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Black Box Effect in the structural project: avoiding it with BIM

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Abstract

The use of structural design software and their lack of transparency can provoke some uncontrolled errors in the structural design that put in danger the reliability of the structure due to the Black Box Effect. By integrating the structural project into BIM this effect can be greatly reduced. The article explores the effects of the black box in the structural software and their causes and consequences. From this point a study of how to deal with it integrating the design process in BIM is held with the will to prevent the Black Box Effect and ensure that the users have at any time a total knowledge of the project. At the end, different possibilities for the structural design project, that arise from its integration in BIM while avoiding the BBE and the advantages that the BIM environment brings to the design, are studied.

Keywords

Black Box Effect; BIM; Structural design; Architectural risk; Lean Construction.

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Introduction

Recently there has been a great change in the Engineering, Architecture and Construction Industry (AEC), due to the appearance and expansion of software based in Building Information Modelling (BIM) technology. The use of these programs has been growing since the 2000's decade and they are based in a completely new approach for the AEC. As Chuck Eastman stated, "This is an exciting time to be an architect, an engineer, or any other AEC industry professional" (Eastman et al. 2011). BIM has received a lot of attention both in the academia and in the industry, it provides technical benefits and an integrative working platform to improve the industry.

The concept BIM has experienced a significant diffusion nowadays and is used to refer to the software, the finished product or the working methodology, so it is necessary to stablish a definition. Based on Eastman's (2011) and the National BIM Standard of the United States (FAQ BIM 2016) definitions we can describe BIM as a technology related to the AEC based in the production of three-dimensional parametrical models of the project, but it is not only about the production of the models. In addition, these models must have the capacity of communicate, modify and analyse themselves. Everything in the model is updated in real time and is using parameters linked among the elements to share their properties. Thus, BIM technology has allowed us to create an n-dimensional model of a project that can be modified at any dimension at any time while keeping the parameters linked and updated.

This technology opens up a large number of possibilities in the AEC Industry as it allows a better control over the project and the exploration of new horizons to the AEC Industry. Several authors have proposed some possibilities: in (Sacks et al. 2010) and (Chong et al. 2017) we can find big matrixes analysing different proposals for the BIM future by different authors. Other researchers have started to work in a great variety of tools, to quote some interesting examples: Diao et al. (2011) present a tool that optimizes a project based on sustainability; Porwal (2012) has developed a plug-in which diminishes the trims in the reinforcement bars and Schlueter and Thesseling (2009) worked in a tool that reduces the energy consumption of the building through the life cycle. We can also find other researchers, whose work tries to implement Augmented Reality technologies or motion capture technologies into BIM (Eastman et al. 2011). Others are working in several industrialization processes coordinating the BIM with precast concrete in various ways. In conclusion, there is a lot of study being held these days around BIM, taking advantage of its potential. But if there is a main explored feature this is the process automatization in BIM.

Due to the n-dimensional nature of BIM it works like a big database with shared parameters linked between themselves. This promotes the use of different kinds of algorithms that seek to automatize several tasks. One of the most studied fields is the addition of sustainable criteria into the architectural project through the automatization at any project phase since the beginning. Diao's tool previously presented is one of these (Diao et al. 2011). We have developed a tool that optimizes a concrete beam based on economic and sustainable criteria (Fernández-Mora and Yepes 2017). There are also automatizations processes focused in other fields like the reduction of the shear amount of reinforcement bars used in slabs (Cho et al. 2014).

Every automatization developed has an overlooked risk inside it and the user can be induced to several errors by it. Automatization processes need to be previously programmed and follow different steps to arrive at a final result. The coder decides the way that it should work and has made some decisions about it, stablishing consciously or unconsciously criteria in the internal computation. The user must be aware of the internal procedure or is possible for him to commit some mistakes simply by not using the same hypothesis or criteria that the programmer. These unconscious errors are unknown by the user and are really hard to find out. What we have just described right now is

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Figure 1.
Black Box diagram.

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Introduction

In computing and engineering a Black Box is a system or a device which can provide an output from a given input, without any knowing of the internal procedures. Its implementation is completely unknown and opaque to the user (Cauer et al. 2000). This is a really wide concept and it includes almost any decision-making process -even human ones-. In this article the Black Box concept is used to describe any decision taken by the software without informing the user of it. In the AEC there is a lot of software that take this kind of decisions, but we are going to be centred around structural software only, due to big number of verifications that are held by it. There are of course, other verification processes which are affected by this and most of this research can also be applied to them.

The lack of transparency in plugins developed for BIM involves an uncertainty when using them. The more complex and difficult an automatized process gets and the more freedom that the program has to take unknown decisions, the higher the chance of errors created by the BBE. Additionally, the BBE control is more important whenever exact calculus is needed, and it becomes even harder to uncover the errors produced by it. Usually these mistakes are critical for the project's outcome. In this paper, we are going to analyse the presence of the BBE in the structural project integrated in BIM and find ways to avoid it. The first step would be to study at which point in the structural project the effect can appear and the potential errors that can cause. From there several solutions will be proposed and discussed. After that, we will argue the different ways to integrate the structural project into BIM avoiding the BBE, using the advantages that it brings.

Development

i. The computational need in the structural project

Nowadays there exists a tendency about structures that gradually increases the complexity in calculation. Historically two-dimensional structures with low hyper staticity or isostatic ones have been utilized and, this allowed them to be manually calculated. With the introduction of new structural typologies, like three-dimensional frames or two directional and waffle slabs, the structure's degree of hyperstaticity has increased. These typologies have a higher number of unknown values and need more difficult mathematical processes to be solved.

There is more than one reason to explain why the difficulty in the structural project has increased. The industry has been pushing for an augment in the demand and the requirement and to reduce the time used in developing a structural project. Moreover, the regulations have also increased the exigency and the sheer amount of verifications while new knowledge about the structural behaviour and different breaking mechanisms of the structures has been understood and studied. This obligates the structural engineer to obtain stresses and strains in a lot of points of the structure. In the end, due to these three reasons the difficulty of the structural project has grown exponentially in complexity and necessarily the professionals have to use a computer to solve it.

As tendency shows, in the near future this will not become simpler. Right now, questions away of the structural resistance have been proposed, like the sustainability or the constructability of the project and are gaining progressive importance. The classic tools have proved themselves insufficient to solve these new criteria and they are also unreachable to the hand-held calculation processes accurately. For this reason, in a near future the use of structural software will be even more man-

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datory to achieve a structural project and the software will be even harder to handle by the user.

New demands to the structural project, are an additional layer of requirements. So, to improve the current design and calculation process or to study how the BBE can be diminished we must start by analysing the working process used nowadays in different structural software. From this point, we could find a way to palliate the opacity in the software and start to add new functionalities.

As the software is essential to the structural project, we need to know how the calculation is held internally. Through history a lot of methods based on empirical experience had existed, but right now there are three that stand out from the others. These methods are the ones used by most of the actual regulations (Ministerio de Fomento 2008) and (European Commission 2010). For that reason, the structural software follows them. The first one is the permissible stresses method, based in the lineal elasticity theory and the idea of guaranteeing a stress value for each element that do not exceeds its resistance. The second one is the global coefficient method based on a condition that relates the resistance of the element with its loads. The third and final one is the limit state design method who uses this concept and a correlation similar to the previous one to compare the resistance and the loads, but this time weighted by coefficients in both, loads and material resistance (Cabrera 2016).

Regardless of the chosen method or software, the project must guarantee the reliability of the structure's final design once built. By reliability we refer to structural integrity -safety-, the tenants' security -serviceability- and of course guarantee the durability of the structure through the life cycle -durability-. According to the concept of reliability stated by the ISO 2394:2015.

ii. The design process in the structural project

In order to avoid the BBE and in addition to acquire a deep knowledge of the used software is necessary to know how and when it can appear. Next, we are going to analyse a usual structural project and find when in that process we need the software and what we are going to expect from it at any time. The analysis is based in the design process stated in Chi et al. (2014), the Fig. 2 summarizes the process.

In the structural project, there are different roles present since the beginning. Those can be carried out by the same person or not, which does not alter the design process. These roles are the architect, who is in charge of the architectural design; the structural engineer, in charge to verify and modify the structural model and also to guarantee its safety; and the constructor, who leads the building process. These three agents always interact together and constant feedback is necessary among them for the project to be completed. The structural design process starts with an architectural design at a point where structural performance can be requested to it. Due to the structural demands the project changes and adapts itself to them, at this point the most important step is to select a suitable structural typology that will respond to the requirements in an efficient way. This first attempt produces variations in the architectonical project and the subsequent introduction of new data in the structural project. This is an iterative process that goes back and forth a variable number of times until it arrives to a more definitive step of the architectural project. The first structural models are created in this phase and the dimensions of the structural elements are obtained. The architectural project is once more updated and the iterative process keeps going, this time renewing also the structural model and making each step longer and harder while closer to a solution.

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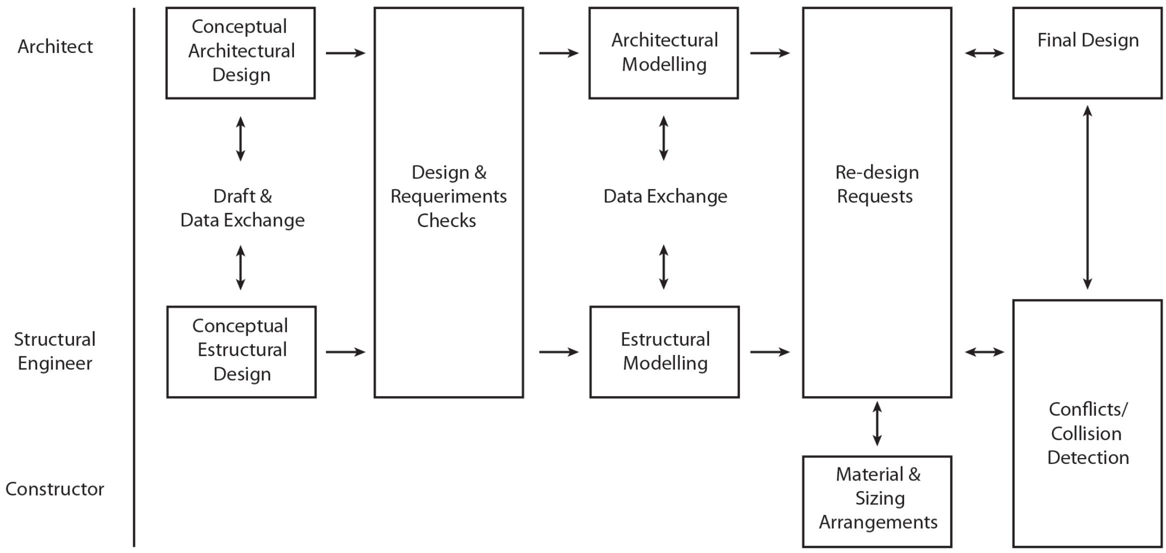

Figure 2.
Structural design process workflow diagram.

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Once the structural and the architectonical project are brought together a new step begins where the material properties are evaluated, and their availability is assured. At the construction site there can appear new issues due to difficulties in building each element. This will create modification in the structural model that will need an ulterior analysis. The design process has to add this procedure in a way according to its importance.

In recent years there a new criterion has been incorporated to the structural project, the sustainability. This criterion is mainly checked at the last steps of the structural design when there is no space for important modifications and most of the decisions have been made. So, the sustainability does not have a real chance to make a difference in the project. These verifications are time consuming and sometimes they are not worth doing when the final design is not settled because it can be wasted effort. This is mainly due to the big amount of data necessary to do this kind of verification -for example CO_2-eq.- which can only be completely acquired by the end of the project with the actual tools.

It stands out the great amount of iterations and data exchange among the different roles intervening in the design process. This implies a lot of feedback between different people that can lead to mistakes or data loss. It is very likely that the reintroduction of data in the structural model carries small mistakes, which are hard to detect, as a result of a lack of attention in the data that have been introduced or revised previously during the design.

iii. Possible errors caused by the BBE

Two things have been stated at the moment: The first one is that nowadays it is mandatory to use the computer to solve a structural project and achieve a detailed calculation that guarantees all the regulations and safety requirements. The second one, the structural design process follows a set of steps lead by different agents that cooperate between them constantly. We can also assert that there is not a single valid solution to the structural problem and this solution will not be found at the first iteration. So, as essential as it is to introduce new data several times in the structural model, each time is a chance of an error to be incorporated. There are different kind of errors that can appear:

-Data entry errors:
The most used structural software nowadays works externally to the design software. This means that when a structural model is made it has to start from a blank sheet and the data has to be inputted by the user and some deviations in the data values can arise. These values can come from the design software -project internal data- or from external sources and usually related to the structural analysis -project external data-. The repetitive modification of the data of each program can increase the error and the risk to it.

-Model errors:
The development of an incorrect structural model assuming a structural behaviour that does not correspond to the model. For example, assigning a wrong constraint to the encounter of two elements or not connecting elements that work together.

-Hypothesis errors: When developing the structural project, it is mandatory to assume some hypothesis -like the small deformations principle- most of the time determined by the calculation method used and the corresponding structural typology. The software can assume a different and erroneous behaviour or avoid some breakage mechanisms of the structure. An example of this is

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the use of shell finite elements when slab finite elements are needed due to the shear stress importance.
-Construction errors:
Errors causing an unbuildable construction, by either one of these two reasons: or the design suggested by the program itself can be unbuildable -beams and cantilevers without connection, non-existent materials, etc.- or the detail solutions proposed by the software are incoherent with the design -reinforcement bars that do not fit, non-weldable joints, etc.

Although experience is considered a great criterion to avoid the previously mentioned errors -because it provides to the user with an extra control tool- it will not avoid them always. Nevertheless, a deeper knowledge of the used software, will help to interpret the results and the data requested by the software in a better way and also avoiding mistakes. Therefore, even if they are completely considered, either of these two possibilities guarantee the completely avoidance of the errors and they are less advantageous the opaquer the program gets.

The BBE is not always responsible for the errors previously listed. Neither can we say that they are failures in the software, which probably has responded perfectly to the given instructions. Probably, the user is the culpable of these mistakes, but a better communication between the structural engineer and the software entails a higher ease to detect the errors and to reduce the risk of making them.

Results

i. Solutions to the BBE

The main cause of the BBE is a lack of transparency in the structural design software. This can provoke some of the errors previously stated. To avoid the effect and to reduce the risks related to it there are two possible solutions, which both modify the actual operational sequence of the software.

The first solution is based in increasing the software's transparency. So, to say, the programs need to show to the user the different steps kept to do the operations and every hypothesis is exposed to the user. To create a software with this in mind would erase the BBE, but it would also delete almost all the advantages of using structural software, because by continuously showing all the data to the user the automatization of the process becomes diminished. Neither would it be suitable for other reason, the computer process develops itself at high speed and a person is unable to keep up. Even if the process stops at each step to show the results to the user, the enormous amount of data will overwhelm him. At the end, the data would be ignored assuming that it is right. So, even if the steps are shown, that does not mean that

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the user gives them proper attention either makes them easier to be checked.
Nowadays the program CYPE[1] uses a similar method to the proposed one, it allows the user to know step by step where the program is in the process and later -when all the calculations have been done- the user can access the results for each structural element. This leads to the stated beforehand, during the calculation step the notifications are shown at such speed that are almost impossible to be followed by the user and later is hard to revise the huge amount of data which normally overwhelms the user who centres the efforts in the main elements and can oversee the mistakes.

The second solution consists in showing an estimation of the result to the user. In this way if the final solution differs from the expected one, the user is conscious that an error has been made. The problem of this approach falls on the fact that the main reason to use a structural software is the ignorance of the result, so to be in the need of knowing the result beforehand to verify it, is quite contradictory.

This can seem like a dead end, but in fact, it points to the right way. There has been a key factor left behind, to have an appraisal of the result and knowing the exact result are two completely different things. To avoid the BBE is enough to have an accurate estimation, a wide range of values where the final solution would probably lay. The smaller that this range of solutions gets, the better of the prediction and higher the control over the project. The method used to get to the rough number shall determine a pre-dimensioning and must reflect in the most accurate possible way the expected structural behaviour, because it needs to have into consideration the most critical breakage mechanisms of the structure. It is possible to have a range of solutions from the beginning if the structural engineer is quite experienced, but as we discussed before, this is not a factor that we can bear in mind. To control the BBE a rough number has to be kept in mind at any phase of the project.

ii. Erasing the BBE through BIM

Working with possibilities that both reduce the influence of the BBE and coordinate the previously stated solutions is something natural for the BIM methodology by using its advantages and working methods. Remember that when working in BIM the user is virtually building the project, not just drawing it in a three-dimensional space. The project is an n-dimensional build which has great control over all the parameters in it. This is one of the great advantages of BIM; the user is able to work with parameters of different kinds since the beginning and to take them into account. With this it is easy to diminish the BBE and to keep the structural design process.

1. CYPE is a compendium of different technical software developed by CYPE Ingenieros which is able to assist the AEC professional during the different verifications in the project. It can verify structures and installations, write reports, make budgets, etc.

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From the previous analysis, we can conclude that doing just one attempt at the structural project may accent the BBE, because there is less control over the real structural behaviour. So, the best strategy is to make iterations that slowly approach to the final solution that coordinates the structural and architectonical design. The studied design process already uses this method and keeps evolving the project whenever there is a modification, but due to the restrictions in the models and the amount of time required to re-elaborate them, normally the number of iterations is kept low. So, to implement a way against the BBE the existent working process among the different roles can be of use.

The integration of the design process into BIM allows a potentially infinite number of iterations and modifications over the structural model with almost no effort. It also implies that the architectural model can be modified according to the structural model requirements, in fact they become the same model. Moreover, at any time, modifications and verifications can be done. The data is inside the model and can be easily accessed and verified. This data keeps growing in number as the model progresses allowing the user to have more control over it. So, to say, since the beginning of the architectural model there are some rough numbers that can be done working fully into BIM using the data inside the model. This process can keep going while the data grows and the tests can be more accurate the more the model advances in its design and everything is available to the user. And there is no drawback either if the model is updated by several people. For example, an architect and a structural engineer working at different places or times, because the BIM model can be uploaded to a cloud server and developed from there. Fully integrating the structural design process into BIM does not greatly diminish the BBE, it almost erases it completely. If used in the right way it can avoid any of the mistakes that lead to the effect. On the one hand, there are no data entry risks because the data is always stored in the BIM database and there is no feedback between different software. On the other hand, the ease to repeat the structural computation complicates the existence of model errors or hypothesis errors, because by simultaneously observing both the architectural and the structural model is easy to coordinate the mechanical mechanisms between them. And also for this reason, the construction errors are easier to prevent.

The space for improvement of the structural design project by the use of BIM does not end here. Thanks to BIM being a n-dimensional model, new dimensions can be added to it and from there the structural project can be improved. I can easily incorporate new criteria like sustainability into the project, through a dimension that allows controlling it -like CO2-eq.-, or using several dimensions together to implement optimization algorithms in the structural elements to obtain the best possible solution for each element based on their performance in those dimensions. The potential for BIM is limitless right now and it can avoid the BBE with ease while incorporating new tools which right now are still undeveloped.

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Conclusion

In this essay, risks derived from the BBE in the structural building project have been revised, which is to say, the risks of committing a mistake due to the lack of transparency of the structural software. In addition, the causes of this effect have been exposed and the errors motivated by it have been classified. Finally, two ways of diminishing the BBE have been studied and the advantages and method of integrating them and the structural design process into BIM have been discussed.
Next, we are going to quote the most important reached conclusions:

- The black box effect is a real risk that can induce important errors in the structural project which can compromise the reliability of the structure.
- The most important thing to have in mind when using a structural design software is a critical view over the results obtained and the ability to check them.
- It is necessary a deep knowledge of the software chosen for the structural project to be able to understand the results with accuracy.
- A great way to reduce the BBE is achieved integrating the structural project into a BIM environment.
- The BIM environment offers a huge number of new possibilities to explore in the structural project and they allow the project to focus the study from new points of view and to take into account new factors that previously were almost impossible to handle.

The use of BIM is not only attached to advantages, like every method it has its drawbacks and deficiencies. It is a new paradigm with great potential and unknown limits, but with a completely different focus that the one used until now. To project using a Building Model implies that the team knows and assumes the corresponding methodology. In the contrary, taking BIM can be a total failure and cause some unwanted effects even worse that the ones that are prevented or the achieved advantages.

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