Use of Predictive Analyses for BIM-Based Space Quality Optimization: A Case Study, Progetto Iscol@

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Abstract Predictive analyses on future uses, developed through usage patterns, provide a solid basis for space quality check. This paper aims at setting a methodology for the use of predictive analyses for project quality and effectiveness of school buildings design. Crowd simulations and pre-occupancy simulations are applied on BIM models of school buildings: data related to users' interactions, comfort evaluation help in increasing space quality and avoiding overcrowding or ineffective space distribution. The proposed approach is iterative, allowing the optimization of design, based on educational approach. This method has been tested in the design of a new school building located in Sardinia, in the framework of Progetto Iscol@.

Keywords Pre-occupancy simulation · Crowd simulation · Design optimization · Educational approach · Usage patterns

1 Introduction

The traditional design process implies the check for compliance of design solution with standards and requirements in order to get administrative approvals, during the phase of definition of the Progetto Definitivo (corresponding to RIBA Plan of Work's Technical Design (Royal Institute of British Architects (RIBA) 2013)) Referring to dimensional verification, two main categories of checks are necessary:

- Fire prevention regulation checks: these checks regard compliance with the minimum requirements set out in the regulations, as the length and width of escape routes and stairways, number and width of emergency exits, and the total evacuation time (Italian Parliament 1998);

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- Minimum dimensions of spaces: the minimum size of rooms depends on their functions, the building use, and the number of users attending each space.

Nonetheless, the observance of minimum requirements and standards for hallways and spaces does not guarantee space quality in terms of use and user comfort, that are key elements of the Client's requirements. In a traditional process, the management of these aspects mainly comes from intuition and previous experience of the designer, supported by standards and requirements; nonetheless, these intuitions cannot be verified until the designed building is built and used. In most cases, the building is a prototype of itself with regard to the real use (Zimmerman and Martin 2001). In addition, during the phase of definition of the Progetto Definitivo, most aesthetical and technological features, layout and functions of the design are defined. As a result, the evaluation of the effective use of the building should take into account a large amount of aspects. It is relevant to detect high crowding and discomfort, both in ordinary and emergency conditions, such as fire emergency evacuations. These evaluations are essential when considering hallways, meeting and common areas, as these spaces are hosting a large number of users.

In this context, effective uses of spaces and users' comfort levels are hardly assessed. As stated before, they are usually defined only once the building is built and in use (Schaumann et al. 2016). During the operational phase, discrepancies between the built asset and the users' actual need can provide high costs for changes of the environment (Schaumann et al. 2016). As a result, the investigation of effective uses of spaces during the design phase can be useful to anticipate potential changes, leading to the decrease of costs of future modifications and an increase of design quality.

2 Pre-occupancy Simulations and BIM Approach

This work aims to provide a method to evaluate real use of spaces in design stages, through an integrated BIM approach. Building Information Modelling (BIM) methodology provides, by means of models representing the design alternatives, the association of information, such as number of users, space features, costs, to elements and spaces composing the model (Di Giuda and Villa 2016). The Information Modelling method strongly reduces time spent to produce documents and drawings required for administrative approvals, increasing therefore available time and resources for preliminary decision-making processes (Ciribini 2016). As a result, design alternatives can contain a huge amount of data, which are valuable to perform analyses on the model.

The method provides the application of Pre-occupancy simulations to analyse and verify usage patterns of design spaces and the interactions among users.

Pre-occupancy simulations are based on Crowd Simulation systems, which are computerized analyses of the movement of crowds. The main goal of these simulations is fire regulation check, related to spaces and escape routes and they are generally used for emergency simulations (Almeida et al. 2013; Montella 2012; Tang and Ren 2008): in the case study provided, the simulation reproduces the actual use of spaces, to verify the spatial quality of designed spaces and users' comfort levels. Spatial quality is defined as the ability of spaces to meet the intended use.

There are two kinds of Pre-occupancy simulation: Agent-based and Narrative driven, described below. Microscopic Agent-based simulations are used in the current case study: the users keep their own features and can act independently, while their behaviour influences choices and movements of nearby occupants (Ijaz et al. 2015). There is, therefore, an effect of individualisation of the movement of crowds (Santos and Aguirre 2004). The user reacts to simple motion rules called Keep It Simple and Stupid (K.I.S.S.) (Axelrod 1997) and a widespread A.I. (Artificial Intelligence) drives its actions and ensures randomness of movements in space (Santos and Aguirre 2004). Pure Agent-based simulation has a main limitation: it is possible to populate the model of a building, but the movement of the occupants is extremely chaotic (Simeone 2015).

As a consequence, it is necessary to apply a second type of simulation, defined Narrative Driven, which formalizes the sequence of activities the user carries out. A Narrative Driven simulation also presents some limits: the need to formalize every single activity carried out inside the spaces causes a strong rigidity of the simulation. It provides a reproduction of occupants' behaviour along a sequence of fixed activities, without the possibility of varying users' own path. As a result, the analysis appears more as an animation rather than as a simulation, making it nearly impossible to analyse the usage patterns of a building (Simeone 2015).

The adopted solution involves the mixed use of the two systems, thus removing the above limitations. This kind of simulation is not currently implemented in a traditional design process, resulting in lower quality of the design solution (Simeone 2015).

Pre-occupancy simulations were adapted to the case study to perform ordinary conditions analysis. The output of the simulation is the usage pattern of the building. As a result, the actual use of the building by users is assessed at the design stage, optimizing the design solution according to the results.

3 Case Study: Pre-occupancy Simulations to Evaluate Interactions Among Users

The proposed methodology (cf. Fig. 1) was applied to the design of a primary and secondary school in Posada, Sardinia, in the framework of Progetto Iscola@ (Locatelli and Pellegrini 2017). Progetto Iscol@ is a regional programme for the refurbishment and new construction of Sardinia's school heritage. One of the main goal of Progetto

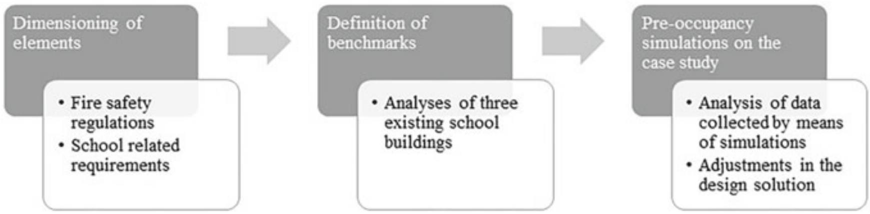

Fig. 1 Workflow of the analysis (image by authors)

Iscol@ is the integration between architecture and educational approach, also thanks to the introduction of innovative learning methodologies.

As mentioned above, a mixed approach based on Agent-based and Narrative Driven simulations was verified and allowed to measure the spatial quality. The model used is unable to replicate and simulate all aspects of human behaviour; it provides just predictive data on number and quality of interactions among users in spaces. The proposed model allows, therefore, to quantify, verify and evaluate the spatial configurations, according to the spatial quality. Spatial quality is defined as the number and variety of interactions, as well as the personal comfort of each user obtained by reducing the crowding phenomena (Locatelli and Pellegrini 2017). As a result, well-designed spaces can stimulate the spread of innovative learning methodologies, such as peer-tutoring and collaborative learning (Locatelli and Pellegrini 2017).

Pre-occupancy analyses allowed the evaluation of design alternatives in terms of layout, dimension, and shape to ensure quality and users' comfort, as well as compliance with educational requirements.

The workflow of the analysis was set as follows:

- dimensioning of hallways, stairs, common areas according to fire safety regulations and minimum size provided by school-related legislation (Italian Parliament 1975);
- definition of benchmarks to achieve, referring to interactions and usage patterns of school buildings;
- performing of Pre-occupancy simulations on the design solution;
- analysis and evaluation of Pre-occupancy simulations results.

The analysis was carried out choosing the time of day with higher probability of overcrowding and discomfort, i.e. school break, when the interactions among students and the number of activities performed are maximum.

The following table (cf. Table 1) shows the main features of the analysis carried out. Actually, the software used to perform the analyses is specific for emergency conditions analyses, therefore it was necessary to adapt simulation parameters in order to approximate ordinary conditions.

Shown parameters derive from the analysis of three existing school buildings, with similar features to the case study of the school in Posada: number of students, size and functions of spaces (Locatelli and Pellegrini 2017). The three schools were chosen as they represent positive examples of the application of innovative educational

Table 1 Simulation parameters

User speed	User speed was decreased in order to fit user behaviour in ordinary conditions, instead of panic conditions
	Primary school students move faster than secondary school ones. Indeed most children run, so their speed was set higher
Distance among users	The distance among users was decreased to simulate interaction and conversation
Sequence of activities	Flexibility in choosing the activity to be performed was increased to approximate the decision-making process of users in ordinary conditions. User priority is no longer just to reach the safe place as if in emergency simulations
	Users can choose the sequence and number of activities, according to defined probability functions and attractiveness percentages for each space
	The total percentage, as a sum of the above percentages, is equal to 80%, leaving students a 20% possibility not to choose any activity and stay in class
Duration of the analysis	The duration of the analysis has been set depending on the period of use of each space, related to its function

methodologies. The analysis of the schools by means of Pre-occupancy simulations allowed to measure the levels of crowding, number of interactions, maximum and minimum number of users in common spaces during the school break. As a result, it was possible to define benchmarks to compare the analysis results on the case study.

4 Results of the Case Study

The outputs of the Pre-occupancy simulation software are frequency and density maps (cf. Fig. 2), showing crowding data in any point in the space. Collected data are helpful to define main flows and space occupation indexes, allowing the evaluation of size and ability of the spaces to meet the future users' needs.

Density maps allow to investigate overcrowding, and represent a useful tool for designers to reduce discomfort. The value defined as "uncomfortable" is 3 people/m^2, which is the maximum acceptable value for dynamic crowds (Still 2000): over this value, people moving in a crowd can generate clashes that can be dangerous (Fruin 1993). As a result, it is possible to identify the most crowded areas and correct their size, shape and features.

As previously defined, the number of interactions provided with the analyses can be used to identify the capability of the building to facilitate interactions. For this purpose, spaces can be modified and optimised in order to both increase interactions and decrease overcrowding phenomena (Locatelli and Pellegrini 2017). Simulations on the information model, indeed, allow to anticipate the effects of the future occupants'

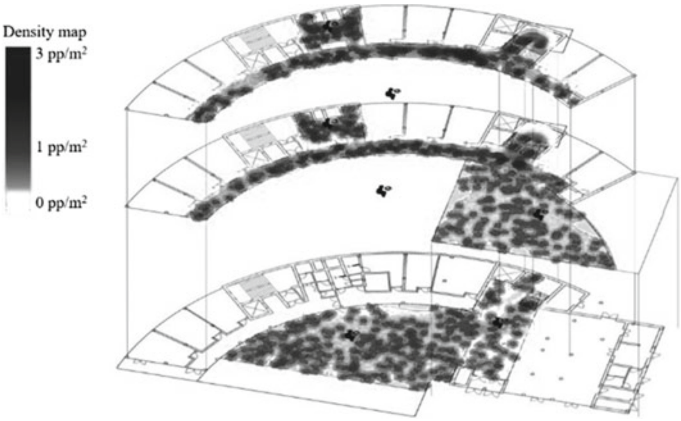

Fig. 2 Density maps showing overcrowding in some exits, stairs, hallways and spaces (Locatelli and Pellegrini 2017)

use of the building and their interactions (Shen et al. 2013), resulting in changes of designed spaces features.

Simulations on the case study identified high density values in some areas causing issues related to management of spaces (cf. Fig. 2). Analyses showed the need to review some aspects of the common spaces' design.

Simulation results highlighted the following issues:

- Overcrowding in entry and exit flows: this led to an increase in the number of exits to reduce the intensity flows.
- Dangerous values of overcrowding on the stairs: this result highlighted the need to review design and features of the stairs connecting the school levels, in order to avoid overcrowding phenomena. Stairs was widened to safely accommodate all the students.
- Spaces with low levels of interactions: the number of interactions in common areas was compared to optimum values defined through the three case studies. Spaces with few interactions were rearranged and their shape adjusted.
- Spaces with high levels of interactions: areas with high quantity of interactions were relocated in the layout, enlarged (when possible), or their exits were redesigned in order to match the expected large flows.

The most remarkable aspect of these results is that exits, hallways and stairs, adjusted on the basis of analysis data, were already sized according to fire regulations and other standards. As a result, the analyses revealed issues related to the actual use of the designed school and to the complexity of the planned users' flows. As stated before, fire prevention regulations define length and width of escape routes and stairways, number and width of emergency exits. These are static values: the legislation does not take into account the effects of possible funnel-shaped flows phenomena occurring in the case of large users' flows. This can cause both delays and discomforts in ordinary conditions, and dangerous situations in emergency conditions. The method proposed, by means of Pre-occupancy simulations, allowed to detect, assess and manage this kind of issues.

5 Conclusions and Further Developments

The proposed method and its application to the case study allowed the optimization of the design solution referring to usage patterns data during the early design stages. It is noticeable that spaces designed according to norms and requirements do not provide efficient levels of comfort, and do not avoid overcrowding, as shown in the simulations. Data collected from the analyses were useful to underline and solve issues related to overcrowding and interactions' level.

One of the main advantages is related to the possibility for designers to check and test their intuition in terms of layout. According to the simulation results, they can therefore modify and change the design solutions, selecting the best fitting one.

The evaluation of interactions among users also allowed to respond to the Client requirements in terms of educational approach. This kind of check would have been almost impossible without these simulations.

Another key aspect is the possibility to carry out Pre-occupancy simulations in the initial stages of the design process, by means of the information model. During these phases, variations on the design spaces provided minimum costs for changing and maximum impacts on the design quality.

The provided case study is a relatively simple building, but was helpful in defining a flexible and valuable methodology to optimise the design solution. Further developments include the application of the method to larger buildings, with several types of users and interactions patterns. The application of Pre-occupancy simulations may ensure the definition and evaluation of usage patterns, resulting in the optimisation of design solutions. Collected data may also allow the definition of a plan to manage user's flows depending on interaction patterns. This may avoid congestion, which can cause discomforts and delays in the operation of buildings such as airports or large facilities. This approach may therefore lead to greater benefits for complex buildings, where compliance with regulatory limits may not ensure quality and safety of spaces.

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