These approaches are therefore, likely to grow in popularity as the profession embraces multiple-domain assessment.

The remainder of this paper focuses on the *integrated* approach in terms of the technical domains to be included and the requirements for extended constructional definition to support these domains.

4. Building physic domains and indicators to include

An important issue in integrated simulation is to determine the physical domains that will impact on the performance issue to be addressed. It is well accepted that energy related indicators, such as energy consumption or daylight utilisation, are insufficient for building performance characterisation. The occupant comfort is also an important issue that has to be included. Several studies [10–12] demonstrated that occupant comfort is the global response to external stressors exposure (environmental, affective, social, etc.) and asserted that a multiple-domain comfort assessment is required. According to these studies, the four primary environmental stressors which can be retained for IEQ could be thermal environment, light, air quality and acoustics. Furthermore, the occupant comfort is not a static response to these external stressors. For instance, Yamazaki et al. [13] suggests that workplace suitability requires higher illuminance levels when sound pressure increases. This demonstrates the importance of providing an integrated approach, which could concurrently assess these connected comfort aspects.

The analysis of the overall performance of a building should also take into account the ecological cost of providing this comfort. The energy crisis in the 70's has resulted in the use of building energy consumption as a performance metric. Furthermore, the Rio Conference in 1992, where the environmental impact of human activities was officially recognised, has introduced limitations in the use of specific materials in the building industry, such as CFCs [14]. Even if there are no 'green' standards which define the maximum allowed impacts, the environmental impacts of a building during its lifetime can already be estimated, and could be included as a new domain requiring performance assessment at the design stage. Therefore, a holistic approach should include building performance indicators as well as comfort and energy and environmental impact indicators, each relating to the building's life cycle.

The holistic approach proposed in this paper focus on the following domains:

- Building intrinsic performances (energy consumption, acoustics, etc.);
- Occupant comfort, including thermal, IAQ, and lighting;
- Life cycle impacts assessment (LCIA), which characterises the environmental impacts of building energy consumption, the construction materials and processes occuring during the building life span (including the construction, use, maintenance and deconstruction phases).

Several metrics could be selected to quantitatively characterise these domains. The retained indicator(s) in each domain generally depends on the project and the focused domain(s). In practice, the indicators required to assess the performance of the building, drive the selection of the simulation applications. On the contrary, the advantage of the integrated application is to become assessment methods and indicators independent when the data model include sufficiently information as it is explained here after.

5. Holistic concept

An important issue in the holistic assessment of performance is the construction of the building model. To allow a multiple-domain simulation, the physical model should hold

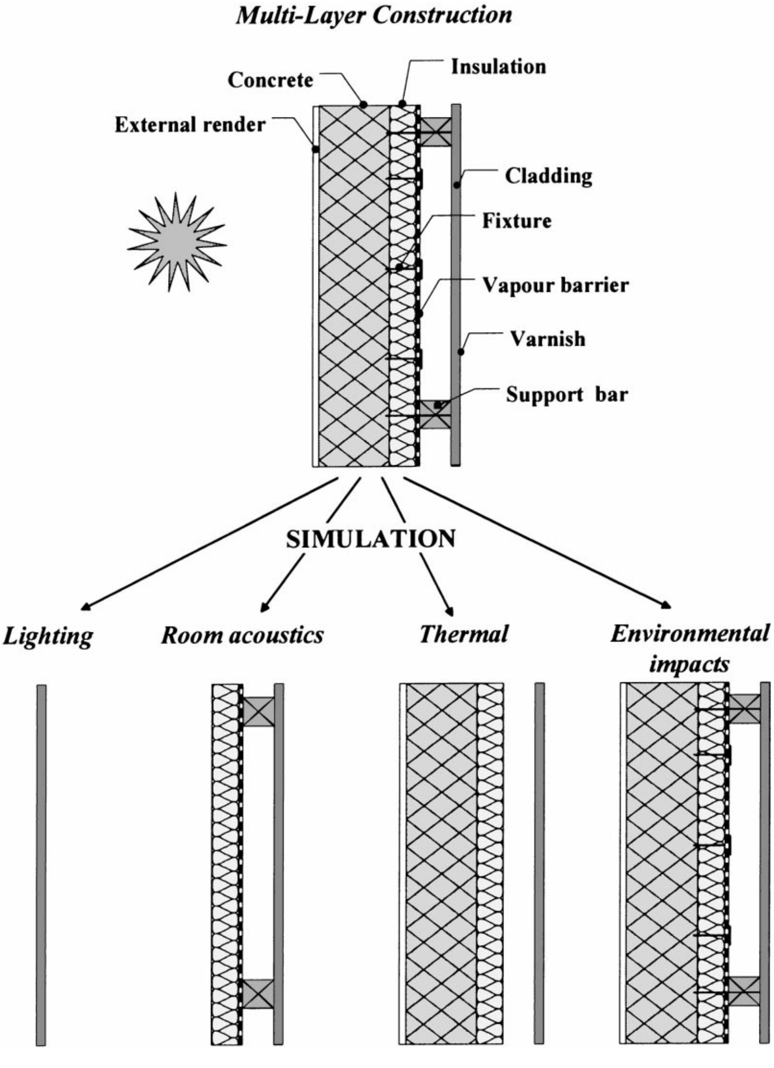


Fig. 9. Differences in the physical model according to the domain under consideration.

the information required by each domain. This information is domain related and, therefore, the physical model depends on the domain(s) under consideration as shown in Fig. 9.

To assess the internal illuminance, the physical model only requires the properties of the most inward material. While the environmental impacts of the construction requires the individual impacts of the constituent materials.

To support the inclusion of different domains within a simulation, each construction material in the database should hold the properties of all possible domains which could be simulated. During model creation, the physical model is then able to extract that part of a construction element which is relevant to the domains under consideration.

6. Simulation and material description

Each material must include the physical characteristics of any domain that is likely to be simulated. Unfortunately, there is currently no unified theory that permits accurate characterisation of specific domains based on basic material properties. For example, the material properties required for a lighting simulation do not provide any information on the environmental impacts of the material. Therefore, for each domain, the corresponding material properties need to be recorded.

These material properties required for the model depend on the domains which could possibly be simulated and on the methodologies used to assess the performance in a specific domain. When the calculation methods have been selected, the material properties required should be at least the lowest common properties denominator for all the methods. On the other hand, if the data model include all the material properties required by different calculation methods, then the model become independent to these methods, which finally allows the assessment of any related indicators.

Table 2, which is not exhaustive, summarises the properties required by the most common calculation methods for energy/thermal, ventilation, lighting, room acoustic and LCIA appraisals.

Table 2
Summary of the material properties required to perform an integrated simulation using the main calculation methods in building physics

Properties	Methods
Material level:	Thermal
Density	Thermal transmittance [15]
Solar absorption	Dynamic characteristics [16]
Conductivity	Thermal bridge: analytical [17], by finite element [18], or by finite difference [19]
Heat capacity	Steady-state energy consumption [20]
IR emissivity	Dynamic behaviour: nodal network, response factor [8]
Vapour diffusion resistance	Thermo-optic properties [21–25]
Visible, solar, IR and UV trans.	Ventilation
Visible, solar, IR and UV ref./abs.	BSI [26]
Dynamic viscosity (for gas only)	ASHRAE [27]
Surface roughness and specularity	Hybrid [28]
Refraction index	Flow/system network [29]
Chromatic co-ordinates	Zonal [30]
Acoustical absorption coefficient	CFD [31]
Environmental impacts	Lighting
	Lumen [32]
	Split-flux method [33]
	DIN 5034 [34]
	Radiosity [35]
	Ray-tracing [36]
Construction level	Room acoustics
U-value	Sabine, Eyring, Milington, Pujolle, etc. [37]
g-value	Image source model [38]
Visible transmittance	Radiosity [39]
Sound reduction index	Ray-tracing [40]
Linear thermal transmittance	Cone/pyramid tracing [41]
Point thermal transmittance	Hybrid [39,42]
Environmental impacts	LCA
	Eco-indicator 99 [43]
	Ecopoints 1998 [44]
	Critical surface-time [45]
	EPS [46]

The selection of a property is based on the following criteria:

- The material property is known or can easily be measured;
- The property is required to support a calculation as listed in the table. To ensure the consistency of the material properties only elementary value are retained. A property that is required by a method, but can be calculated by using more basic properties, is not take into account. For instance, the effusivity is not an elementary property because it can be derived from the density and the conductibility, which are elementary data.
- Properties that are not directly related to the material, but are required in a calculation method are not listed in the following tables. For example, some advanced day-lighting methods require the sky luminance distribution. As this property is not directly related to the construction materials, it is not included here.

It should be noted that according to the domain of simulation, not all properties are necessary for the calculation. Only the relevant material properties for a specific calculation method can be extracted from the model and used during the simulation. This could be done in the background and so no special interactions are required between the

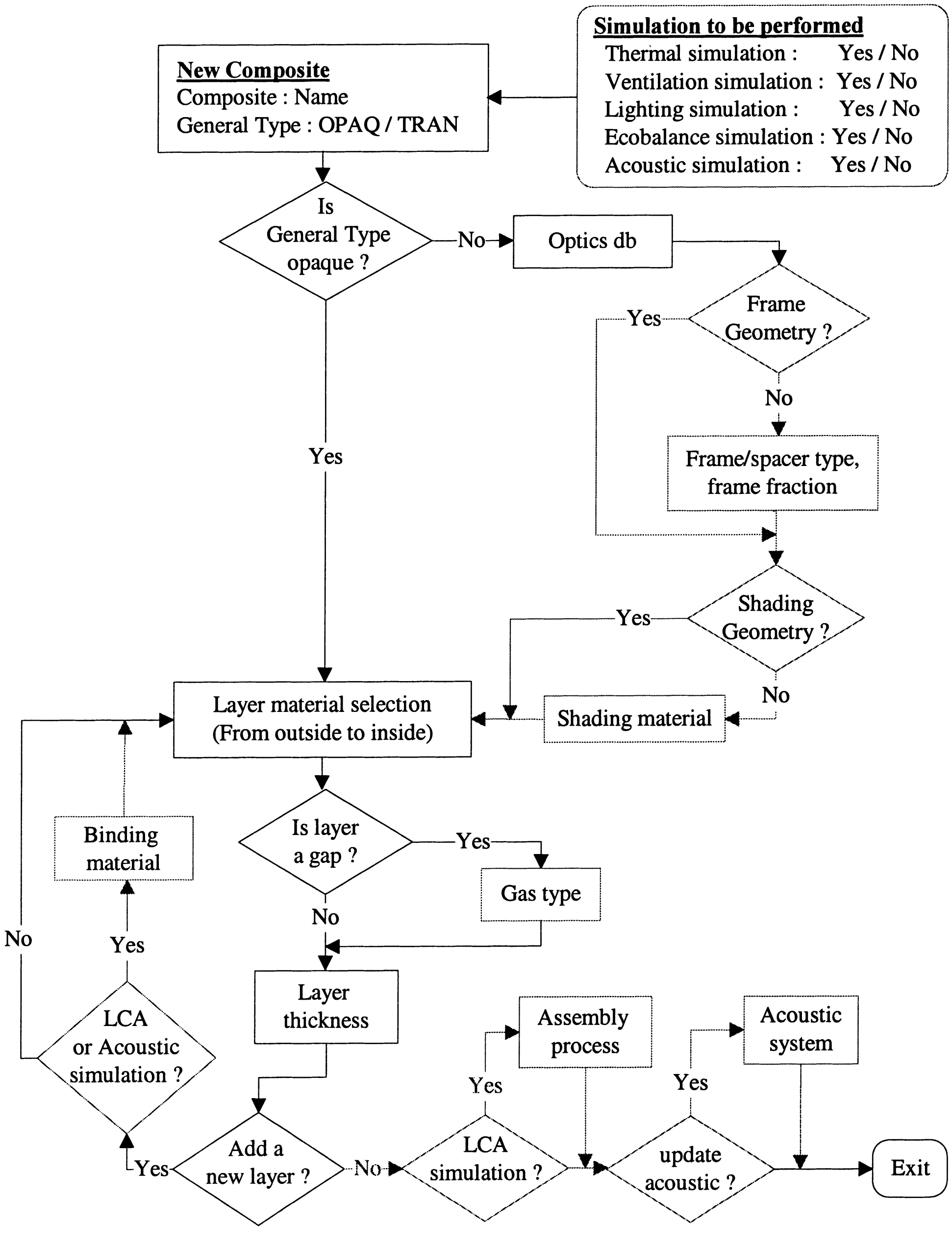
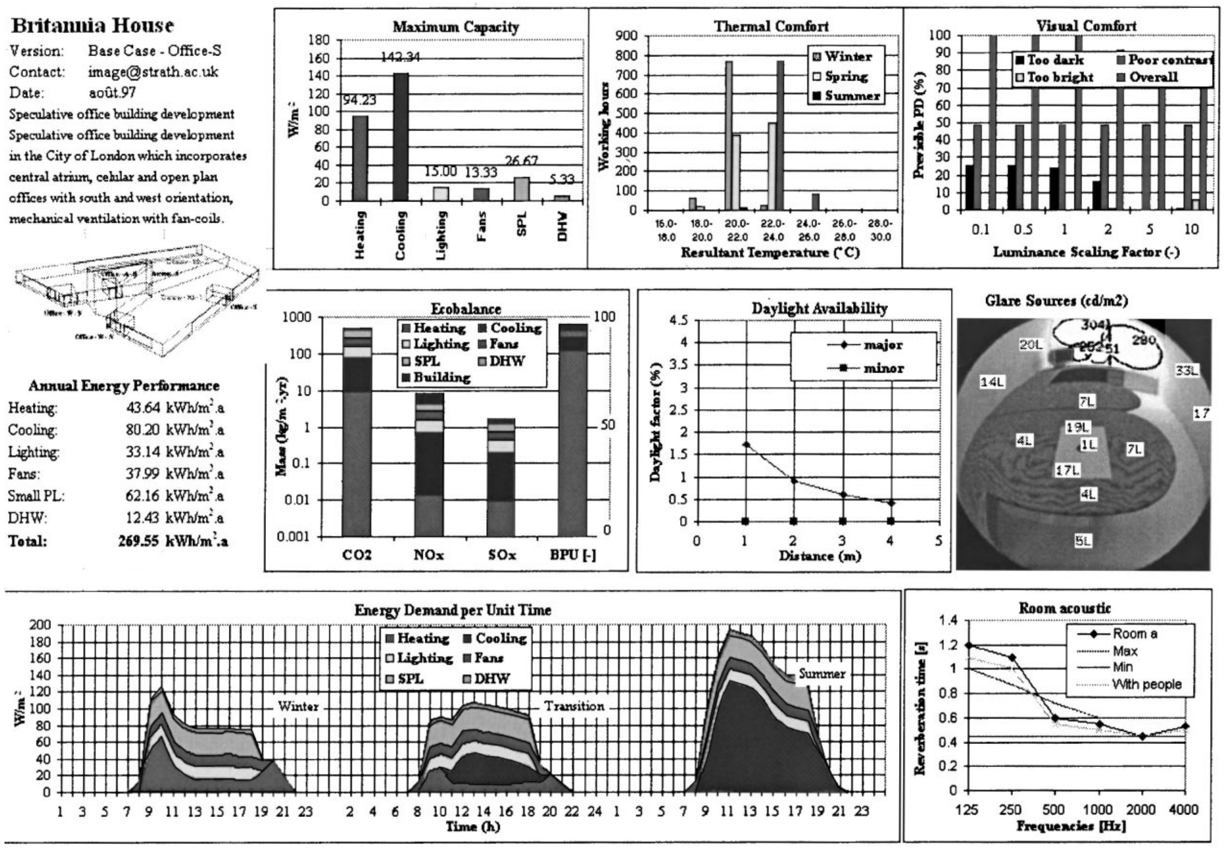


Fig. 10. Flow chart for a possible integrated physical model.



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Speculative office building development
Speculative office building development in the City of London which incorporates central atrium, celular and open plan offices with south and west orientation, mechanical ventilation with fan-coils.

Annual Energy Performance

Heating:	43.64 kWh/m^2.a
Cooling:	80.20 kWh/m^2.a
Lighting:	33.14 kWh/m^2.a
Fans:	37.99 kWh/m^2.a
Small PL:	62.16 kWh/m^2.a
DHW:	12.43 kWh/m^2.a
Total:	**269.55 kWh/m^2.a**

Fig. 11. Example of an integrated performance view (IPV) for a multiple-views in building physics.

database and the user. While building physics applications are commonly domain related, the proposed solution is *material properties related*. The flow chart in Fig. 10 shows a possible physical model construction that takes into account the previous remarks and is currently under construction within the framework of the ESP-r program.

When complete, it will be possible to assess the impact on comfort, energy, room acoustics and LCIA of alternative construction solutions. Unfortunately, it is out of the scope of this paper to describe the product data model in more detail.

7. Results

The third stage of the integrated simulation is the result analysis. The user should have the possibility to bring together and display the disparate performance metrics resulting from the different simulation domains. It is convenient to group these performance metrics together to ease result interpretation and variants comparison.

Clarke [47] proposes the use of an integrated performance view (IPV) which is a collection of relevant performance metrics for energy consumption, thermal and visual comfort, and environmental impacts. As shown in Fig. 11, the concept as been extended to include metrics related to the room acoustics and the environmental impacts of the building during its whole life cycle.

The temptation to aggregate these indicators into a single one must be resisted. The limitation of such an approach can be illustrated using a parallel with the car industry. When a customer buys a car, there is no single indicator that describes its characteristics and performance of. The customer is interested in specific indicators, such as fuel consumption, the engine power, the car boot volume, the NO_x emission level, etc.

In the construction industry, building performance is also assessed at different levels, with the detail scrutinised by the different partners involved in the project. A composite indicator would only serve to confuse because it will mask weaknesses in specific domains.

8. Conclusion

An integrated building performance analysis is essential at the design stage in order to prevent the delivery of buildings with unacceptable performance characteristics. The most appropriate method to achieve this is computer simulation. Currently, the market offers several interoperable programs. The disadvantage of this mode of operation is the complexity of use and the potential for model inconsistency. This can best be overcome by an integrated simulation approach. Currently, there are no simulation programs that can estimate energy consumption, comfort conditions and, in parallel, provide data on the energy and environmental impact of the building throughout its whole life cycle.

This paper has proposed a possible approach which has a new physical model of construction elements at its core. This approach is currently being implemented within the ESP-r system to facilitate the concurrent assessment of building performance, comfort (thermal, lighting, ventilation), room acoustic, and environmental impacts.

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