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3D and 4D Models Used in Bridge Design and Education

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Abstract

A bridge is the type of structure whose appearance normally deserves more attention because it not only has an evident impact on the environment but also represents considerable investment, both of which justify careful evaluation. The aesthetic analysis is an important issue that must be considered when designing a new bridge, especially when it is to be built in an urban or road environment. In this context, the automatic generation of three-dimensional (3D) geometric models of the bridge under analysis, and the walk around and aerial simulation allowed over it, which can be generated, helps bridge designers to evaluate its aesthetic concept and environmental impact. The bridge construction process can also be simulated, helping designers and builders to review the progress of the construction work in situ. For that, 4D (3D + time) models of the most frequent bridge construction methods were generated, using virtual reality (VR) technology. The simulation of the construction activity made possible by the developed interactive 4D model helps bridge designers to analyse the whole construction process. The present study aims to analyse the mechanisms of how to generate 3D models of a bridge automatically and how to simulate its construction using VR capacities.

Keywords: bridges, automation, 3D models, 4D models, construction, virtual reality

1. Introduction

The visual impact of an urban overpass or bridge inserted into a road network requires a careful study of its aesthetic aspect by its engineers. The importance of the aesthetic analysis of the infrastructure design in serving the public good demands special attention because of the densely built-up nature of the site where it is to be inserted that necessarily calls for order, discipline and aesthetic values [1]. Moreover, it is also important to analyse the environmental

impact of a bridge, especially true of urban overpasses with regard to their more intrusive location close to areas of the pedestrian use.

Much of the public focus has been centred on several "landmark" bridges [2]. Denn [3] specifies aesthetic guidelines for bridge design, remarking that a careful and early application of aesthetic concepts can make a significant improvement in the appearance of bridges and structures. Every bridge is, to some degree, a historical document, a demonstration of structural technique, a performance test of building materials, a comment on the values of a society which produced it and a reflection of the richness or poverty of its designer's imagination. So, the bridge designer must strive to understand the creative process, together with scientific and technical principles. The aesthetic aspects that stimulate the senses in most viewers are proportion, order, simplicity, balance, colour and texture. Design bridges must incorporate these aesthetic principles with the physical and geometric components of the structure.

In this context, the generation of three-dimensional (3D) geometric models of bridges, which are to be designed and analysed, can play an important role. For this purpose, a computer graphic system, which enables the 3D geometric modelling of decks of the most frequent types of bridges, was developed. With this tool, the geometry of the bridge shape can be directly inserted into the computer application, using the user-friendly interfaces with geometric parameters of the longitudinal view and cross section of the bridge deck. In this way, the description of the geometry, conceived for each case, is easily achieved. In addition, it satisfactorily supports a rapid definition of several suitable alternative solutions for the bridge.

In addition to the 3D model of a bridge allowing its aesthetic analysis, it also supports the creation of 4D (3D + time) interactive models simulating the construction work. In order to create interactive 4D models, simulating the sequence and progress of the construction process, techniques of virtual reality (VR) were used. The designer links each construction task, established in a Gant map, to specific 3D model components, and programs the simulation of the bridge construction process, using the VR software. The virtual interactive 4D model allows users to view and interact with these construction stages and with the equipment involved in the process.

The incorporation of VR technology into 3D geometric models allows greater realism in the simulations; it is, now, often applied in the field of engineering perhaps because VR technology constitutes a good interface and provides the possibility of finding solutions to real-life problems in the construction field.

2. Automatic generation of 3D models

As aesthetic value is important for civil engineering projects, which impact urban and natural environments, it can be incorporated in curricular programs in engineering schools. However, the attention to structures traditionally dominates in the modern day university education of civil engineering, and the teaching of aesthetics meets obstacles. The main difficulty is the thought that aesthetic values are unfamiliar to engineers. This leads to the need for the

formulation of main aesthetic thought into clear principles and rules that will help designers to learn and apply aesthetics to their design work.

Because aesthetics must be a part of the program for a bridge from the very beginning, this consideration must become the responsibility of every bridge engineer and must be an essential part of bridge engineering decisions at every step of the bridge design process; aesthetic consideration must be integrated carefully into the design of each detail of the bridge and its approaches [3].

To allow an easy and accessible evaluation of the visual appearance of a bridge, an intuitive tool to generate 3D models of bridges was developed. The application is an important tool to stimulate the diffusion of aesthetics in engineering projects and to simplify and support its analysis. The computational application allows the introduction of geometric data and organizes them in order to create three-dimensional models of the bridge. It also allows the user to generate the usual technical drawings required in the graphical documentation of a bridge design.

The computer application developed supports two bridge types: overpasses and box girder bridges. The computer application generates 3D models based on DXF format, an exchange code recognized by many CAD systems.

2.1. Overpass bridges

Overpasses are structural solutions that allow crossroads on different levels. They are usually used when a high-speed road or a road with intense traffic must be crossed, usually by a secondary road that passes above the dominant one (**Figure 1**).
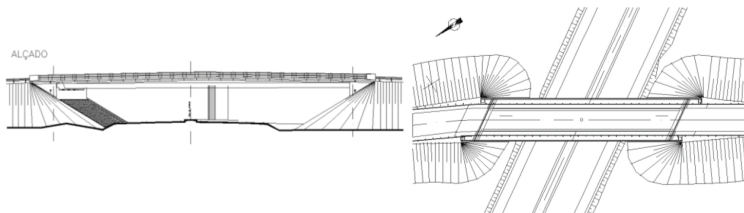

Figure 1. Overpass longitudinal and top views.

An overpass has a very significant visual impact but usually, such a careful aesthetic evaluation as that conducted for bridges is not considered necessary/worth the effort. The aesthetic analysis can be organized into two categories [3]: visual design elements and aesthetic design qualities. These structures have a high level of exposure, especially when they are in urban areas, so they should receive a special aesthetic analysis so as to provide a comfortable level of impact. The focus of the analysis is oriented to the shape of the bridge aesthetic aspects such as linearity, setting, brilliance, roughness and smoothness or aggression of shapes.

In the aesthetic study of an urban overpass, the implemented 3D modelling tool allows the easy creation of several solutions for the bridge, with distinct longitudinal shape and different

type of deck cross section. The ability to create of 3D models easily, allowing the visualization of each alternative option, supports decision-making regarding the best solution for the bridge [4]. The interface of the overpass 3D modelling tool is composed of three main windows where the required parameters and supplementary information must be introduced. **Figure 2** shows the interface windows concerning the longitudinal deck shape and two types of cross-sectional shapes.
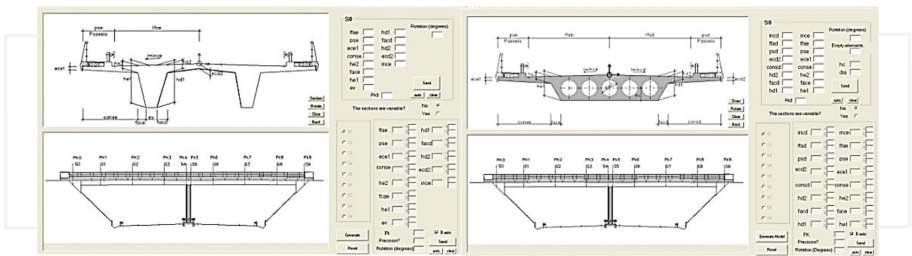

Figure 2. Interface of T-beam and slab section types.

The modelling process is based on geometric parameters allowing the definition of the bridge geometric configuration. It is not needed to indicate the vertices coordinates and the type of drawing element. Based on the parameter's values, the program allows the automatic generation of the desired bridge shape. So, the program makes possible to automatically generate 3D models. The parameterization was applied to two types of most used overpass sections, T-beam and slab (**Figure 2**); to linear and parabolic longitudinal variations of the deck and to the road geometry in plant and vertical views.

The program was created using Visual Basic programming language, and it is made up of three main windows. The cross-sectional window is presented in **Figure 2** and the horizontal and vertical alignment windows in **Figure 3**. The interfaces enable the definition of all the possible variations of the geometry of the road. For this purpose, the tool allows the geometric characterization of all design parameters needed, namely linear alignments, circular curves, transition curves and parabolic curves.
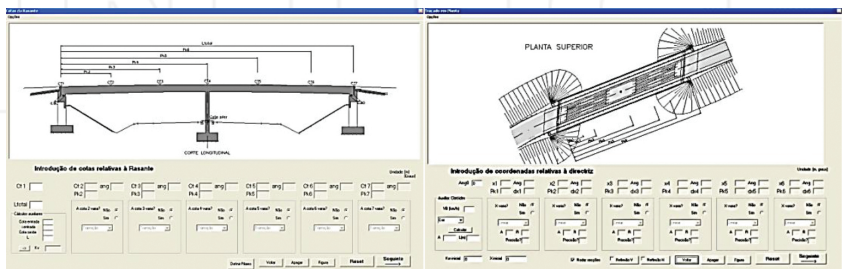

Figure 3. Vertical and horizontal alignment windows.

The program was tested in a case study. A first 3D model of the bridge was created, followed by several possible alternative solutions (**Figure 4**). The initial solution is a solid slab cross section with constant height, and the alternative options are as follows:

- a slab cross section with longitudinal linear height variation and parabolic height variation;
- a T-beam cross section with constant height, longitudinal linear height variation and longitudinal parabolic height variation.

Figure 4. 3D model of the original and alternative solutions.

In addition, the program enables the consideration of as many pile forms as the engineer wishes for, with any longitudinal or transversal forms. This versatility made offered by the program facilitates a more thorough aesthetic study. The use of parametric computer programming makes it possible to quickly obtain the 3D model of the overpass and many alternative solutions under analysis. So, it allows users to carry out a more accurate study of the overpasses' aesthetics, supporting the comparative analyses between different possibilities and consequently the choice of the most suitable option. The modelling process should be done in steps, beginning with a global analysis of all the possible solutions, continuing with the consequent elimination of some of them and going on to more accurate and detailed analysis of a smaller group of possible solutions. This provides the opportunity to choose the solution that presents a good rhythm and a pleasant sense of continuity to the structure.

2.2. Box girder bridge

The same application has the capacity to generate 3D box girder deck superstructures [5]. The tool allows the creation of consecutive cross sections, exactly defined and correctly located,

along the deck (**Figure 5**). The interface presents diagrams linked to dimensional parameters, in order to facilitate the description of the geometry established for each concrete case of the deck. The 3D model is the result of an appropriate combination of two longitudinal geometric components: the deck morphological evolution and the layout of the road, which acts simultaneously over a cross section, defining the exact deck shape'. The Annex item includes the algorithms used to calculate the 2D coordinates of each vertices of this type of cross section.

The geometric database, needed to create the 3D model of the deck, is formed by a set of geometric parameters, which the bridge designer deals with at the conceptual design stage. To obtain the 3D model of a deck segment, consecutive sections corresponding to the construction joints are generated using the algorithms of the program and connected to surfaces. The final configuration of the deck is comprised of two longitudinal surfaces: one representing the exterior side of the deck and the other its interior. The top cross sections are finally added to the 3D model (**Figure 5**). As this model uses cross sections correctly defined in shape and in their spatial orientation, it represents the real form of the deck. After the deck, 3D model is completed with the pillars and abutments, and it is inserted into the landscape. The aesthetic evaluation can then be carried out.
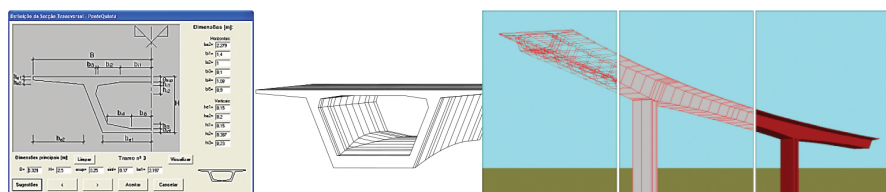

Figure 5. Box girder cross-sectional interface and 3D model.
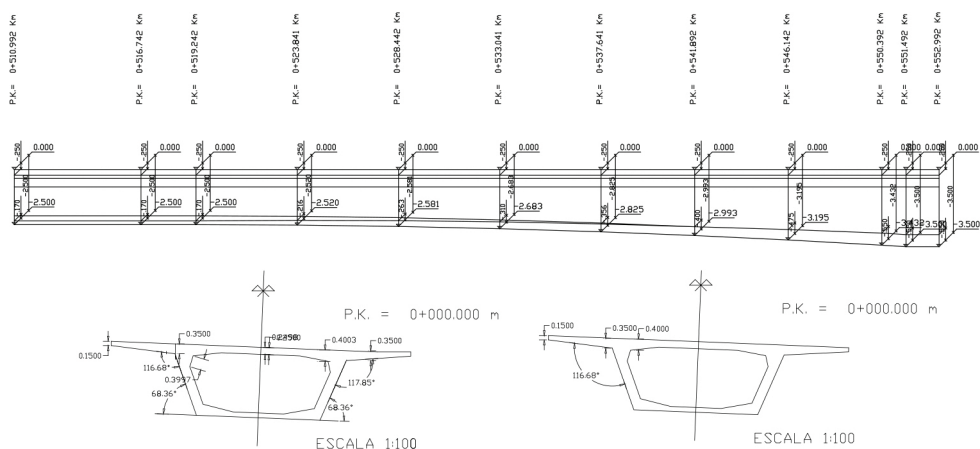

Figure 6. Longitudinal section and cross sections with different shape and transversal slope.

The implemented software allows the definition of traditional drawing usually required in a bridge project. As the horizontal alignment of the road is normally curved (**Figure 5**) and the road surface is never horizontal, the longitudinal deck section drawing must correspond in order to make a plan of the cut vertical surface defined along the deck axis (**Figure 6**). In this type of drawing, the elevation of the deck at distinct points along it needs to be calculated (**Figure 6**). These values depend on the elevation alignment characteristics. It is also a complex procedure to represent a set of consecutive cross sections with different interior and exterior shapes along the deck.

3. The simulation of the construction of a bridge

Technologies supporting 3D modelling and interaction with the models, which add to a better understanding in the teaching-learning in the classroom, have been introduced into schools [6, 7]. In particular, information and communication technology applications in higher education have been reported as improving learning, especially in course – based team learning and collaborative learning [8, 9]. In the field of education and training virtual reality (VR) technology has been used as a leading way for a better understanding of didactic issues, performed in face-to-face classes or in e-learning platforms. VR technology has proved very useful in the teaching of incremental processes [10]. The models that allow the visualization of the construction process of a building or bridge are 4D models, that is, they use the time factor linked to 3D construction components.

When implementing a 4D application, the designer must have a clear idea of what to show, because the objects to be displayed and the details of each one must be appropriate to the goal that the teacher wants to achieve with each specific model. In the development of the 4D bridge models, VR techniques were used, in order to improve their efficiency by allowing the interactivity by all parties involved in each type of bridge construction [11].

The 4D applications that were developed concern some of the most widely applied method-ologies in bridge deck construction [12]. The 4D models allow users to demonstrate a process and present, briefly, the fundamental theory of the process or provide full information concerning the experiments. In the field of civil engineering, there are several construction methods for the building of bridges. The most frequent constructive processes for bridge decks are (**Figure 7**): bridge deck formed by precast beams [13]; cantilever construction [12] and the incremental launching method [14].
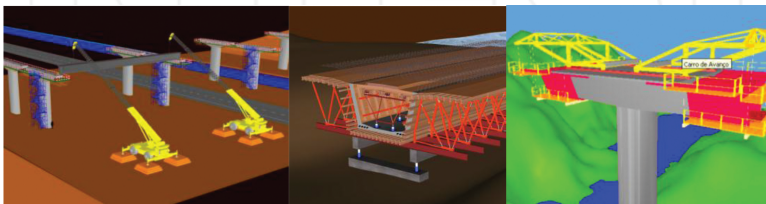

Figure 7. Methodologies of deck bridge construction.

In order to establish the principal characteristics of each construction method, to define the type and quantity of the construction components needed to be modelled for the simulation of each construction work and, also, to perform the correct sequence of operations, the bibliographies concerning the three methodologies of bridge construction were consulted [12–14]. Based on this information, the 3D model of each type of bridge was generated and the corresponding sequence animation of each construction process was programmed. Because specialists in construction processes and bridge design were consulted in the implementation of these 4D models, the final product is efficient and accurate. Through direct interaction with the models, the progress of the actual construction process of the bridges can be monitored.

3.1. Bridge deck composed of prefabricated beams

The construction method for decks composed of prefabricated elements is frequently chosen in construction works over railway lines, and, in general, in areas where the placement of trusses is difficult. This is because these bridges offer several advantages in urban areas, as they allow quick and economical construction without generating significant local constraints [1]. In a bridge deck, the prefabricated beams present an equidistant distribution. The slab complemented "in situ" uses pre-slabs as lost shuttering and as reinforcement during service, contributing to the structural strength of the deck. The most common cross-sectional type of the prefabricated beams is an I-shape.

The first step of the constructive method consists of placing the prefabricated beams on the pillars and can be carried out by means of cranes (**Figure 8**). The connection between the beams is made using pre-slabs.

The 4D virtual model that was implemented presents the construction of a deck composed of 4 precast I-beams, lifted by cranes onto the pillars and supplemented with composite pre-slabs [13]. Initially, 3D geometric models of all the elements necessary to simulate the construction process were created, including the surroundings of the construction site, the pillars, the stair towers, the worker platforms, the provisional and the definitive supports and two cranes needed to lift the precast beams (**Figure 9**). The 3D model of a prefabricated beam includes reinforcements running out of the beam.

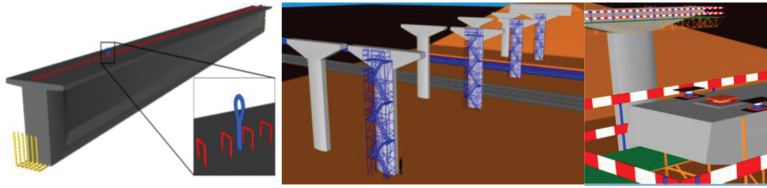**Figure 8.** Placement of precast beams and pre-slabs.

Figure 9. 3D models of beams, pillars, stair towers and worker platforms.

The virtual simulation of the construction activity starts with the presentation of the workplace, followed by the insertion of additional elements, such as the stair towers (for access to the top of the pillars) and the work platforms (which allow the workers to move around and complete their tasks). The sequences of activities in the virtual space are as follows (**Figure 10**):

- the definitive and temporary supports are placed on the top of the pillars;

- the beams are raised by two cranes and placed on the support elements;

- next the pre-slabs are placed on the prefabricated beams;

- the reinforcements of the slab are placed, and finally, the deck slab and the transversal beams are concreted.
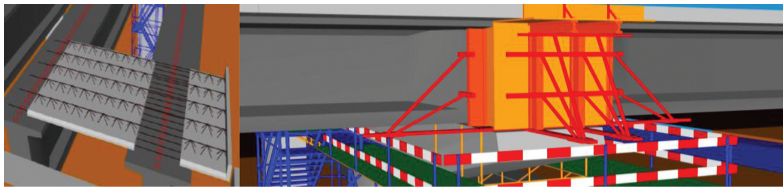

Figure 10. Construction sequence deck composed with prefabricated beams.

After finalizing the construction of the deck, the provisional support devices are removed, and all complementary elements necessary for road traffic are placed above the deck. The complete bridge can now be observed from any point of view (**Figure 11**). The model allows the user to use the zoom sufficiently well in order to understand the final configuration of the bridge.
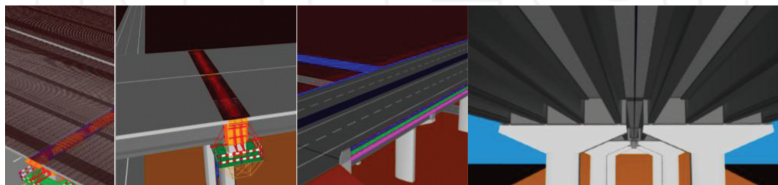

Figure 11. Views of the complete deck.

3.2. Incremental launching method

Another interactive model for the construction of bridge decks was created. The construction of bridge decks using the incremental launching method has existed from the 60s. This method consists of casting segments of the bridge deck in a provisional formwork, and then, each segment is pushed forward along the bridge axis. This method is used in viaducts crossing high valleys. The cross section of the bridge must have a constant height, and the most suitable type of cross section is the box girder.

Using the VR model is possible to follow the visual simulation of the construction sequence and to learn how the equipment is moved [15]. In order to perform correctly, the construction simulation activity every construction components and equipment was generated as 3D models (**Figure 12**), and the EON studio, a VR-based software, was used [16].

The main steps of the construction process are as follows (**Figure 13**):

- the external panels of the shuttering are first placed followed by the reinforcement mesh;

- after, the interior false work is placed incrementally in sequence, starting with the metallic element, followed by the longitudinal beams, the shuttering panels and finally the launching nose are assembled;

- a first segment is casted, the nose is removed, the segment is separated from the shuttering, and displacement of the element takes place.

For the following segments, the process is identical. In the final phase of the construction the worksite yard is removed. Finally, all the finishing elements are positioned. Because consideration was given during its development, both to technical knowledge and to its use in education, in particular how and what to show, the 4D model could be an important teaching tool to illustrate bridge construction issues during training. The application is designed, not only as a learning tool, but also for use by professionals involved in the construction of these types of bridges. Note that a film was created showing the interaction with the VR/4D model (available in [14]).
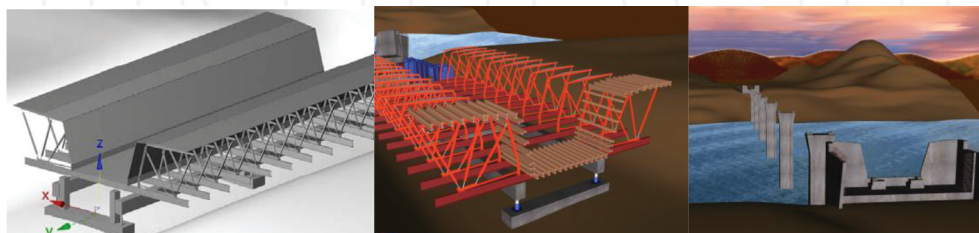

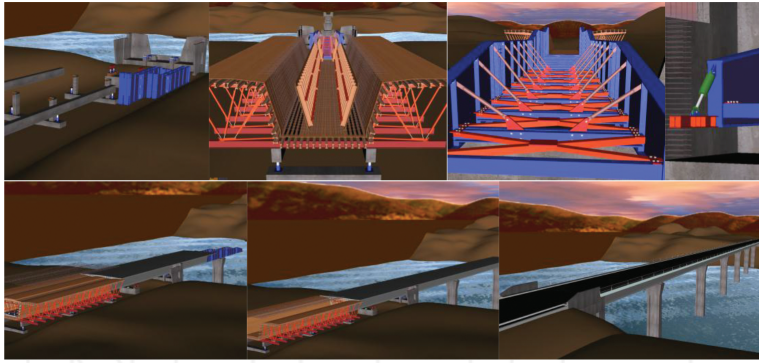**Figure 12.** 3D models of the construction elements and landscape.

Figure 13. Sequence of the incremental launching process.

3.3. Cantilever bridge deck construction

A further 4D model allowing the simulation of the cantilever method was created [17]. Students and teachers are able to dictate the speed of the process, in order to observe the movement of advanced equipment and how to place each elements of the bridge. The sequence performance is programmed using the VR software followed by an appropriate planning guides for this type of construction.

The case study has a box girder cross section, and its height varies parabolically along three spans. The most common construction technique for this typology is the cantilever method of bridge deck construction.

The aforementioned computer graphic system allows the generation of the deck segments needed for the construction simulation of the bridge [5]. To complete the virtual scenario of the construction site, the advanced equipment, the formwork adaptable to the size of each segment, the platforms for the workers and the false work to be placed near the abutments were also modelled (**Figure 14**).
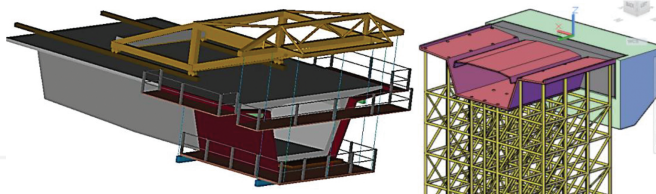

Figure 14. 3D models of a deck segment, the scaffolding and the advanced equipment.

The input and support of bridge designers, not only on the geometric definition of the bridge components and devices, but also on the establishment of the progression sequence and the way the equipment operates (**Figure 15**) were essential to obtain an accurate model:

- a first segment is concreted on each pillar and is installed the work equipment on it;

- the process of concreting segments is defined in symmetrical way, starting from each pillar and using the advanced equipment;

- the continuity of the deck is established with a closing segment, using just one advanced equipment;

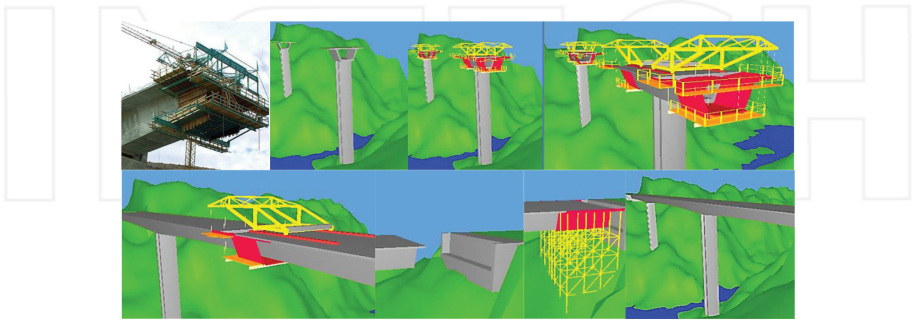- finally, near the abutments, the deck is constructed, using a false work.

Figure 15. Sequence of the cantilever construction process.

In a real construction site of a bridge, for security reasons, the student is obliged to stay far from the zone where a bridge is under construction and thus cannot observe, in detail, the methodologies or the progression of the construction. However, while using the interactive virtual model, by moving the camera closer to the virtual bridge and applying to it routes around the zones of interest, the student can follow the sequence specifications and observe the details of the configurations of the construction components. Being able to interact with the bridge models therefore should help students gain better understanding.

3.4. Integration of interactive capacities

The attribution of virtual properties to the models in each application was defined by using the VR-based tool, the EON studio [16]. The implementation of the interactive model, con-
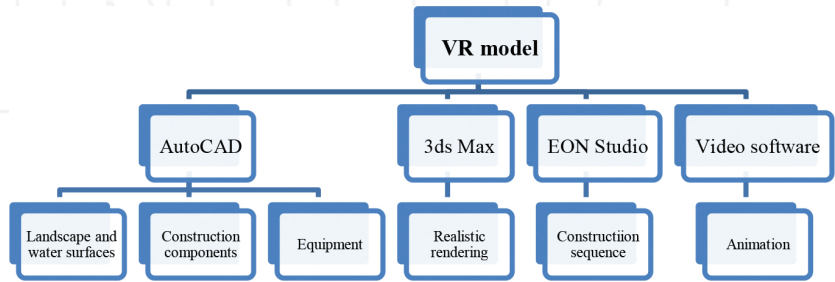

Figure 16. Software used on the implementation of a VR model.

cerned with the incremental launching method, is based on several linked applications as shown in the chart in **Figure 16**.

In the implementation of the 4D model for cantilever method, 3D models of the box girder bridge and of the environment were transposed (as 3D Studio Objects in **Figure 17**) to the EON Studio. The EON system is object programming-based software: the nodes window contains all actions that can be associated to the elements included in the simulation tree window. For instance, the advanced equipment model is identified, in the simulation tree shown in **Figure 17**, as a group or frame, designated as a "car."
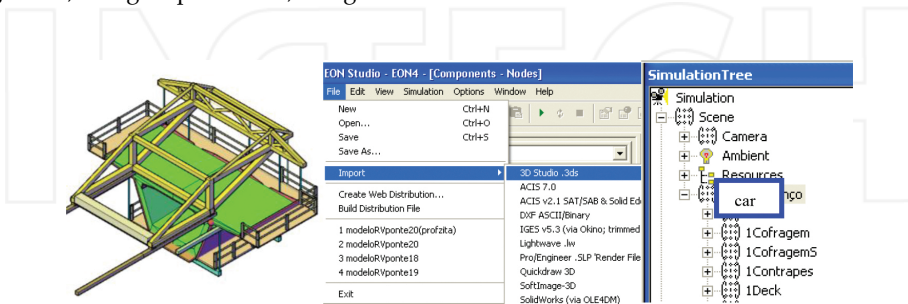

Figure 17. 3D model of the advanced equipment in 3DS format and the EON system main interface.

The definition of the construction sequence is based on a *counter* option button, which determines the next action in the process. The first action consists of the insertion of pillars in the landscape. When the components of the model are transposed to the EON, every element, except the landscape, is associated with the hidden characteristic The order to display an element is commanded by the counter node (**Figure 18**), which contains the logical instruction, which means when the value in the *counter* is accurate, then the associated element will be displayed. Consequently, when the mouse is clicked, the counter indicates the next element to be displayed. The correct programming will simulate the steps of the real bridge deck construction.
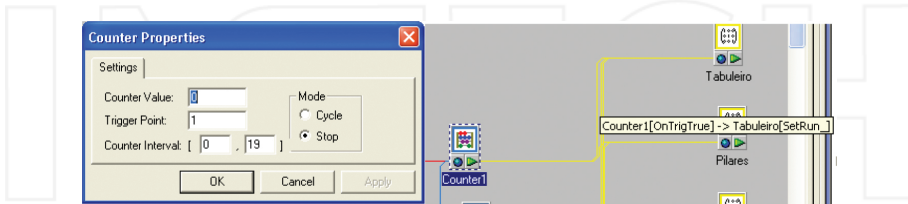

Figure 18. Counter node.

3.5. Educational considerations

The aim of the practical application of the VR models is to provide support in civil engineering education, particularly in those disciplines relating to bridges and construction processes in

classroom-based education. They can also be used to assist professional training and distance learning based on e-learning technology. When this visualization tool was being designed, human perceptual and cognitive capabilities were taken into account [18]. It means that the program is suitable for use in a wide range of learning environments or stages of education.

The traditional way to present the curricular subjects involved in these virtual models is through 2D layouts or pictures. By using the 4D models, teachers may help the students to visualize and engage with the construction process more interactively. The following are some advantages of using the 4D models:

- The 4D bridge models show the complexity associated with the construction work on the deck. The models also illustrate, in detail, the movement of the equipment. In class, the teacher can/has to explain how the process must progress and the way the equipment operates (**Figure 19**).

- The incremental method model presents the geometry of the different elements and the materials used in real work processes in all their complexity. The camera movement shows the model in a consistent manner when presenting the sequences of all events that are programmed. It allows the user to acquire a correct understanding of the most important aspects of the construction method. In addition, to allow consultation of the required data in any phase, information about the construction process is integrated into each new component or step (**Figure 20**).

- The fact that the models are going to be used by undergraduate civil engineering students was taken into consideration. The models support the learning process by illustrating the bridge construction issues and by presenting the geometric details involved and the technical information that must go with each constructive step. The details available in the 4D models complement the educational applications, rendering them more useful and efficient. The students will get better understanding of the construction operation and be able to make full use of this knowledge when they go on an educational visit to the construction site as they will have been previously exposed to the essential information This type of model allows the participant to interact in an intuitive manner with the 3D space, to repeat the sequence or task until the desired level of proficiency or skill has been achieved, with the extra advantage of this practice being carried out in a safe environment.

The introduction of the VR model as a new teaching tool in construction and bridge disciplines has been well accepted, although some difficulty in the manipulation of the model was reported. However, this kind of new technological material, based on 3D/4D interactive models, is important in a modern class setting and deserves attention.

Teachers are the key players in the educational process and are the main determiners of quality in the classroom, so they must be kept up to date with new technological material that can contribute to the enhancement of quality in education. Therefore, this new concept of VR technology applied to educational models can bring new perspectives to the teaching and learning process for civil engineering education.
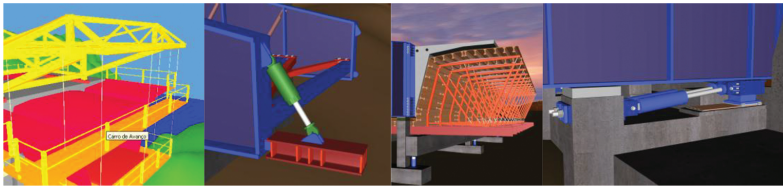
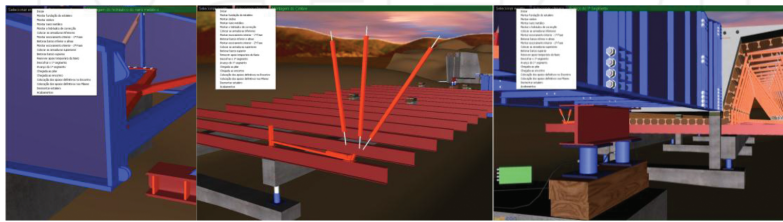**Figure 19.** The models show in detail the movement of the equipment during the construction process.

Figure 20. The menu of events supports interactivity with the model.

4. Conclusions

Aesthetics has an important role to play in civil engineering education and must become an integral part of all civil engineering disciplines in order to minimize their possible negative impact on the environment and maximize the possibilities of improving it. The world is becoming more sensitive to this necessity, and the range of tools at our disposal for this is increasing. The new technologies are becoming more powerful, and we should make them more usable. This work describes the implementation of software that contributes to the visual analysis of bridge structures. A generative program to define bridge decks with several cross-sectional types was created by using 3D geometric bridge deck models. The usefulness and applicability of the program were successfully tested on several cases showing that the 3D models are simple to create and to adapt with those modifications clearly needed during the development of the bridge design.

In addition, the text describes the implementation of interactive models that simulates the construction work activity of some constructive processes concerning bridge deck methodologies. Virtual reality (VR) capacities applied over the 3D models of the bridges allow interaction with the construction process contributing to better understanding of the whole construction methodology. The model 4D (3D + time) offers important advantages in the construction field, allowing the student to learn about the composition of a bridge, the sequence established for each construction method and observe the movement of the equipment.

The text shows the application of new technologies to stimulate the diffusion of aesthetics in engineering projects, to follow the construction process and to simplify bridge analysis. The
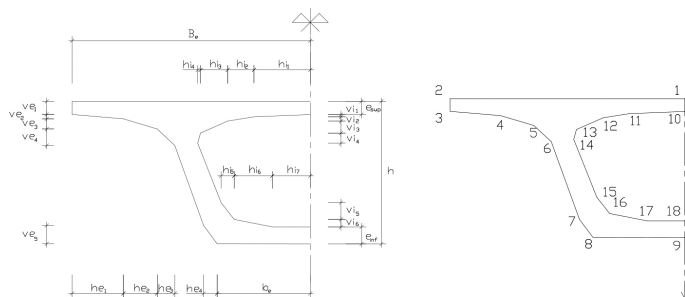
bridge VR/4D tools developed can be considered as improvements when compared with traditional ways of presenting the bridge construction issues in support of the construction activity and of training in these processes.

The main objective of this practical application of the model is to support the understanding of the construction process and to assist training professionals. This chapter shows that the applications with these characteristics make the advantage of using techniques of virtual reality more self-evident, especially when compared to the simple manipulation of complex models, which cannot be broken down, in it a useful contribution to the field.

Annex

The parametric cross sections of the box girder deck and algorithms to obtain the (x, z) coordinates of each vertices.

The geometric parameters set is {*Be, be, h, ve1, ve2, ve3, ve4, ve5, he1, he2, he3, he4*}. The coordinates *x* and *z* of each vertices of the box girder cross section are obtained using the following algorithms.

$x(1) = 0$	$z(1) = 0$	$x(2) = -Be$	$z(2) = 0$
$x(3) = -Be$	$z(3) = ve1$	$x(4) = x(3) + he1$	$z(4) = z(3) + ve2$
$x(5) = x(4) + he2$	$z(5) = z(4) + ve3$	$x(6) = x(5) + he3$	$z(6) = z(5) + ve4$
$x(7) = -be - he4$	$z(7) = h - ve5$	$x(8) = -be$	$z(8) = h$
$x(9) = 0$	$z(9) = h$	$x(10) = 0$	$z(10) = esup$
$x(11) = x(10) - hi1$	$z(11) = z(10) + vi1$	$x(12) = x(11) - hi2$	$z(12) = z(11) + vi2$
$x(13) = x(12) - hi3$	$z(13) = z(12) + vi3$	$x(14) = x(13) - hi4$	$z(14) = z(13) + vi4$
$x(18) = 0$	$z(18) = h - einf$	$x(17) = x(18) - hi7$	$z(17) = z(18)$
$x(16) = x(17) - hi6$	$z(16) = z(17) - vi6$	$x(15) = x(16) - hi5$	$z(15) = z(16) - vi5$

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