A Case Study of 3D Imaging Productivity Needs to Support Infrastructure Construction

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Abstract: The national infrastructure system is at a crossroads with a need for renewal and expansion in the most efficient manner possible. Light railway construction requires the installation of embedments in reinforced concrete pavement along the length of elevated sections of the railway system. Conventionally, wooden dowels are manually placed into the reinforcing steel mat before concrete placement to form the slot for the embedments; however this is labor intensive and can yield inconsistent spacing. An alternative method is digitally mapping the locations of the reinforcing steel-free space prior to concrete placement to identify where holes could be drilled without hitting the steel reinforcement. The challenge is avoiding impacting production. Using field-based data, this study identifies the number of hours to create the map without impacting production for a typical railway section. Discrete event simulation (DES) modeling is utilized to conduct the analysis. To substitute the alternative method, scanning a typical railway section falls within the capabilities of most laser scanning technologies; however, the processing of images to create a useable model controls. This research demonstrates a case study of applying DES to analyze productivity impacts on a repetitive process and investigates the capabilities of 3D imaging technologies for effective field use.

PROJECT BACKGROUND

Traditionally, the resources required to support a construction crew included manual labor, equipment, and materials. Over time as information systems and sensing agents have advanced in their capabilities and durability, advantages are becoming more apparent in providing greater information and automation to crews as well. If the realm of construction resources is to be expanded to include information, then the pertinent restraints to providing the necessary information when required has to be planned as is the case with labor, equipment, and materials. The following case study involving the construction of a railway line presents how adequate planning to provide the required information to construction crews can have an impact on the methods of construction.

The construction of a railway line, in this particular instance, required embedments in the steel reinforced concrete pavement to be placed underneath the length of railway tracks. Not knowing where the reinforcing steel cages are placed within the concrete makes drilling into the concrete risky in terms of worker safety and structural integrity of the pavement. Therefore, the drill bit must avoid contacting the reinforcing steel. The conventional method required the placement of wooden dowels in the reinforcing steel cage to create voids in the concrete. After the concrete was placed, the dowels were removed, most commonly requiring repeated drilling using a combination of wood and masonry drill bits. The work-hour requirement to both install the dowels and the time to remove them after concrete placement proved to be especially labor intensive. A potentially more efficient method would be to digitally map the locations of the reinforcing steel prior to concrete placement.

The conventional method required the use of 3.8 cm (1.5 in) diameter wooden dowels to mark the embedment locations in the reinforcing steel voids every 0.38 m (15 in). The dowels were screwed into the bottom of wooden planks to hold them in place. The wooden planks were then tied to the top layer of reinforcing steel. The planks were also necessary to create a recess along the length of the pavement. The top surface of the wooden planks matched the final grade of the concrete. After the concrete was placed and cured, the wooden planks and dowels were removed. Plinth stirrups were anchored into the voids left by the dowels with epoxy.

The addition of the wooden dowels and planks increased the congestion in the reinforcing steel mats and could adversely affect the quality and integrity of the concrete by creating honeycombs and voids. Additionally, it was more labor intensive as it restricted access and movement of the workers while placing, vibrating, and finishing the concrete. The removal of the dowels involved locating the wood planks as they were often covered with concrete. Once located, removing the dowels required two drill bits, a 3.5 cm (1 3/8 in) wood bit to remove most of the dowel, and a second 3.8 cm (1.5 in) masonry bit to remove the remainder. The sleeves were covered with a foam plug to prevent debris from entering the hole and to protect the concrete surface within each hole from damage (Figure 1).

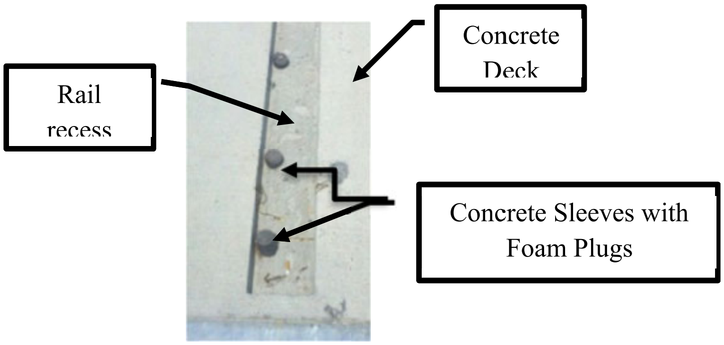

Figure 1. Sleeves with dowels removed and foam plugs inserted

The alternative method, to digitally map the reinforcing steel layers including the voids using 3D imaging techniques, would provide the ability to measure and mark the locations for the embedments after the concrete is placed. This method eliminates the time and cost required to place the wooden dowels within the steel reinforcement mats and remove them from the cured concrete. It would improve access during concrete placement by eliminating obstacles to the flow of concrete. In addition, digital maps of the reinforcement locations would be a valuable tool for future retrofit or repair of the railway decks. This method also eliminates manual activities that are associated with wooden dowels using the already described conventional method. The proposed alternative would obviously add new, different steps in the construction of the railway line as well. The added steps are setting up the equipment, measuring registration targets, acquiring data, processing data, and finding and drilling out the locations for the dowel sleeves.

Measuring the reinforcing locations quickly and accurately prior to concrete placement could improve the productivity of the reinforcing steel placement, concrete placement, and finishing activities. It would eliminate the steps required to place wooden dowels (or other negative shapes) within the reinforcing steel, improve access to the reinforcing steel during concrete placement, and may allow the use of concrete finishing machines. In addition, maps of the reinforcing steel locations would be a valuable tool for future retrofit or rehabilitation of the railway decks. However what is not known is the required productivity of the 3D imaging processes in order for the proposed alternative method to break even in comparison to the overall time required using the conventional method. The analysis the authors used to address this issue is described below.

ANALYSIS STRATEGY

The strategy for the productivity analysis is to compare the time for the conventional method where the dowels are prepared, attached to the planks, and removed after concrete placement (conventional method) versus mapping the reinforcing steel locations using either laser scanning or photogrammetry (3D imaging method). The analyses presented are meant to identify the maximum duration of the 3D imaging methods that would still provide a productivity advantage over using the conventional method to build the bridge decks. The analyses do not differentiate whether laser scanning or photogrammetry is used in developing the required 3D image, as the method does not impact productivity.

The following assumptions are made:

- A deck paving machine could not be used in either method because the wood planks were necessary to make the recesses on the surface.
- Estimates in this paper are based on one typical railway span reinforcing steel design, as seen in Figure 2.

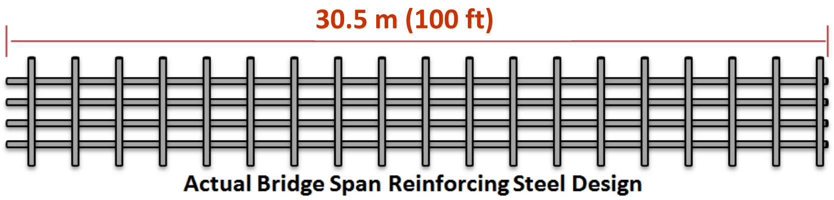

Figure 2. Typical reinforcing steel mat used on a railway bridge span

METHODOLOGY

To calculate the potential time savings achieved from using either 3D imaging method, a discrete event simulation (DES) modeling approach was used. In DES modeling, a process can be modeled with logical relationships with time as a factor. Each task to be performed can be associated with prior task completion or the release of a dependent resource for that task.

Several simulation systems have been developed for typical construction processes. EZStrobe was selected for this analysis since it allows for creation of a network based on activity cycle diagrams and time constraints (Martinez, 2001). Figure 3 outlines the DES model developed in EZStrobe for the conventional method of installing the wooden dowel rods for the embedments. The model logic was derived from several visits to the jobsite and discussions with managers, engineers, and foremen on the project. For this study, each span was divided into three zones; A, B and C (see Figure 4). This allows for parallel processes; (e.g., placement of reinforcing steel, typing of reinforcing steel, and installation of the wooden dowels) that were coordinated by field supervision. The times, in hours, it takes for individual activities were also obtained during the site visits. The durations in the DES model (Figure 3) used a normal frequency distribution with ranges that incorporate six standard deviations from the mean (three each way).

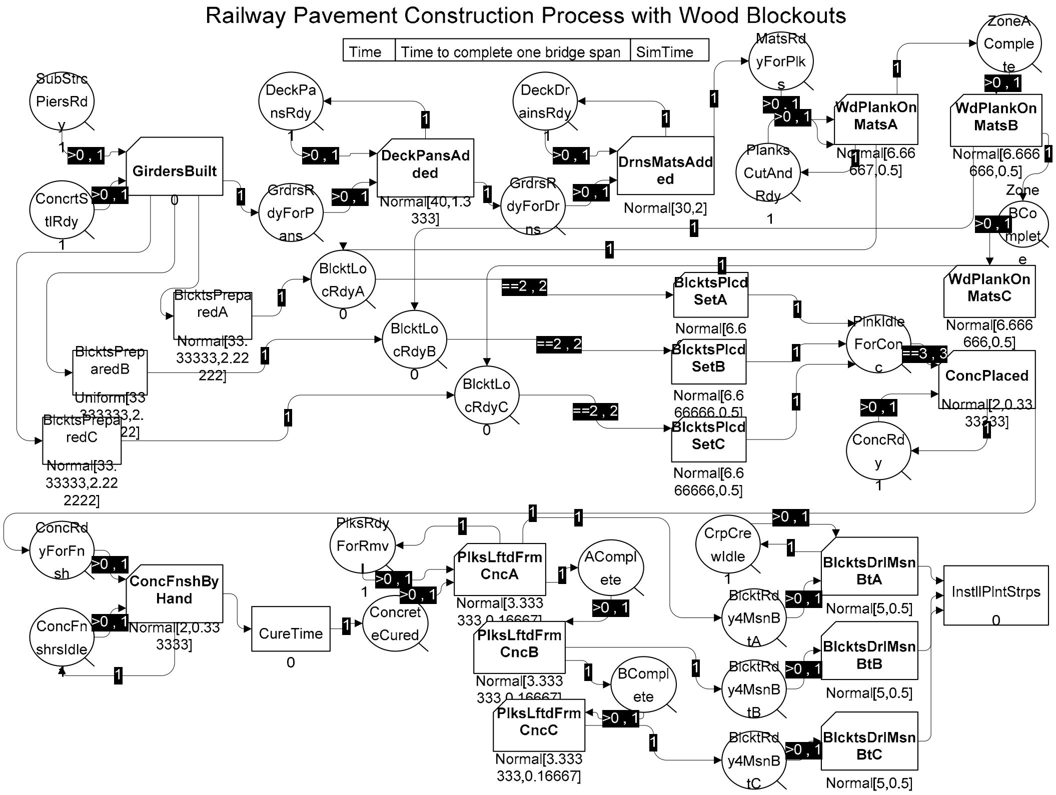

Figure 3. EZStrobe DES model for the conventional method.

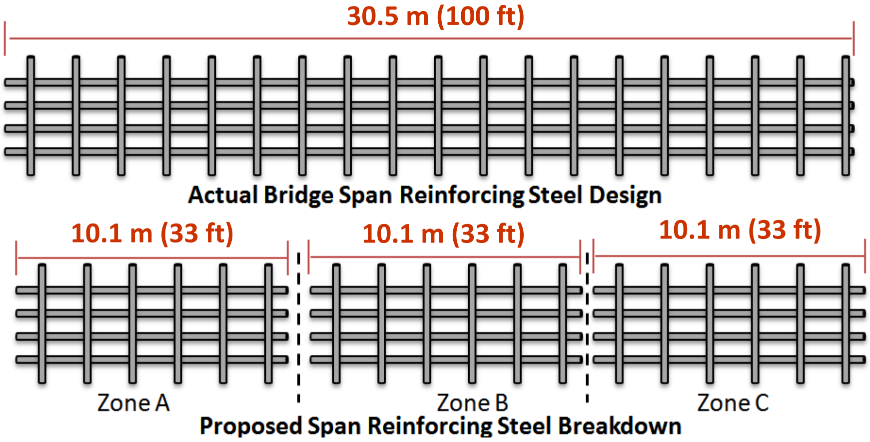

Figure 4. Breakdown of bridge span for parallel processes.

BREAKEVEN ANALYSIS AND RESULTS

The DES models provide a breakeven analysis for the use of a 3D imaging method in the construction of a typical railway bridge span. After proper setup, the original model was run over 100 iterations to develop an average duration for all activities. That average duration then became the target total duration for the 3D imaging model. Logical durations for activities involved in the 3D imaging method were input at a level that resulted in an overall duration similar to that of the conventional method. At this point, the two models are similar in total duration, and the breakeven analysis can occur. The time it takes for activities involving the 3D imaging method were summed to identify the breakeven point. The times in the conventional method were based on the input of managers and field engineers on the project. For the DES 3D imaging model, the tasks and durations for 3D imaging practices were used in place of installing the dowels used in the conventional method. Essentially, the tasks in the conventional method that would not be performed in the 3D imaging method are eliminated. They are replaced by 3D imaging tasks such as equipment setup, image acquisition and processing of the data, which could be required irrespective of whether laser scanning or photogrammetry was used.

The conventional method results in an average duration of approximately 115 hours (or 11.5 days based on the project's standard 10 hour work days) and a standard deviation of 2.90 hours. The model was set with a parameter of 100 iterations to achieve a significant sample size. The fastest possible time the model suggests is 109 hours, while the slowest time is 123 hours. This information is summarized in Table 1. To help clarify results, the DES original model is reproduced as a process diagram in Figure 5 with the durations for each task shown as well.

Table 1. Summary of the conventional method's simulation results.

Method (100 iterations)	**Average (hours)**	**Standard Deviation (hours)**	**Minimum (hours)**	**Maximum (hours)**
Original (dowel)	115.46	2.897	109.15	123.34

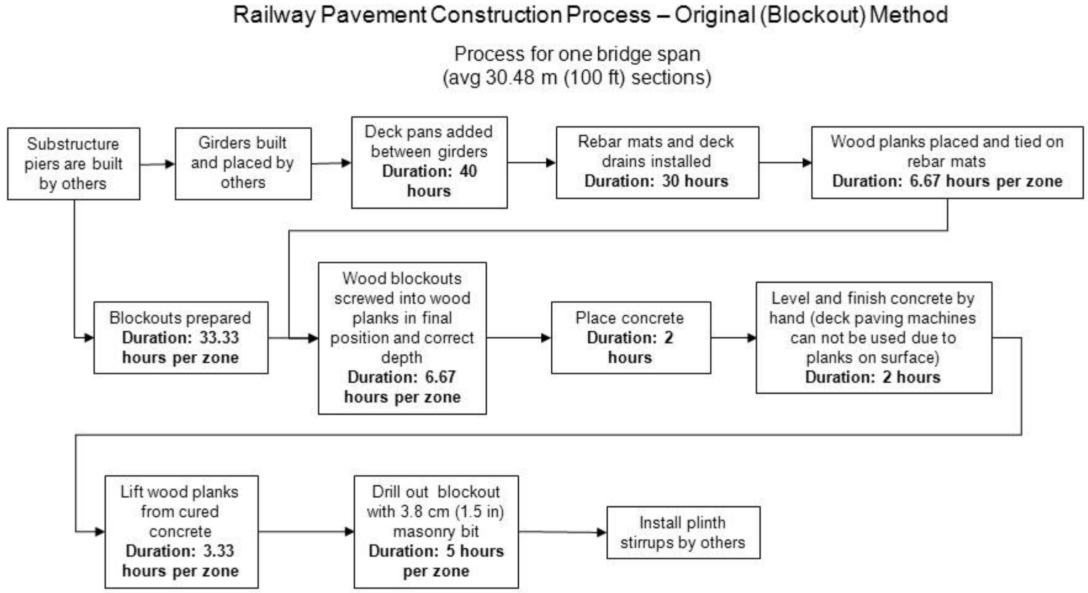

Figure 5. Process flow diagram for the original (dowel) method.

With an average of 115 hours using the conventional method for a typical 30.48 m (100 ft) bridge span, the researchers modified the time for the activities related to the 3D imaging method to reach the breakeven threshold. The resulting DES model can be seen in Figure 6. The 3D imaging method eliminates activities that are associated with wood dowels in the conventional method. Preparing the dowels, placing and attaching them to the wood planks and removing/drilling out the dowels are no longer necessary in the 3D imaging method. The added steps involved are measuring targets in the site coordinate system (SCS), setting up the equipment, measuring registration targets, acquiring data, moving and repeating for a full model, processing the data, and finding and drilling out the locations for the dowel sleeves.

The 3D imaging model produces an average of 110 hours and a standard deviation of 2.61 hours. Similar to the conventional method DES model, the software ran 100 iterations of the process and produced a minimum of 104 hours and maximum of 116 hours (see Table 2). Table 2 also reports the total time for image acquisition and image processing from the model (based on one model iteration) as 14.19 hours and 18.09 hours, respectively. The numbers are similar to the conventional method results using wood dowels, since all are within 4 % of the original value. Similar to the original model, the DES 3D imaging model is reproduced as a process diagram in Figure 7 with the durations for each task shown.

From the durations based on field data from the described project and logic built into the 3D imaging model, the 3D imaging activities (image acquisition and processing) for a single 30.48 m (100 foot) bridge span would need to occur within a range of 21.5 hours to 38.5 hours. This is due to data processing not lying on the critical path because of parallel processes. The processing can take up to 18 hours.

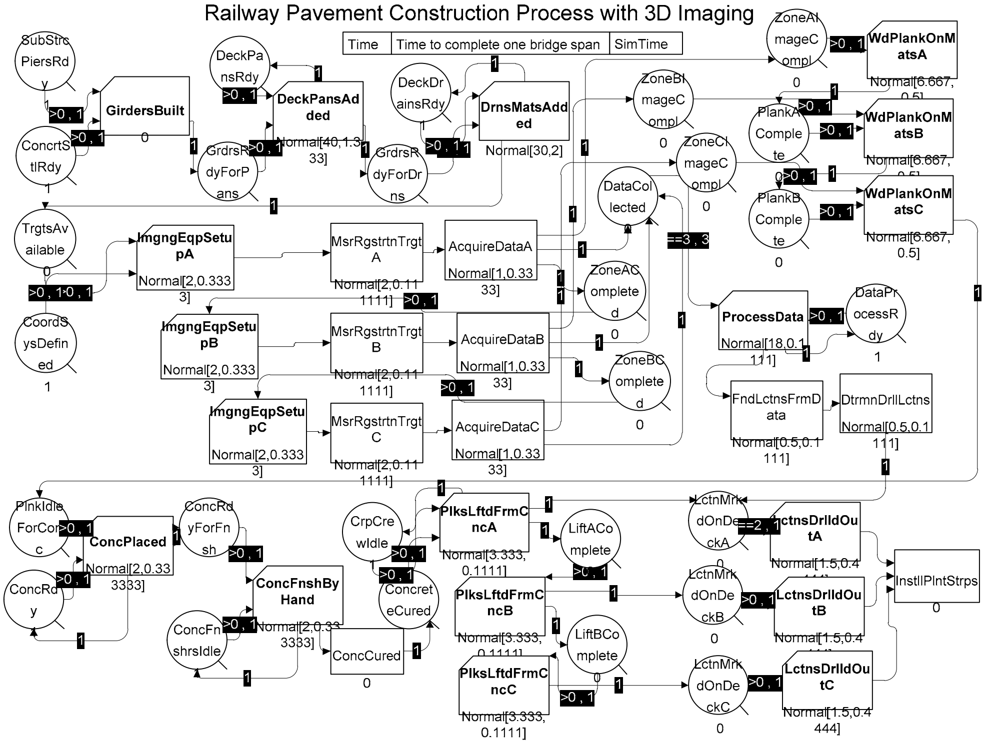

Figure 6. EZStrobe DES model for the alternative method (i.e., using 3D Imaging).

Table 2. Summary of 3D imaging simulation results.

Alternative Method (100 iterations)	Average (hours)	Standard Deviation (hours)	Min. (hours)	Max. (hours)
3D Imaging Method (including construction and 3D imaging activities)	110.09	2.614	104.56	116.00
Image Acquisition (1 observation)	14.19	N/A	N/A	N/A
Image Processing (1 observation)	18.09	N/A	N/A	N/A

The National Institute of Standards and Technology (NIST) recently conducted a study of reinforcing steel imaging for this exact construction process. A team of NIST researchers created the Intelligent and Automated Construction Job Site (IACJS) Testbed and modeled the reinforcing steel cage. By comparing the durations in the 3D imaging model to a model based on the reinforcing steel cage in the IACJS Testbed, the durations for individual activities are within a reasonable expected range. In the Testbed model, the time to measure and register targets, set up the equipment, and acquire the data all occurred within a few hours. In the DES model, the time for all of those activities to occur was 15 hours total, or five hours per zone. The activity that may cause issues in a breakeven analysis is the data processing. This is discussed further in the following section.

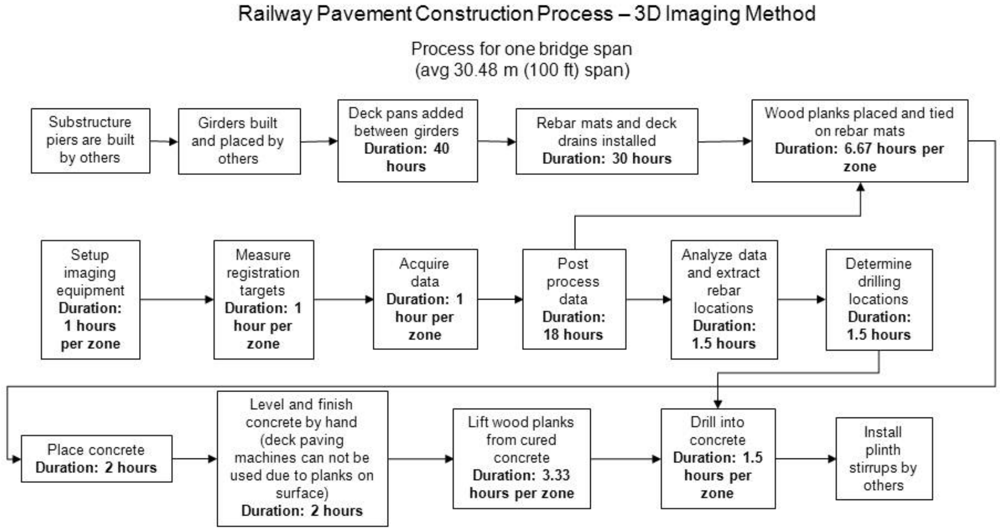

Figure 7. Process flow diagram for 3D imaging method.

DISCUSSION

While the 3D imaging method provides a more reliable approach than the wooden dowel approach, there are some drawbacks suggested by management and craftsmen at the jobsite. The main issue is that setting up and acquiring images for a 3D model while the reinforcing steel is exposed could potentially delay the craftsmen from placing the concrete. A proposed process for acquiring the 3D image would be for field crews to first install all of the steel reinforcement mats for a single bridge span and then allow the engineers or surveyors to take the images. After the image acquisition and processing is complete, the field crews would commence with placing the concrete. The craftsmen and foremen found the proposed process to be disruptive and would likely decrease worker motivation.

Instead, possible solutions to this issue include parallel work, off-shift image acquisition, and acquiring the 3D imaging data from airborne equipment. Subsequently, the models previously presented implemented parallel processes by splitting up each span into three zones. This allows for minimum wait time for the craft while the 3D imaging data is being collected and more importantly processed. If the crews still have to wait, the 3D imaging data acquisition can be easily scheduled prior to or at the end of the normal work day.

Another potential issue is the amount of time that would be required for processing the data. Figure 4 provided a simplified visualization of the 3D imaging process for the steel reinforcement mats. A study of 4D augmented reality technologies (D4AR) looked at using the visualization techniques for scanning of a similar testbed (Golparvar-Fard, 2009; Golparvar-Fard, 2010). The results of applying the D4AR technology to the reinforcing steel cage in the IACJS Testbed required approximately 32 hours to process 380 images (Saidi et al, 2011). The reinforcing steel cage consisted of a 2.44 m x 3.66 m (8 ft x 12 ft) reinforcing steel mat, which is smaller in layout than the mats required for the actual rail project. Through linear interpolation, the time to process the bridge span images at the same scale as the Testbed would be approximately 320 hours per zone. That figure is unreasonably high, however, the Testbed images produce an extremely high quality output with redundancy in image acquisition that may be unnecessary. It is likely that significantly fewer images of the reinforcing steel mat could provide the necessary data. A more reasonable and desirable level of quality needs to be established.

To help provide a benchmark for this objective, Figure 8 shows the estimated durations based on the DES models that would need to be obtained for each process using either laser scanning or photogrammetry technologies on a typical bridge span broken up into three 10 m (33 ft) sections in order to minimize crew disruption. The image acquisition per zone can take up to five hours in duration, while the processing of the data can last up to six hours per zone. This would allow processing of Zone A to begin before field work starts on Zone B. The same logic applies to Zones B and C. It is assumed that there would be minimal effort to stitch the images of Zones A, B and C together to create a cohesive image of the steel mat for the overall bridge span. In summary, image acquisition and processing for a typical bridge span that can be done within 33 hours (3 sections total at 11 hours each for image acquiring and processing) provides a time-saving alternative to the original (dowel) method. The next logical step in this research effort is to determine the minimum time that current 3D imaging techniques require to create the necessary image to adequately locate drill locations for the embedments after concrete placement.

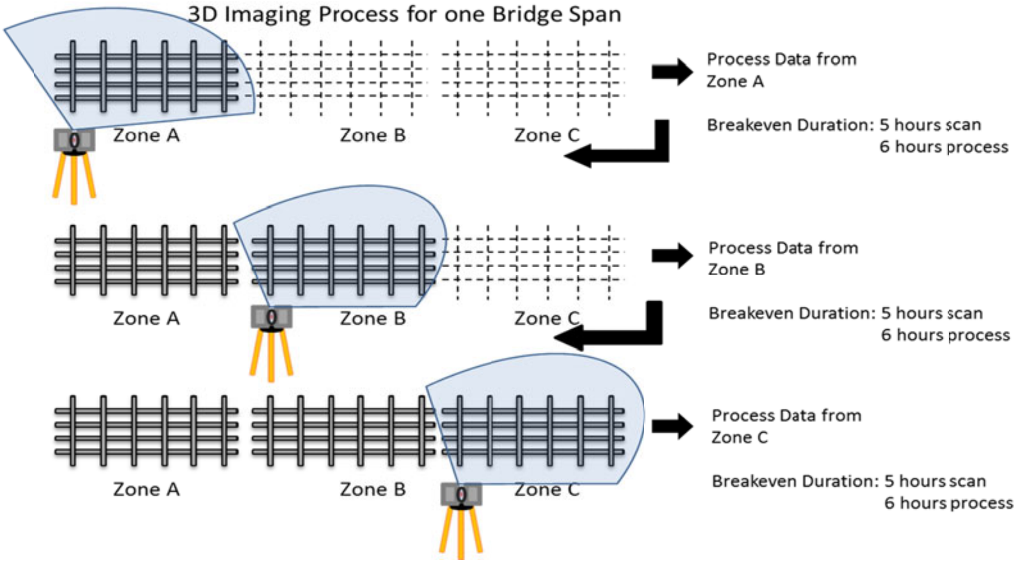

Figure 8. Simplified visualization of the 3D imaging process.

SUMMARY

The methodology included in this section provides a process for analyzing a proposed alternative construction method using discrete event simulation (DES) models. By setting the total duration for the conventional method using wood dowels and a 3D imaging method using either laser scanning or photogrammetry, a breakeven analysis was performed. Activities in the 3D imaging method must be completed within the durations identified in the model.

The proposed 3D imaging method provides a reasonable substitute for the original dowel method for determining embedment locations within a reinforcing steel mat. However, the challenge of successfully acquiring and processing a 3D image without delaying the placement of the concrete by a construction crew exists. The management team has critical decisions to make if the 3D imaging method is adopted; specifically the sequencing of the imaging process and the desired quality of the reinforcing steel mat model. The results of the analyses include the following:

1. If an entire steel reinforcement mat for a typical 30.48 m (100 ft) bridge span on the proposed railway bridge deck is photographed and processed at once, the photographing and processing would need to occur within 33 hours in order for 3D imaging to provide any benefit over the existing wood block out method. While this may reduce the entire duration for the construction of a single bridge span, it would still create undesirable wait times for the construction crews.
2. If a 30.48 m (100 ft) section is photographed in 3 sections, thus allowing processing and field construction to occur in parallel and thereby minimizing wait times, each 10 m (33 ft) section would need to be photographed and processed within 11 hours.

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