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Analysis of the Surroundings Impact on the Building Energy Performance by Means of a BIM Analytical Model Coupled with Dynamic Simulation

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Abstract

Building design often does not result in an actual limitation of energy consumption during the building occupation phase since a performance gap emerges. This gap is often related to occupant behaviour, but other factors, such as uncertainties and errors occurring during the design, construction and management phases, may also have an impact. Because of this, the correct evaluation of the interactions between the building and the context is an important consideration, but is often not correctly incorporated into energy analyses. The correct modelling of neighbouring buildings can be an expensive activity due to the difficulty in gathering data.

The research reported here describes a methodology to develop a simulation model of an existing building and its surroundings by using a drone survey. With reference to a point cloud created from a drone survey, a geometric description of an existing building is developed in the BIM environment (Building Information Modelling). Following this, the BIM model is converted into a dynamic simulation model and the impact of neglecting the building's surroundings is quantified. The aim of this complete and complex approach is to propose a working methodology and a process that integrates geometric-architectural and energy disciplines. The results suggest that it is possible to develop an innovative operating methodology for intervention in existing built heritage.

1. Introduction

The coming into force of the EU Directive 2010/31/EU led to the need to reduce energy demand and carbon emissions in the European building stock. Retrofitting the existing building stock is a key strategy for reducing greenhouse gas emissions and mitigate climate change, as the effectively designed renovation of existing buildings can provide high energy savings. The importance of the refurbishment of the existing building stock, with a strong focus on energy saving, has become a key theme both in the literature and also in practice. (Li et al., 2017, Vilches et al., 2017).

Although building performance simulations (BPS) can provide a valuable support in the design of effective energy efficiency measures, the effort needed to create a complete and accurate model can hinder its application in practice. The development of an energy simulation model is an error-prone activity that relies on manual and time-consuming input activity (Lobos-Calquin, 2017). Furthermore, this step requires the energy modeller to replicate the 3D geometric model definition already prepared by the architect. Designers often adopt building information modelling software (BIM) in order to support the building design and lifecycle management as it contains a great deal of rich geometry and information.

Another important aspect of the design of energy efficiency interventions is that it may fail to achieve the expected performance. A building design often does not result in an actual limitation of energy consumption during the building occupation phase and a performance gap emerges. This gap is often related to the occupant's behaviour but many other factors may impact on it. In this regard, the correct evaluation of the interactions between the building and the local context is an important consideration, but is very often not correctly incorporated into energy analyses because of the difficulty in gathering the data required to model neighbouring buildings.

The automated generation of simulation models based on the interoperability of building information modelling (BIM) and building performance simulation software (BPS) offers a promising solution to these problems (Bres et al., 2017). To achieve the main objective of an effective reduction of energy consumption, an integration between the existing building heritage and energy efficiency measures is tested in this study, making use of innovative digital technologies. Parametric digitalization operations of an existing building and the development of three-dimensional model in the Building Information Modelling tool were performed (Fig. 1).

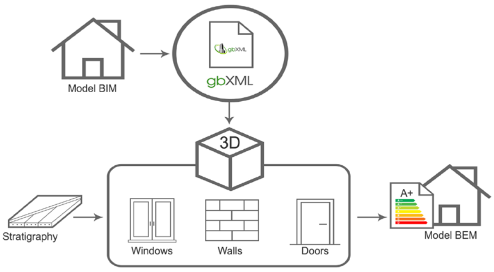

Fig. 1 – Evolution from the BIM model to the BEM model

The proposed approach is based on a model developed in a BIM (Building Information Modelling) environment, which acts as a coordination tool for the modelling, design, implementation and management phase of the chosen case study. The BIM to BEM interoperability is tested and the energy saving measures are evaluated by evaluating different energy saving scenarios.

2. Methods

2.1 Research Objectives

This research aimed to ascertain whether it is possible to integrate BIM and BEM modelling to evaluate different energy saving solutions for an existing building. One of the research goals was to define a workflow to develop a building energy model starting from a geometric survey. Furthermore, the research aimed to investigate the extent to which the surrounding buildings affect the building performance simulation. It was decided that an effective and efficient survey strategy would be to use a drone in order to represent the building's surroundings. The objectives of the proposed workflow are to:

- determine how the context affects the energy consumption of the building;
- propose an example of an enhanced geometrical survey for the definition of the BEM of an existing building;
- compare the results obtained from the model with those of the model including the surrounding buildings.

2.2 Test Case

The test case is an existing social housing block located in the province of Trento (Italy) in a neighbourhood with other social housing (Fig. 2). The test case is a poorly insulated five-floor building with 32 apartments built in the 1970s.

Table 1 – Actual energy consumption of the test case

Period	Consumption [kWh m^{-2}]	Degree Days [K day^{-1}]
2006/2007	158.0	2344
2007/2008	149.5	2759
2008/2009	161.1	2767
2009/2010	159.3	2776
2010/2011	162.0	2605
2011/2012	146.1	2617
2012/2013	165.5	2776
2013/2014	147.0	2409
2014/2015	160.2	2252
2015/2016	170.8	2539

The heating system of the building uses a centralized boiler and the terminal units are radiators fed with a single pipe loop for each apartment.

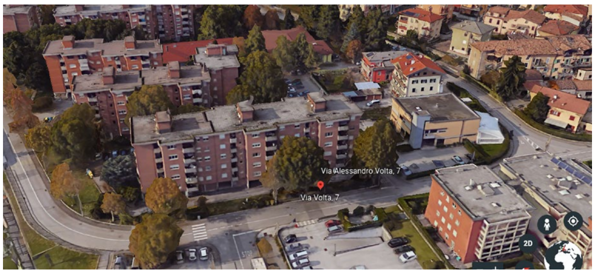

Fig. 2 – Framework of the context in which the case study is located

The building has high energy consumption for heating since it predates the first Italian energy law (enforced in 1976); details of the energy consumption are shown in Table 1.

2.3 Proposed Workflow

A good knowledge of the existing building is essential for designing effective retrofit measures. For this reason, the development of an accurate energy model was considered key. The study took five steps, as follows:

- the analysis of the as-built building and its surroundings
- the development of a three-dimensional model in a BIM environment (Building Information Model),
- data transfer from the BIM to BEM (Building Energy Model) (Fig 3) in order to create an energy analysis model (EAM),
- refinement of the EAM model in the energy simulation software,
- running of the simulation and post-processing of the results.

The first step involved the detailed analysis of the artefact chosen as a case study, the conformation of the orography and the building's surroundings. The analysis of the building's surroundings is key, as it effects the amount of solar radiation and, consequently, may have a significant impact on actual energy needs.

An analysis of a building's surroundings is often neglected in the energy analysis, as it is an expensive and time consuming activity, and involves difficult data collection. However, it is something that can, to a certain extent, impact on a building's performance and can also become one of the causes of the performance gap.

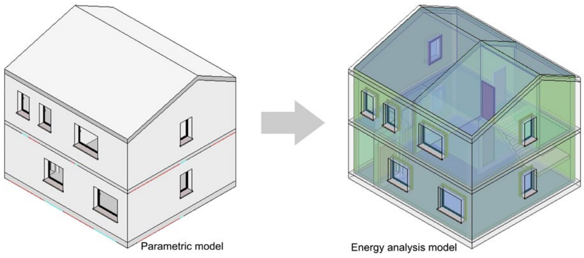

Fig. 3 – From the parametric model (BIM) to the energy analysis model (EAM)

In this study, the evaluation of the building's geometry and surroundings was carried out by exploiting advanced survey techniques.

The internal geometry of the apartments was detected through the use of a 3D laser scanner. This technique speeds up the survey and makes it possible to collect the internal dimensions. The procedure therefore allows the development of a BIM model that is more accurate than one based only on available original design documentation.

Similarly, an enhanced analysis of the urban context was carried out by using pictures taken by a drone (Fig. 4). A point cloud was obtained from the overlap of the different pictures taken by the drone through the use of post-processing software. The point cloud represents the size of the building and of the neighboring buildings. This cloud was subsequently imported into the BIM software (Fig. 5) and converted into a parametric three-dimensional model of the building (Fig 6). The three-dimensional model of the existing building and its surroundings is the first phase of the adopted methodological process.

The operational approach typical of Building Information Modeling, allows the organization of complex and structured three-dimensional models based on energy, architectural, structural and thermal data. Furthermore, a BIM model contains a systematized database, which can be used both for integrated building design and for the management of the building throughout its life cycle.

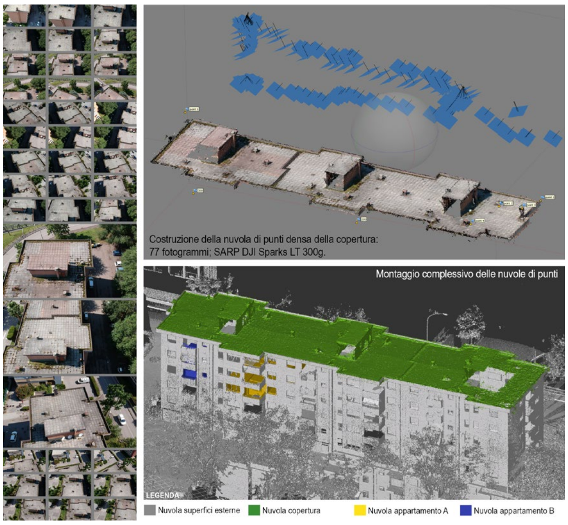

Fig. 4 – Point cloud acquisition through drone survey

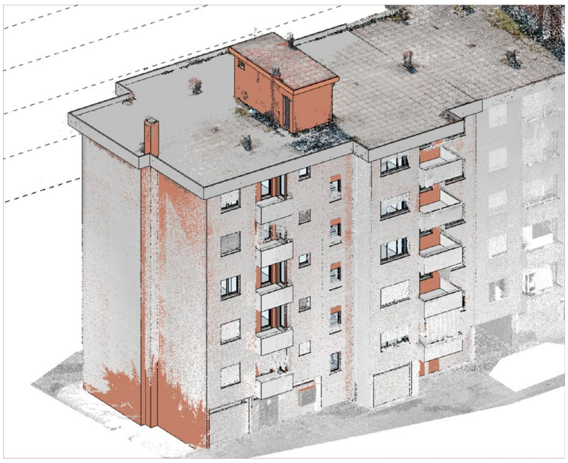

Fig. 5 – Parametric modeling based on the acquired point cloud

Fig. 6 – Importing the north block modeled into the context in Autodesk Revit 2019

The BIM to BEM interchange was divided into three distinct operational phases.

- **Analytical model**. According to the software definition, an analytical model is a simplified 3D representation of a structural physical model (Fig. 6). The analytical model consists of those structural elements, geometry, material properties, and loads, that together form the building. Autodesk Revit 2019 software was used for the development of the three-dimensional model in a BIM environment.
- **File interchange format**. The BIM software converts the analytical model in the gbXML (Green Building XML) export file (Fig. 7). This is one of the common interchange formats between BIM and BEM software (Fig. 9). The gbXML file includes all of the information about the building and HVAC systems. Fig. 9 identifies the surfaces that delimit the air volume of each thermal zone. This is the control volume on which the dynamic simulation software performs energy balances. Furthermore, information regarding wall layers, wall exposures and wall adjacency are connected to these surfaces, while air conditioning systems, internal gains etc. are linked to the volumes.
- **Import of the gbXML model** into the chosen energy simulation software. In this research, we used the Design Builder GUI to set up the Energy Plus model, run the simulation and to post-process the results;

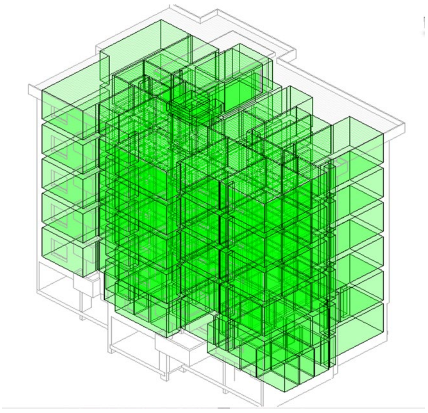

Fig. 7 – Export procedure using the gbXML format

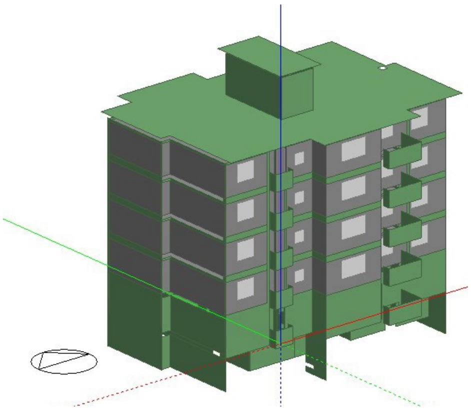

Fig. 8 – Importing the BIM model into Design Builder GUI

Two different exports of the interchange file were carried out in order to assess the influence of surrounding buildings on the energy performance of the test case. For this reason, in the first model, only the test case building was converted to BEM, while the neighbouring buildings were converted into shading elements only in the second model (Fig. 9).

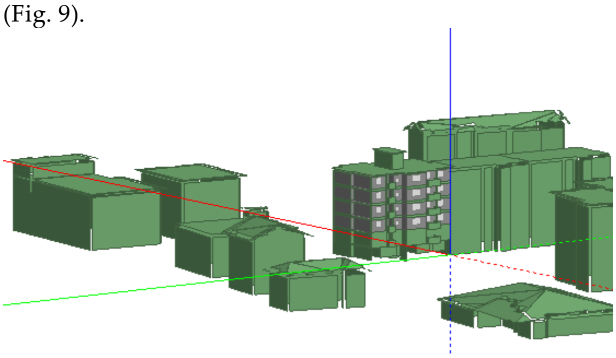

Fig. 9 – Importation of the context modeled within Design Builder

For both models, the simulations were performed by using a sub hourly time step, according to the Energy Plus references.

Internal heat gains were defined using a time dependent function, according to the utilization profiles specified in the Italian technical specification UNI/TS 11300-1 for different zones. The maximum gains were equal to 20 W·m^{-2} for the kitchen and living room, and 6 W·m^{-2} for the other conditioned zones. The natural ventilation rate (including infiltration effects) was assumed to be equal to 0.5 ACH (air changes per hour) according to std. UNI/TS 11300-1.

2.4 Retrofit Design

After a careful comparison of the results describing the building's performance, both with and without the surrounding buildings, the research turned to the analysis of possible energy saving measures. In this first phase, we focused on possible interventions to improve the building envelope. As suggested by the European Commission, the application of mature and off-the-shelf technologies can lead to a reduction of one third of total energy consumption. Insulation of the envelope and the replacement of windows are two common solutions.

One important issue can be the high initial investment cost of the energy saving measures on the façade, if the owner of a building has a low income. For this reason, an integrated and prefabricated façade solution was designed in order to limit the initial costs by reducing the amount of work required on site and the use of scaffolding. A second skin, made of timber panel, was anchored to the existing structure. The new windows were integrated into the prefabricated panels.

Through the dynamic simulation model, the optimal characteristics of the new wall were evaluated in order to limit energy consumption while taking into account construction constraints. A parametric evaluation of different insulation levels was performed by coupling a custom Matlab code to the Energy Plus simulation engine.

3. Results

3.1 Impact of Surrounding Buildings

The first results are those from the comparison between the performances predicted by the model, depending on whether the shading brought by the surrounding buildings is considered or not. Fig. 10 shows how the adjacent buildings cast shadows on the windowed surfaces of the case study building during some hours of the day. This aspect obviously affects energy performance and the peak power required by the cooling system. The graph in Fig. 11 shows the simulation outcomes when the interactions between the building and its context are neglected. The results show how the net energy required is mainly used for heating, with 103.8 kWh m^{-2} per year; energy use for cooling, by comparison, is 10.66 kWh m^{-2}. These figures are quite compatible with the data in Table 1, taking into account that the data in Table 1 relate to primary energy consumption, which also includes HVAC efficiency and the domestic hot water demand.

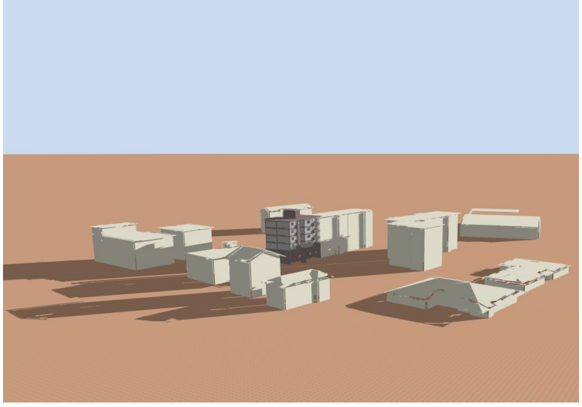

Fig. 10 – Shadows cast by surrounding buildings

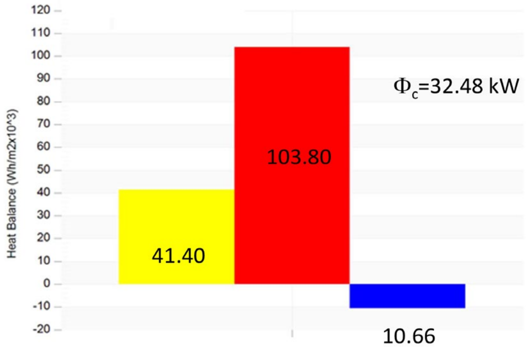

Fig. 11 – Solar gains (yellow bar) heating (red bar) and cooling demand (blue bar) predicted by the model which does not consider building surroundings

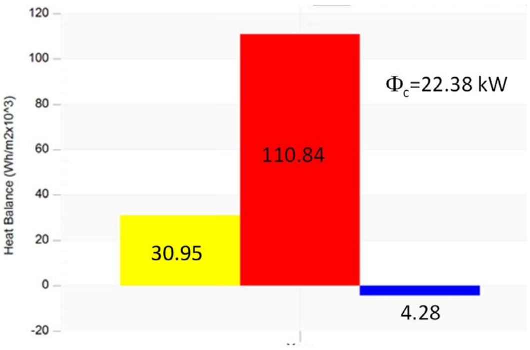

Fig. 12 – Solar gains (yellow bar) heating (red bar) and cooling demand (blue bar) predicted by the model which considers building surroundings

The graph also shows annual solar gains of 41.4 kWh m^{-2} and peak cooling power of 32.48 kW. Fig. 12, in comparison, shows a similar graph with the performances calculated using the detailed model which considers the shadows cast by the neighboring buildings. As can be seen, solar inputs are reduced by almost 25% during the entire year, which causes a 7% increase in heating demand and a 60% reduction in cooling demand. The more detailed model estimates a 31% reduction of the peak power required for the cooling system. These appreciable variations were obtained considering a passive use of the building. That is, variations in internal gains related to lighting fixtures or the activation of external screens by occupants were not considered. These aspects are closely connected to the urban context that the building is situated in: the illuminance distribution is affected by the shadows cast by the surrounding buildings. For example, Fig.s 13 and 14 show the different illuminance distribution on the third floor in the mid-afternoon on a winter's day.

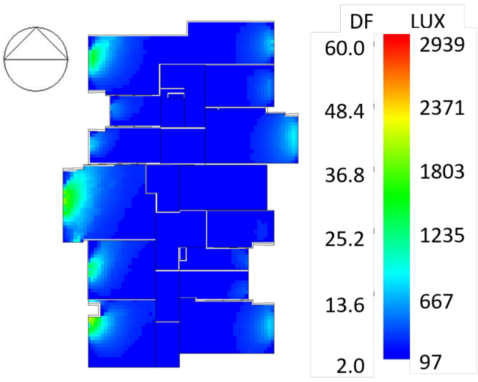

Fig. 13 – Illuminance and Daylighting Factor on the third floor on January 15 at 3 PM without surrounding buildings in the model

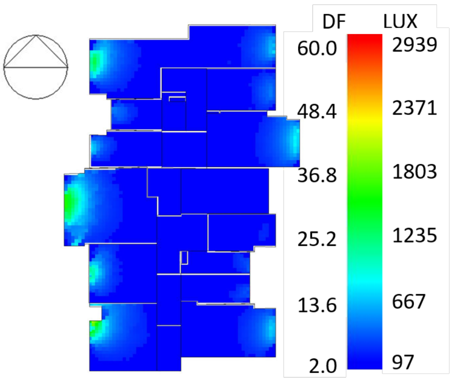

Fig. 14 – Illuminance and Daylighting Factor on the third floor on January 15 at 3 PM with surrounding buildings in the model

Although it is possible to note a different percentage of space in which the illumination level reaches the minimum threshold, this comparison still remains punctual and tied to the particular time of day. The daylighting autonomy (*sDA*) was therefore evaluated in order to obtain a metric that was more accurate in terms of lighting consumption, and therefore to internal gains. The *sDA* quantifies how often a minimum work plane illuminance of

300 lux can be maintained by daylight alone. It is defined as the percentage of occupied hours in a year when a minimum work plane illuminance threshold of *300 lux* can be maintained by daylight alone.

An appreciable variation in the percentage of hours of the year in which the minimum lighting level is guaranteed by daylighting can be seen by comparing the results in Fig. 15 to those in Fig. 16. These variations may have further impacts on energy requirements.

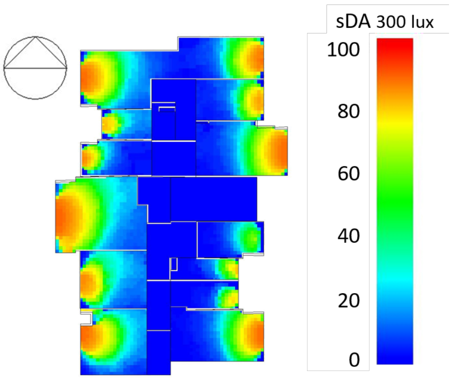

Fig. 15 – Spatial daylight autonomy with a 300 lux level on the third floor without surrounding buildings in the model

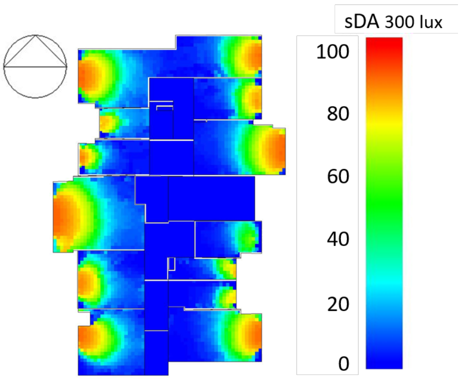

Fig. 16 – Spatial daylight autonomy with a 300 lux level on the third floor without surrounding buildings in the model

3.2 Retrofit Design

After the analysis on the impact of the shadows on heating requirements, a parametric analysis was conducted on the optimal thickness of the insulation to be installed on the external walls. Multiple EnergyPlus simulations were carried out by means of a custom Matlab script with the purpose of evaluating the extent to which insulation thickness affects energy use for heating the entire building (Fig. 17).

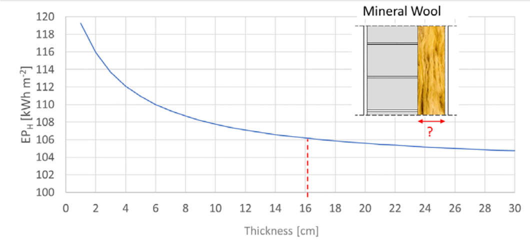

Fig. 17 – Results of the parametric analysis on the optimal insulation thickness

The graph in Fig. 17 shows a negligible energy performance increase for an insulation thickness greater than 16 cm. Furthermore, there are higher construction costs of the façade for a thickness greater than 16 cm, since this also requires a greater depth in the timber pillars. For this reason, during the design phase this insulation thickness was selected.

4. Conclusions

This paper has proposed a methodology to develop a simulation model of an existing building and its surroundings, using a drone survey and a BIM approach.

BIM and aerial drone mapping are suitable for building a context model. This method highlighted the importance of the correct modelling of the urban context even with simplified simulation input and despite the external obstructions not being particularly intrusive. Significant variations emerged in the building's heating and cooling needs. The biggest impact was on the cooling performance because of the key role of solar radiation. However, high performance buildings may also be more sensitive in the heating period.

Furthermore, the detailed modelling of the shadows cast by the surrounding buildings made it possible to evaluate the proper peak power for cooling. Neglecting the urban context leads to a 31% increase in peak power for the test case and, consequently, to the system being oversized, with a consequent reduction in operating performance.

Proper modelling of the urban context makes it possible to achieve a better characterization of the initial state of the existing building and therefore to design more effective energy performance solutions. In this work, for example, the detailed simulation model was used to evaluate the optimal insulation thickness to be installed on vertical walls.

Acknowledgement

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