Project Acronym

SmartBridge

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White Paper
SmartBridge - Digital platform for Structural Integrity Management of Bridges

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Acknowledgement

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1 Introduction

This white paper is being written as a consequence of problems completing part of the second level plan for the 'SmartBridge' project, which is a collaborative project supported by InnovateUK. SmartBridge aims to develop 'Smart Monitoring and Inspection of Bridges Infrastructure'. Affected by the Covid-19 crisis, completion of WP6, 'Demonstration and testing of hardware and software' was not possible. To complete demonstration of the system outside of the project, investors are being sought. This White Paper aims to generate interest from investors in taking the technology forward. It is based on the premise that the hardware and software is sufficiently developed within SmartBridge and that further work is needed only in the context of improve the 'Smart' aspects of the technology.

This White Paper has two objectives:

1. To show that SmartBridge meets a strong market need.
2. To promote SmartBridge as an attractive investment opportunity

To meet the first objective, this 'White Paper' uses the 'Lean Canvas' methodology (Figure 1) This is often used for presenting business plans in a succinct less-wordy format. It is particularly helpful for business start-ups.

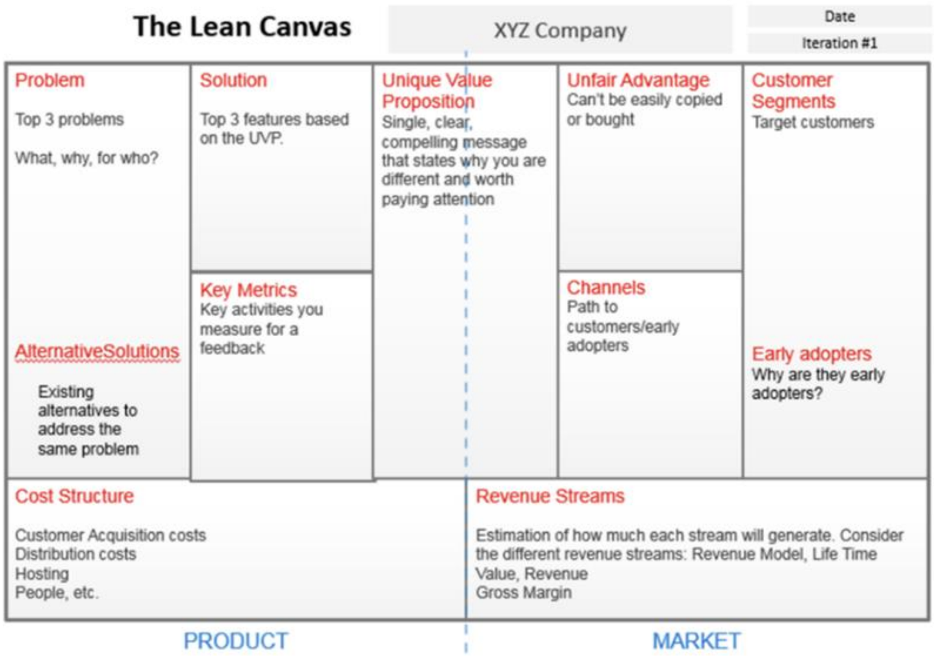

Figure 1: Lean canvas methodology

To meet the second objective, this White Paper uses the 'Technology Qualification' (TQ) methodology (Figure 2) to assess the risks to any investment in developing the SmartBridge technology from present Technology Readiness Level (TRL), to an operational system. The TQ goes on to make an estimate of the costs involved in making

SmartBridge ready for market, based on a development work programme that aims to mitigate these risks.

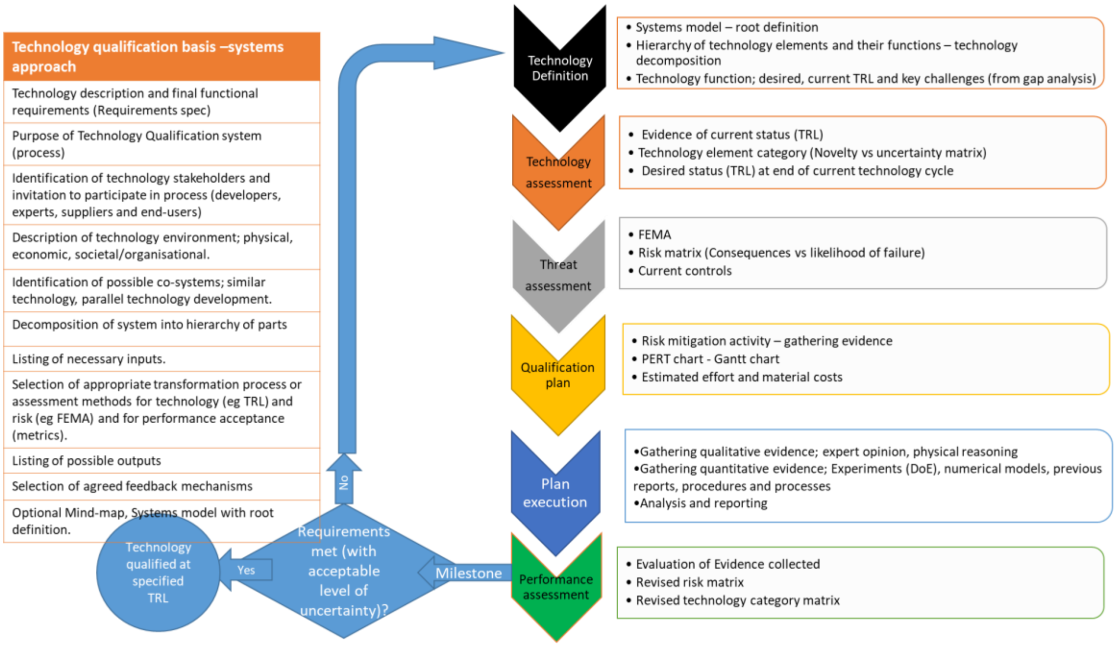

Figure 2: Technology Qualification methodology

As stated in the proposal to InnovateUK, 'the SmartBridge project aims to revolutionise the monitoring and maintenance of bridge infrastructure by developing an innovative knowledge-based digital platform that will enable the visualisation of bridges condition and degradation'. It is therefore in line with current thinking in the development of 'Digital Twins'.

Digital Twins are a set of "virtual information constructs that fully describe a structure. At its optimum, a digital twin is a dynamic virtual representation of the structure across its lifecycle, using real-time data to enable understanding, learning and reasoning". Digital twins are closely related to Building Information Models (BIMs). Indeed, a BIM can be regarded as the foundation for a digital twin. BIMs are "information repositories" related to a built asset, but up until now have been implemented within the design and construction phases, and these have different data requirements and objectives compared with structural health management.

Digital twins are receiving a great deal of attention at Cambridge Centre for Digital Built Britain, and the SmartBridge consortium have had contact with this organisation. However, Digital Twins are at the 'cutting edge' of digital modelling, requiring extensive computing resources, even for simple structures such as pressure vessels and SmartBridge can only build a digital platform that forms the basis of a digital twin.

For the work that was carried out during the SmartBridge project, a bridge with easy access was identified. This bridge was on the London Underground network near Watford. It was already being monitored by partner James Fisher. At its core is a bolted cast iron Victorian structure, but with some recent structural additions modifications.

A concept for the SmartBridge digital platform on this bridge is illustrated in Figure 3. The three essential components are:

1. A sensor network: sensors to measure displacement, vibration, temperature etc are arranged over the bridge, in order to collect data that provide information about the structural health of the bridge. For SmartBridge uniquely, Acoustic Emission (AE) sensors have been added, in order to detect actively growing cracks.
2. Data acquisition, storage and analysis: enormous amounts of data are collected in monitoring the health of a structure, necessitating the use of 'Cloud' storage. There follows the problem of analysing the data and identifying trends and events that indicate that damage is occurring.
3. Intelligence: The 'bridge inspector', who normally examines the bridge and identifies damage, has to be replaced by Artificial Intelligence, if the data are to be analysed. Although initially, there must be some human involvement in bringing experience and previous knowledge into the analysis.

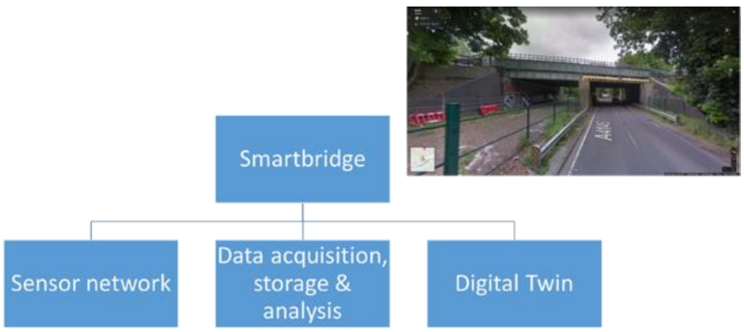

Figure 3: SmartBridge concept for Watford bridge

2 The market need for Smart Bridge - Lean Canvas

The Lean Canvas model is divided into sections as shown in Figure 1. The sections as they are ascribed to SmartBridge are described below.

2.1 Unique Value proposition

SmartBridge provides a digital platform for producing a Digital Twin of a bridge. It combines state-of-the-art technology in sensors for structural health monitoring, finite element modelling of bridge structural elements and data gathering, storage and analysis, with experienced based methodologies for management of risk and engineering critical assessment of bridges.

Taken as a whole, and applying Smartbridge technology to other types of structure, it can be seen as a concept linking new inspection technologies, such as the use of inspection drones, personal hand-held inspection recording devices with a range of continuous monitoring sensors on any structure, including wind turbines, process plant and power stations, as well as bridges (Figure 4). Here, the SmartBridge Digital Platform receives data from inspectors and sensors monitoring the structure in the field and the data is transferred to an office environment that is able to provide a total site experience through the digital twin.

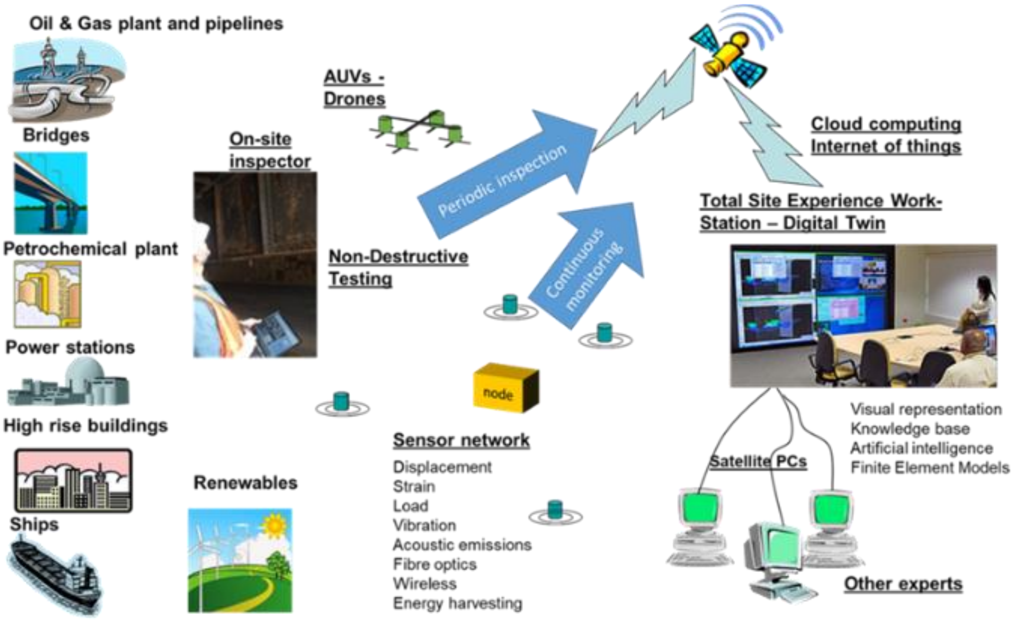

Figure 4: SmartBridge Concept as a unique selling proposition

2.2 Problems identified and solutions offered by SmartBridge

Maintaining the structural health of bridges through periodic inspections can be problematic for a number or reasons.

1. Bridge design includes a very high level of redundancy in structural performance. Even if damage occurs shortly after an inspection, it is unlikely that failure will occur before the damage is detected at the next inspection, allowing corrective actions to be taken. However as bridges age, their rate of decline in structural performance starts to increase, as depicted in the so-called 'Bath-tub Curve' (Figure 5), and failure might occur before the next inspection.

   By continuously monitoring the bridge, SmartBridge is able to provide real-time assessment of the structural health of the bridge.

2. Continuous monitoring of the bridge produces an enormous amount of data, which must be collected, stored and analysed

   SmartBridge provides cloud storage of data and infrastructure for data gathering and analysis.

3. Obtaining information from sensor data to provide real-time SHM is a complex problem. Vibration data from accelerometers requires a knowledge of the resonance characteristics of the bridge structure, if meaningful analysis of data is to be achieved.

SmartBridge uses finite element models of the bridge among other tools for creating a so-called ‘Digital Twin’, which takes in sensor data directly.

4. Inaccessibility for inspection. The massive nature of bridge structures means that many areas cannot be reached for inspection.

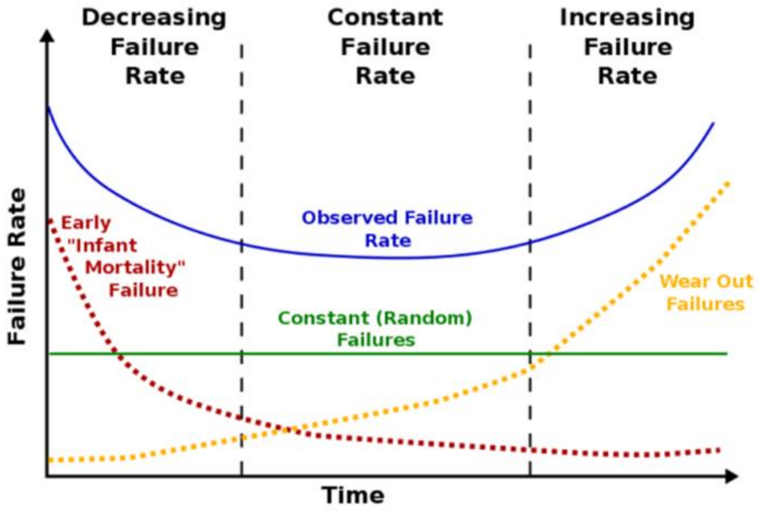

Figure 5: Bathtub curve

2.3 Alternative solutions

There are bespoke SHM systems for bridges that offer solutions to specific SHM problems. An example is an acoustic emission sensor system for monitoring breaks in the strands of suspension bridge cables. Another example is the use of accelerometers to detect hits from passing road traffic, as is the case with the Watford Bridge. None of these provides a holistic platform for multiple sensor data gathering, storage and analysis for whole bridge.

As already discussed, the SmartBridge digital platform is the first step in developing a digital twin for a bridge. Mention has already been made of similar emerging technology, based on so-called ‘Building information modelling (BIM)’

BIM is a process supported by various tools, technologies and contracts involving the generation and management of digital representations of physical and functional characteristics of places. Building information models (BIMs) are computer files (often but not always in proprietary formats and containing proprietary data), which can be extracted, exchanged or networked to support decision-making regarding a built asset. BIMs provide repositories for bridge data, dimensions, geometries materials; design loads etc., and can be expanded to included inspection reports.

However, unlike Digital Twins, BIMs are not continuously updated with sensor data that is analysed to provided information about the structural health of the bridge in real-time. They are more aligned with the needs of bridge design and construction, than maintenance.

Of course, an alternative to continuous monitoring of a bridge remains the use of periodic inspection. Access has always been a problem however, because of the massive nature of many bridge structures. Recent innovations have included the introduction of so-called ‘rope-access’ inspections, where inspection and Non-Destructive Testing (NDT) is carried out by specially trained inspectors, and more recently still, the introduction of drone inspections. Both these processes will continue, even with continuous monitoring, because they will be needed to evaluate any degradation detected by the monitoring system. Indeed, data recorded on video during inspections might be fed directly into a digital twin.

2.4 Key Metrics

SmartBridge is ground breaking technology, therefore having it accepted as an industry norm will be the key metrics. This can only be achieved through successful demonstration in multiple applications.

Key metrics for each demonstration include:

- Having a workable procedure for selecting hardware (instruments and sensors), setting up and calibration, data gathering, data storage, and data analysis at a base station. The procedure will be specific to the application and in the first instance, will be limited to a specific part of the bridge structure.
- Ease of system installation, operation and maintenance.
- System reliability over an extended period
- Extraction of relevant data that provides useful information for the finite element model of the selected part of the bridge structure.

By this time, there are likely to be competitors and there must be a clear strategy for dealing with these.

2.5 Unfair advantage

The SmartBridge consortium will endeavour to protect its Intellectual Property and patent key components of the technology.

However, hardware and software can be copied easily, but the third key component, intelligence, cannot be. It is by continually enhancing the intelligence component, SmartBridge system will be able to stay ahead of the competition.

Enhancing intelligence will be accomplished by learning from experience gained by careful qualification of procedures used in each application. Learning from mistakes will be part of this.

2.6 Promotion channels

There are two parts to this:-

1. Promotion for obtaining funds for further development. This will have to rely on ‘leg work’, going to potential early adopters and asking for funds for to demonstrate the technology in demonstrations that meet their specific needs. Relationships will have to be developed. Partner TWI, as a membership based Research and Technology

Organisation (RTO) is able to bring groups of its members together to sponsor development work, as this would be a way of sharing the development costs.

2. Promotion of operational system for sales of products and services. This will follow normal practice for 'high tech' products and services. Full use will be made of social media, in particular of webinars. First however the technology will have to be qualified and evidence provided that the SmartBridge technology is at an operational level of performance (TRL8)

2.7 Customer Segments

The UK government has made its intention known that investment in infrastructure will be a key priority. This may encourage customers for SmartBridge.

The envisaged customer segments are:

- Owners of Bridges e.g. Network rail, Transport for London, the highways agency.
- Contractors that provide bridge maintenance services
- Bridge builders – if it can be shown that bridge designs can be less conservative, with less built-in redundancy and less materials by implementing SmartBridge technology. There may already be new bridge designs ready for building, if only SmartBridge technology was available.

As well as the UK, the USA will also have potential customers for SmartBridge technology. Startling statistics show that a high proportion of bridges in the USA are structurally deficient in some way and there have been spectacular bridge failures recently, such as the I35 bridge in Minneapolis.

Closer to home, Italy has also had problems with bridges, re the Girona bridge collapse.

2.8 Early Adopters

London Underground Limited (LUL) have been involved in SmartBridge from its start. They have yet to be approached with regard to funding the next stage of SmartBridge development.

2.9 Cost structure and Revenue streams

SmartBridge has to go through Technology Qualification process to provide evidence that it is an operational system, and is therefore mature enough for market, before a cost structure can be formulated. Similarly with the revenue streams.

Technology Readiness Level (TRL) is a useful metric for assessing the maturity of a technology. Originally developed in aerospace, the various levels are described differently in different applications. The definitions used here are given in Figure 6. The graph illustrates important aspects of costs involve in technology development.

At low TRL, the costs rise relatively slowly, but accelerate from when a prototype has been built (TRL5) until operational equipment is ready (TRL8). This reflects the higher costs of engineering, which includes quality assurance management and acquisition of reliable and durable components for use in an operational environment.

Unfortunately, R&D funding tends to dry up at TRL5 and separate exploitation funds are needed, often from private investors. These must be willing to take on the risk that the functional requirements for the technology are not met.

The gap between R&D funding and exploitation funding gives rise to the so-called ‘Valley of Death’. This is often where technologies fail to develop. The aim must be to bring the R&D funds and exploitation funds together.

Smartbridge overall is at TRL5, though many of its components are already at TRL8. The Technology Qualification process described in the following section identifies the components that require substantial development.

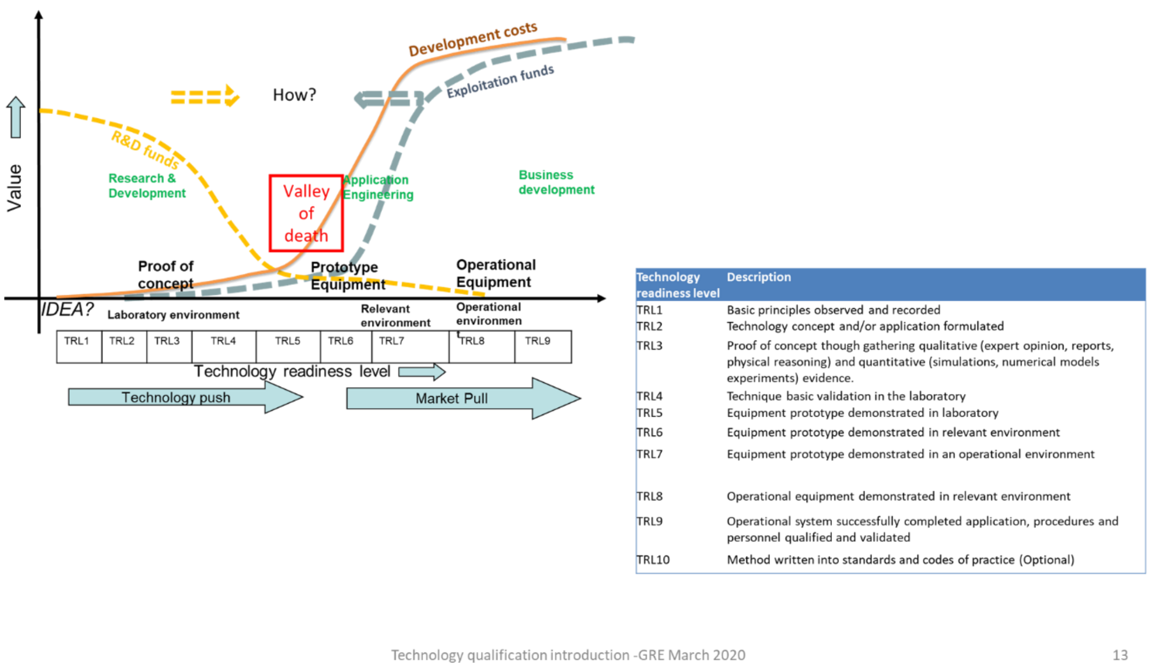

Figure 6: Technology reference level costs

3 The investment opportunity presented by Smartbridge - Technology qualification

3.1 Technology qualification basics

Technology Qualification (TQ) is the process of providing the evidence that a technology will function within specified operational limits with an acceptable level of risk. As mentioned in section 2.9, the aim of this TQ is to help potential investors that this risk is manageable.

An outline only for this process is presented here. In practice, it must be instigated using a team of experts involved in and potential end-users of SmartBridge.

TQ is an iterative process (Figure 3), starting with the formulation of a Technology Definition Basis.

This normally uses a ‘brain storming’ session among stakeholders in the technology. One approach is to use a ‘systems’ methodology than considers the TQ process as a transition from inputs to outputs, with feedback to ensure flexibility in purpose, consideration of the effects of environment and existing co-systems, and uses a hierarchy to divide the system into subsystems, components, items and so on to a usable level of granularity to the process. The functional requirements specification for the technology must be defined along with an agreement on the metrics used to measure progress.

The Technology Definition will state what the desired functions of the system are. It is useful to divide the technology into a hierarchy of parts to do this.

The technology assessment looks at individual parts of the system and assesses their Technology Readiness Level (TRL) and degree of novelty and uncertainty, the so-called Technology Category. An example Technology Category matrix is shown in Figure 7. TQ can be seen as a process for reducing the Technology Category rating, until the uncertainty is at acceptable rating, it never being possible to completely eliminate uncertainty. The Technology Category will help identify Commercially available Off-The-Shelf (COTS) parts of low rating, which will not need development. This is important as it may be possible to reduce costs by using parts that already meet functional requirements.

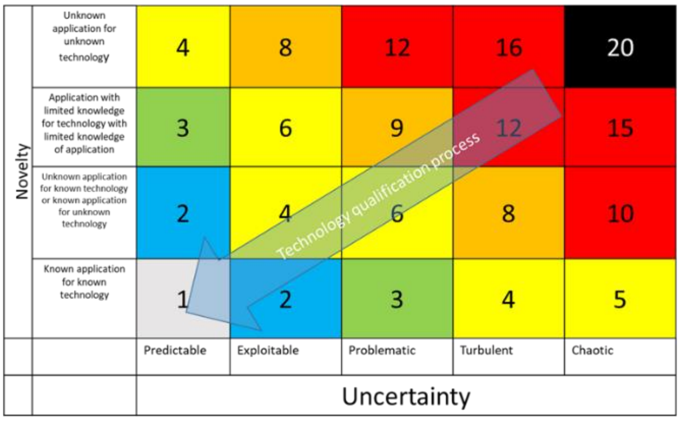

Figure 7: Technology Category Matrix

The threat assessment assesses the risk that the individual parts of the system to not perform their desired functions as specified in the Technology Definition. A Failure Effects and Modes Analysis (FEMA) is one way of assessing the risks. Risk of failure can be represented by a matrix with consequences of failure along one axis and likelihood of failure along the other (Figure 8). Risk assessments rely on the opinions of experts. These experts must have the necessary knowledge about consequences and probabilities of failure. This knowledge is rarely available in one person. It is best to have a risk assessment team. Generally speaking, experts with a knowledge of the technology itself can assess the likelihood of failure. To assess the consequences of failure, experts with a knowledge of the technology’s end-use and application is required and preferably some knowledge of the business. This is not possible without knowledge provided by at least one potential end-user. The TQ process identifies the parts of the technology with the highest risk of not functioning to requirements.

The Qualification Plan becomes a series mitigation exercises to reduce the risks to acceptable levels, bearing in mind that risk can never be entirely eliminated and there is always a risk/reward balance associated with any technology development.

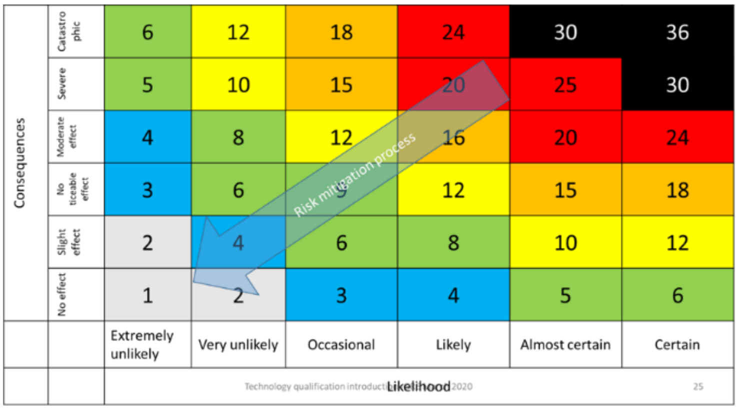

Figure 8: Risk matrix

Execution of the plan may involve experiments, modelling, physical reasoning and other methods for providing qualitative or quantitative evidence that the risk is at an acceptable level.

The final performance assessment evaluates the evidence and decides whether or not the technology has been qualified to the level defined at the start of the process. If not, the TQ cycle might be repeated. If it has met the functional requirements of the technology definition, then it may be the case that the TQ cycle is repeated to raise the TRL to the next level.

Two important aspects of TQ are:

- All evidence of technology category and risk is documented
- Assessments are made by a suitably qualified team, representing both technologists and end-users

3.2 Outline TQ process for SmartBridge

This process has been only partially, because it has not involved a team of experts.

An Excel spreadsheet has been constructed to hold all the factors and variables. Screen shots of the spreadsheet are given in this section. For the purpose of this exercise, the SmartBridge system has been decomposed into a hierarchy of parts as shown in Figure 9. This has been developed from the hierarchy shown in Figure 3 to cover hardware, software and intelligence sub-systems.

The hierarchy is transposed the Technology Definition of the TQ spreadsheet, along with the Technology Category as shown in Table 1.

Table 1: SmartBridge Technology Definition and Category

Technology Definition: Technology decomposition						Technology function			Technology Assessment: Current performance assessment				
Ident	System	Sub-system	Component	Sub-component	Item	Desired final function	Current status (TRL)	Key challenges	Evidence of current status	Novelty rating	Uncertainty rating	Technology category	Desired status at end of current TQ cycle
0	SmartBridge digital platform					An innovative knowledge-based digital platform that will enable the visualisation of bridges condition and degradation'	TRL5	Providing opportunities for demonstrating function performance	SmartBridge reports and deliverables	3	3	9	TRL8
1		Procedures				Processes for implementing SmartBridge, including equipment selection, setting and calibration, data gathering, data storage and data analysis requirments. They are specific to each structure and must be qualified	Relevant to operational system only (TRL8)	Qualification of procedure	None	1	3	3	TRL8
2		Hardware				Physical components of system as below	COTS components	Reliability	Site work conducted on Watford bridge	2	2	4	Bespoke equipment as part of SmartBridge system
2.1			Power			Solar power and energy harvesting from bridge movement to be investigated	Hard wired to mains	Reducing power requirements of system to minimum	Site work conducted with battery power on Watford bridge	2	1	2	Renewable energy used to power system
2.2			DAQ systems and sensors			Collection of sensor data from the bridge	COTS components	Reliability and sensitivity to bridge damage	Site work conducted on Watford bridge	2	2	4	Bespoke equipment as part of SmartBridge system
2.2.1				Vibration monitor		Detection of bridge damage through changes in resonance frequencies	COTS components	Reliability and sensitivity to bridge damage	Site work conducted on Watford bridge	1	1	1	Bespoke equipment as part of SmartBridge system
2.2.2				Displacement monitor		Detection of bridge damage through bridge movements	COTS components	Reliability and sensitivity to bridge damage	None	1	1	1	Bespoke equipment as part of SmartBridge system
2.2.3				Acoustic emission (AE) system		Monitoring of cracks and corrosion in high risk damage areas of bridge	COTS components	Reliability and detection of crack/corrosion initiation and growth	Site work conducted on Watford bridge	2	2	4	Bespoke equipment as part of SmartBridge system
2.2.4				Bridge loading monitor		Provide parametric data for correlation with other sensor data; particularly AE)	COTS components	Fusion with other sensor data	none	1	1	1	appropriate load sensors selected, possibly from existing SCADA on bridge
2.2.5				Environmental sensors		Monitoring of temperature, wind speed, icebuild-up	COTS components	Fusion with other sensor data	None	1	1	1	possible link up with existing SCADA on bridge
2.3			Computers			Running of software for control of BridgeSmart, collection, storage and analysis of data	COTS components	Site rubustness	Site work conducted on Watford bridge	1	2	2	Bespoke equipment as part of SmartBridge system
2.3.1				Base station		central hub for all computers and 'cloud'. Possibly linking BridgeSmart on multiple bridge locations	COTS components	Connectivity and user interface	experience of previous on-site data collection systems	1	1	1	Bespoke equipment as part of SmartBridge system
2.3.2				On-site node		Collection of data from sensors on the bridge and communication with base station	not available	connectivity and robustness for site	experience of previous on-site data collection systems	1	2	2	Bespoke equipment as part of SmartBridge system
2.3.3				Personal		To allow bridge inspector to upload information to SmartBridge from site	not available	connectivity to base station	none	1	2	2	COTS system (i-phone) with 'app'
2.4			Communications			data transfer	wired on site, web-based between partners during project	data bandwidth	data transfer between partners during project	1	2	2	operational
2.4.1				Wi-fi		data transfer between sensors and nodes and between nodes	wired	data bandwidth	Site work conducted on Watford bridge	1	2	2	operational
2.4.2				wired		data transfer between sensor nodes and base station	data transfer routines developed specifically for SmartBridge	data bandwidth	data transfer routines successfully implented during project between partners	1	1	1	operational
3		Sofware				see component functions below				2	3	6	
3.1			Data acquisition			control of sensor data collection, calibration, performance checkes etc	as supplied with COTS equipment	interfacing of software controlling different sensor systems	Site work conducted on Watford bridge	1	1	1	separate sensor DAQ's amalgamated in one SmartBridge system
3.2			Data storage			Cloud storage of sensor data	complete	data transfer	project deliverable report	1	1	1	complete
3.3			Data analysis			to provide relevant SHM information from bridge raw sensor data	From Watford bridge, vibration data used in FEM, but AE data not useable because of signal attenuation	linking sensor data to information about structural health of bridge	data collected from Watford bridge	2	3	6	Demonstrate that relevant information is being gathered
3.3.1				Data filtering		removing non-relevant data and noise	-	selection of optimum recording threshold levels, frequency bandwidth,	-				
3.3.2				Data integration		integration of vibration/AE/displacements sensors	-		-				
3.3.3				Software analysis algorithms		Transformation of filtered data from multiple sensors into useful information	-		-				
3.3.4				Data visualisation		correlation, or waveform and frequency spectra or continuous mode or transients	-		-				
3.4			User interface			Control of DAQ, analysis of data, record of results	separate user interfaces for each sensor DAQ	Integration of existing user interfaces into specific user interface for SmartBridge	data collected from Watford bridge	1	2	2	operational
3.5			Finite element model			numerical stress model of bridge that accepts information from sensors and BIM	FEM of girder structure supporting Watford bridge	Expand to more complex structures	deliverable - FEM of Watford bridge girder structure	2	3	6	FEM of whole bridge
3.5.1				FEM of actual bridge		FEM of actual bridge	-	Computing power of existing FEMs	-				FEM model of critical parts of a bridge
3.5.2				Sensor/FEM interface		Data from sensors fed directly to FEM	Data added manually	File transfer	-				FEM accepts sensor data automatically
3.5.3				FEM/BIM inteface		Digital twin for bridge using BIM as static base and FEM as dynamic model of bridge	-	File transfer	-				FEM and BIM integrated
4		Intelligence				SmartBridge capability to monitor structural integrity of bridge in real-time, without human interferance and make decisions without human supervision	Intelligence resides within human expertise only	complexity of bridge structure	Complexity of technology recognised, roadmap being developed	3	3	9	Increment in performance - requires several TQ cycles to develop
4.1			AI			Machine learning to analyse data, detect anomalies and recognise trends	AI can only be developed with operational equipment in operational environment	development of successful algorithms for analysing sensor data	none	3	3	9	cannot start until data is being gathered from SmartBridge at TRL8
4.2			Digital Twin			FEM model of bridge able to take in data directly from sensors in real time	simple FEM model, that requires manual feeding in of displacement data	Limitation of computer power in existing FEM software, which is very slow to process data	deleverable reports	3	3	9	cannot start until data is being gathered from SmartBridge at TRL8 and BIM is available for the bridge
4.3			Human resources			supervision of bridge structural integrity management	partner (James Fisher &TWI) expertise in bridge structural integrity management	Ensuring benefits of BridgeSmart are fully realised	Partner backgrounds	1	2	2	Knowledge of capalities of SmartBridge
4.3.1				Bridge inspectors		Ensure compliance with national standards for bridge inspection	TRL8	Interface of inspection and current bridge maintenance working practices with SmartBridge	Knowledge of bridge maintenance codes	1	1	1	Information from inspection fed into SmartBridge
4.3.2				SmartBridge operatives		Operatives for installation of equipment on structure, maintenance, interpretation of data	Relevant to operational system only (TRL8)	Training and qualification of personnel	None	1	2	2	Trained personnel

The Technology Category matrix plotted from the spreadsheet is shown in Figure 10. Note this is only a 3x3 matrix, having been evaluated by the author on his own. A team of experts would be needed to increase the matrix to as shown in Figure 7. The labels refer to the ident used to number the lines of the spreadsheet.

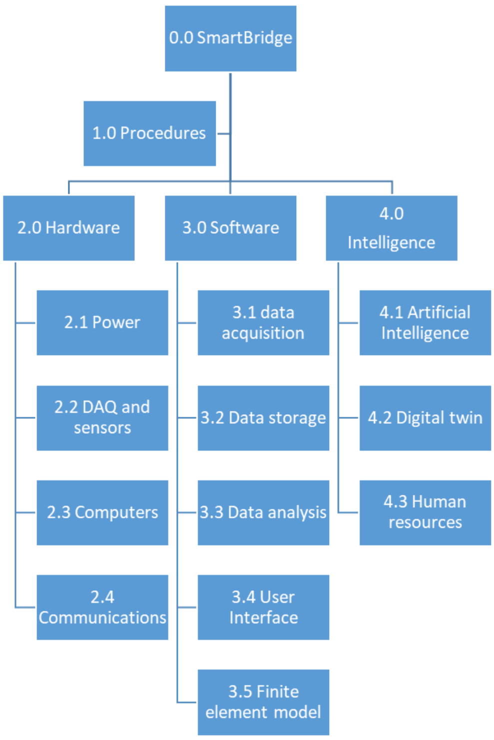

Figure 9: SmartBridge hierarchy of parts

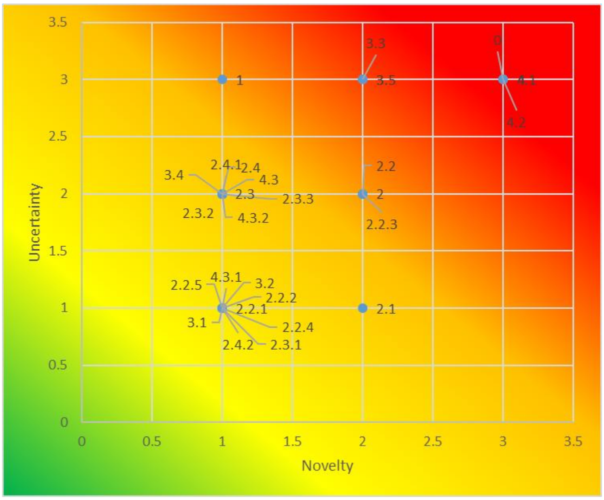

Figure 10: SmartBridge Technology Category Matrix

The matrix shows that most of SmartBridge's technology parts are at a low category rating. This low level of uncertainty and novelty is a result these parts being at high TRL. Only the parts in the red section of the matrix have been taken forward to a threat assessment. These are concerned with the Data Analysis (Ident 3.3) and Finite Element Modelling (ident 3.5) components of the software subsystem and the AI (Ident 4.1) and Digital Twin (Ident 4.2) components of the Intelligence siubsystem.

These are subjected to a threat/risk assessment in Table 2. The corresponding risk matrix is shown in Figure 11. Again, only a 3x3 matrix has been used.

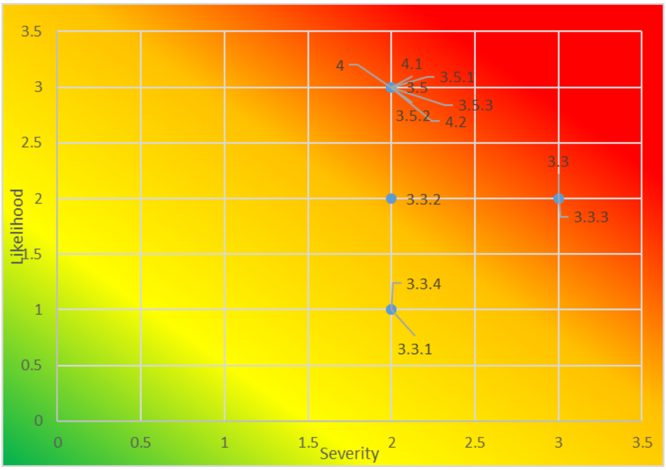

Figure 11: SmartBridge parts identified as being high risk

A cursory attempt has been made at building up a work programme to mitigate these risks. This is shown optimistically being conducted over a period of 12 months after the project completion and is shown in Table 3. A speculative cost for carrying out this work is £337k.

Table 2: Threat/risk rating of high Technology Category parts

	Risk assessment							TQ Plan
	Assessment of risk of not achieving desired performance							TQ plan
Ident	Failure mode	Consequencies of failure	Severity rating	Causes of failure	Likelihood rating until proven	Risk rating	Current controls	Mitigation activity (gathering evidence to mitigate threats)
3.3			3		2	6		
3.3.1	Signals not separated from noise	BridgeSmart development pauses	2	filtering method unsatisfactroy	1	2	Procedure qualification	Assessment of essential data filtering influencing parameters
3.3.2	Signals from various sensors not integrated	BridgeSmart development pauses	2	integration not optimised	2	4	Technology qualification	equipment testing
3.3.3	Signals/measurments not indicative of structural health	BridgeSmart development abandoned	3	Unable to find suitable algorithm	2	6	Technology qualification	Comprehensive algorithm development
3.3.4	Visualisation does not provide evidence of structural health	BridgeSmart development pauses	2	visualisation unsatisfactory	1	2	Technology qualification	equipment testing
3.4								
3.5			2		3	6		
3.5.1	FEM of bridge structure does not meet requirements	BridgeSmart development pauses	2	FEM too slow for real-time	3	6	Technology qualification	search alternative FEMs
3.5.2	FEM does nor accept sensor data	BridgeSmart development pauses	2	sensor data too complex	3	6	Technology qualification	software testing
3.5.3	FEM/BIM do not combine	BridgeSmart development pauses	2	FEM unable to match BIM	3	6	Technology qualification	FEM programme development
4			2		3	6		
4.1	Significant damage not detected automatically	BridgeSmart development pauses	2	software algorithms not sufficiently developed	3	6	Technology qualification	Sustained data gathering over an extended period of time to allow algorithms to be learn
4.2	Significicant damage not visualised.	BridgeSmart development pauses	2	interface with BIM and sensor data/measurments not sufficiently developed	3	6	Technology qualification	

Table 3: Speculative work programme for delivering SmartBridge

TQ Plan															Monthly rate	
TQ plan																
Mitigation activity (gathering evidence to mitigate threats)	Responsibility	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	Estimated effort Person Months	Material costs & travel	Materials description
Assessment of essential data filtering influencing parameters	TBA													3	£5,000.00	equipment hire, mock-up build, travel
equipment testing	TBA													4	£5,000.00	equipment hire, mock-up build, travel
Comprehensive algorithm development	TBA													9	£20,000.00	equipment hire, mock-up build, travel
equipment testing	TBA													3	£2,000.00	equipment hire, mock-up build, travel
search alternative FEMs	TBA													3	£30,000.00	alternative FEM software
software testing	TBA													3		
FEM programme development	TBA													6	£10,000.00	software upgrades
Sustained data gathering over an extended period of time to allow algorithms to be learn	TBA													12	£10,000.00	Miscellaneous
														6	£10,000.00	Miscellaneous
														49	£92,000.00	
													at	£5,000.00	per month	
														£245,000.00		
														Total	£337,000.00	

4 Conclusions

A Lean Canvas has been used to show there is a market need for SmarBridge.

A TQ process has been described to assess the levels of uncertainty and risk in taking SmartBridge forward to an operational system. Limiting the matrices to 3x3 reduces the value of this exercise, but the estimated costs of £337k for carrying out this work will hopefully concentrate minds.