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ALAMILLO BRIDGE: CONSTRUCTION SIMULATION MODELS IN EZSTROBE

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The Puente del Alamillo in Seville, Spain, designed by Santiago Calatrava, has a single pylon that rises at an angle away from the deck, and which together with the deck resembles a harp whose strings are the cable stays from the pylon to the deck. It is the only bridge of its kind in the world whose pylon is not back-anchored, and its deck and pylon balance at a single massive footing below the pylon. This design made construction of the bridge very risky because the unfinished bridge had to be kept in balance like a giant teeter-totter until it could rest at the secondary support away from the pylon. A total of three construction plans were investigated by the contractor with the first two rejected and the third used for construction. Previous research presented simulation models for these three plans in CYCLONE along with construction time estimates for the bridge deck and pylon. Unfortunately, the published simulation models had mistakes that led to incorrect statistical results and conclusions. This paper describes these mistakes and presents three simulation models in EZStrobe that produce appropriate statistics and conclusions. These models can be used as practical examples for the application of discrete-event simulation to construction.

Keywords: Calatrava, Cable-stayed bridge, Modeling, statistics, CYCLONE, STROBOSCOPE.

1 INTRODUCTION

The Puente del Alamillo, designed by Santiago Calatrava, crosses a channel of the Guadalquivir River in Seville, Spain. Its shape is asymmetric and resembles a harp whose strings are the cable stays that connect the deck to a single pylon on the west bank that rises away from the deck at an angle of 58º. It is the only bridge of its type in the world that is not back-anchored—the 250m deck is balanced over the pylon foundation by the weight of the massive 162m inclined pylon. The absence of stabilizing back-stays meant that the bridge had to be perfectly balanced (like a giant teeter-totter) at all stages during construction and this made Calatrava's original "balanced-cantilever" construction plan too risky for the contractor (Dragados y Construcciones of Spain). The original plan and the two plans developed later by the contractor are described as Cases 1, 2 and 3 below. Detailed descriptions of the design and construction of the Puente del Alamillo can be found in several sources, including Gregory and Blockley (2019), Guest *et al.* (2013), Orr (2008), Moncla *et al.* (2019), and especially in Pollalis (1996) and Pollalis (1999).

Case 1 is the original plan conceived by Calatrava. It called for cantilever construction where successive segments of the deck and the pylon would be constructed concurrently and connected with cable stays to balance each other. Although cantilever construction is typically cost-effective for cable-stayed bridges, Dragados rejected Calatrava's plan as too risky. Without a back-anchor to provide a safeguard, any miscalculations during construction could have led to an imbalance between the weight of the pylon and that of the deck with possibly catastrophic results.

Case 2 is the plan that Dragados used to bid the job. This plan called for temporarily damming the river channel (on both sides over the length of the bridge) and supporting the hexagonal box girder for the bridge deck (as well as the road deck wings on either side of each box segment) on continuous falsework placed on the mostly-dry river bed. Portions of this falsework would then be removed as needed for the deck to balance the erection of the pylon.

Case 3 is the plan used by Dragados to construct the bridge. Deck construction was similar to Case 2. For the pylon, however, instead of temporary concrete formwork, steel caissons were used, both as concrete formwork and as an outer continuous shell. The steel caissons for the pylon and the deck steel segments (for the hexagonal box girder and the road-deck steel wings on either side) were premanufactured off-site and were brought to the site for final assembly.

Based on Pollalis (1996) and Pollalis (1999), Yamin-Lopez (2019) and Yamin-Lopez and Halpin (2000) used the CYCLONE methodology to develop simulation models for the above Cases 1, 2, and 3. Unfortunately, the representation of the construction processes in these three models was incorrect and led to incorrect statistics and conclusions. These are corrected in the three EZStrobe (2019) simulation models presented below. It must be made clear that the models in CYCLONE, as well as the models in EZStrobe, are simplifications of the actual construction plans. Their purpose is to illustrate the appropriate application of discrete-event simulation to construction.

2 CASE 1 - CALATRAVA'S BALANCED CANTILEVER CONSTRUCTION PLAN

The EZStrobe model for Case 1 is shown in Figure 1. It is based on the CYCLONE network shown in Yamin-Lopez (2019) but also includes the feedback loop formed by queue "*NextPylonSeg*" and the links from combi "*CblInstlPretens*" and to combi "*SlideFormWork*". This feedback loop is a requirement for the bridge to remain balanced during construction—it prevents the construction of a new pylon segment (i.e., it prevents the start of combi "*SlideFormWork*") until after the previous pylon segment has been pretensioned to the corresponding deck segment (i.e., until after the end of "*CblInstlPretens*"). The *absence* of this feedback loop in the CYCLONE model allows each pylon segment to be poured right after another, without waiting first to connect each pylon segment to its corresponding deck segment to maintain stability. The consequences of this modeling mistake are evident in the reported CYCLONE simulation statistics in which queue "*PylonSegReady*" had as many as three unsupported pylon segments waiting to be pretensioned. This means that at some point during the simulation, three pylon segments were not anchored to their matching deck segments (because the simulated model had not constructed those deck segments yet). Thus, the significant excess weight of the extra pylon segments could not be balanced by the weight of the already constructed deck segments. This is clearly not the balanced cantilever construction process that was meant to be modeled. Also, instead of recognizing that these statistics point to *a mistake in the model*, a more important error was to interpret them (incorrectly) as an inherent imbalance in the construction plan for Case 1.

The EZStrobe model in Figure 1 corrected these errors and resulted in a project duration of 368 days, which is close to the 371 days given by the incorrect model for Case 1 in Yamin-Lopez (2019).

3 CASE 2 - CONSTRUCTION PLAN BID BY DRAGADOS

The EZStrobe model for Case 2 is shown in Figure 2. It is based on the CYCLONE network in Yamin-Lopez (2019) but has been corrected to rectify the following errors.

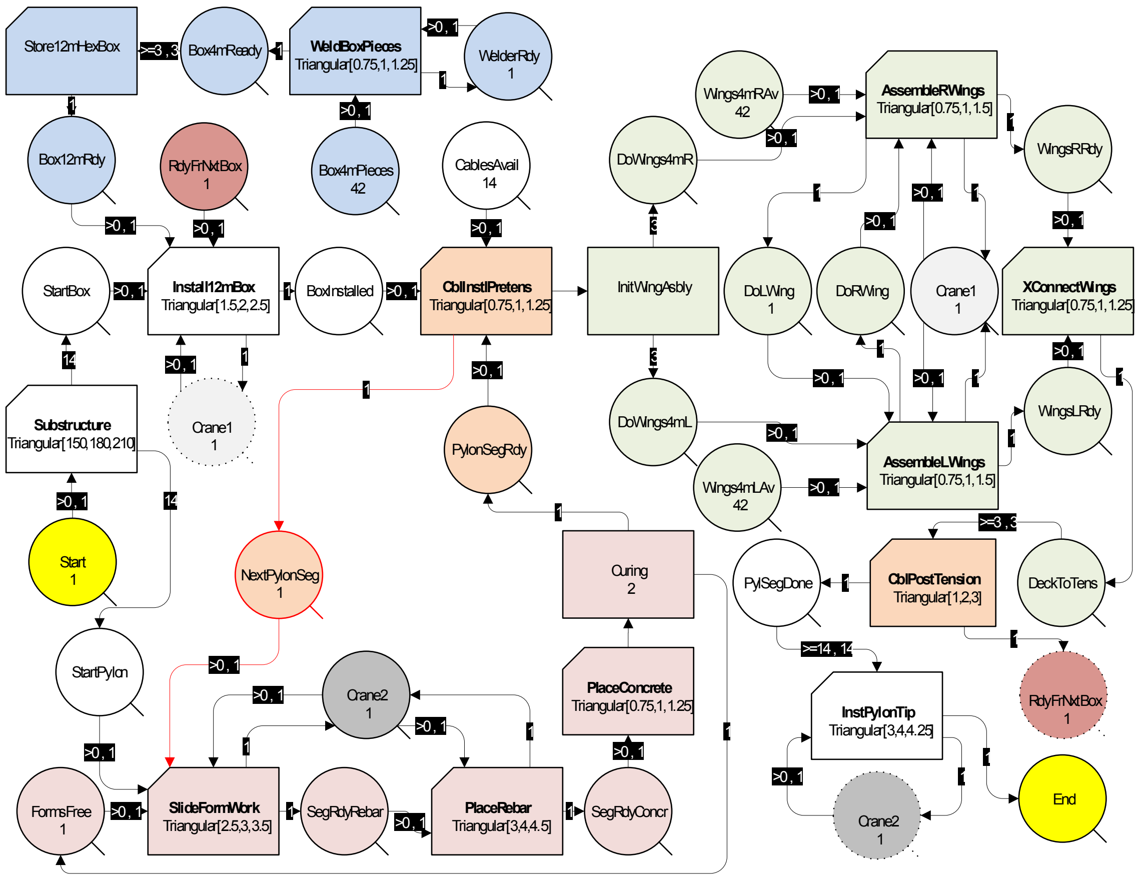

Figure 1. EZStrobe model for Case 1 – Calatrava's balanced cantilever construction plan.

The CYCLONE network for Case 2 shows nodes 10 and 11 as circles when both nodes should have been queues with GEN3. Also, combi "7 *Install Box*" has a smaller number (i.e., "7") and thus has higher priority for the use of *Crane* 1 over combis "12 *Assemble Right Side Wings*" and "13 *Assemble Left Side Wings*". This subtle modeling mistake changes significantly the sequence of operations that are actually represented. The inappropriate relative numbering and priority of combi activities forces the CYCLONE simulation model to dedicate *Crane* 1 to combi "7 *Install Box*" and thus to assemble *all* hexagonal box segments for the spine of the deck (one after another, over the entire length of the bridge) *before* allowing *Crane* 1 to be used for attaching any of the deck wing segments on the left and right sides of the hexagonal deck boxes. Because of this mistake, the model constructs the deck as if it were one long thin hexagonal tube, without the deck wings on either sides and thus the deck would not have enough weight to balance the weight of the pylon segments through the stay cables. Clearly, what is represented by the CYCLONE model for Case 2 in Yamin-Lopez (2019) is not the sequence of construction operations that the contractor and the modeler had in mind.

It is easy to correct the above mistakes in EZStrobe by setting the priority of combi "*Install12mBox*" to "-5" (i.e., to a number lower than the default priority of "0") as shown in Figure 2. This prevents the construction of a new 12m box segment until after *Crane* 1 has completed the three 4m-left-wings and the three 4m-right-wings for the previous 12m-box-segment (the corresponding wing combis have the default priority of 0 (higher than -5) for using *Crane* 1). Thus, *Crane* 1 starts the construction of a new 12m-box-segment only after the wings for the previous 12m-box-segment have been installed (and while the wings are being interconnected, which does not require *Crane* 1). The result is that *Crane* 1 installs each 12m hexagonal box and then its three 4m wings on either side before it starts the next 12m box.

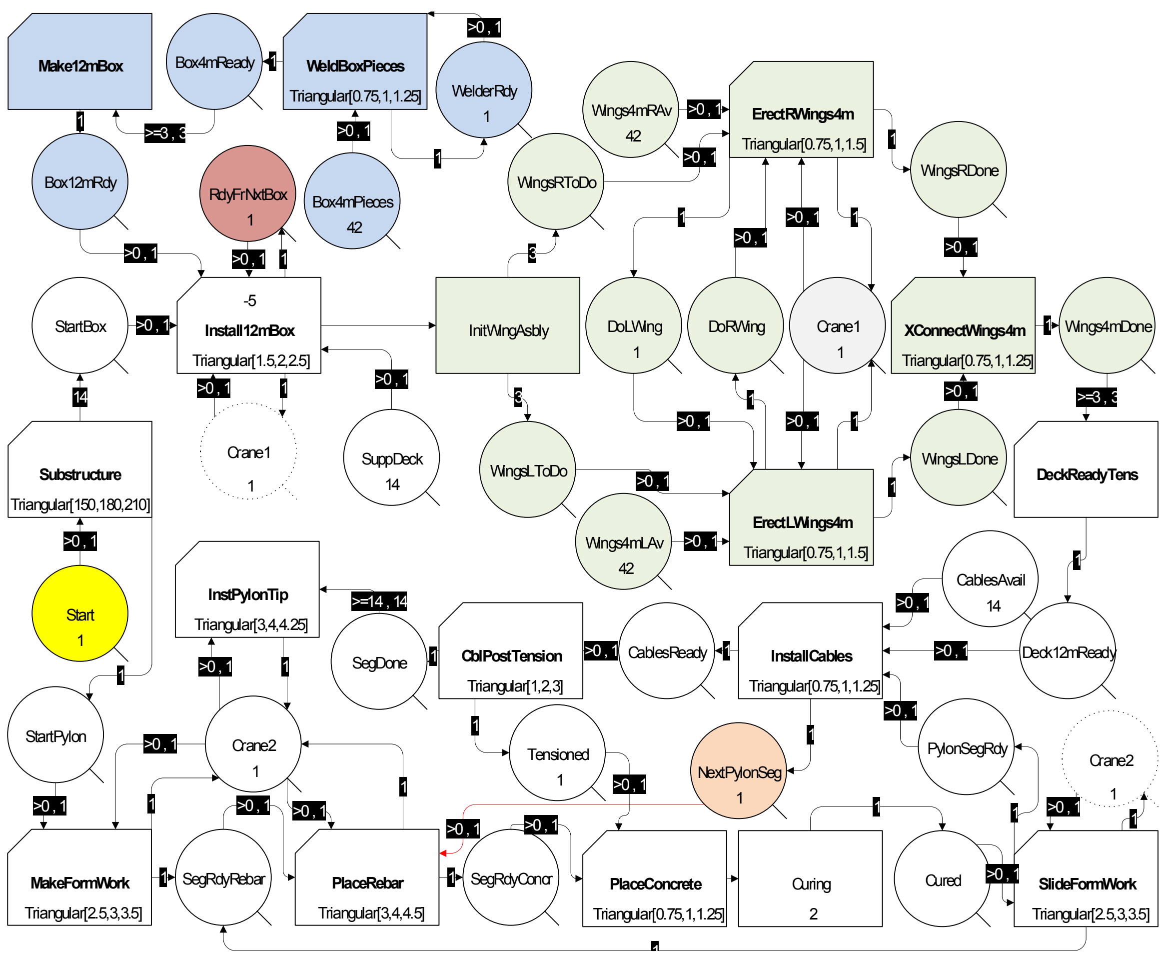

Figure 2. EZStrobe model for Case 2 - Construction plan bid by the contractor (Dragados).

The maximum content of queue "*Deck12mReady*" (for the installation of cables) over 100 replications in EZStrobe ranges between 2 and 3 (12m-deck-segments). This indicates that contrary to the conclusions in Yamin-Lopez (2019), when the construction of the deck on temporary falsework is modeled correctly, it is not significantly ahead of pylon construction.

Other subtle corrections to the CYCLONE model for Case 2 shown in the EZStrobe model in Figure 2 ensure that the installation of stay cables can start only after sliding up the formwork for the previous pylon segment (to expose the holes through which to pass the stay cables). Also, the placement of rebar for the next pylon segment is prevented from starting until after the stay cables for the previous segment have been installed (red link). Moreover, the addition of a link from "*Tensioned*" to "*PlaceConcrete*" ensures that the concrete for the next pylon section is placed only after the stay cables for the previous section have been tensioned. Thus, the last pylon segment that was cast and cured, is first anchored to the corresponding deck segment, before taking on the additional load of wet concrete for the next pylon segment.

It is stated in Yamin-Lopez (2019) that the construction plan for Case 2 would allow assembling the deck twice as fast as in Case 1. This is an overestimate, possibly due to the incorrect priorities of combi activities in the CYCLONE network for Case 2. The EZStrobe model shows that on average, the assembly of the deck in Case 2 takes 120 days instead of the 181 days in Case 1 (i.e., 2/3 of the duration of the initial proposal). The correct EZStrobe model for Case 2 shown in Figure 2 resulted in an average project duration of 338 days, which is a little longer than the 304 days for the incorrect CYCLONE model reported in Yamin-Lopez (2019).

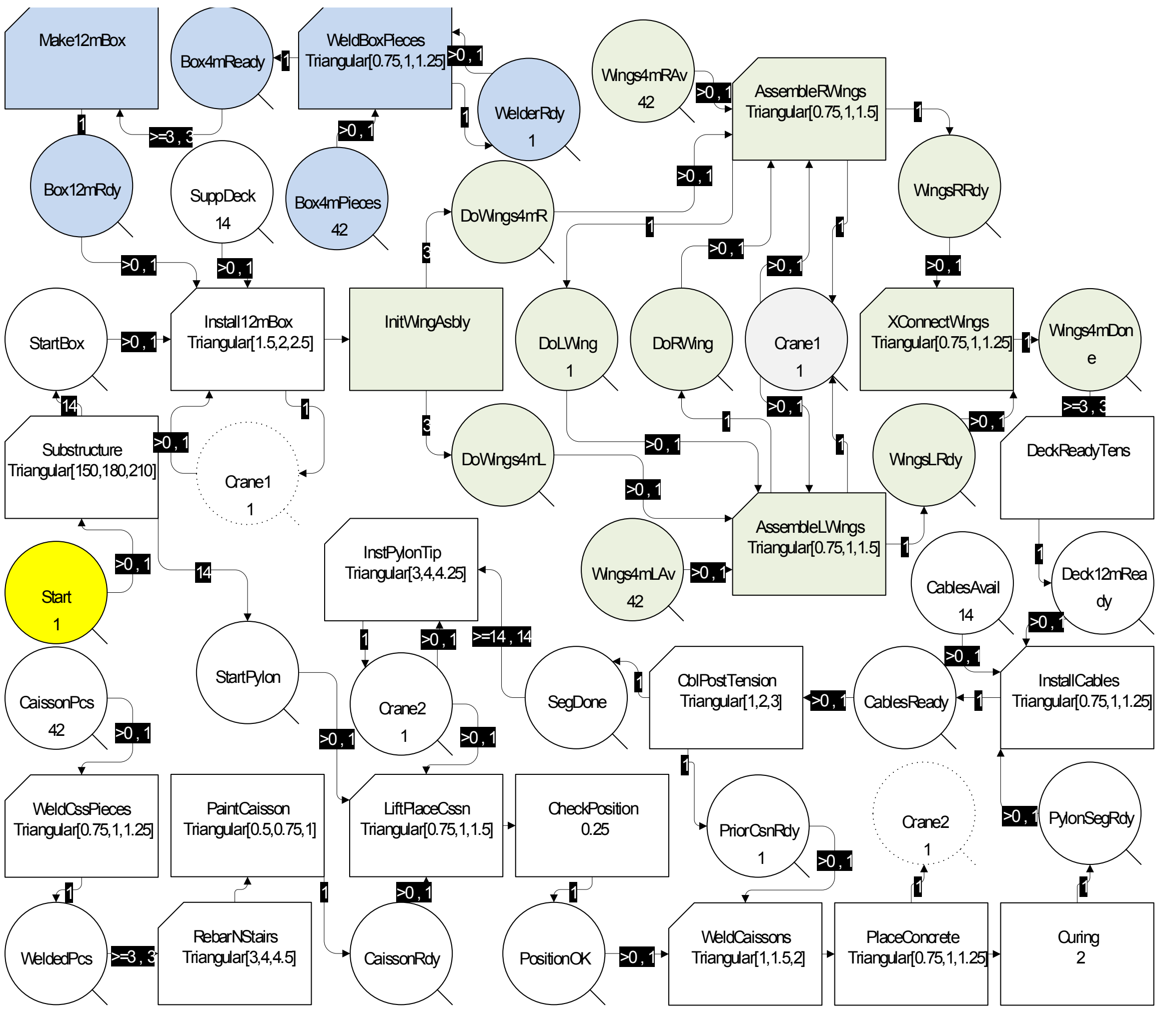

Figure 3. EZStrobe model for Case 3 - Construction plan as built by the contractor (Dragados).

4 CASE 3 – THE PLAN USED BY DRAGADOS TO CONSTRUCT THE BRIDGE

The EZStrobe model for Case 3 is shown in Figure 3. It is based on the CYCLONE model in Yamin-Lopez (2019) after it was corrected as outlined below.

A clear mistake in the CYCLONE model for Case 3 in Yamin-Lopez (2019) concerns the starting conditions for combi "45 *Lift and Place Caisson*". In this model, as soon as the substructure is completed, combi "45 *Lift and Place Caisson*" and its successor activity "48 *Check Position*" will start 14 times sequentially, and place all 14 caissons for the pylon in queue "49 *Position OK*" (as if all 14 caissons for the pylon can be lifted up, unsupported, without being welded to each other). Moreover, *Crane* 2, which is shown as used only by combi "45 *Lift and Place Caisson*" and "47 *Install Pylon Tip*" is made idle after each activity. This is incorrect. *Crane* 2 is needed to support each caisson while several other activities take place: "48 *Check Position*", "52 *Weld Caisson to prior Caisson*" and "55 *Place Concrete*". These errors are corrected in Figure 3 by returning *Crane* 2 to queue "46 *Crane* 2" only after "55 *Place Concrete*". A related error in the CYCLONE model is that queue "51 *Prior Caisson Ready*" (to support the next caisson) is shown to be a successor to activity "57 *Curing*". This is corrected in Figure 3 by making queue "51 *Prior Caisson Ready*" a successor to activity "*Cable Post Tension*". I.e., the previous caisson cannot be welded to a new caisson until after its own cables have been tensioned—to support its own weight before the load of the next caisson is added on top.

The corrected EZStrobe model for Case 3 shown in Figure 3 resulted in an average project duration of 307 days, which is still close to the 305 days reported in Yamin-Lopez (2019).

5 CONCLUSIONS

Together, the three EZStrobe models for the Alamillo Bridge in this article, and the three CYCLONE models in Yamin-Lopez (2019) and Yamin-Lopez and Halpin (2000), make a good tutorial in discrete-event simulation of construction processes. Studying the modeling mistakes in Yamin-Lopez (2019) and their corrections in this article has educational value and illustrates by example the need to verify that simulation models represent the intended construction processes and to draw appropriate conclusions from the resulting simulation statistics.

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