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Semantic Enrichment Engine for Bridges
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Technological Readiness Level
Internal Assessment Report

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1 Objective

Evaluating the technological maturity of the SeeBridge Project and all its pertaining components, in an exclusive and holistic manner.

2 Introduction

SeeBridge (Semantic Enrichment Engine for Bridges) proposes a comprehensive approach to revolutionize surveying and inspection for bridges. Primary information about bridges is obtained through terrestrial laser scanning, laser scanners mounted on vehicles, high resolution cameras and video recorders, to produce high density colored point clouds of bridges. These point clouds can then be used for development of 3D models of bridges using advanced algorithms. Using this information, a semantic enrichment step is performed, where new and meaningful information about bridge elements, their classification, aggregation, numbering, axes and geometrical parameters is added. Finally, high-resolution photographs of the bridge surfaces are mapped onto the model objects' surfaces, defects are identified and measured using machine vision, and the information is all stored as BIM models.

The process comprises the following parts, ordered chronologically:

1) Information Delivery Manual (IDM) and Model View Definition (MVD)
2) Point Cloud Data Acquisition
3) 3D Geometry Reconstruction
4) Semantic Enrichment
5) Damage Detection and Modeling

This document reports the results of an internal ‘Technology Readiness Level (TRL)’ assessment for each of the sections mentioned above, and provides an evaluation of the overall TRL of the entire SeeBridge project. As a standard for the assessment, the following criteria, developed and provided by the US Department of Defense, were used.

Table 1. Technology readiness levels in the United States Department of Defense (DoD).

Technology readiness level	**Description**	**Supporting information**
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.

Technology readiness level	**Description**	**Supporting information**
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3. Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4. Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively “low fidelity” compared with the eventual system. Examples include integration of “ad hoc” hardware in the laboratory.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include “high-fidelity” laboratory integration of components.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the “relevant environment” differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?

Technology readiness level	**Description**	**Supporting information**
6. System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8. Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
9. Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the	OT&E (operational test and evaluation) reports.

Technology readiness level	**Description**	**Supporting information**
	system under operational mission conditions.	

The assessment was performed for two kinds of bridges – Slab Bridges and Girder Bridges. Each kind was evaluated against the aforementioned criteria, both at the local/sectional as well as global levels (see Figure 1 below).

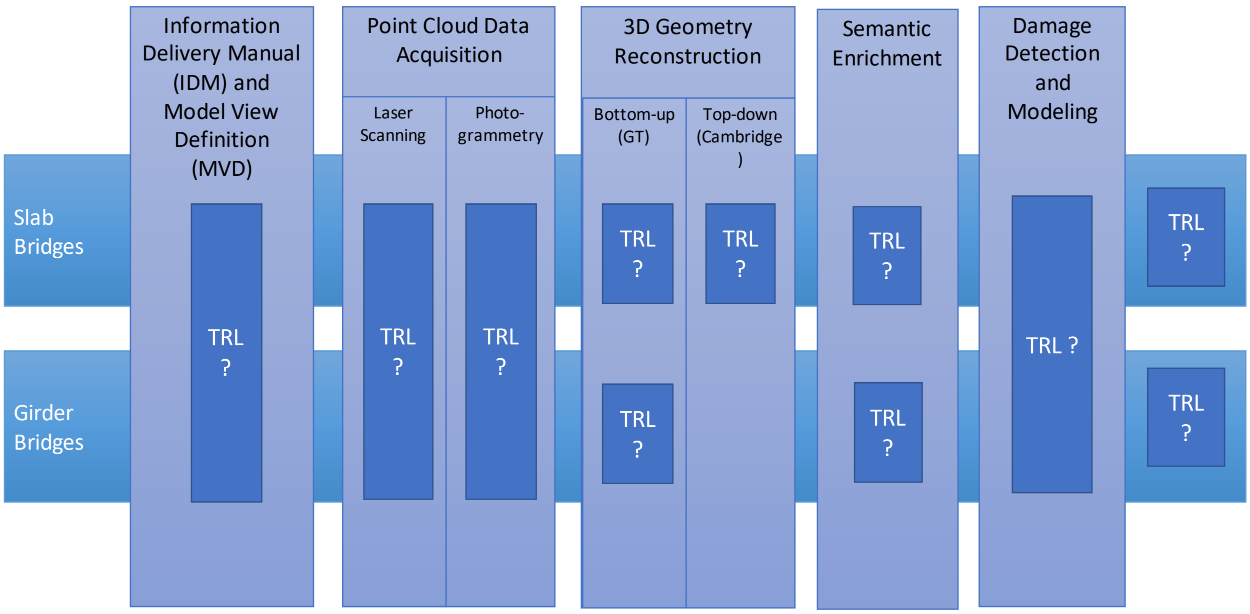


Figure 1. Scope of SeeBridge TRL Assessment. The process was evaluated for five steps and two bridge types.

3 TRL assessment questions

The following set of questions are used as a guideline to perform the assessment. There are general questions that are relevant for all parts of the system, and part-specific questions.

Overall assessment questions:

1) What needs to be done to reach the next TRL (to be answered after first assessment)?
2) To what degree is the scope of the system limited? What actions are required to extend this scope to additional bridge types?
3) To what extent is the overall output complete?
4) Which option for point cloud data acquisition (scanning or photogrammetry) is the most effective?
5) Which option for 3D geometry reconstruction (top-down or bottom-up) is the most effective?
6) Is the system output useful for a BMS?

Part-specific questions:

Point Cloud Data Acquisition

For a) Scanning and for b) Photogrammetry:

7) Is the output accurate (are the dimensions accurate)?
8) Is the output adequate (sufficient detail and resolution)?

3D Geometry Reconstruction

For a) Top-down and for b) Bottom-up

7) Are the 3D objects accurate compared to the real objects?
8) What are the degrees of precision and of recall?

Semantic Enrichment

For a) Slab bridges and for b) Girder bridges

7) What kinds of slab/girder bridges can be treated?
8) How easy/difficult is it to expand the scope to cover additional variations of slab/girder bridges?
9) How extensively has SeeBIM 2.0 been tested for this type of bridge?
10) Is the output correct (are the data correct)?
11) Is the output useful for a BMS?

Defect Detection

7) How does the camera quality influence the damage detection phase? Was the resolution used adequate?
8) What kinds of defects can be treated? How easy/difficult is it to expand the scope of defect types?
9) Is the output correct? Is it accurate – are the correct defects identified? Are the measurements of their parameters accurate?

4 Information Delivery Manual (IDM) and Model View Definition (MVD)

Model View Definitions (MVDs) define particular subsets of model schema to prescribe the information that needs to be delivered in order to fulfill the exchange requirements, which are generally defined in Information Delivery Manuals (IDMs). In principle, MVDs can be bound to any implementation schema, but in our case, they exclusively use the IFC schema.

The Model View Definitions in SeeBridge are a derivative of the developed IDM. The MVD itself is encoded through the mvdXML format, which allows checking any given IFC instance file against conformance with the definition of the model view.

The following are used for MVD compliance checking:

1) BIM*Q (Requirements and Quality Management Database) developed by AEC3, and
2) the ifcdoc Tool, developed by buildingSMART

Table 2. TRL Assessment: IDM and MVD

TRL Question	Answer	TRL score
To what extent is the IDM complete? Does it cover the full range of information needed for a Bridge Management System?	The IDM specifies a methodology that unites the flow of construction processes within the specification of the information required. The IDM extensively covers all the relevant information such as, the point at which information is needed and the minimal amount of data that has to be exchanged for each predefined ER (exchange requirement).	8
To what extent is the MVD complete? Does it cover all of the information defined in the IDM?	The MVD defines a subset of the IFC model, which is required to satisfy one or more Exchange Requirements that are defined using the IDM.	7
How does the thoroughness of the IDM and of the MVD determine the performance of the software components?	The performance of the software components in the SeeBridge workflow is affected by the expected compliance rate of the mvdXML and the IFC files produced. The expected compliance rates are shown in Figure 2.	7
Who evaluated the IDM?	The IDM was evaluated by the whole consortium and research team. It was also evaluated by GDOT, in their role as a supporter of the project and a potential user of the system.	8
Who evaluated the MVD?	The MVD was evaluated by the Technion. TUM, AEC3, Kedmor and Cambridge members of the research team.	8
What are the plans, options/possibilities to resolve any information missing from the IDM?	The overall SeeBridge process defined in the IDM is applicable to all bridge types. The exchanges are all identified. The information concepts and their properties are fully defined for	7

TRL Question	Answer	TRL score
	girder and slab bridges. Extending it to cover the components of other bridge types is purely technical work, no new knowledge required.	
Plans, options/possibilities to complete sections missing from the MVD?	The MVD is complete for girder bridges and all defect types. Extending it to cover the components of other bridge types is purely technical work, no new knowledge required.	7
Were the bridge drawings/design on which the IDM was based realistic?	Yes – only full-scale bridge design data (drawings and specifications) were used.	7
Is the technology limited to any particular bridge types?	Yes: • Concrete Beam/Girder Bridges • Concrete Box Girder Bridges • Steel Beam/Girder Composite Bridges • Concrete Slab Bridges	8
Overall TRL score (minimum of all TRL scores)		**7**

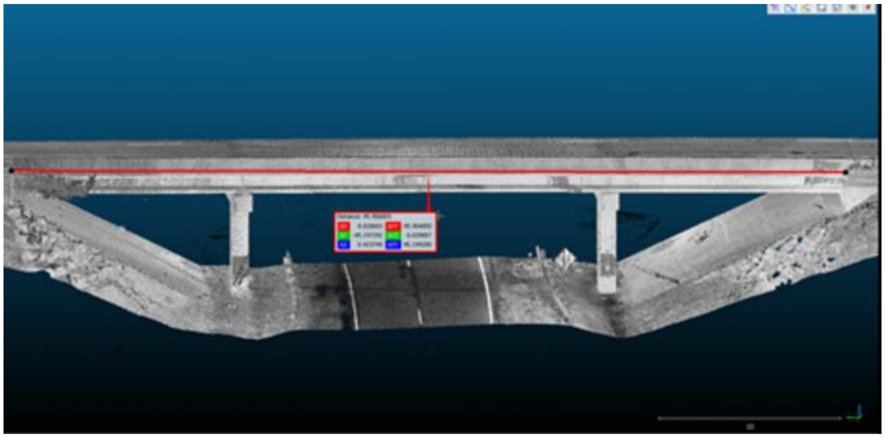
5 Point cloud data acquisition

The objective of the point cloud data acquisition stage is to produce detailed spatial raw data (3D point clouds), using high density surveying technologies which include laser scanning and photogrammetry. The data obtained was further processed to produce spatial raw 3D point clouds. This section of the report discusses each method used at this stage and performs a TRL assessment for the same. As part of testing, the bridges described in the following table were scanned using both technologies.

Table 3. PCD Preparation for Bridges

Bridge	Laser Scanning		Photogrammetry
	Terrestrial	Vehicle-borne	
Atlanta Acworth 067-52520 Gwinnett 135-01150 Gwinnett 135-50880	Trimble TX 5	Trimble MX7	iPhone 4MP
Cambridge Bridges 1 -10	Faro Focus 3D X330	None	None
Haifa Kiryat Bialik route 79	Leica Scanstation C-10	None	GoPro 4M

LIDAR
Bridge Length: 45.97 ft



PHOTOGRAMMETRY
Bridge Length: 45.93 ft

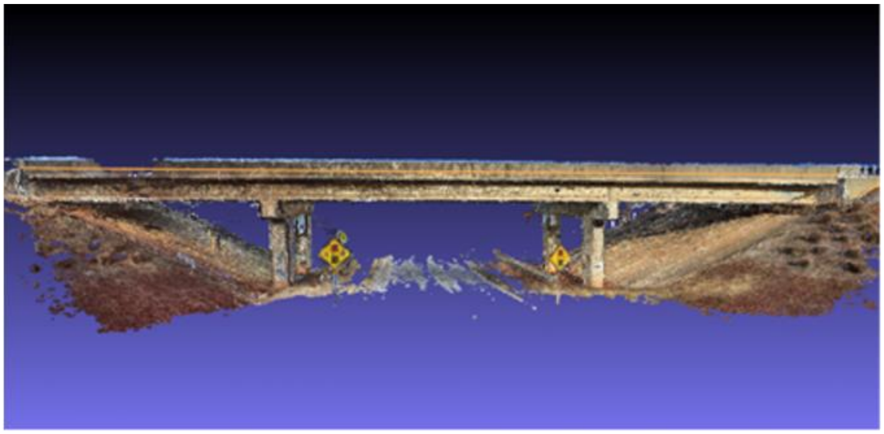


Figure 2. LIDAR and photogrammetric scan samples of the GDOT Bridge 135-01150

5.1 Laser Scanning

To perform laser scanning, the inspector evaluates the site and sets up points where laser scanning can be conducted from, to ensure collective coverage of the entire span of the bridge. Each laser scanning point captures a 3D point cloud and the data is exchanged from all the point clouds using an automated software.

It should be noted that this technology was not developed as part of this research, and is commercially available for use in various projects. The laser scanning solution uses equioment such as Trimble's TX8 high performance laser scanner, with a scan range of 340 meters, and able to scan with high end consistency throughout the given range. Hence, for this research the measurements and readings obtained from Trimble TX8 are assumed to be the standard.

The technology is well into industrial use and has been proven to work in its final form and under expected conditions.

Table 4. TRL Assessment: Point Cloud Data Acquisition – Laser Scanning

TRL Question	Answer	TRL score
To what degree is the stage automated? Semi-automated?	Scanning: The stage is semi-automated since it requires the inspector to physically set up points where laser scanning can be conducted from. Registration: The scans need to be registered with one another on the computer. This process is time consuming and requires a lot of human effort. Sometimes the point cloud is not registered properly and manual work is required to rectify it.	8
Under what conditions is the system expected to perform without compromising the quality of the output? What restrictions are placed on the input?	The system is expected to perform without compromising output quality given that the scan range is within 340 meters. If the range is exceeded, consistency cannot be guaranteed. Rainy conditions are expected to influence the output.	9
To what extent is the output of the phase ready/appropriate for processing by the next stage?	High density point clouds can be acquired from laser scanning as long as the scan range is controlled, and the number of times the bridge is scanned is sufficient. In our testing, each Atlanta bridge was scanned 20-45 times, and the process was repeated 3-4 times. The Haifa bridge had approx. 14 scan positions.	8
To what degree is the scope of the phase limited?	The scope of the phase is not limited since any bridge can be scanned using laser scanning. In certain situations, access to necessary scan positions is limited – for example, where a bridge crosses a river.	8
How complete is the output?	The density of the point cloud is high enough and can be thoroughly used for 3D modeling. Occlusion problems, particularly girder	8

TRL Question	Answer	TRL score
	occlusions, persist in the scan, however they can be resolved by setting up more scan positions.	
How did the test compare against the expectations?	For this research, the measurements and readings obtained from Trimble TX8 are assumed to be the standard.	9
Plans, options/possibilities to resolve the problems that were encountered during testing?	No major problems were encountered during testing.	9
How does the test environment differ from the operational environment? Were the test samples realistic?	No major differences should be expected between the testing and operational environments. The results should be of same standard provided that the guidelines are complied with.	9
How does the performance of this stage directly affect next stages?	The 3D reconstruction phase models the bridges regardless of how dimensionally accurate they are. Geometric reconstruction is, however, influenced by the density of the point cloud.	8
Is the technology limited to any particular bridge types?	The data collection is the same for all bridges.	9
Has it been tested on bridges in a real environment?	The data was collected from real bridges (see Table 3).	9
Is the output accurate (are dimensions accurate)?	Since the resolution of laser scanning is greater than the requirement expressed in the criteria document (see Figure 3), it can be assumed that the output is accurate.	9
Overall TRL score (minimum of all TRL scores)		**8**

5.2 Photogrammetry

This method requires the inspector to predetermine the camera resolution based on the intended accuracy, distance of the camera to the bridge surfaces, and the required point cloud resolution. Photos or videos are then captured from the bridge, capturing every surface of the bridge from multiple viewpoints. A processing and integration software, called Pointivo, then integrates the given images and videos into a cohesive and dense point cloud.

The following tables present the results of data obtained from Pointivo compared to Lidar for the three Atlanta bridges.

By comparing the absolute errors of deck lengths, the between beams lengths (transverse beam lengths) and the beam widths, against the corresponding tolerance thresholds, it is concluded that all measurements obtained from Pointivo are within the given thresholds.

It should also be noted that that the error in the data obtained from Pointivo is less than 0.5% for all cases. Since, in most cases the bridges being dealt with have decks of over 15m (over 40 ft.) and beams of over 3m length (10 ft.), the dimensional error is insignificant.

Table 5. Relative accuracy of Pointivo photogrammetry

Bridge	Dimension	Lidar (m)	Pointivo (m)	Abs. Error (m)
067-52520 Acworth	Deck Length	12.27	12.27	0.01
	Between Beams	5.21	5.20	0.02
	Beam Width	0.37	0.37	0.00
135-01150 Gwinnett 1	Deck Length	14.02	14.00	0.01
	Between Beams	5.92	5.91	0.01
	Beam Width	0.27	0.27	0.00
135-50880 Gwinnett 2	Deck Length	14.40	14.36	0.04
	Between Beams	3.47	3.47	0.00
	Beam Width	0.23	0.23	0.00

Element No.	Element name	Geometric accuracy thresholds [m] Defined in element local axis direction		
		Element Length [m]	Element Width/ thickness [m]	Element Height/Depth /Perimeter [m]
Primary elements				
111	Primary Girder	±0.1	±0.025	±0.025
112	Box Girder	±0.1	±0.025	±0.025
131	Monolithic Slab	±0.1	±0.1	±0.025
201	Transverse beam/Diaphragm	±0.05	±0.025	±0.025
301	Deck Slab	±0.1	±0.1	±0.025
202	Half Joint	±0.1	±0.1	-
204	Cantilever	±0.1	±0.1	±0.025
403	Abutments/End walls	±0.1	±0.1	-0.00/+0.05
405	Pier/Column	-0.00/+0.05	±0.025	±0.025
406	Cross head/ capping beam	±0.1	±0.025	±0.025
Secondary elements				
504	Bridge deck expansion Joint	±0.1	±0.025	-
602	Safety Barriers/ handrails	±0.1	±0.025	±0.05
702	Aprons/parapets/ edge beams	±0.1	±0.025	±0.05
706	Wing Walls	±0.1	±0.05	±0.25

Figure 3. SeeBridge geometry dimension tolerance thresholds per bridge element. Table taken from deliverable 1.2 Criteria for Evaluation.

Pointivo point clouds are well into industrial and commercial use, and have been proven to work in the final form under expected conditions. However, the process suffered two important drawbacks:

a) The processing time needed to compute the point clouds from the video frames is long, usually requiring many days.
b) The resulting point clouds are too sparse and insufficiently continuous for the segemntation procedures of the 3D reconstruction step. Tests of segmentation of the point clouds run in WP3 failed to compile 3D geometry from the resulting 3D faces.

Table 6. TRL Assessment: Point Cloud Data Acquisition – Photogrammetry

TRL Question	Answer	TRL score
To what degree is the stage automated? Semi-automated?	The process requires the inspector to predetermine the camera resolution based on the intended accuracy, distance of the camera to the bridge surfaces, and the required point cloud resolution. The camera setup is an important part of photogrammetry; hence the process is semi-automated. Manual work required if the registration is not performed correctly.	7
Under what conditions is the system expected to perform without compromising the quality of the output? What restrictions are placed on the input?	The system is expected to perform under good weather conditions if the camera quality is sufficient to capture high resolution photos or videos. The distance limitation for photogrammetry is 15-20 meters between the surface and the camera. The quality of the output is also influenced by the type of surface being scanned. Concrete surfaces are expected to produce higher density point clouds compared to steel surfaces.	8
To what extent is the output of the phase ready/appropriate for processing by the next stage?	It can be seen from the results tables that the maximum dimensional error that is obtained from Pointivo is 0.5%. However, the density of the point clouds proved to be insufficient for good 3D reconstruction in the following stage.	5
To what degree is the scope of the phase limited?	The scope is not limited since this method and the Pointivo software is currently being used in the industry to collect point cloud data. The data can be collected using any hi-res mobile camera. As long as the surface texture is made of concrete, high density results are expected.	8
How complete is the output?	Pointivo integrates the given images and videos into a cohesive and dense point cloud. This means that if the photos are clear enough, the output will be good too. . However, in practice, the point clouds produced for the Atlanta and Haifa bridge proved to be too sparse and the resulting 3D reconstruction was not of sufficient quality.	5
How did the test compare against the expectations?	The tests were performed under normal conditions and the results were as expected. The average dimensional error obtained from this was approximately 0.25%, which is reasonable. However, although dimensional accuracy was good, the point cloud was not extensive enough for effective 3D reconstruction.	6
Plans, options/possibilities to resolve the problems that were encountered during testing?	No major problems were encountered while capturing images or videos. However, the image output could have been improved if the use of	7

TRL Question	Answer	TRL score
	drones was implemented. The time for processing is still relatively long, although it can run un-attended.	
How does the test environment differ from the operational environment? Were the test samples realistic?	The test environment does not differ from the operational environment since data collection is the same whether a tester is conducting the collection or the inspector. The samples were realistic since the data that was obtained from was from real bridges.	8
How does the performance of this stage directly affect next stages?	The 3D reconstruction phase models the bridges regardless of how dimensionally accurate they are. Geometric reconstruction is, however, influenced by the density of the point cloud.	6
Is the technology limited to any particular bridge types?	The data collection is the same for all bridges.	9
Has it been tested on bridges in a real environment?	The data that was collected was from real bridges	9
Is the output accurate (are dimensions accurate)?	The dimensions can be considered accurate, however there is a dimensional inaccuracy of less than 1 percent, which is expected.	8
Overall TRL score (minimum of all TRL scores)		**5**

6 3D Geometry Reconstruction

The objective of this step is to develop a point cloud data processing solution, which takes a registered point cloud of a bridge obtained from laser scanning as input, and generates a solid model estimate of the bridge structure with semantic labels for its constitutive components as output.

The 3D Geometry Reconstruction phase of the project utilizes data obtained from the point cloud phase, and converts the same into a workable 3D geometry model using IFC format. Preparing the point cloud data (PCD) modeling is an application oriented task and requires Computer Aided Design (CAD) software for aligning the bridge model to the X axis and for removing extraneous points (vegetation, vehicles, etc.). The figure below demonstrates the result of a model created from a point cloud.

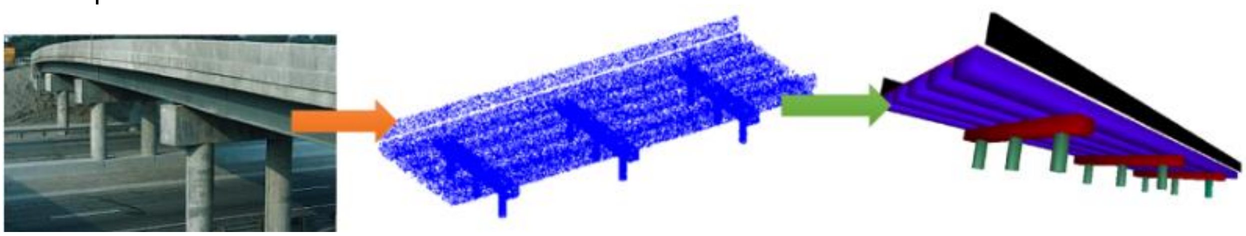


Figure 4. A concrete highway bridge, a point cloud and a 3D geometry model.

6.1 Top-down

The Cambridge team pursued what can be called a 'top-down' strategy, in which the software first divides the registered point cloud into clusters (segmentation) that correspond to the major bridge assemblies: substructure, supports, superstructure, etc. It then attempts to fit known bridge elements to the specific point clusters (fitting).

The BIM models that were originally compiled manually were used as the ground truth data for testing and developing the algorithms.

Table 7. TRL Assessment: 3D Reconstruction – Top-down

TRL Question	Answer	TRL score
To what degree is the stage automated? Semi-automated?	It is a semi-automated process, which requires the user to clean the point cloud so that it consists mostly of bridge points. The registered bridge point cloud includes a lot of noisy points which are irrelevant to the bridge information modelling task. There is also a user confirmation step regarding the identified faces. The rest is automated.	7
Under what conditions is the system expected to perform without compromising the quality of the output? What restrictions are placed on the input?	The input conditions, in particular the scan density, must be met. Surfaces that were not initially scanned cannot be recovered. Careful preparation of the scans can ensure thatthe point cloud will not compromise the output.	8

TRL Question	Answer	TRL score
To what degree is the scope of the phase limited?	The piers should have the same orientation when seen from the plan view. It will work best when their positioning is collinear, however some translational shifts are acceptable. This method cannot tackle the bridge curvature challenge. Classification errors were faced which cannot be ignored at the boundaries between deck and pier caps. This is because the pier caps don't lie on the same level due to slight curvature of the deck.	7
How complete is the output?	The solution was tested on ten bridges from the database. The detection results are shown in the following tables and the point-level performance metric precision (P), recall (R) and F1-score (F1) were generalized to multi-class settings.	7
How did the test compare against the expectations?	The output meets the LOD 300 requirements for all components below the deck, which are the important structural components. It will meet LOD 100 for the deck and above, which are non-structural components.	7
Plans, options/possibilities to resolve the problems that were encountered during testing?	The following problems were encountered during initial testing: 1) The proposed histogram-based method largely depends point counts. It's noise sensitive and cannot handle missing or sparse data robustly. This method can only generate one single point cluster for one bridge component. This is unrealistic especially for the deck which cannot be fitted with a "one-size-fits-all" model. One way of resolving the problems is by recursively breaking down a large bridge point cloud dataset into sub-datasets through a slicing algorithm. The slicing algorithm is used within each sub-dataset until target objects are found and all small detection problems were solved through more sophisticated object recognition techniques. 2) The curvature problem (discussed above) can be addressed by fitting a parabola (quadratic equation: $y=Ax^2+Bx+C$) to the deck points which are projected onto plane XY. Then slice the deck into multiple equal width segments as per a set of normal to the parabola.	6

TRL Question	Answer	TRL score
How does the test environment differ from the operational environment? Were the test samples realistic?	It does not differ. The samples were realistic.	8
How does the performance of this stage directly affect next stages?	The precision achieved in modeling in this phase directly affects, to some extent, the semantic enrichment process that follows. The semantic enrichment engine runs on rule sets based on parametric and dimensional relationships between elements. It was seen at this stage that some models had overlapping instances, or instances that were completely contained in another. Moreover, some instances, which should be modeled as a single instance, were modeled as multiple fragmented instances. Such modeling errors may hinder the enrichment process.	6
Is the technology limited to any particular bridge types?	The proposed solution of object detection in point clouds only focuses on slab bridges and beam-slab bridges with parallel piers (same orientation) and was tested only on ten bridge samples.	7
Is the output accurate (are dimensions accurate)?	After initial testing (first), the results reached precision 92.3%, with 92.3% recall and 85.7% accuracy.	8
Overall TRL score (minimum of all TRL scores)		6

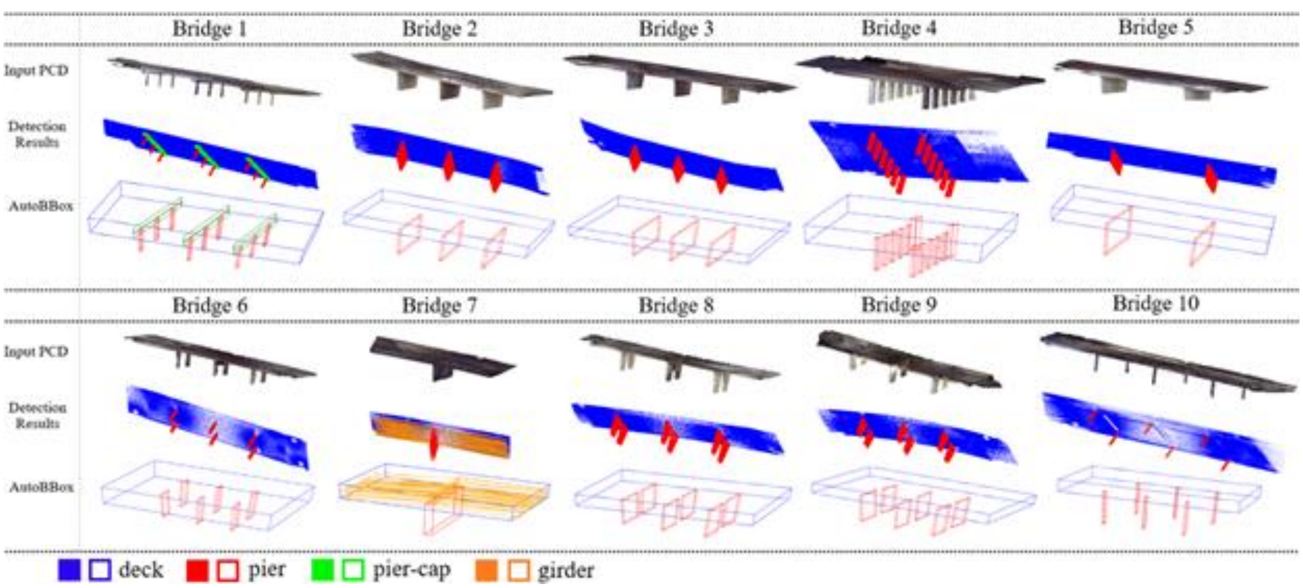


Figure 5. Detection results of 10 bridges and AutoBBox (Automatic Bounding Box) for components

Bridge ID	1	2	3	4	5	6	7	8	9	10	Avg
macro-avg PRE	98.40%	99.95%	99.92%	99.86%	99.90%	99.98%	94.35%	99.97%	99.98%	99.97%	**99.15%**
macro-avg REC	99.15%	99.44%	98.86%	99.82%	99.04%	99.41%	87.81%	99.47%	99.75%	99.08%	**98.08%**
macro-avg F1	98.77%	99.69%	99.39%	99.84%	99.47%	99.69%	90.96%	99.72%	99.87%	99.52%	**98.60%**

Figure 6. Performance evaluation results in Macro-average (see deliverable 3A for details).

Bridge ID	1	2	3	4	5	6	7	8	9	10	Avg
FN	1	0	0	1	0	0	2	1	1	0	
FP	0	0	0	0	0	0	0	0	0	0	
TP	12	4	4	12	3	7	18	6	6	7	
precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	**100%**
recall	92%	100%	100%	92%	100%	100%	90%	86%	86%	100%	**95%**
F1-score	96%	100%	100%	96%	100%	100%	95%	92%	92%	100%	**97%**

Figure 7. Component-level detection performance (see deliverable 3A for details).

6.2 Bottom-up

The Georgia Tech team developed the 'Bottom up' approach for the 3D Geometry Reconstruction stage. This approach consists of surface primitive estimation, which leads to feature extraction, which in turn is followed by detection and classification of components by segmenting the point cloud data into clusters. Reconstitution of solid model geometry is then carried out, and the model is packaged into an IFC file that is BIM compatible. The following diagram illustrates the concept succinctly:

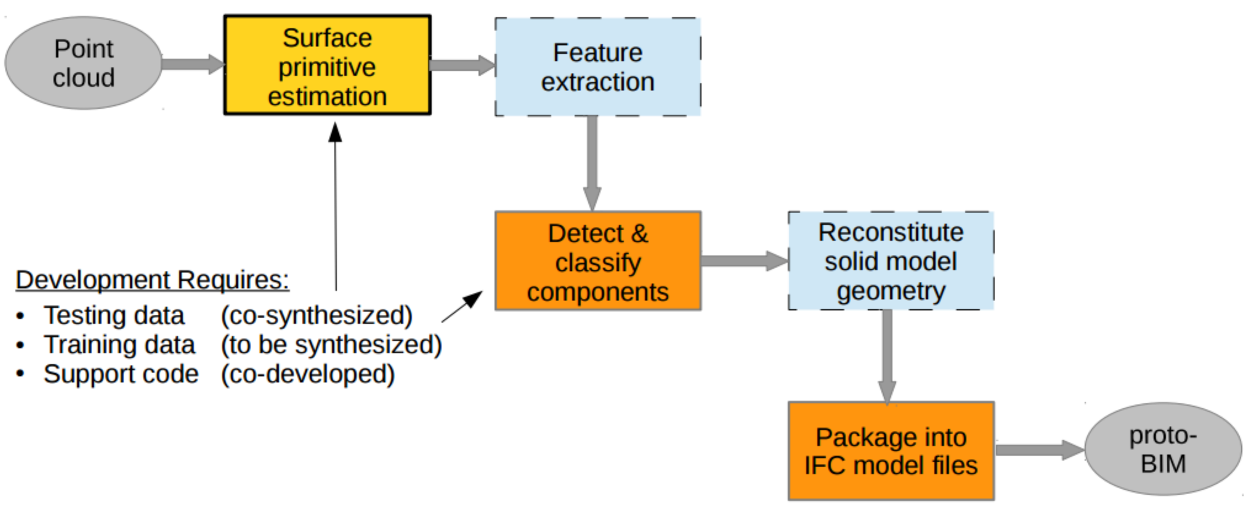


Figure 8 Bottom-up method pipeline

6.2.1 Slab Bridges

Table 8. TRL Assessment: 3D Reconstruction - bottom-up - Slab Bridges

TRL Question	Answer	TRL score
To what degree is the stage automated? Semi-automated?	It is a semi-automated process that requires the user to clean the point cloud so that it	6

TRL Question	Answer	TRL score
	consists almost only of bridge points. In particular, the bridge should be cropped so that only the two-horizontal surface of the deck and the piers remain.	
Under what conditions is the system expected to perform without compromising the quality of the output? What restrictions are placed on the input?	As long as the input conditions defined are met, the system works. It will also work under lower input quality conditions than are specified in the IDM for the input.	7
To what extent is the output of the phase ready/appropriate for processing by the next stage?	The LOD is at 200 for the structural elements.	7
To what degree is the scope of the phase limited?	The bridges must have straight span segments and cannot have significant curvature. They must be capable of being aligned to a coordinate axis.	6
How complete is the output?	Most objects classified correctly with no false positives. Abutments were not recognized due to wrong reconstruction of the width of the abutment.	6
How did the test compare against the expectations?	LOD 200 was met.	7
Plans, options/possibilities to resolve the problems that were encountered during testing?	There is a plan to perform segmented top-down processing to better fit the deck.	7
How does the test environment differ from the operational environment? Were the test samples realistic?	It does not differ. The samples were realistic.	8
How does the performance of this stage directly affect next stages?	The missing components cannot be processed or corrected by the next stage, however the detected components are still correctable by the next stage. The missing components cannot be enriched with damage information or other data associated to steps beyond WP4.	6
Is the technology limited to any particular bridge types?	Girder and slab bridges.	8
Has it been tested on bridges in a real environment?	Yes, it has been tested in a real environment.	8
Is the output accurate (are dimensions accurate)?	Yes, the dimensions are accurate. The tolreances are well within the criteria etsablished in WP1.	8
Overall TRL score (minimum of all TRL scores)		**6**

6.2.2 Girder Bridges

Acworth

Haifa

Cambridge

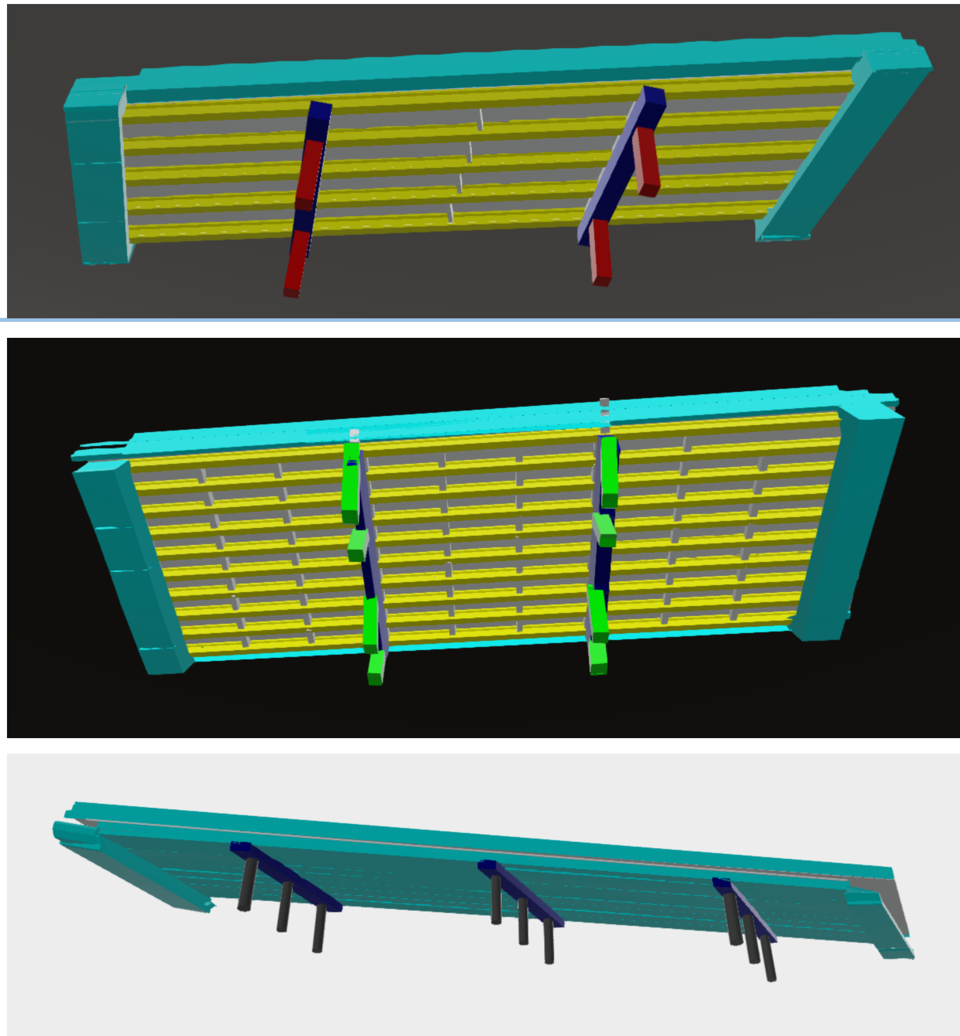


Figure 9. Reconstructed models of girder bridges using Bottom-Up approach

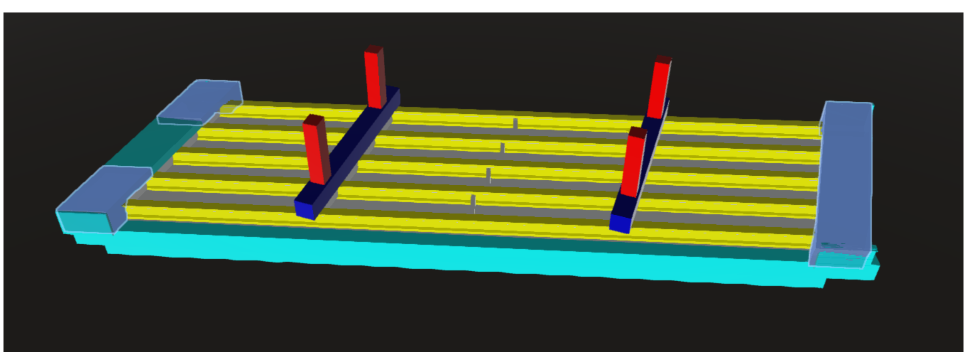


Figure 10. Incorrect and fragmented modeling

In Figure 10, the selected elements show incorrect modeling of abutments. The right abutment is correctly modeled as one element, whereas the left abutment is modeled as multiple elements.

Table 9. TRL Assessment: 3D Reconstruction - bottom up – Girder Bridges

TRL Question	Answer	TRL score
To what degree is the stage automated? Semi-automated?	This is a semi-automated process, as it requires cleaning up the point cloud to so that it only consists of bridge points.	6
Under what conditions is the system expected to perform without compromising the quality of the output? What restrictions are placed on the input?	As long as the input conditions defined are met, the system works. It will also work under lower input quality conditions than are specified in the IDM for the input.	7
To what extent is the output of the phase ready/appropriate for processing by the next stage?	The LOD is at 200 for the structural elements. However, some important structural elements are missing. The delivered output models still contain inconsistencies, such as overlapping elements and incorrect modeling of elements which may give rise to problems in the following phases, including semantic enrichment. Occasionally the elements modeled are fragmented: elements that should appear as one object, appear as multiple adjacent objects.	5
To what degree is the scope of the phase limited?	The bridges must have straight span segments and cannot have significant curvature. They must be capable of being aligned to a coordinate axis.	7
How complete is the output?	Only major structural components are modeled.	6
How did the test compare against the expectations?	LOD 200 was met.	7
Plans, options/possibilities to resolve the problems that were encountered during testing?	There is a plan to perform segmented top-down processing to better fit the deck, girders, transverse beams and abutments.	7
How does the test environment differ from the operational environment? Were the test samples realistic?	It does not differ. The samples were realistic.	8
How does the performance of this stage directly affect next stages?	The missing components cannot be processed or corrected by the next stage, however the detected components are still correctable by the next stage.	6
Is the technology limited to any particular bridge types?	Girder and slab bridges	8
Has it been tested on bridges in a real environment?	Yes, it has been tested in a real environment.	8
Is the output accurate (are dimensions accurate)?	Yes, the dimensions are accurate. The tolreances are well within the criteria etsablished in WP1.	7

TRL Question	Answer	TRL score
Overall TRL score (minimum of all TRL scores)		**5**

7 Semantic Enrichment

The semantic enrichment phase enriches the bridge model obtained from the 3D reconstruction phase and incorporates meaningful information to the IFC model, including grid creation, element classification, geometry recreation and grouping, etc. This process is conducted using rule sets developed using physical and shared parameters of elements, such as relative centroid location, relative element, elevation etc., in the IFC bridge model.

In order to facilitate the semantic enrichment process SeeBIM 2.0 was developed, which uses the rulesets and automatically performs the desired operation on individual elements, as well as the entire model. Figure 11 shows an interface example of a rule set run in SeeBIM 2.0 that checks if the two given bridge elements are in contact:

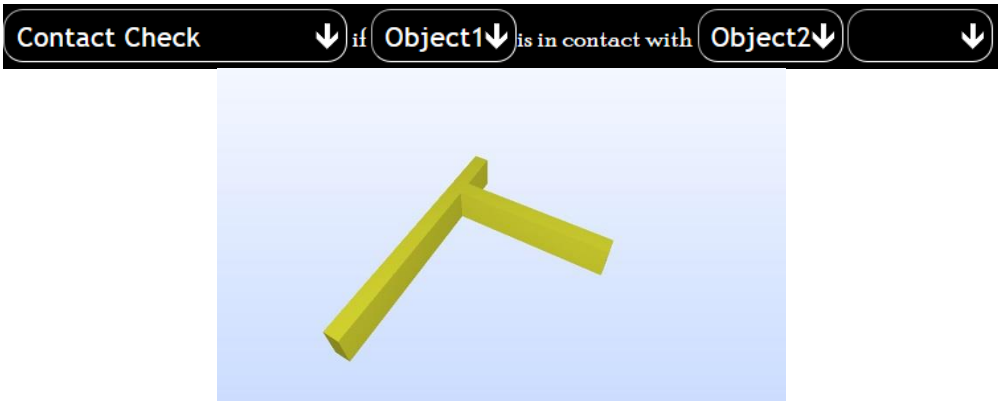


Figure 11. Example of a SeeBIM 2.0 interface, showing a single clause with an operator to check for contact between two BIM objects of a bridge. In this case, the operator returns that the two objects are indeed in contact.

This stage of the project is directly dependent on previous stages.

The semantic information added to the model by the SeeBIM 2.0 module covers the following aspects, in order of execution:

1) Element classification
2) Addition of abstract objects (e.g. ‘span’, ‘axis’)
3) Completion of partially occluded elements
4) Addition of completely occluded elements
5) Addition of relationships:
    a. Aggregation (‘part-of’ relationships and assembly elements)
    b. Connection (‘supports / supported by’ relationships and node elements)
6) Element numbering and/or notation

Items 1, 3 and 4 are covered in the above evaluations of identification, dimensional and location accuracy. In order to assess the conformity of the output against the MVD, the following criteria are used: for item 2 ‘Abstract Objects’, as listed in Table 10, and; for item 5 'Relationships', as listed in Table 11.

Table 10. SeeBridge ‘Abstract objects’ criteria

Abstract Object	Accuracy required	Explanation
Span	100%	All of the span objects are generated
Axis	100%	All of the axis objects are generated

Table 11. SeeBridge 'Relationship' criteria

Relationship Type	Relationship		Accuracy required
Aggregation	Physical Assembly	Deck array Girder array	100% 100%
	Logical Assembly	Elements in span Structural system Other systems	100% 100% 60%
Connection	Structural support	Bearing Shear	50% 50%

The following tables demonstrate the expected compliance rates, elements detectability based on element importance, and evaluation result classification based on element category.

Table 12. Expected Compliance Rate.

	Scope		
Element importance	**Class compliance**	**Compliance of properties**	**Compliance of relationships**
Very high -high	100%	100%	100%
Medium	90%	90%	80%
Low	80%	80%	70%

Table 13. Element identification evaluation categories**.**

		Element importance				
		Very High	High	Medium	Low	-
Elements Detectability	Detectable	Category 1	Category 2	Category 3	Category 3	Category 4
	Partially detectable	Category 2	Category 3	Category 3	Category 4	Category 4
	Non detectable	Category 5	Category 5	Category 5	Category 5	Category 5

Table 14. Criteria for performance.

	Element Category				
Evaluation result classi-fications	**Category 1**	**Category 2**	**Category 3**	**Category 4**	**Category 5**
Very good	**100%**	**100%**	**100%**	**≥85%**	≥25%
Good	-	**≥90%**	**≥80%**	**≥70%**	≥10%
Satisfied	-	**≥80%**	**≥70%**	**≥60%**	-
Less-satisfied	< 100%	< 80%	< 70%	< 60%	-

7.1 Girder Bridges

Tests were performed on girder bridges to evaluate the automated semantic enrichment process. SeeBIM 2.0 software has successfully carried out the enrichment operations in a lab simulated environment on the Haifa Bridge model obtained from the previous stage.

Specific SeeBIM 2.0 operator tests on Haifa Bridge were carried out under close inspection of the tester and the results are displayed in the following table. Throughout the test, SeeBIM 2.0 automatically conducts the given task or operation and the user involvement in minimal, other than specifying the required input demanded by the operator and the required action to be conducted by the software. The test results are either classified as ‘passed’ or ‘failed’ based on the outcome and the personal judgement of the tester.

The enrichment process for girder bridges is fully automated and the only input required from the user is regarding the operator that is meant to be implemented and its sub-operational sections, on the intended bridge.

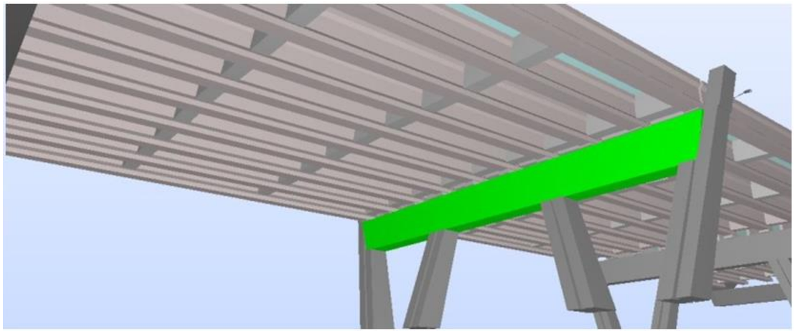
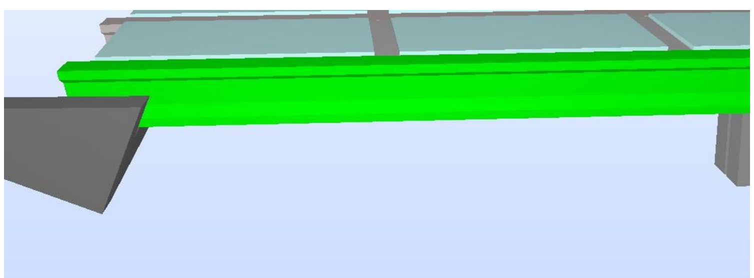
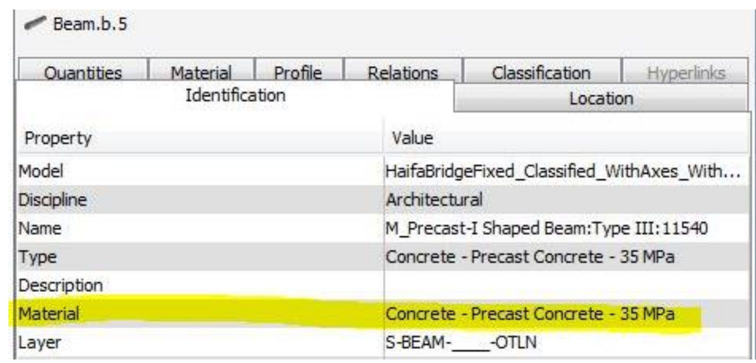
Table 15. Test results for semantic enrichment. The percentage number is the degree of precision (i.e. number of correct results / number of candidate objects)

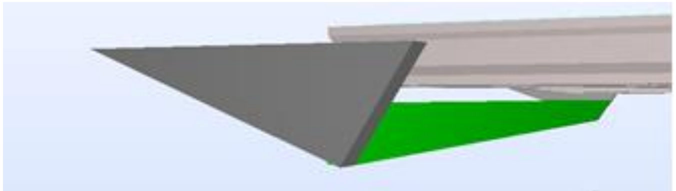
Bridge	**Haifa Bridge on Route 79**		**Atlanta Acworth**	**Cambridge 8**	**Cambridge bridges 4, 6, 8 and 9**
	Manually created model	**Automatically generated model (bottom-up)**	**Automatically generated model (bottom-up)**	**Automatically generated model (bottom-up)**	**Automatically generated model (top-down)**
Classification	100% All objects classified correctly with no false positives (columns, capping beams, plinths, transverse beams, abutments, girders, shear keys, slab and light posts).	27% 8/30 primary girders were recognized. 8 transverse beams were classified as slabs and 8 plinths as primary girders.	34% All of the columns, capping beams, deck slabs and 6/20 girders classified correctly. No transverse beams or abutments were classified.	96% Most objects classified correctly with no false positives. Abutments were not recognized due to wrong reconstruction of the width of the abutment.	100% All objects classified correctly, with no false positives. Object types included: abutments, columns, deck slabs, railings.
Numbering	100% All objects numbered, no numbers were repeated or omitted.	- Numbering was not tested due to small number of classified objects.	100% / 34% All classified objects were correctly numbered, but these were 34% of the objects.	100% / 96% All objects except abutments were numbered. No numbers were repeated or omitted.	100% All objects numbered, no numbers were repeated or omitted.
Grid reconstruction	100% All axes reconstructed correctly.	- Grid reconstruction was not tested due to small number of classified objects.	100% / 44% 4/9 axes were reconstructed correctly.	100% All lateral axes except those beneath the abutments were reconstructed.	NA Only lateral axes beneath the abutments were reconstructed. There are no capping beams and no objects to define longitudinal axes.
Aggregations	100% Objects were correctly aggregated to systems. No inadequate aggregation or objects not aggregated.	- Aggregation was not tested due to small number of classified objects.	100% / 34% All objects that were classified correctly were correctly aggregated to systems.	100% / 96% All objects that were classified correctly were correctly aggregated to systems.	100% All objects were correctly aggregated to systems. No inadequate aggregation or objects not aggregated.
Occlusions	100%	Not tested.	No occluded objects.	No occluded objects.	No occluded objects.

Table 16. TRL Assessment: Semantic Enrichment – Girder bridges

TRL Question	Answer	TRL score
To what degree is the stage automated? Semi-automated?	The enrichment process for girder bridges is fully automated. The only input required from the user is to select the appropriate rule-set.	8
Has it been tested on a wide range of girder bridges?	Not enough. Tested on Haifa, Atlanta and Lab emulated bridges only, i.e. it has not been tested in the full range of operational conditions	6
Under what conditions is the system expected to perform without compromising the quality of the output? What restrictions are placed on the input?	The system is expected to produce the desired results if the input is complete and conforms with the need for 3D geometry. This may be dependent on proper modeling from the previous stage.	8
To what extent is the output of the phase ready/appropriate for processing by the next stage?	The output models are enriched with meaningful information, such as grid creation, element classification, geometry recreation and grouping, etc. The next stage, damage detection further adds information regarding cracks and defects and uses enriched models. However, the information added at this stage can be used for BMS data collection.	8
To what degree is the scope of the phase limited?	The type of bridge (girder bridge) that can be treated is narrowly defined, because the pairwise dependence of the classification means that if one of any pair of object types is absent, the other can be classified only if it associated with another object (redundancy of rules). However, separate rule sets for subtypes of bridges can be defined. The scope is also limited to situations of occlusion repair similar to those encountered in the experimental data (girder lengths, bearings, transverse beams and deck plates). No other element occlusion is fixed at this stage.	7
How complete and how correct is the output? How does the performance of this stage directly affect next stages?	The output executes the intended operator and returns an IFC model with additional information, such as grid creation, labeled elements, girder reconstruction, numbering and aggregations. The output is complete and accurate, and is suitable for the next stage.	8
How closely does the output conform to the MVD?	The output is measured rigorously against the Model View Definition (MVD), and checked using the BIMX tool. The Haifa Bridge output model has successfully fulfilled the SeeBridge 'Abstract objects' criteria (Figure 5), by generating all of the span objects and all of the axis objects with 100% accuracy.	9

TRL Question	Answer	TRL score
Who performed the tests? How did the test compare against the expectations?	Tests on Haifa Bridge and Atlanta bridges were carried out by the research team. It has not been tested by bridge maintenance teams, Results conformed closely with expectations. However, it should be noted that the results were reviewed by a number of bridge inspection professionals and highway administration professionals.	7
Plans, options/possibilities to resolve the problems that were encountered during testing?	Continued development of the system, particularly expansion of the set of rules to provide the redundancy needed to cope with objects missing in the data received from the previous step, and to increase the generality of the rule sets fo coping with ranges of bridge sub-types.	7
How does the test environment differ from the operational environment?	Test environment does not differ from the operational environment since SeeBIM is capable of running on any computer regardless of testing environment.	8
Were the test samples realistic?	The test samples were realistic, using real bridges and using the data produced from the previous step.	8
What needs to be done to reach the next TRL (to be answered after first assessment)?	The testing should be done extensively and more importantly on models that are automatically generated from previous stages. Further improving the modeling approaches at previous stage will improve the TRL.	
Is the technology limited to any particular bridge types?	The semantic enrichment operations on SeeBIM 2.0 are currently limited to Girder and Slab Bridges, but only because no rule-sets have been defined for other types of bridges. The underlying technology is not limited to any given set of bridge types.	8
Has it been tested on bridges in a real environment?	Yes, it has been tested on two real bridges (Haifa and Atlanta. It has achieved 100% precision for Haifa bridge in object type classification, identification and numbering, aggregation and occlusion repair. See test results.	8
Overall TRL score (minimum of all TRL scores)		**6**

	Operator	Before	After	Outcome
IF clause operators	Field Check	 'Field check' checks if the green element is a capping beam.	 'Field Check' returns that the beam is a capping beam	Passed
	Material Check	 'Material Check' checks if the bridge girder is "Concrete – Precast Concrete – 35 MPa"	 Material check returns that the bridge girder is made of "Concrete – Precast Concrete – 35 MPa"	Passed

<table>
<tr><td rowspan="3">THEN clause operators</td><td>Create Axis</td><td>
‘Create axis’ is required to create a set of axes on the XY plane underneath the selected object</td><td>
‘Create Axis’ returns a set of axes as per input.</td><td>Passed</td></tr>
<tr><td>Is a</td><td>Type: ARC-L-R1-H150-AL1-xx-
Description:
Functional Type: NOTDEFINED
Layer: E-LITE-EQPM-OTLN
System:
Geometry: Boundary Representation
Application: Autodesk Revit 2016 (ENU)
GUID: 2cr2CYr$5ANg_hFMM0m9fe
BATID: 206872

Object name not assigned</td><td>Functional Type: NOTDEFINED
Layer: E-LITE-EQPM-OTLN
System:
Geometry: Boundary Representation
Application: Autodesk Revit 2016 (ENU)
GUID: 2cr2CYr$5ANg_hFMM0m9fe
BATID: LightFixture

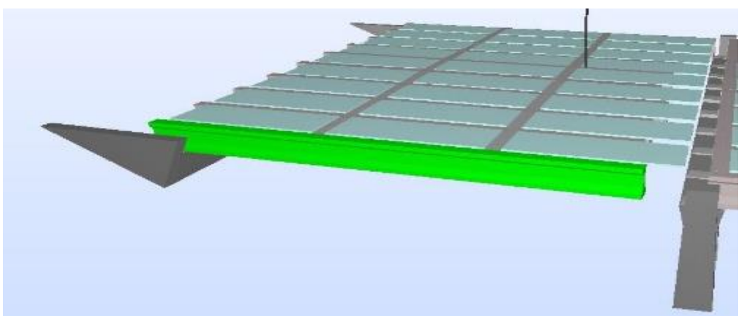
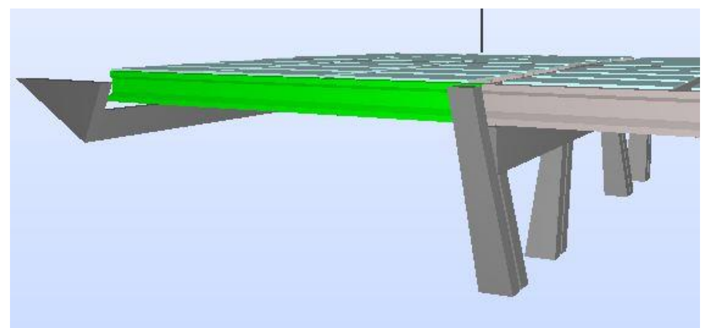
‘Is a’ identifies the object and labels it appropriately.</td><td>Passed</td></tr>
<tr><td>Lengthen Occluded Girder</td><td>
Due to occlusion, the girder is not fully constructed in the model</td><td>
‘Lengthen Occluded Girder’ successfully extends the girder to its appropriate length</td><td>Passed</td></tr>
</table>

Figure 12. MVD data conformace: Illustration of the check of semantic enrichment output IFC files against the MVD requirements.

Although the geometric reconstruction operator – 'Lengthen Occluded Girder' has been shown to successfully perform as intended on multiple bridges, it should be noted that currently SeeBIM 2.0 is only able to rectify occlusions in bridge girders. The operator 'Lengthen Occluded Girder' is designed and programmed to identify occluded sections of girders only and lengthen them accordingly.

There are instances where occlusion occurs in other bridge parts, such as bearings, however, the software is not capable to deal with that yet. This implies that there is potential to expand the idea of correcting occlusions to not just bridge girders, but to other elements as well.

7.2 Slab Bridges

Table 17. TRL Assessment: Semantic Enrichment – Slab Bridges

TRL Question	**Answer**	**TRL score**
To what degree is the stage automated? Semi-automated?	The enrichment process for slab bridges is fully automated. The only input required from the user is to select the appropriate rule-set.	8
Has it been tested on a wide range of slab bridges	The process has been tested on four slab bridges from the Cambridge area, prepared using both bottom-up and top-down methods.	8
Under what conditions is the system expected to perform without compromising the quality of the output? What restrictions are placed on the input?	The system is expected to produce the desired results if the input is complete and conforms with the need for 3D geometry. This may be dependent on proper modeling from the previous stage and the correct, such as the tolerance levels which are already imbedded in the rule-sets. For example, it was realized during testing that due to improper modeling of abutments in certain cases, they were not recognized in the semantic enrichment phase.	7
To what extent is the output of the phase ready/appropriate for processing by the next stage?	The output models are enriched with meaningful information, such as grid creation, element classification, grouping, etc. The next stage, damage detection further adds information regarding cracks and defects and uses enriched models. However, the information added at this stage can be used for BMS data collection. The output, however, lacks geometrical corrections, such as element occlusion errors, which may have been introduced in the original scanning.	7
To what degree is the scope of the phase limited?	There are various sub-types of slab bridges which may require additional and/or different rulesets that have to be defined. However, there are no major limitations on slab bridge type.	7
How complete and how correct is the output? How does the performance of this stage directly affect next stages?	The output executes the intended operator and returns an IFC model with meaningful information. The output is measured rigorously against the Model View Definition (MVD), and checked using the BIMX tool. It is worth mentioning that output is heavily influenced by the quality of the input geometry.	7

TRL Question	**Answer**	**TRL score**
Who performed the tests? How did the test compare against the expectations?	The tests were carried out and reviewed by the research team. It has not been tested by bridge maintenance teams. Results conformed closely with expectations. No significant occlusions were encountered in the slab bridges.	7
Plans, options/possibilities to resolve the problems that were encountered during testing?	One of the major problems that can be potentially encountered is the difficulty of classifying objects in bridges with high curvature of longitudinal axes. Some of the problems associated with this are object identification and axes recreation. This can be resolved by adjusting the tolerance levels in the rule sets of slab bridges with a slight curvature. However, all the bridges tested had minimal slab curvature which did not require any adjustments.	7
How does the test environment differ from the operational environment?	Test environment does not differ much from the operational environment since SeeBIM is capable of running on any computer regardless of testing environment.	8
Were the test samples realistic?	The test samples were realistic, using real bridges and using the data produced from the previous step.	7
What needs to be done to reach the next TRL (to be answered after first assessment)?	In order to reach the next TRL level, the testing should be done extensively on models that are automatically generated from previous stages.	
Is the technology limited to any particular bridge types?	The semantic enrichment operations on SeeBIM 2.0 are currently limited to Girder and Slab Bridges, but only because no rule-sets have been defined for other types of bridges. The underlying technology is not limited to any given set of bridge types.	8
Has it been tested on bridges in a real environment?	Yes, it has been tested on four real bridges in Cambridge area. It has achieved 100% precision in object type classification, identification, aggregation. See tests below.	7
Overall TRL score (minimum of all TRL scores)		**7**

8 Damage Detection and Modeling

Damage detection and modeling uses the models developed in the 3D reconstruction phase, which were further enriched with information in the semantic enrichment phase, and adds structurally relevant information vital for inspection, such as cracks. One of the important features of this, is that it extracts detailed surface texture and maps it onto the provided 3D geometry. In order to obtain the initial texture of structural elements, registered camera panoramas and 3D bridge geometry were used to get an initial texture of elements. Furthermore, features and correspondences in 3D reconstruction and initial texture overlay were found in order to calculate corrective rotation, translation and scale of images. Lastly, the fine texture of elements was calculated using high resolution images. The entire process was completed and implemented using the Gygax platform which was adaptedf for this specific purpose.

Figure 13 illustrates the fully mapped and modeled cracks and defects on a pair of orthogonal beams.

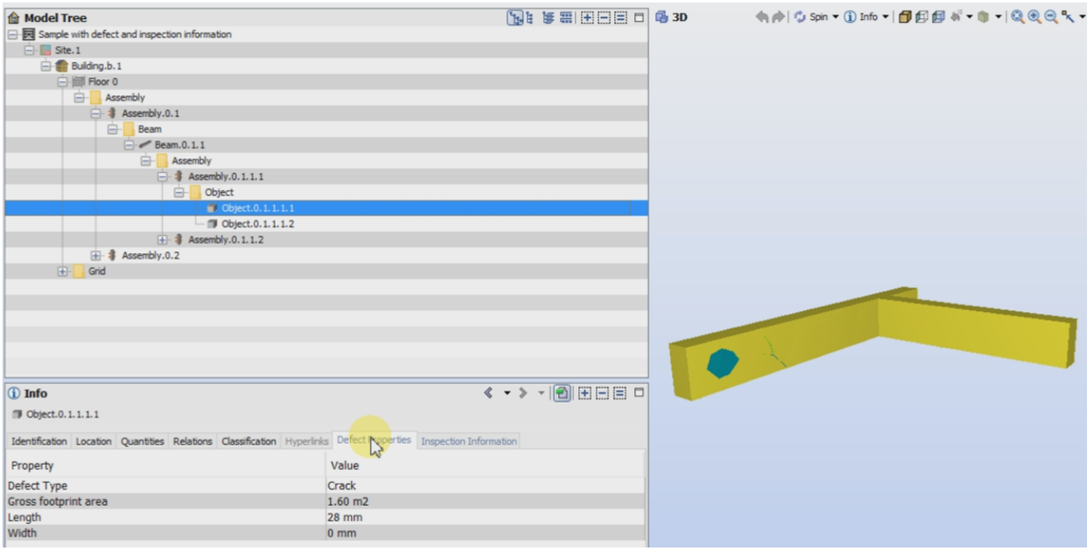


Figure 13. Display of a BIM model in IFC format in the Gygax platform, including defect patches positioned on and associated with the structural objects.

Through experimentation and implementation, it was found that several challenges arose while retrieving the initial texture:
1) the scanner positions exported from registration software were not precise enough to calculate a satisfactory initial texture. The positioning error of the initial texture obtained was approximately 20 cm, subjected to the distance and positioning of the camera.
2) The image quality obtained from the panorama was not good enough to calculate a sufficient number of features and to identify them as correspondences in comparison to the high-resolution images.

As a result, the images from the scanners were not used for this stage. Instead, high-resolution images taken using a 41 MP Sony camera were used, and original camera locations were atuomatically computed using photogrammetric algorithms. This procedure proved to be highly accurate and provided very detailed texture maps.

The damage detection step employed machine-learning algorithms to identify patches of 'healthy' concrete, thereby leading to isolation and identification of patches with defects. Which could then be measured and annotated in the BIM model, as illustrated above (Figure 13).

Table 18. TRL Assessment: Damage Detection

TRL Question	Answer	TRL score
To what degree is the stage automated? Semi-automated?	The stage is semi-automated since each texture image must be labelled manually to identify different damage types.	7
Is it possible to zoom in closely to see the details of the crack and recognize the exposed reinforcement of the spalling?	In the Gygax viewer, which was developed as part of this research, it is possible to zoom in closely and see the details of the crack and recognize the exposed reinforcements. Upon zooming in, even minute details, like minor cracks can be inspected.	8
Under what conditions is the system expected to perform without compromising the quality of the output? What restrictions are placed on the input?	Weather conditions must allow for clear photography. Cloudy conditions are best, to avoid contrast differences.	7
Is the texture of the element defect correctly shown? Is the registration correct?	Yes, the texture of the element defect is correctly shown in Gygax. See the results table below.	8
To what extent is the output of the phase ready/appropriate for processing by the next stage?	This is the last phase in the SeeBridge inspection process. It only influences the overall output from the entire process.	9
Is the relation between a defect and its corresponding element defects evident?	Yes, according to test results shown below, the relation between a defect and its corresponding element can be accurately depicted using Gygax. The data schema developed shows this structure and it is specified in the MVD.	7
To what degree is the scope of the phase limited?	Presented defect properties are vaguely formulated as they have been extracted from existing inspection guidelines. Clarification and consolidation of these guidelines is desirable.	7
Who performed the tests? How did the test compare against the expectations?	The tests were performed in the lab and the outcomes were as expected. During testing, defect type, location, extent, severity and cause were correctly added to the model. Also, conditions and property sets, such as easily shareable and machine readability were also recognized and added to the model. However, automatically extracting the properties is not yet possible. As an example, all cracks on beams from multiple models where crack width is greater than a given threshold were extracted.	7
Plans, options/possibilities to resolve the problems that were encountered during testing?	The problems encountered during testing, which are previously mentioned, can be resolved by using a better registered panoramic camera, including but not limited to Trimble's V10.	8
How does the test environment differ from the operational environment?	The test environment does not differ much from the operational environment since, Gygax can run on any advanced computer.	9
Were the test samples realistic?	The samples that were tested were taken from real bridges modeled and enriched in previous stages.	9
Is the technology limited to any particular bridge types?	No. This stage of the process can be applied to any bridge type.	9

TRL Question	**Answer**	**TRL score**
Is the corresponding general inspection information accessible along with the element defects?	Yes, in Gygax viewer the corresponding general inspection information is accessible along with element defects. See the results table below.	9
Has it been tested on bridges in a real environment?	Yes, it has been tested on bridges in real environment.	9
Overall TRL score (minimum of all TRL scores)		**7**

Table 19. Comparison of existing file formats for storing defect information

	Defect type	Defect location	Defect extent	Defect severity	Defect cause	Additional defect	3D geometry	Group different defect	Group defects affecting	Image registration / defect	Machine Readability	Easily shareable	Fully integrated data type
Paper-based	true	true	true	true	true	true	false	true	true	false	false	false	true
Image-based defect maps	false	true	true	false	false	false	false	false	false	false	true	true	true
DXF Files	false	true	true	false	false	false	true	false	false	false	true	true	true
Existing work based on IFC2X3	false	true	true	false	false	false	false	false	false	true	true	true	false
Bridge Defect Mapping based on IFC4	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**

Table 20. Comparison of existing viewing tools for browsing defect information

	Tested version	Open file	Show 3D geometry Beam	Show element defect geometry	Show element defect texture	Zoom in to see high resolution defect details	Show defect properties	List nested element defects to defect	List element defect properties	General inspection information accessible
Autodesk Revit	16.0.428.0	true	true	false	false	false	false	false	false	false
Solibri Model Viewer	9.6.10	true	true	true	false	false	true	true	true	false
xbim Explorer	2.4.1.28	false	false	false	false	false	false	false	false	false
Tekla BIMsight	1.9.7	true	false	false	false	false	false	false	false	false
DDS-CAD Viewer	30/12-2015	true	true	false	false	false	false	true	false	false
BIM Vision	2.14.0	false	false	false	false	false	false	false	false	false
3D Repo	Accessed 4/7/2017	true	true	false	false	false	false	false	false	false
BIMer	Accessed 4/7/2017	false	false	false	false	false	false	false	false	false
Gygax SeeBridge Viewer	**1.0**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**	**true**

9 Overall Assessment

The overall Technology Readiness Level Assessment is conducted based on the part-specific assessment conducted above, and the influence it carries on the overall readiness of the project. It was agreed among the consortium members that the most appropriate way of determining the overall readiness of the project is by taking the minimum of all TRL stage-scores for a specific bridge type – which will be a representative of overall TRL score of that bridge type. In the case where a stage has more than one sub-stages, the maximum score of all sub-stages is considered. In addition, the overall assessment is further justified, based on the answers to the questions defined below.

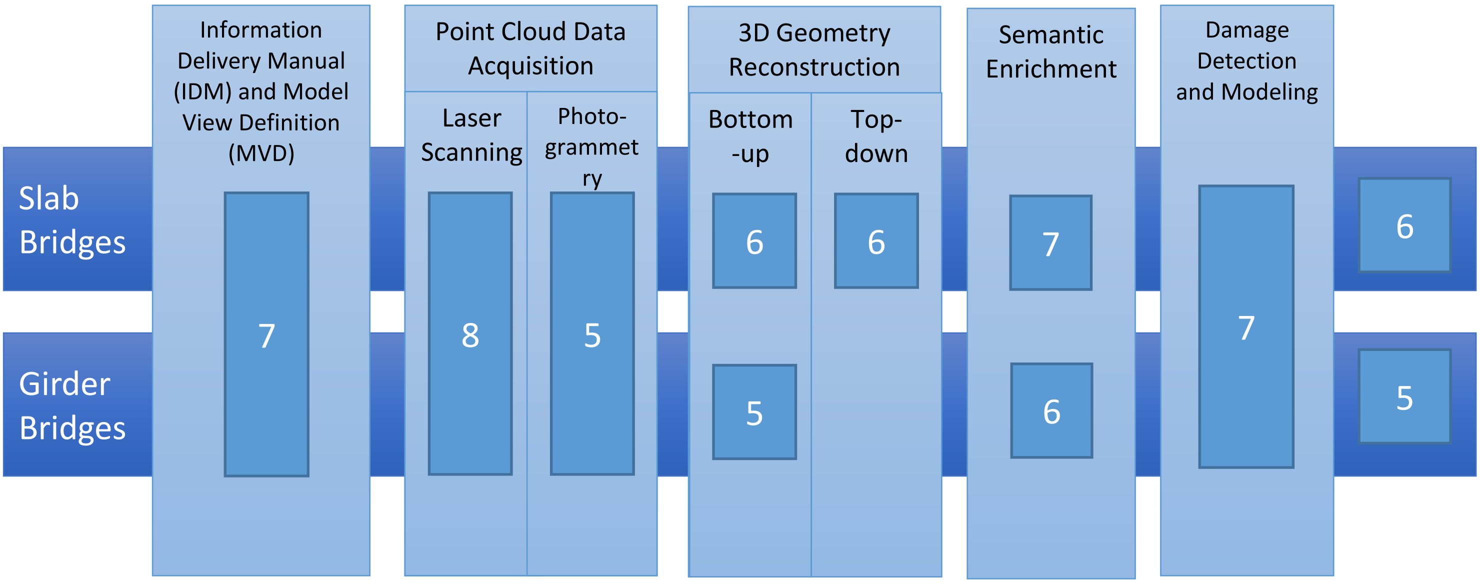


Figure 14. Summary of SeeBridge TRL Assessment

Table 21. Overall Assessment

TRL Question	Answer
What needs to be done to reach the next TRL?	As the overall TRL score is based on the minimum of all the part-specific scores, improving the score of the weakest stage will improve the overall TRL. For both Slab and Girder bridges, the weakest link in the entire process was the ‘3D Geometry Reconstruction’ phase which did not meet the automation as well as the LOD requirements. Hence, investing in and improving the reconstruction phase will drastically improve the overall performance of SeeBridge.
To what degree is the scope of the system limited? What actions are required to extend this scope to additional bridge types?	The scope of the overall system is currently limited to reinforced concrete slab and girder bridges. Of the four SeeBridge system steps, two are independent of the bridge type (i.e. will work for any bridge type) and two are type specific, as follows: 1) Laser scanning is generic, and will work for any type.

TRL Question	Answer
	2) 3D reconstruction requires knowledge of the bridge components that can be expected. Top-down reconstruction steps are specific to each bridge type and must be tailored for it; bottom-up reconstruction requires a library of possible bridge components, but can work with any type if its components are defined with 3D geometry. Extension to other bridge types primarily requires addition of geometry primitives, including review of the IDM and MVD, but very little (if any) adaptation of the core software. 3) Semantic enrichment has rule sets that are specific to each bridge type. Extension therefore requires preparation of feature matrices and derivation of rule sets for classification. Rule sets are defined using the SeeBIM 2.0 interface, so that here too, no changes to the core software are needed. 4) Defect detection and registration, including close-range photogrammetry, is independent of the bridge type.
To what extent is the overall output complete?	The content of the output models is essentially complete, containing all geometry, semantic information, and defect information.
Which option for point cloud data acquisition (scanning or photogrammetry) is the most effective?	Laser scanning is effective for point cloud data acquisition. Photogrammetry is not applicable for this purpose for highway bridges, due to the drawbacks listed in section 2 of the SeeBridge report.
Is the system output useful for a BMS?	Yes. This assumes of course that the BMS is sophisticated enough to use all of the information provided, which is not the case for most current BMS systems.