CRANFIELD UNIVERSITY

DANIEL VAZQUEZ NAVARRO

REQUIREMENTS GAP IDENTIFICATION AND SELF-ASSESSMENT TOOL FOR TECHNOLOGY READINESS ASSESSMENT OF RAIL R&D PROJECTS

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING
Global Product Development and Management

MASTER OF SCEINCE (MSc)
Academic Year: 2019 - 2020

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science
(NB. This section can be removed if the award of the degree is based solely on examination of the thesis)

ABSTRACT

The railway asset management needs to improve significantly, smarter maintenance and repair methods are required. EU-funded programs like In2Smart are expected to bring innovative solutions to the railway sector.

This project has aimed to support the research work performed at Cranfield University for Network Rail in the autonomous repair and inspection rail platform. Network Rail is directly involved in the EU-funded project In2Smart2. One of its objectives (WP 13) is to bring the control and command system of a robotic platform for maintenance of the rail infrastructure from a concept demonstrator (TRL 4) to a more mature level (TRL 7).

For this purpose, an exhaustive analysis of existing documentation was carried out to produce a series of diagrams highlighting the collaborators interactions and activities. A gap analysis was also performed to identify the missing activities from lower TRLs (TRL 1 to TRL 4) and track the activities required to achieve higher TRLs (TRL 5 to TRL 7).

Also, a Validation & Verification (V&V) of an existing TRL self-assessment tool was conducted. The purpose of this instrument was to simplify and systematize the evaluation of innovative technologies development. The tool was then upgraded with improved features like incorporating objective evidences to back up the requirements completion, incorporating Manufacturing Readiness options or improving the overall user interface among others.

The different project diagrams, technology maturity gap analysis and the improved self-assessment TRL tool will provide Network Rail management useful information to build follow up strategies.

Keywords: Technology Readiness Level (TRL), IN2SMART, IN2SMART2, Network Rail, Self-Assessment Gap Evaluation Tool, Technology Maturity, Microsoft Excel, Visual Basic for Applications

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LIST OF EQUATIONS

LIST OF ABBREVIATIONS

AFRL	Air Force Research Laboratory
CP	Control Period
EC	European Commission
EU	European Union
GAO	Government Accountability Office
HLG-KET	High-Level Expert Group on Key Enabling Technologies
IAMS	Innovative Asset Management System
IN2SMART	Intelligent Innovative Smart Maintenance of Assets by integRated Technologies
IRL	Integration Readiness Level
IRP	Individual Research Project
ISO	International Organization for Standardization
KPI	key performance indicator
MRL	Manufacturing Readiness Level
NA	Not Applicable
NASA	National Aeronautics and Space Administration
NR	Network Rail
ORR	Office of Rail and Road
PRL	Programmatic Readiness Level
R&D	Research and Development
RIRL	Rail Industry Readiness Level
RIRS	Robotic Inspection and Repair System
SME	Subject Matter Experts
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
TTRL	Turkish Technology Readiness Level
UK	United Kingdome
UML	Unified Modelling Language
VBA	Visual Basic for Application
WIP	Work in Progress
WP	Work Package

1 INTRODUCTION

1.1 Background

The number of train passengers in the UK and European rail network is expected to increase by between 51% and 99% in the next 30 years [1]. With trains planned to run at a higher frequency, more inspection and maintenance activities would have to be carried out in less time. Therefore, innovative and smarter ways to inspect and maintain the rail infrastructure are required. Moreover, the current rail maintenance operations are undertaken by human personnel which presents a problem in terms of both personal safety and incidents caused by human errors.

Network Rail is owner, operator, and infrastructure manager of Britain's main railway infrastructure. It is defined as arm's length central government body answering to the Department of Transport (DoT) and Transport Scotland and regulated by the Office of Rail and Road (OOR) which reinvests its income into the improvement of the railway infrastructure [2]. Their core purpose is to provide safe and reliable journeys for passengers and freight with an average rate of 1,8m passengers and 200,00 tonnes of goods per day.

To implement novel management methods and to improve the rail operator's safety, Network Rail is involved in European funded programs like In2Rail and In2Smart. Especially where this project takes part, In2Smart and In2Smarts2 are multi-action plans to enhance the railway's asset management through innovative technologies. This seeks to be achieved by developing innovative and optimised strategies, systems, procedures, and tools [3].

1.2 Problem Statement

The European funded program In2Smart2 aims to take the results achieved in In2Smart (TRL 4/5) to implement specific demonstrators (TRL 6/7). In this case, when projects are built from previous ones, it is essential to validate and verify that previous objectives and requirements were truthfully fulfilled.

Network Rail makes significant investments to provide customers with the best service and satisfy their needs. From 2019 to 2024, Network Rail expects to

spend £42bn on operations, maintenance and renewals on the network [4]. Hence, the management that handles and coordinates these projects sometimes needs supportive documentation and information to make decisions. Part of this project would provide clear information at different levels to the head engineering management to plan and manage their resources.

The management of new technologies can sometimes be very ambiguous and challenging. Therefore, a Technology Readiness Assessment tools that could simplify and systematize the technology development process would save resources and time to any organization. During this project, improvements in an existing assessment tool would be performed.

1.3 Aim and Objectives

The aim of the project is to support Network Rail technology development plan by providing an improved TRL assessment tool and by mapping collaborators interactions and deliverables, and supportive improved TRL assessment tool.

The objectives are:

- Conduct a critical literature review
- Analyse the scope of the existing project and create collaborators and activities interactions maps
- Verification of In2Smart WP10 TRL requirements and existing TRL assessment tool
- Improvement of existing TRL assessment tool
- Conduct formal verification and validation processes

1.4 Scope

Projects development is a sophisticated multi-stakeholder assignment with many different phases and levels. Consequently, defining the project boundaries is essential for the proper project development.

The thesis targets no only the analysis of existing work for a previous project phase but also to map the work that needs to be done for the coming project.

Validation and further work in the existing TRL assessment tool is also envisioned. On the other side, project work regarding the system simulation, construction of the conceptual demonstrator among others is out of the scope of the project as shown in Figure 1-1.

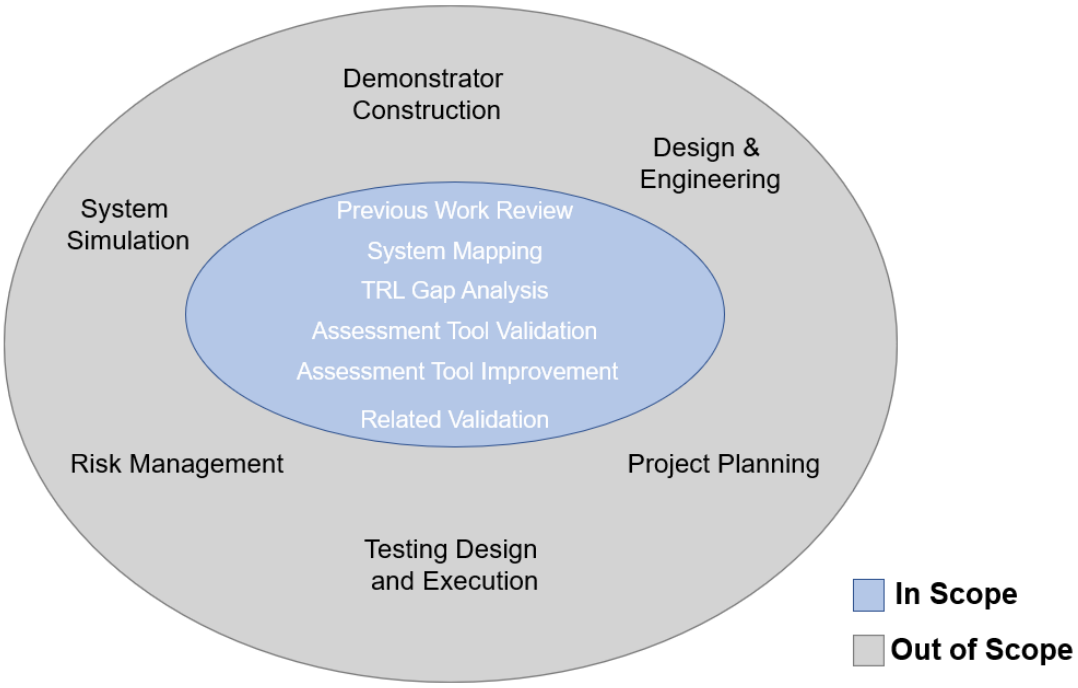


Figure 1-1 Research Thesis Scope and Out of Scope

1.5 Thesis structure

The thesis structure is the following:

Chapter 2 exposes the literature review on the UK rail industry, EU-funded programs, TRL and TRA.

Chapter 3 describes the methodology followed to enclose the research

Chapter 4 contains the analysis of the In2Smart2 project, TRL research assessment of In2Smart, TRL tool validation and upgrade

Chapter 5 outlines the validation process

Chapter 6 and 7 closes with the discussion on the results, conclusions, and further recommendations

2 LITERATURE REVIEW

2.1 Introduction

The following chapter reviews the relevant literature that will provide the necessary grounds to understand the project scope and achieving the intended objectives.

The related areas that have been analysed are shown in Figure 2-1. The literature review has been divided into two main areas: The Railway Industry in the UK, and the Technology Readiness Level (TRL) and its assessment. It has been addressed to answer the following questions:

- How important the rail industry is in the UK?
- How the maintenance and technology development is managed by Network Rail?
- Which European Programs that affects the scope of this project is Network Rail involved in?
- What Technology Readiness Level (TRL) is? What it is used for?
- Why is it important to develop tools in order to assess TRL? What type of tools have been implemented?

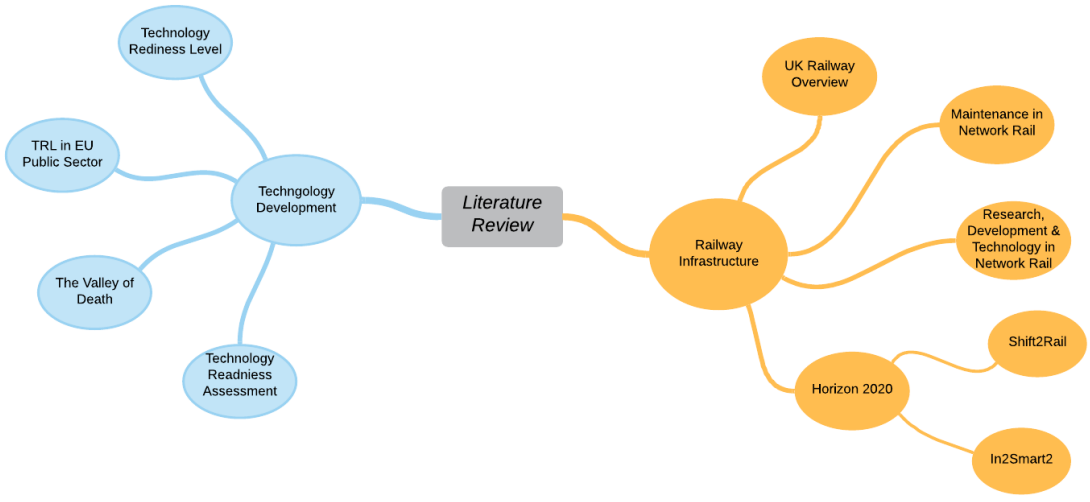


Figure 2-1 Literature Review Mind Map

2.2 Railway Industry

The railway infrastructure is one of the most important, fast and cost-effective ways of transporting passengers and goods for either short or long distances. However, the train transport expenses for construction, maintenance and overhead are higher than other modes of transport [5].

According to the UK Rail Industry Finance Report for 2018-2019 from Office of Rail and Road (ORR) [6], the total net expenditure in the Rail industry was £22.1bn, a 4.1% increase from 2017-18. Approximately 58% of the running costs were incurred by the train operators, 37% to manage the network and 5% to other expenses like freight as shown in Figure 2-2.

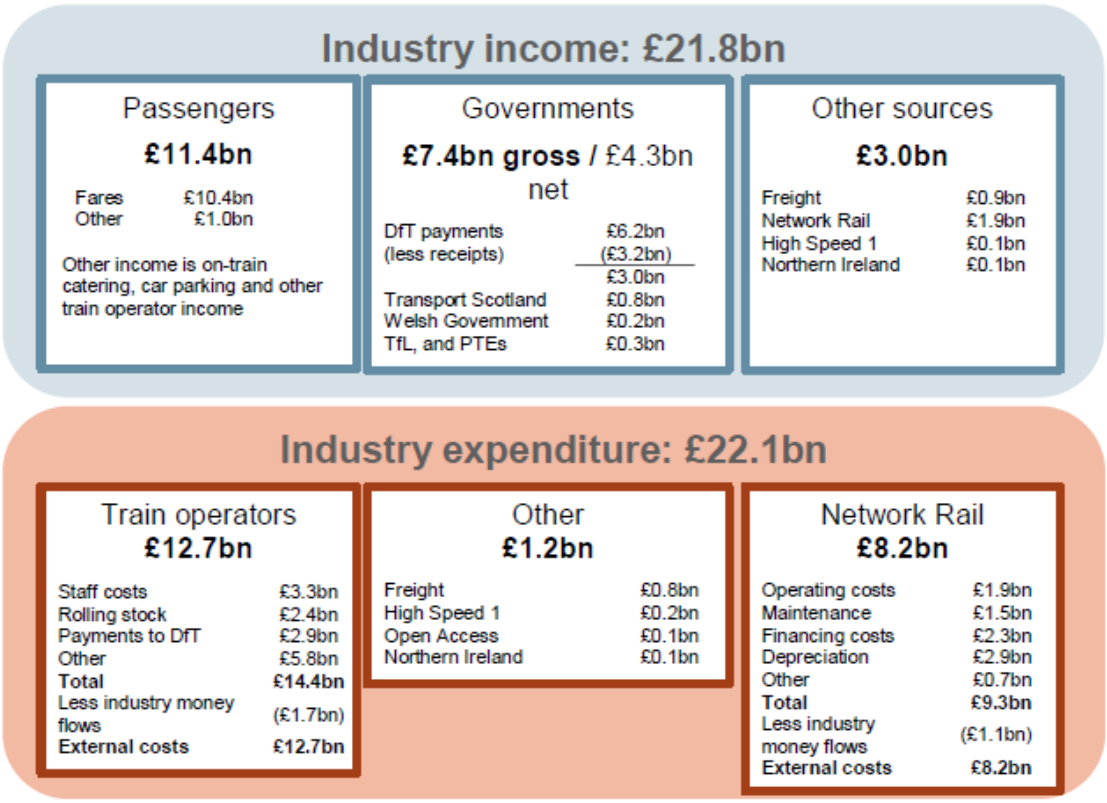


Figure 2-2 UK Rail Industry income and expenditure in 2018-2019 [6]

2.2.1 Maintenance and Research, Development & Technology in Network Rail

Network Rail is responsible for the good working order of more than 20,000 miles of track, almost 6,000 level crossings, 30,000 bridges and around 2,500 stations

[7]. Therefore, NR is spending half of their yearly budget on the maintenance of the track, structure, bridges and tunnels [8]. Furthermore, the number of passengers is increasing at a high rate over the years and has even doubled over the last 20 years – from 892m passengers' journeys in 1999 to 1756m in 2019 [9] and the rail infrastructure is dealing with more passengers than they were ever built for.

In the UK trains are expected to run 365 days a year, thus to keep the railway infrastructure, ready and safe for all the passengers with the lowest impact on the traffic, new innovative solutions and technologies need to be developed [7]. NR not only encourage partners to bring innovative solutions or ideas, but it also leads the Britain and international railway infrastructure research and development of technology. Therefore, within the Control Period 6 (CP6) from 2019 to 2024, Network Rail expects to spend £42bn on operations, maintenance and renewals on the network [4].

Among all the projects and programmes where it is involved, NR is a founding member of the European Programme Shift2Rail along with 54 other partners across 14 countries [10]. Shift2Rail is a European technology, research and development fund programme under Horizon 2020, seeking to deliver "the most sustainable, cost-efficient, high-performing, time-driven, digital and competitive customer-centred" solutions to the European railway infrastructure [11].

2.2.2 In2Smart2

The "Intelligent Innovative Smart Maintenance of Assets by integrated Technologies 2" (In2Smart2) project is part of the funded European Scheme Shift2Rail Horizon2020. The aim is to improve significantly the asset management in the railway sector through innovative technologies, new economic possibilities and enhanced legislative standards [12].

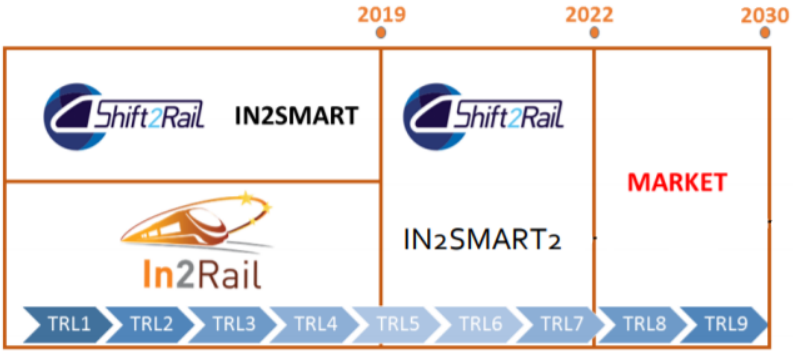


Figure 2-3 Horizon2020 projects, timeline and TRL relation [13]

As shown in Figure 2-3, this project is a continuation of the work initially conducted through the In2Rail and In2Smart, where levels of maturity of TRL4 and TRL5 where achieved. Those conceptual technologies are expected to be raised to TRL6 and TRL7 within In2Smart2 before the end of it in November 2022.

One of the objectives within In2Smart, and the one where this project takes part, was the introduction of autonomous robotics in the railway's assets inspection and maintenance activities. This workstream from In2Smart was carried within WP10 and was dedicated to validating the integration of inspection and tamping processes and the robotic maintenance execution. Figure 2-4 shows a prototype of the RIRS (Robotic Inspection and Repair System) used in the laboratories for the verification and validation and Figure 2-5 shows the software simulation used to test the software in the loop.

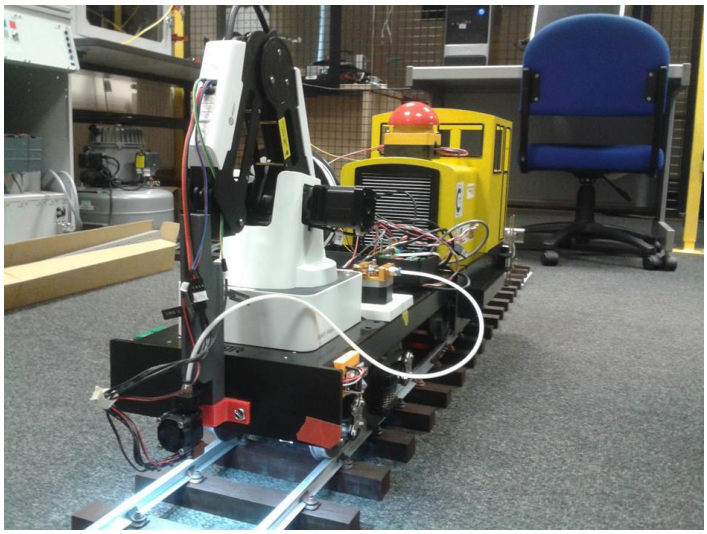


Figure 2-4 RIRS hardware demonstrator [14]

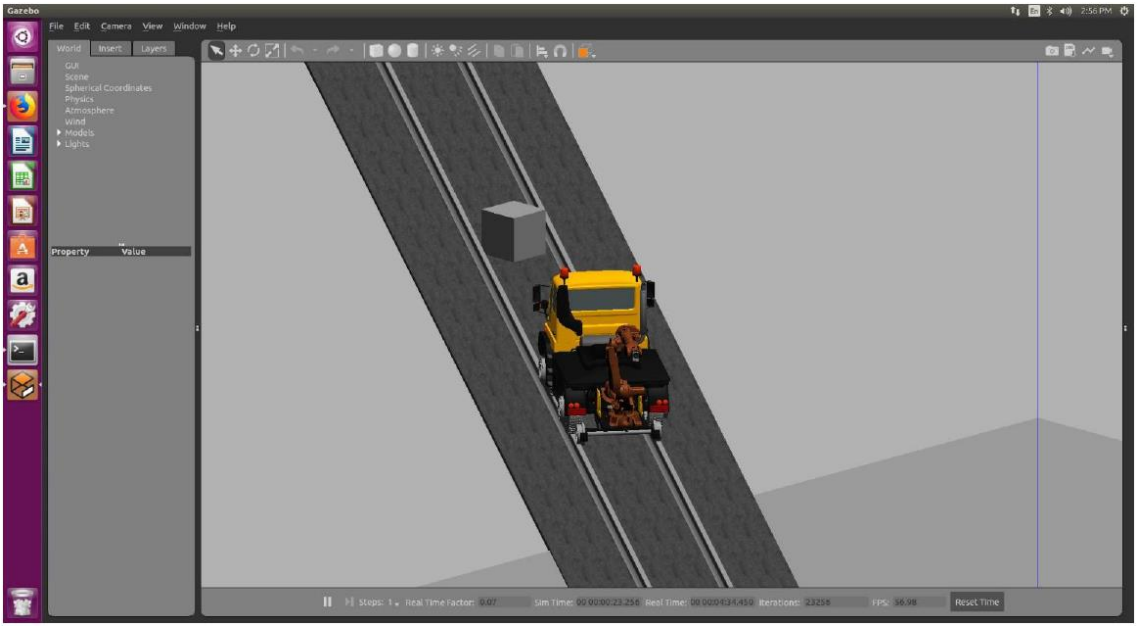


Figure 2-5 RIRS Software Simulation [14]

It is also worth to mention that for more than 5 years Cranfield University has been supporting Network Rail by conducting different research projects. Multiple projects have been subject to the European founded programs previously mention (In2Rail, Shift2Rail or In2Smart) like the design, simulation and construction of the RIRS demonstrator [15] [16] or the feasibility studies on inspections techniques. Other projects like the development of cost models [17], a system engineering framework [18] or a study about the use of cobots for maintenance [19] among others have enhanced this partnership.

2.3 Technology Development

2.3.1 Technology Readiness Level (TRL)

The concept of Technology Readiness Levels was established at the National Aeronautics and Space Administration (NASA) in 1974 by Sadin and then formally defined in 1989 in the paper [22]. It was conceived as a methodology to assess different developments of technologies for space programs.

Initially, it was a seven-level scale, but in the 90s the NASA adopted the today's used nine-level scale [23]. Nowadays, TRL is defined by NASA as a "type of measurement system used to assess the maturity level of a particular technology"

[24]. Institutions and organizations frequently use TRLs to characterise the maturity of a given technology within its life-cycle of development [25]. The scale goes from the lowest level (TRL 1) where the basic principles are observed to the highest level (TRL 9) where the system is proven and ready to be “launched” as shown in Figure 2-6. Each level is like a gate, meaning that only a level is achieved if all its requirements are completed.

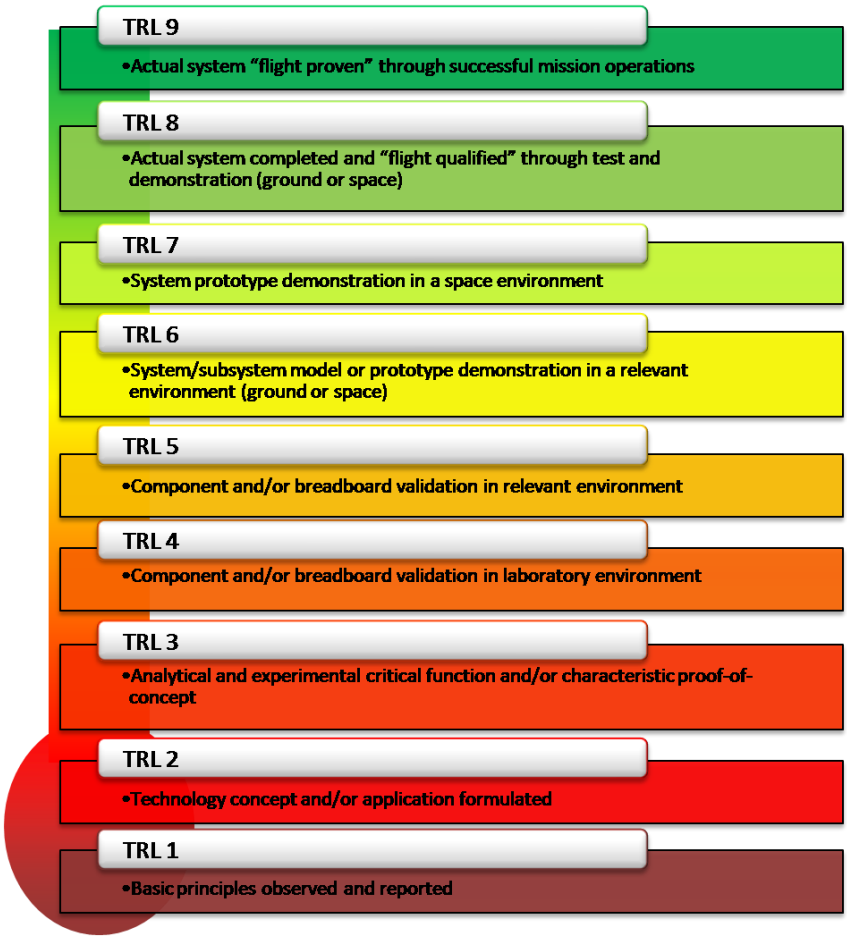


Figure 2-6 Technology Readiness Level (TRL) [24]

2.3.2 TRL in Europe and EU Public Sector

The TRL scale arrived in Europe through the European Space Agency (ESA) which adopted the scale in 2008 in their handbook [26]. This definition of TRL used by ESA was then replaced by the ISO 16290:2013 “Space systems – Definition of the Technology Readiness Levels and their criteria of assessment”

released on 2013 [27]. The ISO 16290:2013 is principally suited to the space system hardware, despite the definitions could be extrapolated to other fields [28].

In 2009 the communication from the European Commission (EC) "Preparing for our future: Developing a common strategy for key enabling technologies in the EU" [29] introduced the use of the TRL scale in the EU. This scale was then spread and used to set boundaries in funded projects like the EU Horizon2020 (EU Framework Programme for Research and Innovation) in 2014. The TRLs from the EC defined in Annex G from [30] slightly differs from the NASA definition compared in 7.1Appendix B. The main difference is that the NASA uses it for the space sector while EC uses it in a wider meaning, interpreting it as a product's readiness to be marketed [28].

2.3.3 The Valley of Death

The High-Level Expert Group on Key Enabling Technologies (HLG-KET) – a group established in 2010 by the European Commission to elaborate a coherent European strategy to develop six KETs in Europe [31] – identified the problem of *The Valley of Death* as one of the major obstacles for the EU progress [28]. The Valley of Death is known as "a metaphor for the lack of resources and expertise that impedes new ideas in their transition from lab to market". [32].

The root of this problem is that innovation is not a linear process. As shown in Figure 2-7, the major part of the financial resources is required for high TRLs (TRL5 onwards) at the stage where the decision of whether to commercialise a new research technology is made, as it is the most risky stage. Hence, a wide number of results in theoretical areas will never be translated into commercial technologies due to the lack of funding or profit-making. Therefore, EU programs like Horizon 2020 have been implemented to remove the innovation barriers and to overcome this "death valley" [33].

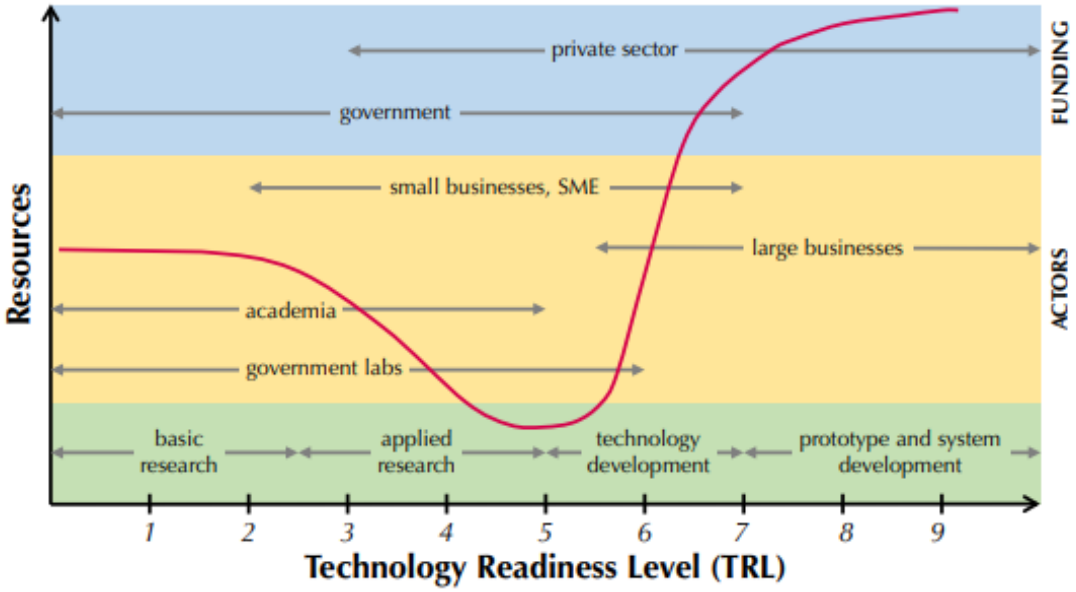


Figure 2-7 "The Valley of Death" of resources for new product development and each TRL [32]

2.3.4 Technology Readiness Assessment

According to Mankins [34], Technology Readiness Assessment (TRA) is a systematic and evidence-based methodology used to conduct the TRL scale evaluation process. The use of TRA at the start of system development has been identified as having a substantial impact on assessment and planning activities like schedule and cost estimation or risk assessment plans. TRAs brings especially a common language and framework to enhance communication across companies and organisations [35].

The first attempt of a TRA was in 2003, the U.S. Department of Defence (DoD) asked to the Air Force Research Laboratory (AFRL) to develop a TRL *Calculator* for hardware and software projects. The outcome was a Microsoft Excel self-assessment application that allowed the user to answer a series of questions written by Bilbro [36] about a technology program to calculate and display the TRL achieved [37]. The top-level decision algorithm shown in Figure 2-8, determined the level of maturity achieved based on a colour scale (green, yellow, red or blank) looking to the number of questions checked and the colour of the previous TRL (A TRL with previous red or yellow level couldn't appear as green) [37].

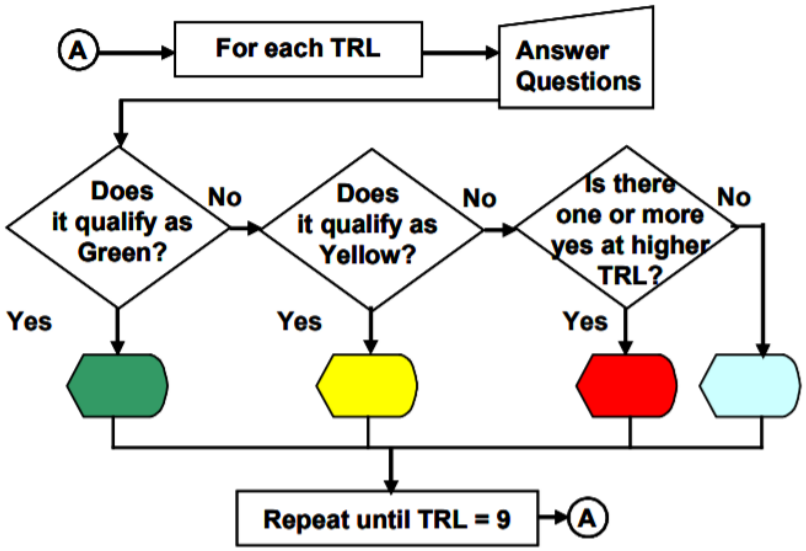


Figure 2-8 Top level decision algorithm used in the TRL Calculator from DoD in 2003 [37]

One year later, a second version was released (AFRL TRL v2.2) [38], with newer features like (see Figure 2-9):

- segregating the questions by technology type (Hardware, Software or both), arranging the questions by TRL
- adding Manufacturing Readiness Levels (MRL) questions
- aggregating as single overall TRL number the different Readiness Levels questions (TRL, MRL and PRL).

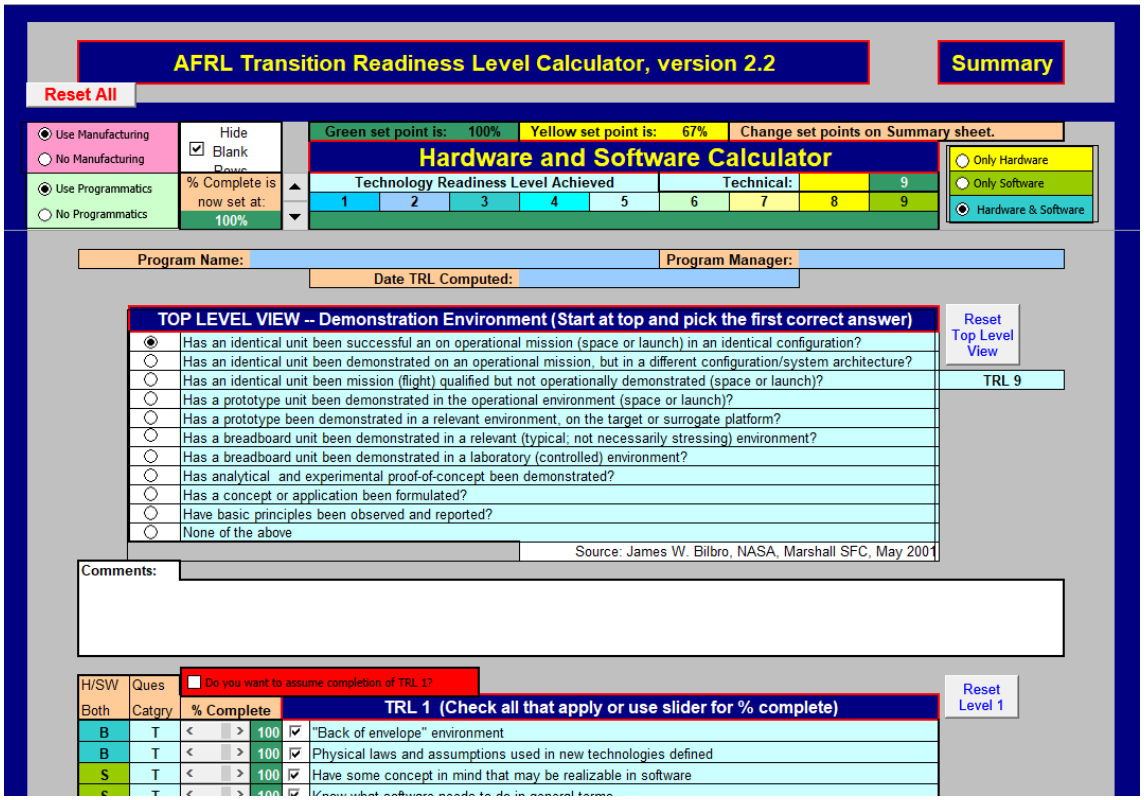


Figure 2-9 Section of the AFRL TRL Calculator v2.2 [39]

This tool was defined as the first standard and repeatable method for determining the TRL maturity. Therefore, it has been then used in several organizations as a reference to develop a newer tool, like for the TTRL (Turkish Technology Readiness Level) v1.0 developed by the Turkish defence industry in 2010 [38]. This newer tool had new features like (see Figure 2-10):

- differentiating the question into critical and non-critical (hidden to the tool's user to reduce the opportunity to cheat and only critical question served to determine the TRL level)
- adding documents as evidence bringing more objectivity
- including a grey level in the algorithm representing that the technology has been transferred at that level and there is no need to answer the questions
- adding the *Integration* to questions categories:
  1. *Technical*: Only technical maturity of the program questions (TRL)
  2. *Programmatic:* Measure some program management concerns, like customer focus and program documentation (PRL)

3. *Manufacturing:* Measures the readiness of the production system to manufacture the technology (lowest MRL is associated with TRL 3)
4. *Integration:* Measures the integration readiness of technology to the system (IRL)

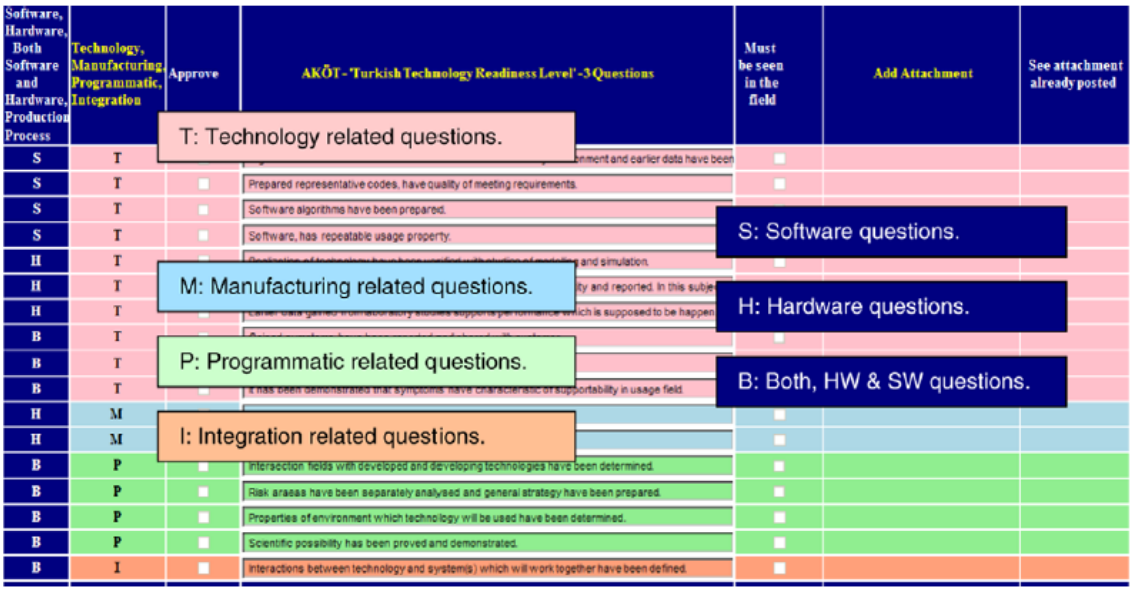


Figure 2-10 Snapshot TTRL questionnaire [38]

In harmony with the existing TRAs, in 2011 U.S. DoD developed a list of supporting information (see Appendix C) for each TRL to provide more objectivity incorporating material regarding technical requirements and documentation, system engineering and validation and verification [40]. Later, in 2016, the U.S. Government Accountability Office (GAO) published a report [35] with the TRA's best practices such as:

- The TRA responsible should be a Subject Matter Experts (SME) in which operates the technology.
- Clear information like requirement documentation, report and testing is needed for more reliable assessment.
- It's necessary to adapt the definition for each TRL level to better fit the technology application.

It is worth noting also that due to different judgment of the TRL scales, Austin et al. [41] used a Bayesian Network to provide the TRAs a mathematical method

leading to a more confident TRL evaluation. Bayesian Network is a directed acyclic graph with a probability distribution that depicts a set of variables and their conditional dependencies [42]. This was a first attempt using graphs and visual management in the TRA.

Lastly, during his MSc individual thesis in 2017 [43], Giuseppe Gorgoglione developed a gap assessment Microsoft Excel tool to assess railway technology development projects. Following a series of questions regarding the achieved requirements for each TRL, the tool then prints out a report that contains graphical information about the percentage of each TRL achieved, the completed and missing activities per TRL and the skills needed in order to achieve the desired level. However, the tool has some weaknesses like errors that need to be solved or the introduction of documents proving that back up the achievement of the requirements for a more subjective assessment.

2.4 Summary and Discussion

The review underlines that the railway industry is one of the most important ways of transport. However, the UK rail infrastructure is not up to the current demand which has hugely increased for the last decade. Therefore, Network Rail is planning to significantly invest in maintenance and technology development like the Shift2Rail European funded programme among other initiatives.

It has also been identified that TRL provides a common language across different institutions for discussing technology maturity however over the last decade many agencies and institutions have defined their slightly different scale definition that has led to a fragmentation of the TRL. Hence, standard and repeatable assessment methods (TRA) are necessary especially to overcome the *valley of death* and transform low maturity technology into physical products.

In conclusion, the review has been able to solve all the preliminary questions bringing the needed grounds to assess the research gap and effectively perform along the project.

2.5 Research Gap Analysis

This thesis is a follow up to Giuseppe Gorgoglione's IRP [43] and therefore, the research gap is in the same line with the following milestones.

Within multi-collaborators projects, like In2Smart, managing partners' interactions and tasks' ownership can be challenging. So, graphical methods such as UML diagrams can be used as a reference to understand the project deliverables status and depict and depict the overall project responsibilities picture.

Secondly, the TRL process has been widely accepted to assess the level of maturity in the development of new technologies. However, few structured traceable and evidentiary methods of assessment have been implemented.

Finally, the development of new technologies is a process that assures a competitive advantage. Therefore, relevant technology readiness data or assessment tools are normally kept as much confidential as possible, making the TRA benchmarking much more difficult.

3 RESEARCH METHODOLOGY

This chapter outlines the research methodology adopted for the completion of the project. Based on the main steps of the research process [44] the followed methodology for this project is shown in Figure 3-1.

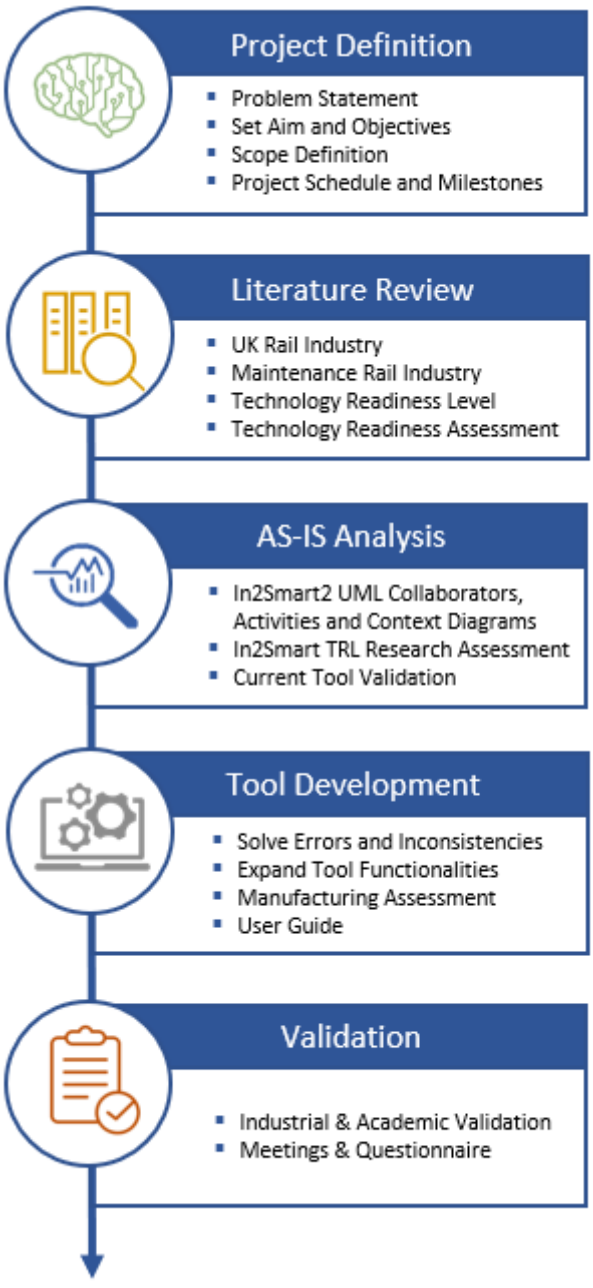


Figure 3-1 Research Methodology

3.1 Project Definition

The first phase of the research methodology targets to define the problem statement along with the definition of aim and objectives. Meetings with Network Rail academic and industrial supervisors contributed to the scope of the research and associated challenges which need to be addressed within the scope of the project. Additionally, key milestones and time schedule are defined to set and further meet the expectations and deadlines.

3.2 Literature Review

The second phase is the literature review which provides an overview of the rail industry relevance, research, and maintenance investments, and introduces the EU-founded programs where this project takes places. It also presents the technology development concepts as the Technology Readiness Level, Valley of Death and Technology Readiness Assessment.

3.3 AS-IS Analysis

The third phase covers the analysis of the current state of In2Smart and In2Smart2 projects. To support Network Rail in the project planning for In2Smart2 WP13 different UML diagrams have been developed to map the collaborators' interactions. As explained in depth during Giuseppe's IRP [43] the implementation of UML to project management helps to illustrate the relations between people by giving a base to create a common framework. Three different levels of detailed diagrams have been created from a general In2Smart overview to the specific WP13 activities along with a context diagram that helps to set the boundaries and expectations.

The next step in the AS-IS analysis is the In2Smart TRL research assessment. In2Smart2 is an extension of In2Smart which was planned to achieve concept demonstrator of TRL 4/5. In particular, In2Smart WP10 aimed to achieve a TRL 4 of a robotic inspection and repair control and command system. Therefore, it is indispensable to objectively assess what has been the achieved TRL analysing

each TRL requirement separately to highlight the gaps in order to adequately build In2Smart2 plan.

Finally, the last step of the AS-IS analysis has been a verification of the current TRL assessment tool developed by Giuseppe during his IRP [43]. He successfully developed an Excel-based tool to self-assess the achieved TRL for a specific project. However, in order to find the tool's weaknesses and areas of improvement, a verification plan has been carried out.

3.4 Tool Development

The fourth phase of the research methodology is the improvement of the existing TRL tool. Based on the finding from the previous verification exercise, and industrial and academic supervisors' feedback a series of modifications have been carried out. The aim is to improve the user satisfaction and value-adding capacities to provide Network Rail an objective, robust and useful tool. Improvements both in the functionalities and visualization have been implemented. Extensive Visual Basic for Application (VBA) coding modifications have also been carried out to fixe repeated problems and providing some coding best practices.

To complement the tool, a user guide has been produced to support the user interaction with the displayed windows and explaining in depth the tool capabilities. A final section explaining the whole VBA code has been added in case anyone would like to extend the tool's features or make some modifications

3.5 Validation

The last phase is the validation process for the achieved work. The UML diagrams and In2Smart TRL research assessment have been validated throughout web-meetings and emails. While the tool and complementary user guide have been validated with a questionnaire that aimed to numerically quantify the weaknesses and strengths.

4 RESULTS

4.1 Current State Analysis

The understanding of the current state follows a cascade approach, incrementing the level of details from an In2Smart2 general overview to a detailed analysis of the tasks where Network Rail and Cranfield University are involved. The use of UML diagram has been used to represent in a graphical way all the interactions and relations.

Starting with the project In2Smart2 (*Intelligent Innovative Smart Maintenance of Assets by integrated Technologies 2*) which aims to continue the work conducted in In2Smart in order to implement specific demonstrators as shown in Figure 4-1.

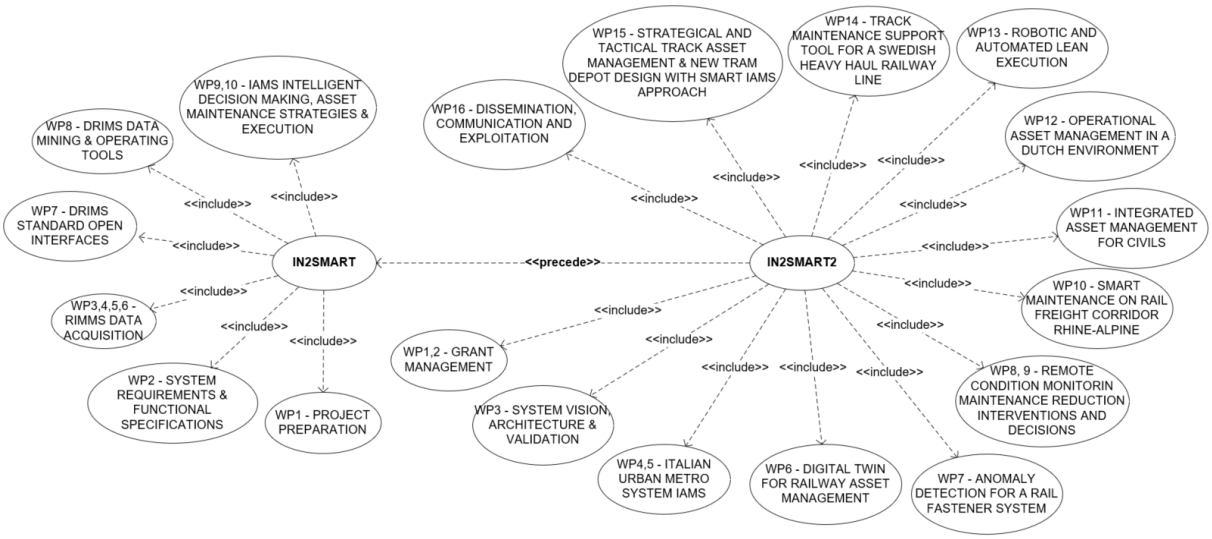


Figure 4-1 In2Smart and In2Smart2 Diagram

In2Smart2 has been divided into sixteen Work Packages (WP), representing ten different Use Cases (UC) as shown in Figure 4-2 in different colours. They run in parallel and they are ensured through the transversal WP3, looking at the overall system vision, architecture, and validation.

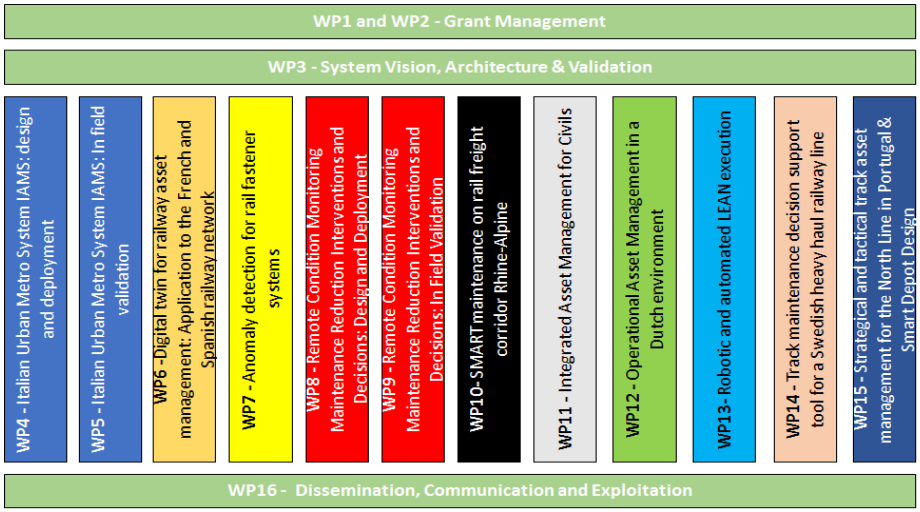
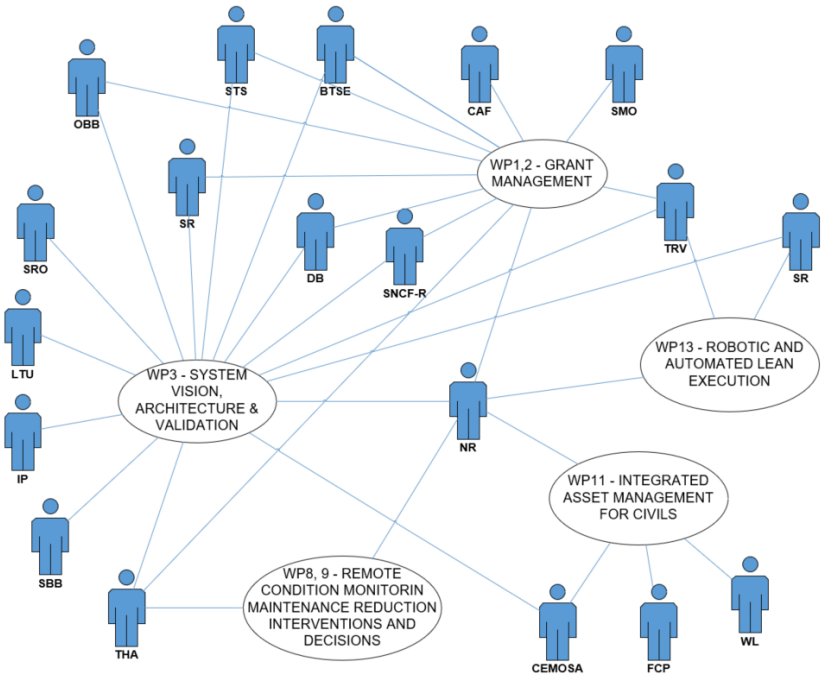


Figure 4-2 In2Smart2 Project Structure [45]

Network Rail is one of the most relevant In2Samrt2 collaborators. It is involved in seven of the fifteen WP and exchanges information with more than fifteen other collaborators as shown in Figure 4-3, which reveals the level of management complexity Network Rail handles.



Acronym	Participant Organisation Name	Country
STS	HITACHI RAIL STS (CORRDINATOR)	IT
NR	NETWORK RAIL INFRASTRUCTURE LIMITED	GB
BTSE	BOMBARDIER TRANSPORTATION SWEDEN AB	SE
CAF	CAF TURNKEY & ENGINEERING SOCIEDAD LIMITADA	ES
SMO	SIEMENS AKTIENGESELLSCHAFT	DE
THA	THALES GROUND TRANSPORTATION SYSTEMS UK LTD	GB
TRV	TRAFIKVERKET	SE
DB	DEUTSCHE BAHN AG	DE
IP	INFRAESTRUTURAS DE PORTUGAL SA	PT
SR	STRUKTON RAIL BV - SR	NL
SNCF-R	SOCIETE NATIONALE DE CHEMINS DE FER - RESEAU	FR
FCP	FRITSCH, CHIARI & PARTNER ZIVILTECHNIKER GMBH	AT
WL	WIENER LINIEN GMBH &CO KG	AT
OBB	ÖBB-INFRASTRUKTUR AG	AT
SBB	SCHWEIZERISCHE BUNDESBAHNEN	CH
CEMOSA	CENTRO DE ESTUDIOS DE MATERIALES Y	ES

Figure 4-3 Network Rail Contribution into In2Smart2 and Other Collaborators involved

However, Network Rails plays an important role and where this project takes place is for WP13 - *Robotic and automated LEAN execution*. It's intended to further develop (TRL 7) the concept demonstrator (TRL4) developed in WP10 from In2Smart [45]. As shown in Figure 4-4 there are three main stakeholders Network Rail, Strukton Rail and Trafikverket and 3 more contracted collaborators: Cranfield University, Altran and Chalmers Technical University.

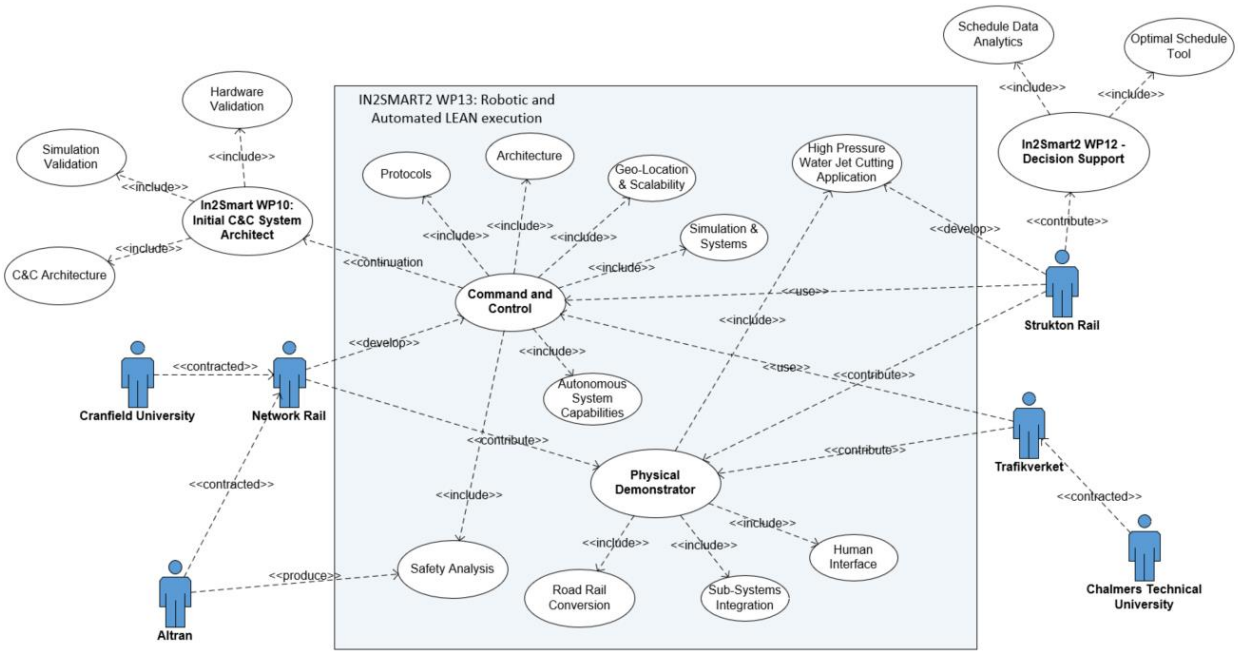


Figure 4-4 In2Smart2 WP13 High-Level Collaborators Interactions

This UC aims to further develop the Command and Control (C&C) system architecture of a rail platform with robotic inspection and maintenance capabilities. This is an extension of the WP10 from In2Smart. It is intended that the C&C system architecture is developed by Network Rail and Cranfield University so other collaborators will then use it applying it to a physical demonstrator to, between all, build a physical demonstrator to validate the architecture. In order to define the boundaries and set the external reviewers expectations, a context diagram has been produced as shown in Figure 4-5.

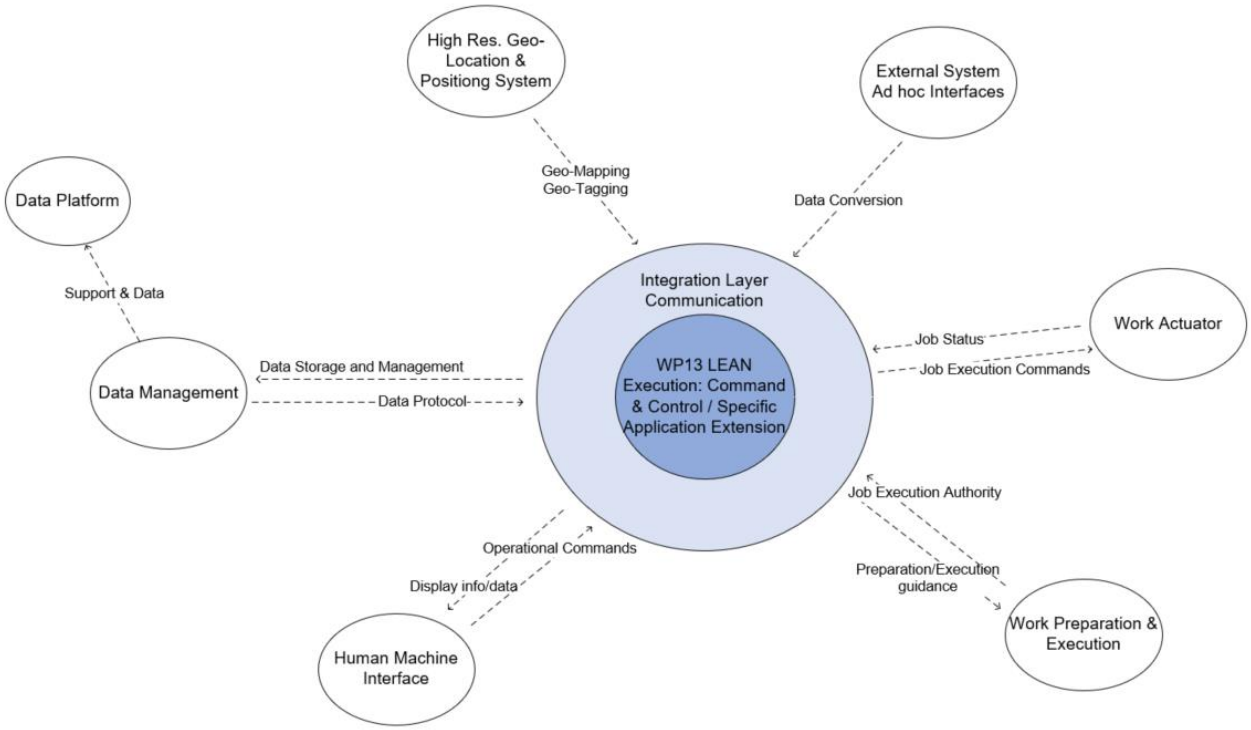


Figure 4-5 In2Smart2 WP13 Context Diagram

The In2Smart2 project started in December 2019 and it is scheduled to end by November 2021. So, at the time where this research thesis takes place (May 2020 - August 2020), the project is in an early stage where the activities that have to be carried out are being defined. Therefore, a diagram showing which activities should be realized and their relations has been made as shown in Figure 4-6. WP13 has been divided in four deliverables, from the use case approach, passing by the environmental and operational tests to the TRL 7 physical demonstrator. Some work from WP3 has also been added as Network Rail involved and has a direct relation with WP 13 tasks. It is worth to mention that, as shown in Figure 4-6, this research thesis (TRL evaluation) is part from the early WP13 work.

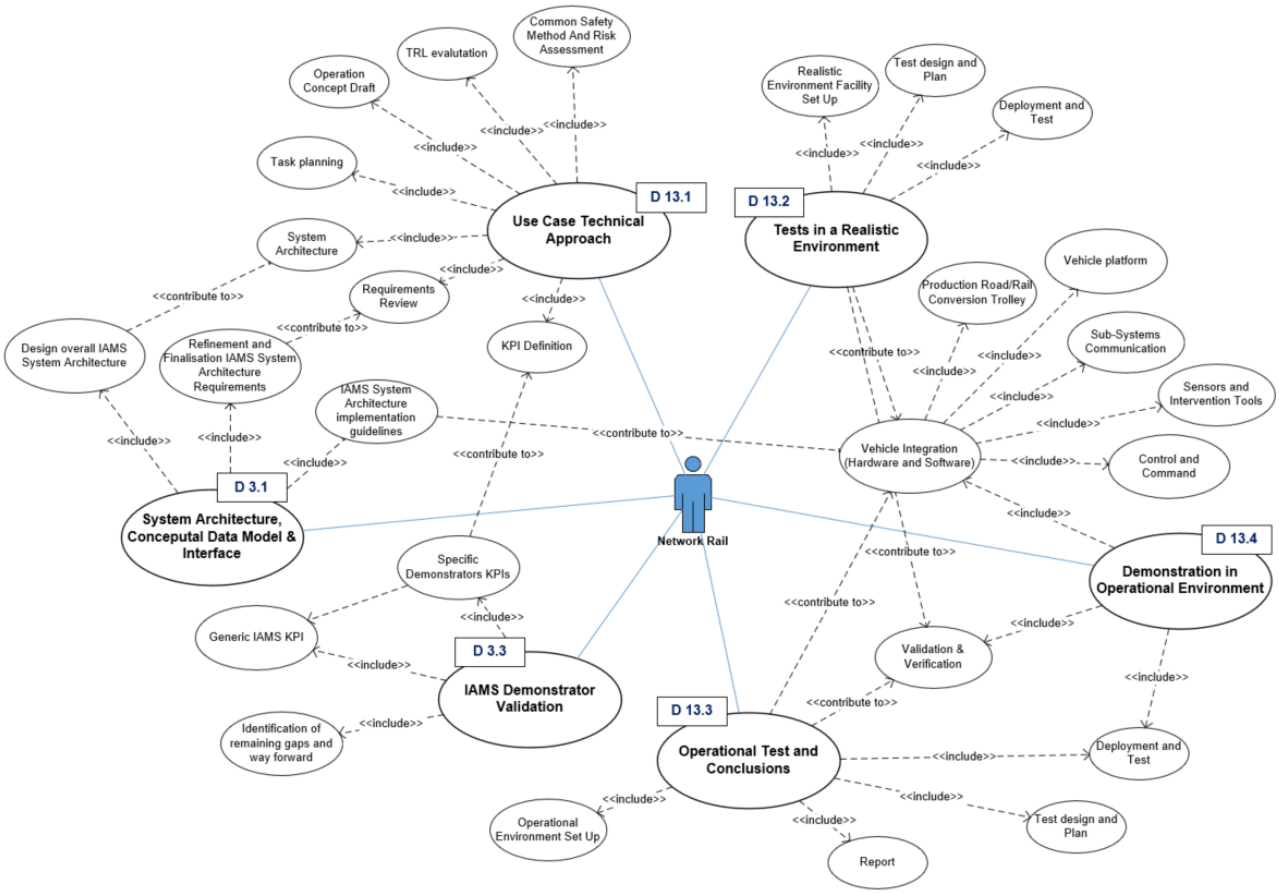


Figure 4-6 In2Smart WP 3 and 13 Network Rail Deliverables and Activities Diagram

Finally, the last diagram, Figure 4-7 that has been build depicts Cranfield University contribution into In2Smart2. The work can be divided in:

- MSc Group Project (GP) on autonomous vehicle Digital Twin and simulation
- MSc Group Project (GP) on design of a rail road conversion platform
- MSc Group Project (GP) on a cost/benefit framework for innovative projects
- MSc Individual Research Project (IRP) on TRL gap analysis
- PhD on location and scalability navigation
- PhD on simulation and system
- Research on supportive WP13 work
- Future Cranfield University external group for validation work

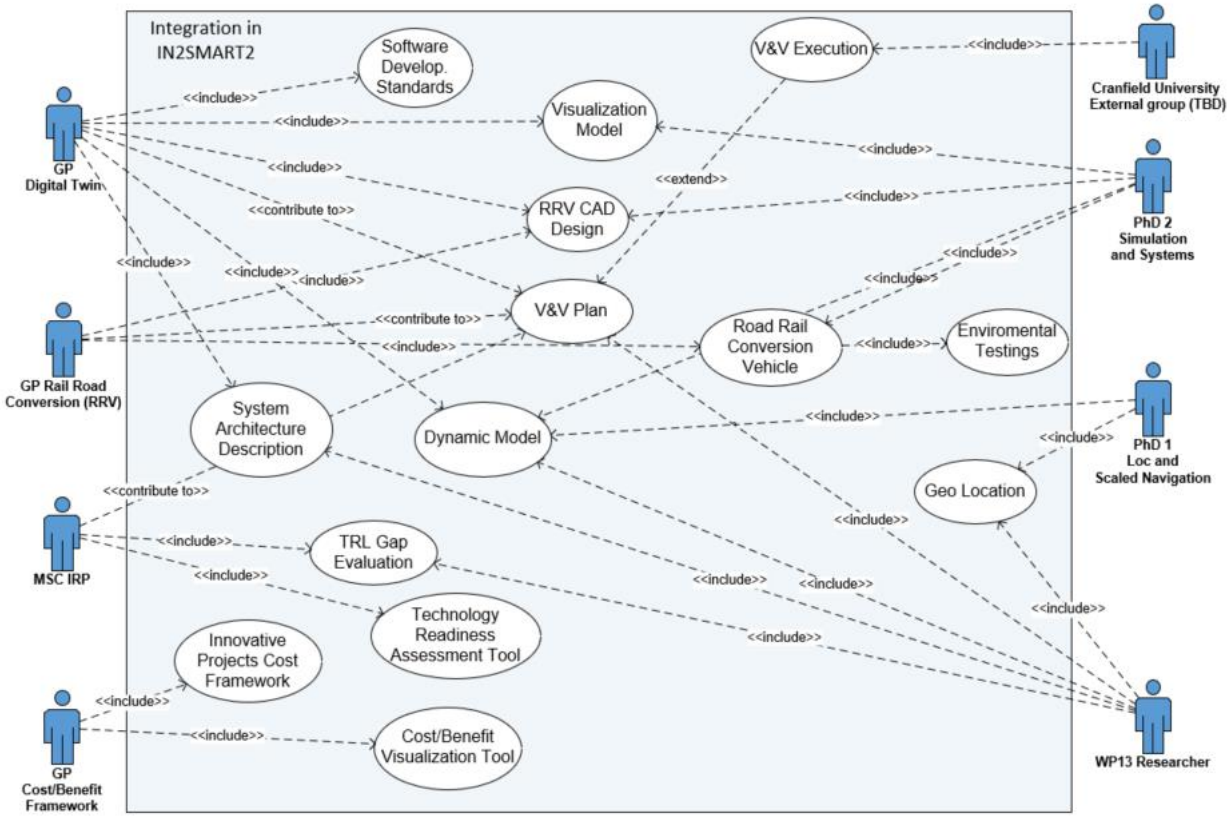


Figure 4-7 In2Smart2 Cranfield University Contribution Diagram

4.2 TRL In2Smart Research Assessment

Part of the research is to objectively assess the achieved TRL in In2Smart WP10, which aimed to achieve a TRL 4 validating the technology in a laboratory environment. The following analysis has been carried out by individual evaluating the requirement following the TRL and requirements definition from the Rail Industry Readiness Level (RIRL) framework that can be found in7.1Appendix D. Each requirement has been validated by providing documents where the work has been accomplished as part of the objective assessment.

It is important to mention that the in the TRL definition from the RIRL framework some requirements have been identified as part of the Manufacturing Readiness which will not be assessed for this analysis. Based on the objectives of In2Smart2, the manufacturing requirements are not considered to be in the scope.

4.2.1 TRL 1

TRL 1 is when the idea is conceived, and the research starts. As shown in Table 4-1, all the requirements have been achieved during the work done in the Human Factors projects, namely in WP1 [46] and WP3 [47] and on a published article “A modular approach to automation of condition monitoring and repair for rail” [48].

Table 4-1 In2Smart TRL 1 Requirements Assessment

Requirement Number	Requirement Description	Status [Y/N/NA]	Document of Evidence	Document's Owner
1	Initial 'laboratory' research and opportunities to explore idea possible development routes	Y	Human Factors WP1: Horizon scanning	Transport System Catapult & University of Nottingham
2	Structured research into extant material/technology and development of hypothesis	Y	Human Factors WP3: Automation Framework	University of Nottingham
3	Quick 'look-see' to ascertain the possibility / viability of the new / novel idea	Y	A modular approach to automation of condition monitoring and repair for rail	Network Rail & Transport System Catapult
4	Articulate the opportunity, identify potential need and speculate exploitation	Y	Human Factors WP1: Horizon scanning	Transport System Catapult

4.2.2 TRL 2

TRL 2 is the first verification of the technology with experimentation. In this TRL all the requirements have also been validated by the same project and reports except for the sixth that has been classified as “Not Applicable” (NA). The identification of the Key Process Indicators (KPI) has been considered that does not apply to this innovation project because any specific numerical targets could be defined and subsequently pursued. Therefore, the achievement of respective TRL has been considered as the only targets to meet.

Table 4-2 In2Smart TRL 2 Requirements Assessment

Requirement Number	Requirement Description	Status [Y/N/NA]	Document of Evidence	Document's Owner
5	Continued desktop research and analysis to consolidate and develop understanding of key principles and establish key variables	Y	A modular approach to automation of condition monitoring and repair for rail.	Network Rail & Transport System Catapult
6	Identification of key performance indicators	NA	-	-
7	Articulation of how to achieve proof of concept	Y	A modular approach to automation of condition monitoring and repair for rail.	Network Rail & Transport System Catapult
8	Documented desktop modelling to explore and establish expected technological parameters (including but not limited to factors / indicators / measures)	Y	Human Factors WP3: Automation Framework	University of Nothingam
9	Asset / Technology capability requirements defined along with key variables	Y	A modular approach to automation of condition monitoring and repair for rail.	Network Rail & Transport System Catapult

4.2.3 TRL 3

TRL 3 is when proof of concept is ascertain using robust and repeatable processes. This TRL has been 100% achieved during In2Smart WP10 and has been captured in 3 different deliverables. Deliverable D10.3 - *Remote Command and Autonomous System Architecture System Design Proposal* - captures the operational concept definition, system safety plan and the gathers the stakeholders' and system's requirements. Deliverable D14.4 - *Prototype Technology Validated in Laboratory* – reveal the description of technology and the control and command system and introduces the simulation overview along with the Demonstrator Development Plan. However, the description on the work that has been realized on the hardware and software is detailed in the D10.5 - *Prototype Integration, Assessment and Lab System Trial Report*. D10.5 also captures the Verification and Validation execution including all the hardware and software tests, results, and conclusions.

Table 4-3 In2Smart TRL 3 Requirements Assessment

Requirement Number	Requirement Description	Status [Y/N/NA]	Document of Evidence	Document's Owner
10	Development of technology to enable 'proof of concept' to be undertaken	Y	In2Smart D10.4: Prototype Technology Validated in Laboratory	Network Rail & Cranfield University & Transport System Catapult
11	Range of recorded & qualitative experimental and modelling activities to validate main technology factors (including but not limited to factors / indicators / measures)	Y	In2Smart D10.5: Prototype Integration, Assessment and Lab System Trial Report	Network Rail & Cranfield University & Transport System Catapult
12	Produce functional description and commence identification of boundaries and interfaces with external systems / equipment	Y	In2Smart D10.4: Prototype Technology Validated in Laboratory	Network Rail & Cranfield University & Transport System Catapult
13	Production of 'A models' to support / assist proof of concept	Y	In2Smart D10.5: Prototype Integration, Assessment and Lab System Trial Report	Network Rail & Cranfield University & Transport System Catapult
14	Produce 'Space models' of equipment (may be 'virtual')	Y	In2Smart D10.5: Prototype Integration, Assessment and Lab System Trial Report	Network Rail & Cranfield University & Transport System Catapult
15	Draft all technical requirements and specification	Y	In2Smart D10.3: Remote Command and Autonomous System Architecture System Design Proposal	Network Rail & Cranfield University & Transport System Catapult
16	Safety Analysis	Y	In2Smart D10.3: Remote Command and Autonomous System Architecture System Design Proposal	Network Rail & Cranfield University & Transport System Catapult

4.2.4 TRL 4

Finally, TRL 4 is when the technology is validated against high level requirements in a laboratory environment. In this TRL, five requirement have been achieved, while 3 have been defined as *Not Applicable* . Requirements 7, 8 and 23 are related with the hardware, and software demonstrator and refinement which has been identified to be carried out in D10.5. Requirements 24 on the human factors and implications is captured in the WP3 from the Humans Factors project. Moreover, Altran has started with a preliminary safety plan that will be updated as the project progresses.

On the other side, requirement 21 has been identified as Manufacturing Readiness related, and as explained before, manufacturing requirements are not in the scope. However, requirements 20 and 22 have also been defined as *NA* because they are related to a future technology or asset exploitation and this is not the aim of the project.

Table 4-4 In2Smart TRL 3 Requirements Assessment

Requirement Number	Requirement Description	Status [Y/N/NA]	Document of Evidence	Document's Owner
17	Production and bench qualification of 'B Models' utilising appropriately available technologies	Y	In2Smart D10.5: Prototype Integration, Assessment and Lab System Trial Report	Network Rail & Cranfield University & Transport System Catapult
18	Development of asset / technology and refinement of function to demonstrate output performance and variability	Y	In2Smart D10.5: Prototype Integration, Assessment and Lab System Trial Report	Network Rail & Cranfield University & Transport System Catapult
19	Identification and quantification of technology risks; Risk Reduction Plan	Y	Preliminary Safety Plan	Altran
20	Improved business plan, identification of route to market	NA	-	-
21	Improved project plan; better understanding of production path	NA	-	-
22	Interface testing and initial integration	Y	In2Smart D10.5: Prototype Integration, Assessment and Lab System Trial Report	Network Rail & Cranfield University & Transport System Catapult
23	PESTLE implications and market expectations understood and planned / accounted for	NA	-	-
24	Human Factors	Y	Human Factors WP3: Automation Framework	University of Nottingham

In conclusion, WP10 from In2Smart has achieved TRL 4, with 20 and 4 requirements achieved and not applicable, respectively.

4.3 TRL Self-Assessment Tool Verification

During Giuseppe's IRP [43] in 2018, a TRL self-assessment tool was developed in order to simplify and automate the technology maturity assessment process. The tool is Microsoft Excel-based extended using Visual Basic for Applications (VBA) to enhance the user interface with a series of users forms that guide the user through the assessment.

A verification process has been conducted in order to find the tool's areas of improvement. Thus, a stress test has been carried out by completing the self-assessment exercise thought all the different possible paths integrated 10 times.

The results of the conducted tests have been satisfactory, finding that the TRL self-assessment gap tool truthfully adheres to the expected functionalities and needs. However, few errors and therefore potential areas of improvements have been identified:

1. The users form is not “error-proof”, for instance, any character (letter or number) can be added as “Desired TRL” creating a conflict in the algorithm
2. The table of versions has 8 rows but if the assessment has more than 8 versions, the tables remains the same and the new versions get below the table as shown in Figure 4-8

Version	Date	TRL Aimed
1.0	11/3/2009	1
2.0	11/4/2009	2
3.0	11/5/2009	3
4.0	11/6/2009	4
5.0	11/7/2009	5
6.0	11/8/2009	6
7.0	11/9/2009	7
8.0	11/10/2009	8
	11/11/2009	9

Figure 4-8 Show case of the tool’s versions history table overpopulated

3. The Activities & Skills analysis windows is only accessible at the end of the assessment process and cannot be opened again after being closed.
4. The Activities & Skills analysis windows, if any activity is selected before pressing the “>” button, an error occurs, and it doesn’t allow the user to continue with the assessment as shown in Figure 4-9

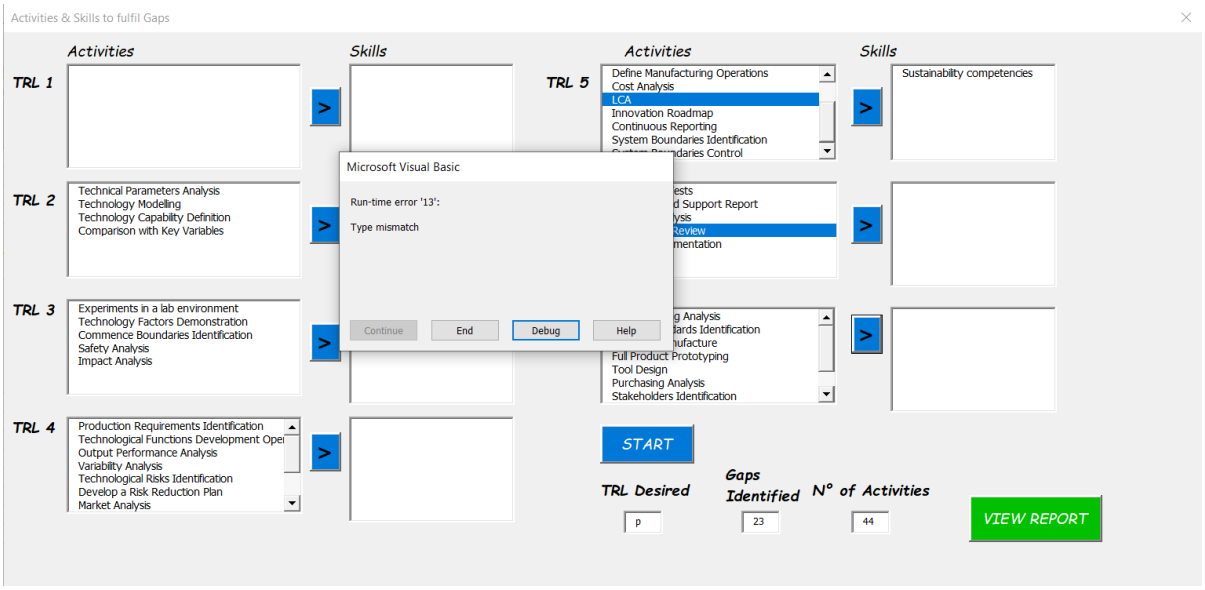


Figure 4-9 Activities and Skills Window Error

5. The selected *Comic Sans* font for the User Form does not provide a professional look as shown in Figure 4-10

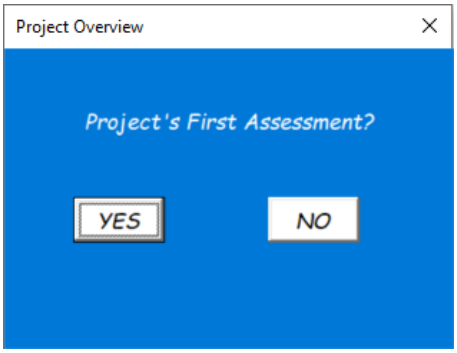


Figure 4-10 User Form Example

6. Most of the VBA code is linked to cells referenced by letter of the row and number of the column, i.e., *Cells(24, 5).Select*. This type of referencing could lead to errors if any other column of rows is added or the layout is modified as the reference is not linked to cell content but to a general reference cell.
7. Inconsistency in the report's text size. As seen in Figure 4-11, the requirements are not readable when the rest of the report is readable.

Version	Date	TRL Aimed
1.0	11/3/2009	1
2.0	11/4/2009	2
3.0	11/5/2009	3
4.0	11/6/2009	4
5.0	11/7/2009	5
6.0	11/8/2009	6
7.0	11/9/2009	7
8.0	11/10/2009	8

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7
100%	60%	57%	25%	25%	50%	40%

TRL	REQUIREMENTS	Comments
1	Initial Laboratory research and opportunities to explore idea possible developmental routes	
1	Structured research into natural material and development of hypothesis	
1	Quick 'hack work' to consolidate the possibility / viability of the new / novel idea	
1	Rationalise the opportunity, identify potential novel and specialist exploitation	
2	Continued desktop research and analysis to consolidate and develop understanding of key principles and establish key variables	
2	Identification of key performance indicators	
2	Rationalisation of basis to achieve proof of concept	
2	Documented desktop modelling to explore and establish required technologies parameters (including but not limited to Factors / indicators / measures)	
2	Novel / Technology capability requirements defined along with key variables	
3	Development of technology to enable proof of concept to be undertaken	
3	Range of recorded & qualitative experimental and modelling collective to establish main technology Factors (including but not limited to indicators / measures)	
3	Produce functional description and summary identification of boundaries and interfaces with external systems / equipment	
3	Production of 'A models' to support / consist proof of concept	
3	Produce 'figure models' of equipment (e.g. 'air foil')	
3	Draft all technical requirements and specifications	
3	Safety Analysis	
4	Production and break qualification of 'B Models' utilising appropriately available technologies	
4	Development of asset / technology and refinement of Equation to demonstrate output performance and variability	
4	Identification and quantification of technology risks; Risk Reduction Plan	
4	Improved business plan, identification of route to market	
4	Improved project plan; better understanding of production path	
4	Interface testing and initial integration	
4	PESTLE implications and market expectations understood and planned / accounted for	
4	Human Factors	
5	Development / acquisition / access to trial and test Facilities to validate technology (using Beta-C Models)	
5	Establish functional performance marks requirements and in repeatable	
5	Produce 'C Models' to be used in validation testing	
5	Produce production plans and establish cost of manufacture	
5	Commence environmental testing	
5	Novel / Technology Support Plans (RAMS, training, documentation, etc.)	
5	Performance boundaries understood and defined	
5	Novel / technology integrated with system; boundary conditions established, interfaces demonstrated	
6	Production of small quantity of 'pre-production' assets / technology	
6	Novel / Technology demonstration trials to support development and marketing	
6	Obtain access to / develop suitable operational [sea-bed] test and demonstration environment(s)	
6	Verify cost of manufacture / selling price / market pricing regime	
6	Evidential confirmation of performance and Feasibility in operational environment	
6	Complete design and development process to meet 'design freeze' status	
7	Formal qualification in an approved and representative operational environment	
7	Manufacture / build of production standard assets / technology	
7	Productionisation processes (build / test / certification, unit target, Quality Assurance, etc.)	
7	Supply chain development and stabilisation	
7	Risk mitigation and asset / technology maturation under formal change control	

Figure 4-11 Tool's Final Report snapshot

4.4 TRL Self-Assessment Tool Improvement

The final contribution of this research project has been to upgrade the existing TRL assessment tool with a newer version: *TRL Self-Assessment Tool v.2*. This tool keeps the older version essence and main functionalities with the main idea of simplifying and systematizing the complex TRL evaluation process.

The tool keeps the interaction with the user through VBA User Form with different forms designs as shown in Figure 4-12.

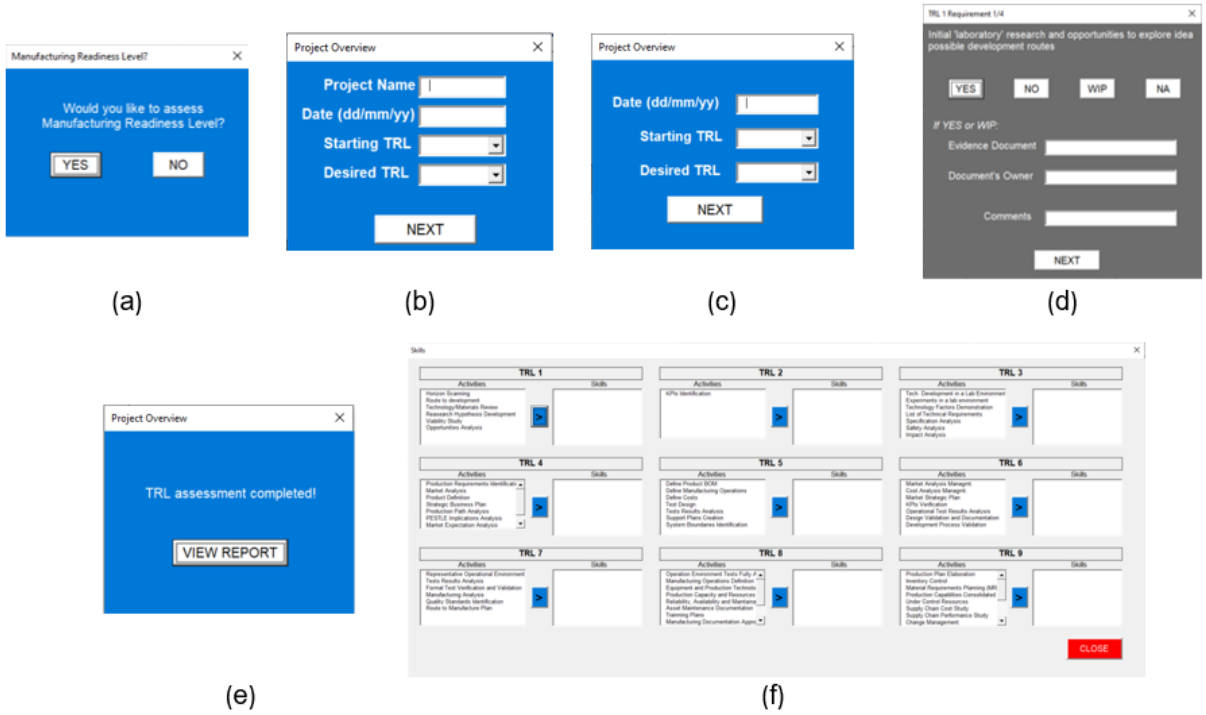


Figure 4-12 (a) UserForm01, (b) UserForm02, (c) UserForm03, (d) UserForm_1 to UserForm_59, (e) UserForm_60, and (f) UserForm_61

Each user form can lead the user to multiple different paths. Therefore, an interaction diagram that represents the tool's algorithm is shown in Figure 4-13.

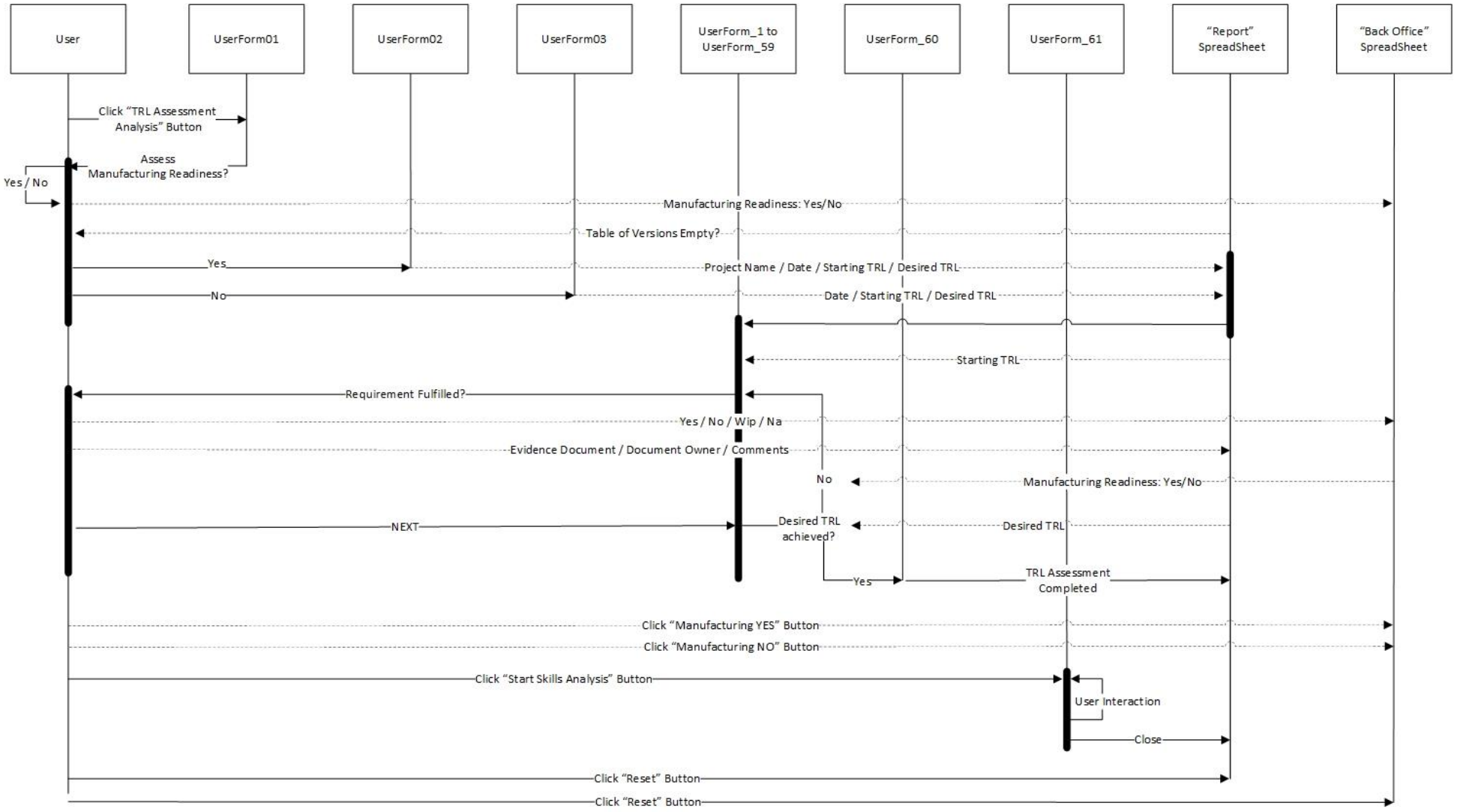


Figure 4-13 Tool's Interaction Diagram

After the assessment process, the user can visualize the information and results in a report. The report has 4 different sections as shown in Figure 4-14 and looks like in Figure 4-15.

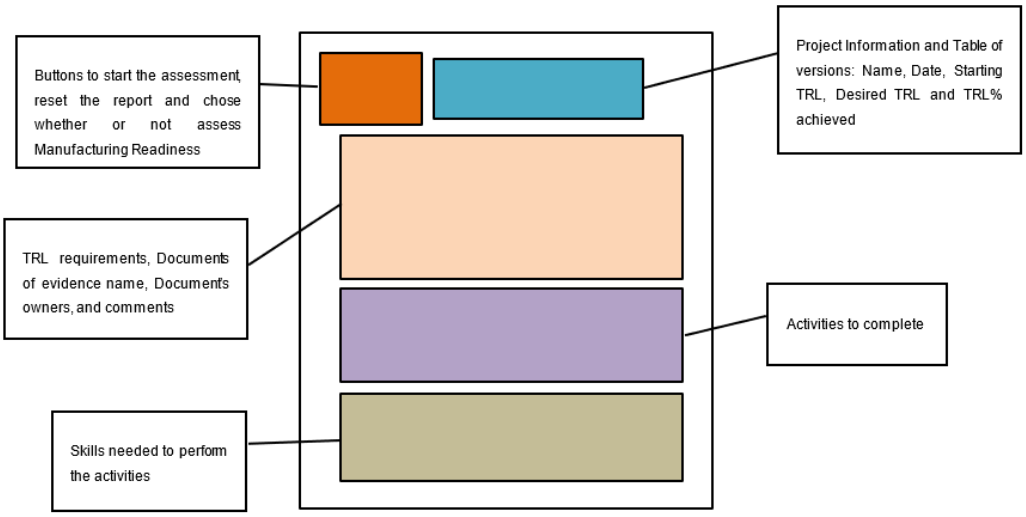


Figure 4-14 Report's Design Layout

The percentage for a particular TRL has been calculated the following formula:

$$TRL_i\% = \frac{1 * NR_{i,YES} + 0.5 * NR_{i,WIP}}{NR_{i,YES} + NR_{i,NO} + NR_{i,WIP}} \quad \textbf{(4-1)}$$

Where $NR_{i,m}$ represents the Number of Requirements for the TRL = "*i*" with a status of "*m*" that can be: YES, NO, WIP (Work in Progress) or NA (Not Applicable).

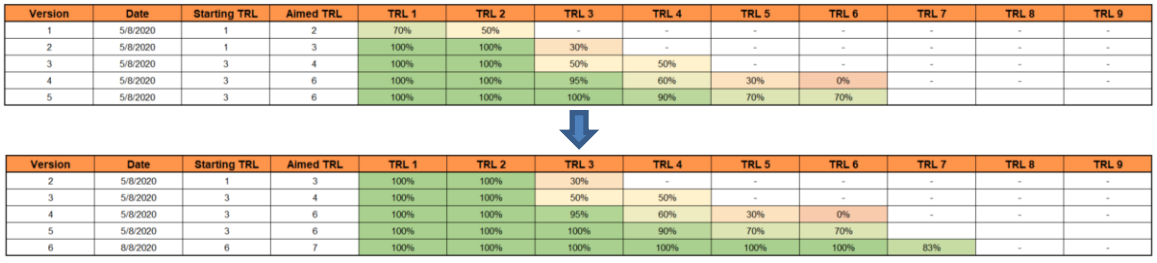
A complementary User Guide has been designed to support the user interaction with the user forms and explaining in depth the tool capabilities. A final section explaining the whole VBA code has been added in case anyone would like to extend the tool's features or make some modifications. The User Guide can be found in 7.1Appendix F.

Figure 4-15 Reports Design

4.4.1 Improvements

Some improvements have been implemented in order to solve the tool's weaknesses explained in section 4.3 but also to extend the functionalities and enhance the user experience. The main functional and visually improvements implemented have been:

1. Incorporation of TRLs 8 and 9 and therefore, the related TRL requirements, activities, and skills
2. Table of assessment version also incorporated the TRL at which the assessment starts and keeps the achieved percentage at each TRL for all the versions
3. When the table of version gets more than 5 entries (the table of versions has 5 rows) the oldest versions gets deleted and the other move one row up to leave space for the new version information as shown in Figure 4-16



Version	Date	Starting TRL	Aimed TRL	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
1	5/8/2020	1	2	70%	50%	-	-	-	-	-	-	-
2	5/8/2020	1	3	100%	100%	30%	-	-	-	-	-	-
3	5/8/2020	3	4	100%	100%	50%	50%	-	-	-	-	-
4	5/8/2020	3	6	100%	100%	95%	60%	30%	0%	-	-	-
5	5/8/2020	3	6	100%	100%	100%	90%	70%	70%			

Version	Date	Starting TRL	Aimed TRL	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
2	5/8/2020	1	3	100%	100%	30%	-	-	-	-	-	-
3	5/8/2020	3	4	100%	100%	50%	50%	-	-	-	-	-
4	5/8/2020	3	6	100%	100%	95%	60%	30%	0%	-	-	-
5	5/8/2020	3	6	100%	100%	100%	90%	70%	70%			
6	8/8/2020	6	7	100%	100%	100%	100%	100%	100%	83%	-	-

Figure 4-16 Table of Versions with 5 versions (above) vs 6 versions (below)

4. Introduction of new possible status for the requirements. While the previous version only allowed the user to answer YES or NO if the requirement was fulfilled, the new versions introduces the categories Work in Progress (WIP) and Not Applicable (NA) as shown in Figure 4-17
5. Introduction of a space to fill with the document's name that back up the requirement fulfilment, another one for the document's owner to trace back the document and another to add any comment if needed as shown in Figure 4-17

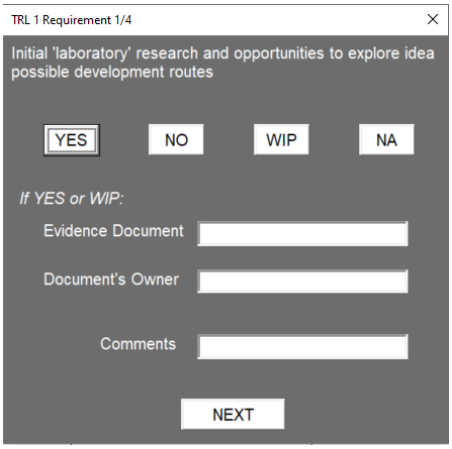


Figure 4-17 Example of Requirement User Form

6. User Forms text font changed from *Comic Sans* to *Arial* to bring a more formal look as shown in Figure 4-17
7. Introduction of Manufacturing Readiness requirements assessment option to avoid the manufacturing related requirements defined in the TRL RIRL framework. As mentioned in section 4.2, some requirements defined in the RIRL TRL framework correspond to manufacturing activities, therefore the user could avoid to answer these questions that would automatically be set as Not Applicable (NA). This option is the first question in any assessment as shown in Figure 4-19 and can be further changed after the assessment with the buttons shown in Figure 4-18

Figure 4-19 Manufacturing Readiness User Form

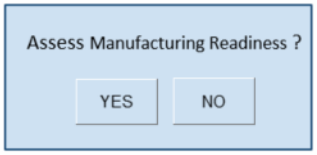


Figure 4-18 Manufacturing Readiness Report Buttons

8. Introduction of drop-down menus for the TRL selection to avoid introducing wrong characters that could mislead the algorithm as shown in Figure 4-20

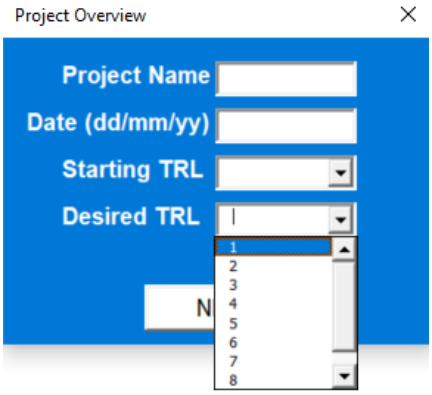


Figure 4-20 Project Information User Form with Drop-Down Opened Menu

9. Introduction of the “Start Skills Analysis” button in the report to access the Activities & Skills analysis windows whenever the user wants.
10. Solved the problem occurred when in the Activities & Skills analysis windows the user pressed the “>” button without any activity selected. A message box has been introduced that pop ups advising to first select an activity.
11. Introduction of a feature that hides the non-assessed TRL requirements. As shown in Figure 4-21 TRL 1, and 5 to 9 are not assessed and therefore, their requirements are hidden to bring a more clear report’s aspect

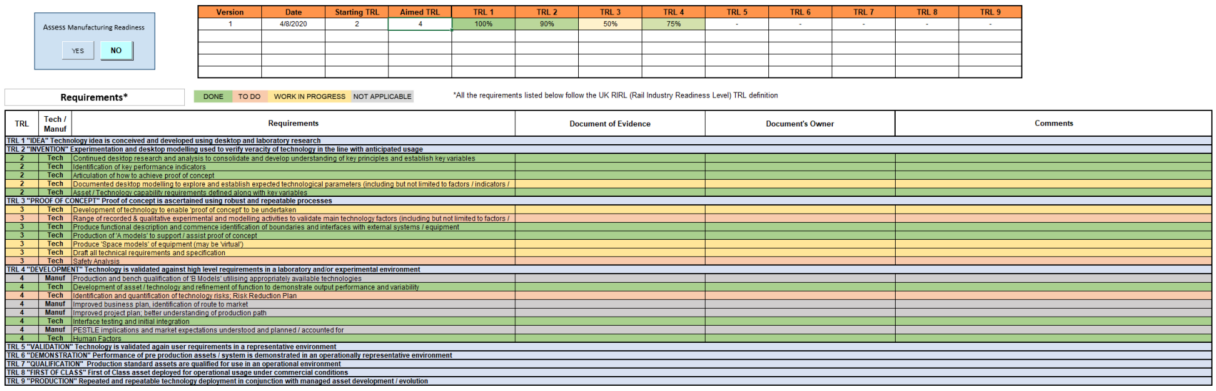


Figure 4-21 Report's Assessment Example

12. Adjustment in the report's text size to have a coherent overall text size harmony
13. Introduction of some coding good practices like introducing comments so non-familiarized user could understand it or avoiding using general referencing, i.e., use of *Range("Evidence1")* instead of using *Cells(24, 5).Select* because the first option will be linked to the cell we want even if the cells is moved to another place

4.4.2 TRL Self-Assessment Tool v.2 Gap Assessment

Finally, the tool has been used in the In2Smart WP10 project as shown in Figure 4-22.

Figure 4-22 In2Smart WP10 Tool's Report

5 VALIDATION

Finally, a validation process for the UML diagrams, In2Smart TRL research assessment, improved tool and complementary user guide has been carried out. It is important to capture stakeholders' feedback with the aim to demonstrate that the work is meaningful for Network Rail.

The process consists of an iterative cycle where the results are presented, and improvements are made based on the feedback. This then converge in a final approval and questionnaire as outlined in Figure 5-1.

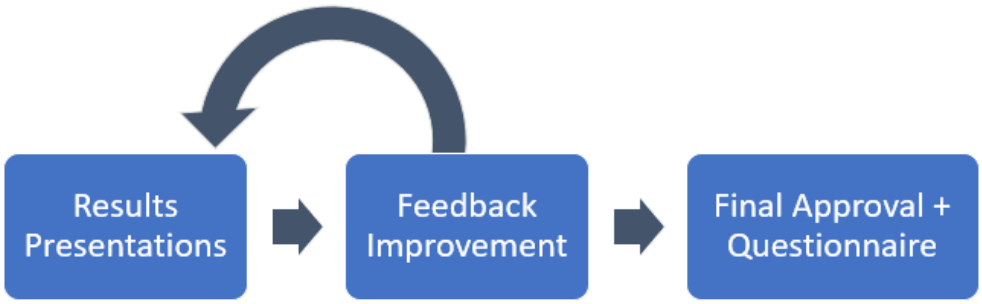


Figure 5-1 Validation Process

The results achieved each time have been presented to Network Rail engineering management through web-meetings for verbal feedback and approval. In the end, the UML diagrams and In2Smart TRL research assessment has been validated during web-meetings, while a questionnaire has been produced to validate the improved tool and the complementary user guide.

5.1 Questionnaire Results Analysis

The questionnaire has been distributed and answered by twelve agents, mostly experienced in the rail and research environment.

The questionnaire aims to numerically capture the tool and user guide satisfaction and relevance. The tool has been divided in evaluated into two different aspects: visualization and functionality. The questionnaire can be found in 7.1Appendix E.

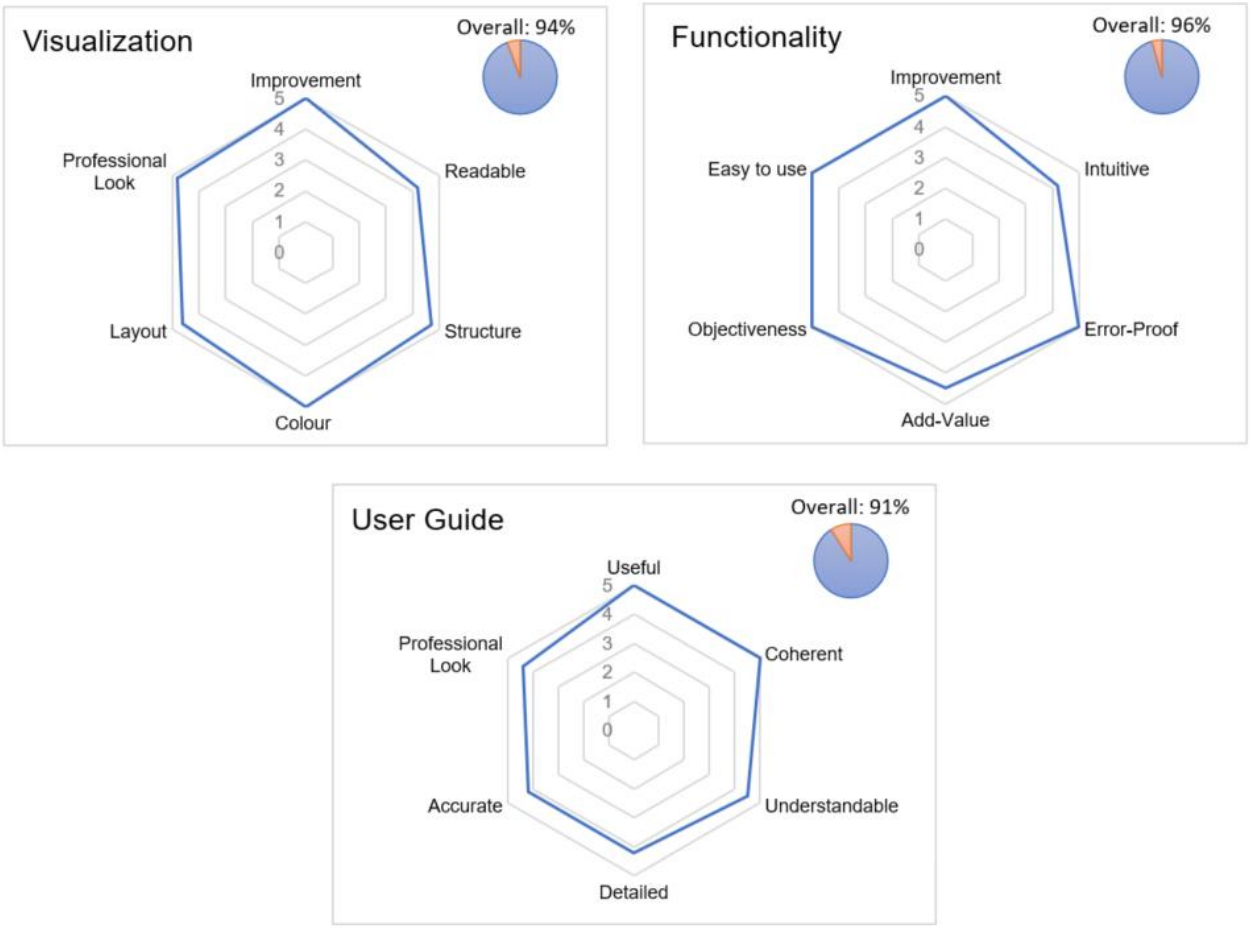


Figure 5-2 Questionnaire Results

A rate between 1 to 5 (totally disagree - totally agree) was given to each category and as it can be seen in Figure 5-2, the overall satisfaction in above 92% is the 3 categories. The tool has been successfully improved in both its functionality and visualization aspect. However, based in the results and feedback comments, it can be highlighted that the tool still has some weaknesses in the path intuitiveness, and some have complained about the readability of the report. The user guide has the lowest overall because even if it is useful, it has been said that it could incorporate some other sections like exemplifying an assessment showing who it is filled and what is the report result.

6 DISCUSSION

6.1 Discussion of the Methodology

The methodology adopted during the project has been crucial in achieving the desired aim and objectives. Its greatest strength is the structure that has made possible a progressive gain in the technology readiness field and project requirements.

The delimitation of the project's aim, objectives, and scope was successfully achieved during the first month, delayed due to a furlough from the principal academic supervisor. However, it was not until the main supervisor returned that the project was completely defined as he was the only that knew the client requirements and needs. Achieved background knowledge during initial literature review while the main supervisor was absence brought an advantage for the later project definition.

The undertaken interviews and documents reviewed have been shown to be a highly efficient method of identifying the AS-IS situation and, in particular, capturing the collaborators' interactions. However, due to the be in the early stage of the project, it has been a long and arduous process to map the new activities and interactions while they were been debated and agreed.

One of the main benefits of this project has been the UML diagrams. The use of UML has been chosen to depict the project because is a standard mapping process, widely use and was the technique proposed by the industrial partner as they were already using it in the definition of the EU-funded program. But it is worth to mention that UML is not the best technique for project management and project analysis because by giving a project's static picture it cannot highlight where the value is added.

6.2 Discussion of the Results

The literature review revealed that the assessment of TRL is a challenging exercise. Previous attempts to create Technology Readiness Assessment (TRA) tools have been made during the last twenty years. However, for competitive

advantage, organizations keep them as much confidential as possible. Those tools and processes require teams and experimented professionals of each field; therefore, it has been difficult to work on a TRA without previous experience in the technology development field. This is also a problem because each organization has their one slightly different definition of TRL that could lead to misunderstanding when groups from different organizations or field need to cooperate.

The TRL assessment tool was developed for Network Rail which has an internal product acceptance process [49] that requires a certified minimum TRL of 6. For this purpose, Network Rail follows the Rail Industry Readiness Levels (RIRL) framework's definition of TRL (7.1Appendix D). For this reason, the tool has been implemented based on the requirements listed in the TRL from RIRL. However, some stakeholders have raised their awareness of a conflict between the requirements previously mentioned and the expected requirements from the different European reviewers. They claim that TRL definition from RIRL does not match with the same requirements needed for this EU-funded programs. The problem is that no detailed definition from the EC has been made just high-level descriptions. Therefore, based on Network Rail perception of what is required from the EC and analysing the TRL requirements from RIRL, it has been identified that in RIRL TRL some requirements are related with Manufacturing Readiness, therefore, those are out of scope for In2Smart. In those lines, an option that ask the user whether we want to assess Manufacturing Readiness has been added in the upgraded version of the TRL self-assessment tool.

Another important aspect of the tool's implemented feature has been to bring a more objective assessment. The user can add an evidence of documents that back up the fulfilment of the requirements. This has been done because TRA is based is providing a systematic but especially objective assessments and because Network Rail, in their product acceptance process [49], also requests for evidence to demonstrate that the product meets the requirements.

6.3 Discussion of the Validation

Despite the absence of measurable metrics, a validation process has been conducted for the research assessing the In2Smart2 diagrams, In2Smart TRL research assessment, upgraded tool and user guide. It is important to capture stakeholders' feedback to demonstrate that the work is meaningful for Network Rail.

A continuous monitoring, especially for the diagrams, has been carried out, getting different stakeholders' feedback, and modifying them accordingly. Therefore, the diagrams and the TRL assessment conducted for In2Smart WP10 have been validated and approved by Network Rail by web-meeting and emails.

On the other side, a questionnaire for the tool and user guide was designed and sent to different rail and research development experts. This enabled to monitor and control the acceptance through numerical results. For this purpose, the results have been plotted in three different radar charts to quickly get a visual information of the strengths and weaknesses. Both the tool and user guide received a positive response with an average overall score over 93%. It can also be seen that the tool had been improved visually and functionally, which satisfactorily demonstrate the effort that was brought into it.

7 CONCLUSIONS AND RECOMMENDATIONS

This project aimed to support Network Rail in the technology development plan by providing an improved TRL assessment tool and by mapping collaborators interactions and deliverables, and supportive improved TRL assessment tool. The global aim has been successfully accomplished by meeting the individual objectives.

The first objective was met by conducting an extensive literature review on the UK rail industry and technology readiness. The second objective was achieved through continuous communication with different stakeholders and documentation review that made possible to map stakeholders' interactions and needed activities to meet the objectives.

The third objective was the verification of the In2Smart WP10 requirements' achievement which has been successfully achieved by individually providing evidences of their achievement and critically assess whether or not they were in the scope. This objective also sought to conduct a verification of the existing TRL assessment tool. By completing a stress test where the tool was tested in multiple different ways about ten areas of improvement have been revealed.

The fourth objective took these areas of improvement to upgrade the tool. Also, other new functionalities were implemented to improve the user satisfaction. The fifth objective was to formally validate the work carried. It has been achieved by conducting regular meeting with different involved stakeholders and a final questionnaire.

In conclusion, the aim and objectives have been successfully achieved. The combination of UML diagrams with the In2Smart WP10 and the improved TRL self-assessment tool have provided the appropriate strategic decision-making material to Network Rail to facilitate management decisions for the In2Smart2 project.

7.1 Future work

After this research is completed, two different possible further stream work have been identified: UML diagrams update and keep improving the TRL tool.

- UML diagrams update: The diagram made during this research are subject to changes and may have to be updated while the project evolves. It has been a first approach to map the collaborators' interaction and duties. The tasks assignation could change and be redistributed to other collaborators.
- TRL tool improvement: The self-assessment tool is already a complete and useful tool; however, it is an Excel-based tool which in some context is not an appropriate platform. If Network Rail wants to use for internal procedures, a web-based tool would be more professional.

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APPENDICES

Appendix A CURES APPROVAL

20 May 2020

Dear Mr Vazquez Navarro ,

Reference: CURES/11120/2020
Title: VISUALISATION AND ANALYTICAL TOOLS FOR TECHNOLOGY REDINESS EVALUATION OF A REIAL R&D PROEJCTS

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/11120/2020 **has been reviewed. You may now proceed with the research activities you have sought approval for.**

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B NASA AND European Commission TRL DEFINITIONS COMPARISON

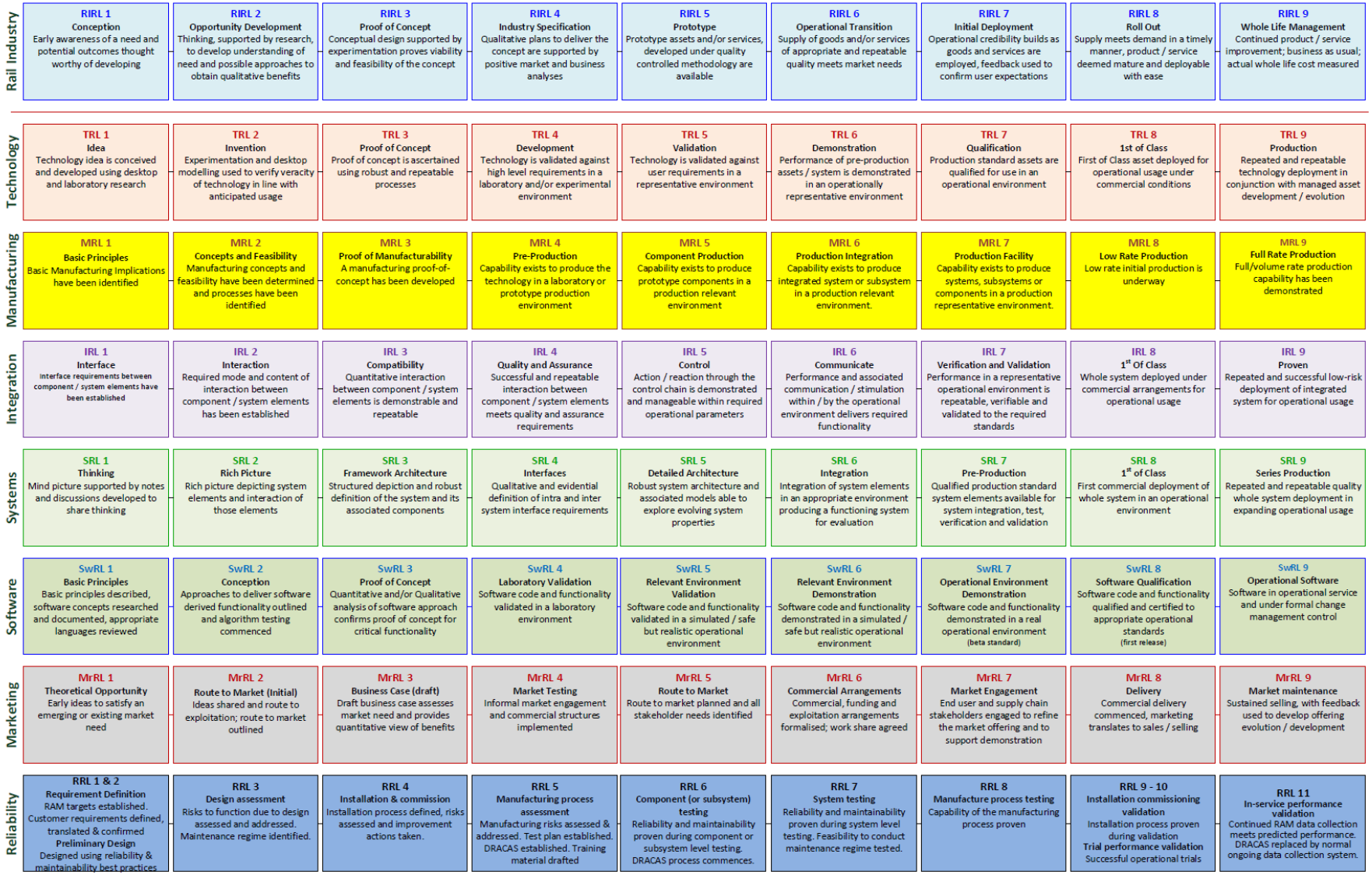
TRLs	NASA TRLs definitions [24]	EC TRLs definitions [30]
TRL 1	Basic principles observed and reported	Basic principles observed
TRL 2	Technology concept and/or application formulated	Technology concept formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of concept	Experimental proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment	Technology validated in laboratory
TRL 5	Component and/or breadboard validation in relevant environment	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstration in a space environment	System prototype demonstration in operational environment
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	System complete and qualified
TRL 9	Actual system "flight proven" through successful mission operations	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies or in space)

Appendix C TRL Definitions, Descriptions, and Supporting Information

TRL	Definition	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.
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 a 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 a 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?
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	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

TRL	Definition	Description	Supporting Information
		laboratory environment or in a simulated operational environment.	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 system under operational mission conditions.	OT&E reports.

Appendix D Rail Industry Readiness Levels (RIRL) and RIRL TRL Framework



Technology Readiness Levels (TRL): Presented in a Railway context

Version 1: 24th May 2016

TRL 1: Idea

Technology idea is conceived and developed using desktop and laboratory research

Initial exploitation of new ideas

- Desktop and initial 'laboratory' research to explore idea and to ascertain possible development routes, identify potential opportunities
- Structured research into extant material and development of hypothesis
- Quick 'look-see' to ascertain the possibility / viability of the new / novel idea
- Articulate the opportunity, identify potential need and speculate exploitation

TRL 2: Invention

Experimentation and desktop modelling used to verify veracity of technology in line with anticipated usage

Exploration of potential through structured experimentation in order to provide understanding of the key technical / technological advances

- Continued desktop research and analysis to consolidate and develop understanding of key principles and establish key variables
- Identification of key performance indicators
- Articulation of how to achieve proof of concept
- Documented desktop modelling to explore and establish expected technological parameters (including but not limited to factors / indicators / measures)
- Asset / Technology capability requirements defined along with key variables

TRL 3: Proof of Concept

Proof of concept is ascertained using robust and repeatable processes

Proof of concept using established methodologies (including hardware / software modelling, synthesis and experimentation

- Development of technology to enable 'proof of concept' to be undertaken
- Range of recorded & qualitative experimental and modelling activities to validate main technology factors (including but not limited to factors / indicators / measures)
- Produce functional description and commence identification of boundaries and interfaces with external systems / equipment
- Production of 'A models' to support / assist proof of concept
- Produce 'Space models' of equipment (may be 'virtual')
- Draft all technical requirements and specifications
- Safety Analysis

TRL 4: Development

Technology is validated against high level requirements in a laboratory and/or experimental environment

Development of asset / technology into a tangible entity which approximates its currently perceived end state

- Production and bench qualification of 'B Models' utilising appropriately available technologies
- Development of asset / technology and refinement of function to demonstrate output performance and variability
- Identification and quantification of technology risks; Risk Reduction Plan
- Improved business plan, identification of route to market
- Improved project plan; better understanding of production path
- Interface testing and initial integration
- PESTLE implications and market expectations understood and planned / accounted for
- Human Factors

TRL 5: Validation

Technology is validated against user requirements in a representative environment

Trial, verification leading to validation of the asset / technology for use in the intended environment

- Development / acquisition / access to trial and test facilities to validate technology (using B or C Models)
- Establish functional performance meets requirements and is repeatable
- Produce 'C Models' to be used in validation testing
- Produce production plans and establish cost of manufacture
- Commence environmental testing
- Asset / Technology Support Plans (RAMS, training, documentation, etc.)
- Performance boundaries understood and defined
- Asset / technology integrated with system; boundary conditions established, interfaces documented

TRL 6: Demonstration

Performance of pre-production assets / system is demonstrated in an operationally representative environment

Demonstration of pre-production standard asset / technology in a realistic, representative (safe) operational environment

- Production of small quantity of 'pre-production' assets /technology
- Asset / Technology demonstration events to support development and marketing
- Obtain access to / develop suitable operational (safe) test and demonstration environment(s)
- Verify cost of manufacture / selling price / market pricing regime
- Evidential confirmation of performance and function in an operational environment
- Complete design and development process to meet 'design freeze' status
- Risk mitigation

TRL 7: Qualification

Production standard assets are qualified to operate in an operational environment

Qualification and verification of assets / technology in an appropriate operational environment

- Formal qualification in an approved and representative operational environment
- Verification of required functionality
- Identification of evolved / evolving properties
- Manufacture / build of production standard assets / technology
- Productionisation processes (build / test / certification, cost target, Quality Assurance, etc..)
- Supply chain development and stabilisation
- Risk mitigation and asset / technology maturation under formal change control

TRL 8: First of Class

First of Class asset deployed for operational usage under commercial conditions

First of Class of asset / technology adding value in an operational environment

- 'First of Class' delivery; first commercial operational use
- Asset / technology benefit / value analysis for operational employment
- Asset / technology qualification completed in intended operational environment
- Series production capability developed
- Support programmes (RAM, Spares / Repairs, Training, documentation, etc.) established
- Programme / Project Closure as part of move to series production
- Marketing

TRL 9: Production

Repeated and repeatable technology deployment in conjunction with managed asset development / evolution

Mature assets / technology deployed across the enterprise

- In series production
- Steady state production
- Established and supported production facility
- Supply chain improvements in cost & performance
- Change Management
- Asset / Technology exploitation
- Asset / technology support regime improvements / expansion
- In-service whole life cost, performance and benefit analysis
- Customer feedback and satisfaction analysis

Appendix E Validation Questionnaire

Questions	Rate (1 to 5)	Comments
Visualization		
Professional Look		
Report Pleasant to Read		
Report Structure Coherent		
Correct Colours Selection		
Correct Screen-wise Layout		
Improvement from Previous Version*		
Functionality		
Easy to use		
Intuitive		
Robust (Error-Proof)		
Useful (Bring Added Value Information)		
Objective Assessment		
Improvement from Previous Version*		
User Guide		
Useful		
Diagrams Coherence		
Easy to Understandable		
Detailed Enough		
Correct Information		
Professional Look		

*Complementary Tool's versions snapshots attached

Appendix F User Guide

TRL SELF-ASSESSEMENT TOOL V.2 : USER GUIDE

MSc Student

Daniel Vázquez Navarro

Academic Supervisors

Isidro Durazo-Cardenas

Andrew Starr

Industrial Supervisors

Amanda Hall

Robert Anderson

Table of Contents

1 Tool's Introduction

The tool was developed in Excel using Visual Basic for Applications (VBA). The tool's objective was the creation of an application that could objectively assess the TRL evaluation process automatically, with the activities and skills gaps identification.

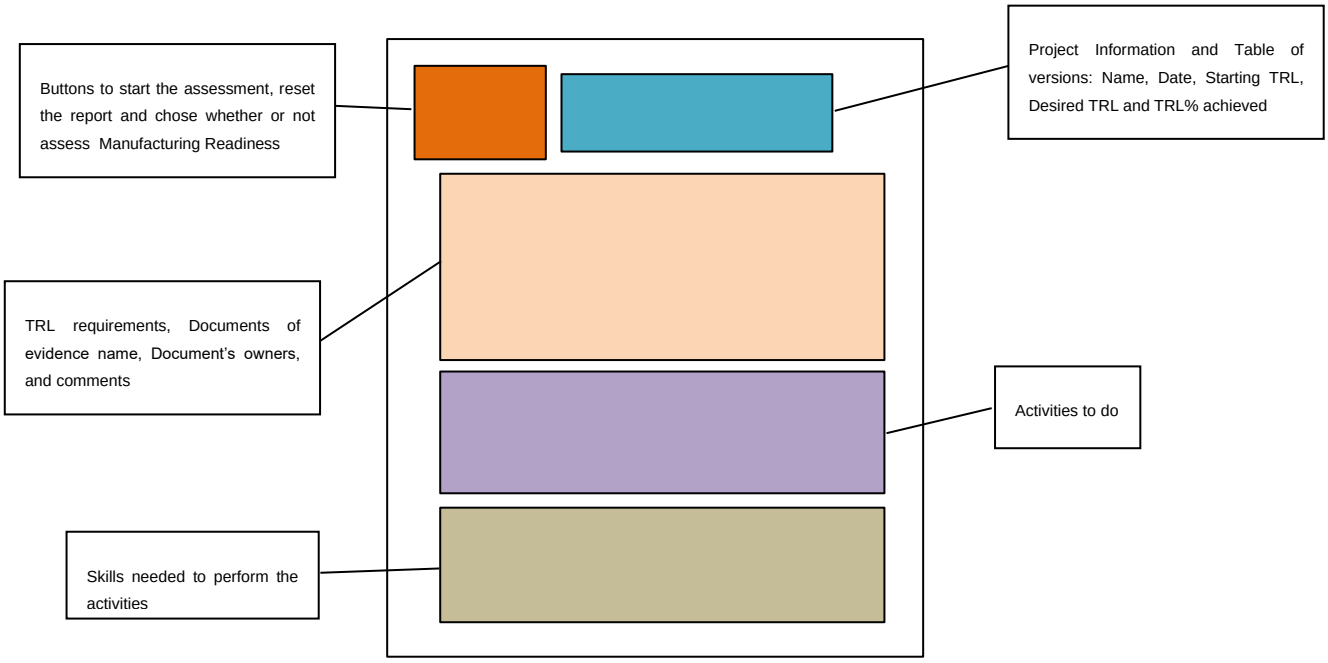
It is important to underline that in the TRL process there are several requirements to satisfy and the tool was based on the requirements of the railway industry, linked to Network Rail's project, towards TRL 7. Its applicability is therefore linked to the industry and projects in this area. However, an option where the Manufacturing Readiness requirements can be avoided which would lead to a purely Technology Readiness assessment

With this instrument, experts in Network Rail will be able to assess easily and objectively which is the level achieved for an innovative project, identifying the gaps, and underlining the needed competencies.

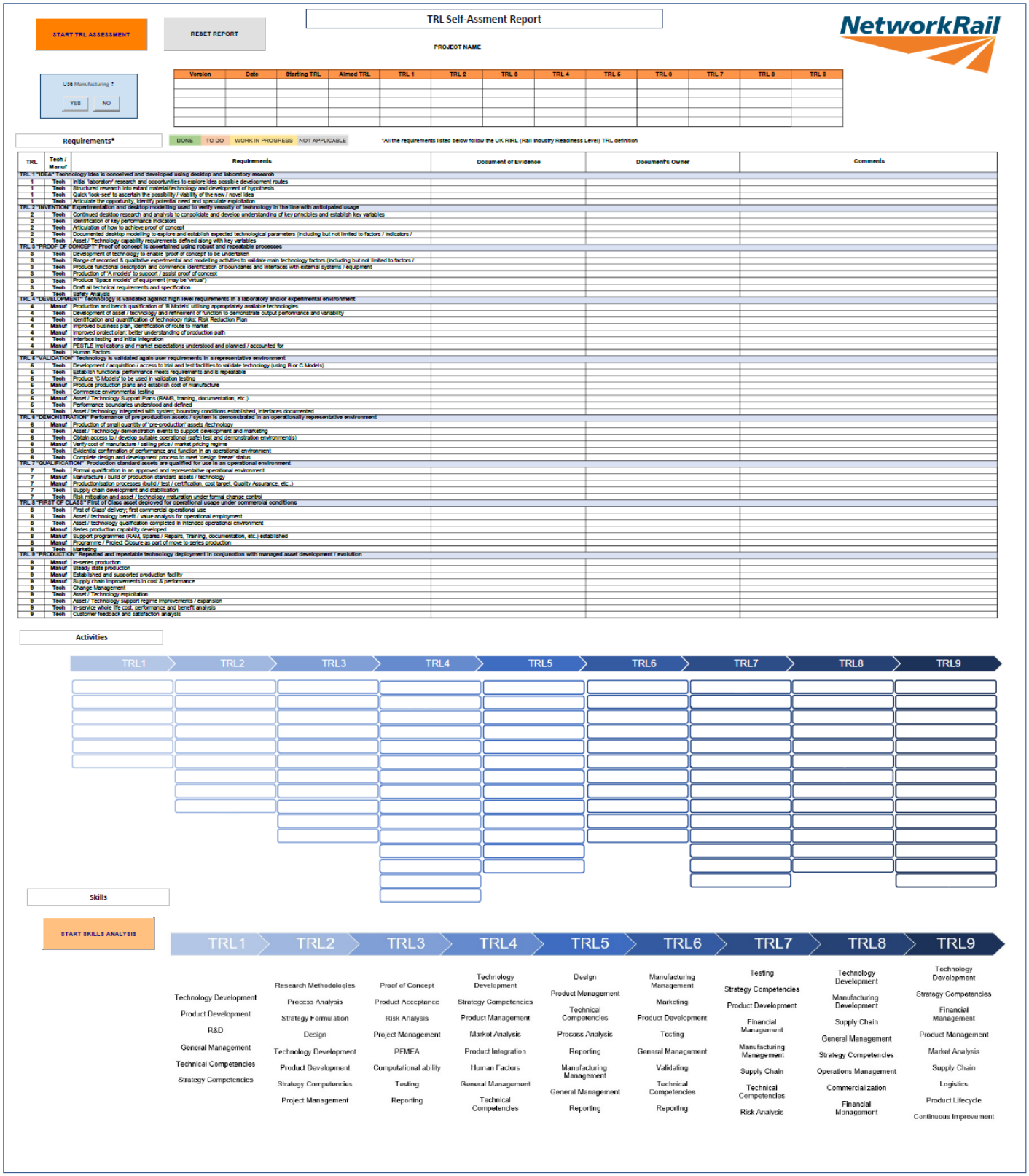
2 Tool's Description

2.1 The Report

The main idea of the report was to automatically have a visual summary of the assessment. Its structure is simple, and it is explained in the figure below:



The following Figure illustrates the an empty report:



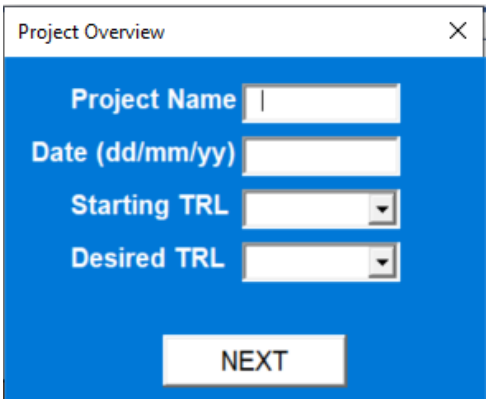
2.2 Assessment Process Flow

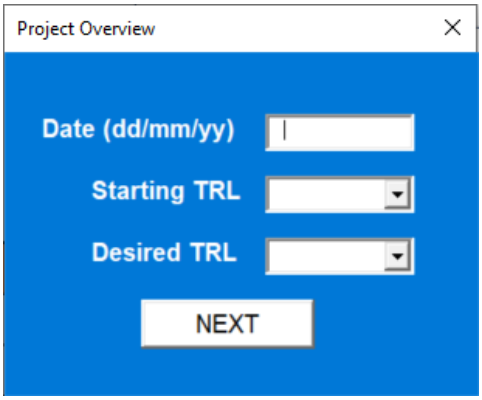
2.2.1 TRL Assessment

When the user wants to start the self-assessment TRL evaluation, the “START GAP ANALYSIS” button must be pressed, as shown in the figure below:

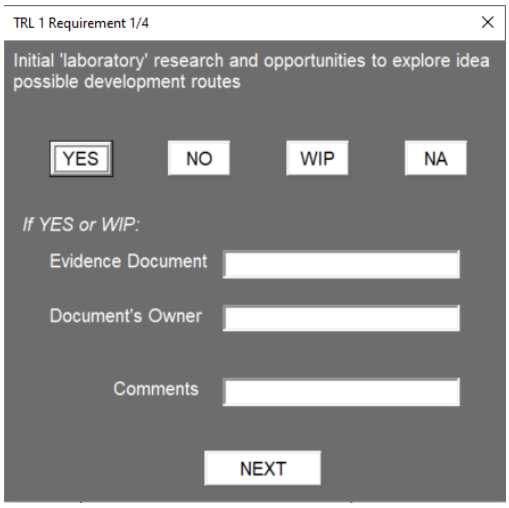
The first form that will appear will ask the user if he wants to consider the Manufacturing Readiness requirements as part of the assessment as shown in the figure below:

The next step is to introduce the assessment information. Depending if the table of versions is empty or not, the form will be different. If the table of versions is empty, the user form will ask the user for: Project Name, Date, Starting TRL and Desired TRL (left figure below). If the table of versions has at least one entry, the user form displayed (right figure below) will ask just for the Date, Starting TRL and Desired TRL because this assessment will be considered as a newer version of the current project assessment.

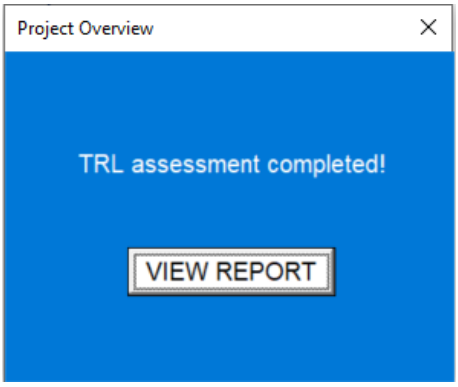




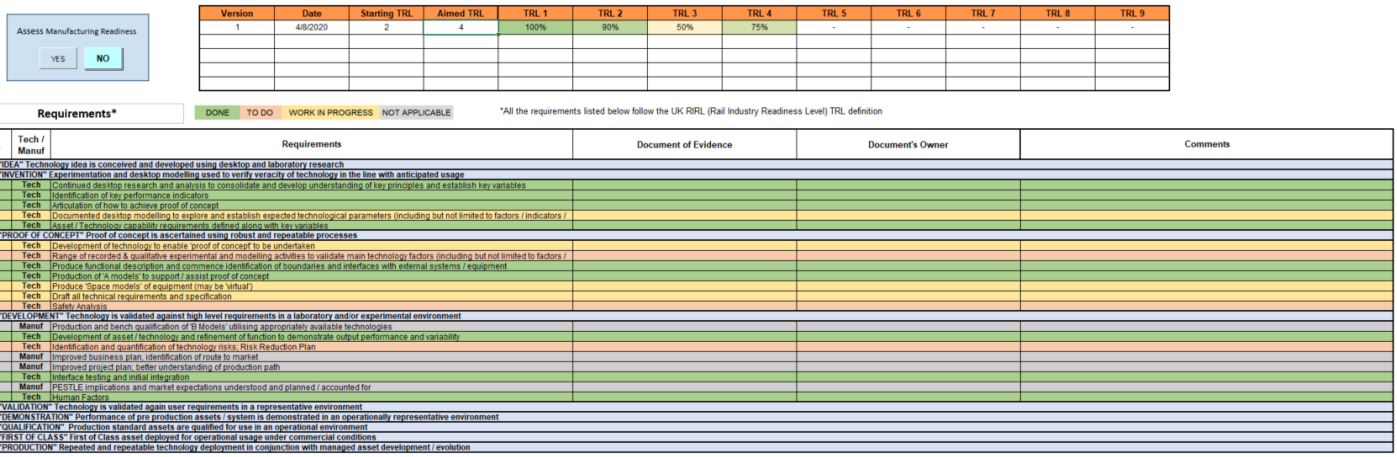
After filling the information, the first requirement form will appear, depending at which level the user have selected as starting TRL. In this form the user will be able to answer whether the requirement has been fulfilled or not or it is work in progress or not applicable. To bring the assessment more objective the user can introduce the name of the report that proves that the requirement has been achieved, in addition to the document's owner and comments if required. The figure below, is an example of a requirement form:



When the desired TRL is achieved, the assessment is finished, and the next form will appear:



When the report is shown, only the requirements' rows of the TRL that are assess will be displayed. That way the report has a cleaner aspect focusing on the relevant requirements only. For example, in the following figure, the assessment starts at TRL 2 and finishes at TRL 4, therefore only the requirements of TRL 2, 3 and 4 are shown and TRL 1, 5, 6, 7, 8 and 9 are shorten to just the TRL header.



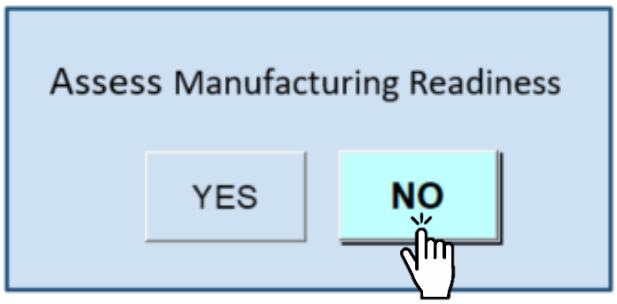
Version	Date	Starting TRL	Aimed TRL	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
1	4/8/2020	2	4	100%	90%	50%	75%	-	-	-	-	-

TRL	Tech / Manuf	Requirements	Document of Evidence	Document's Owner	Comments
TRL 1 "IDEA" Technology idea is conceived and developed using desktop and laboratory research					
TRL 2 "INVENTION" Experimentation and desktop modelling used to verify veracity of technology in the line with anticipated usage					
2	Tech	Continued desktop research and analysis to consolidate and develop understanding of key principles and establish key variables			
2	Tech	Identification of key performance indicators			
2	Tech	Articulation of how to achieve proof of concept			
2	Tech	Documented desktop modelling to explore and establish expected technological parameters (including but not limited to factors / indicators /			
2	Tech	Asset / Technology capability requirements defined along with key variables			
TRL 3 "PROOF OF CONCEPT" Proof of concept is ascertained using robust and repeatable processes					
3	Tech	Development of technology to enable 'proof of concept' to be undertaken			
3	Tech	Range of recorded & qualitative experimental and modelling activities to validate main technology factors (including but not limited to factors /			
3	Tech	Produce functional description and commence identification of boundaries and interfaces with external systems / equipment			
3	Tech	Production of 'A models' to support / assist proof of concept			
3	Tech	Produce 'Space models' of equipment (may be 'virtual')			
3	Tech	Draft all technical requirements and specification			
3	Tech	Safety Analysis			
TRL 4 "DEVELOPMENT" Technology is validated against high level requirements in a laboratory and/or experimental environment					
4	Manuf	Production and bench qualification of 'B Models' utilising appropriately available technologies			
4	Tech	Development of asset / technology and refinement of function to demonstrate output performance and variability			
4	Tech	Identification and quantification of technology risks; Risk Reduction Plan			
4	Manuf	Improved business plan, identification of route to market			
4	Manuf	Improved project plan; better understanding of production path			
4	Tech	Interface testing and initial integration			
4	Manuf	PESTLE implications and market expectations understood and planned / accounted for			
4	Tech	Human Factors			
TRL 5 "VALIDATION" Technology is validated again user requirements in a representative environment					
TRL 6 "DEMONSTRATION" Performance of pre production assets / system is demonstrated in an operationally representative environment					
TRL 7 "QUALIFICATION" Production standard assets are qualified for use in an operational environment					
TRL 8 "FIRST OF CLASS" First of Class asset deployed for operational usage under commercial conditions					
TRL 9 "PRODUCTION" Repeated and repeatable technology deployment in conjunction with managed asset development / evolution					

2.2.2 Manufacturing Readiness

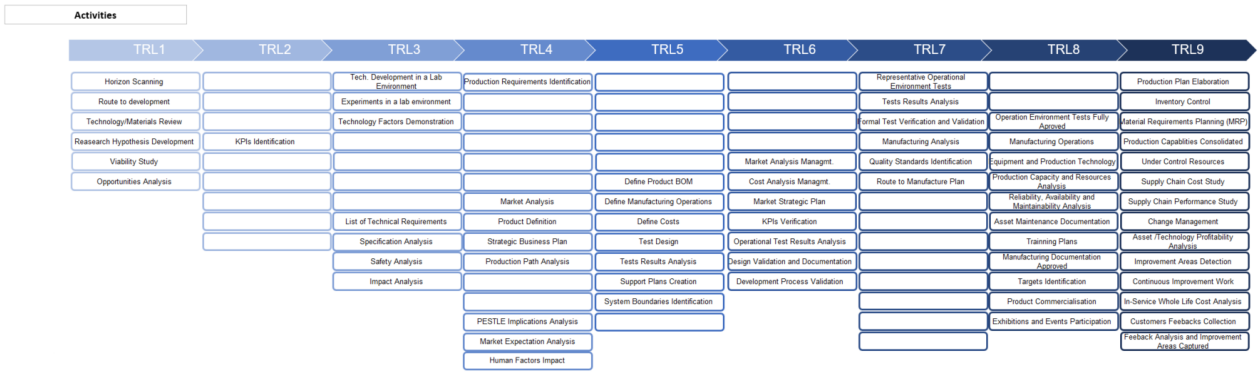
It already has been explained that the first step in the TRL assessment is to choose whether the user wants to assess the Manufacturing Readiness. But this can be also changed whenever the user wants when the Report is shown by using the buttons shown below. The idea is that the main difference is that when the Manufacturing Readiness doesn't want to be assessed, all the requirements related with manufacturing change to a NOT APPLICABLE status an the

requirements forms are not shown and they are not taken into account for the percentage of the TRL achieved.



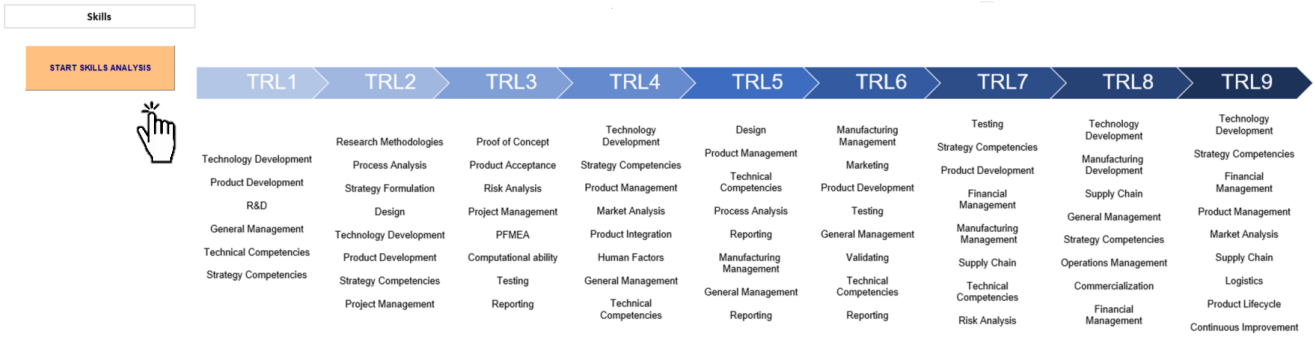
2.2.3 Activities

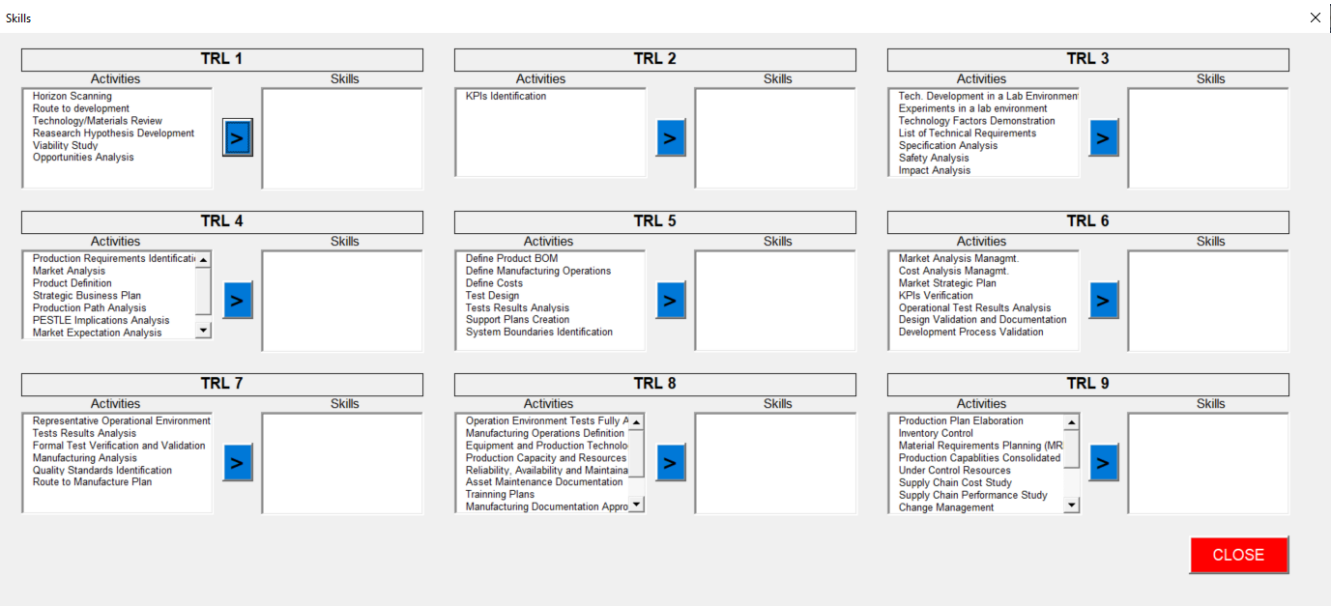
Once the TRL assessment is completed and the report is shown, the user would be able to see which are the activities that have to be done in order to complete the requirements that hasn't been done yet or that are in progress.



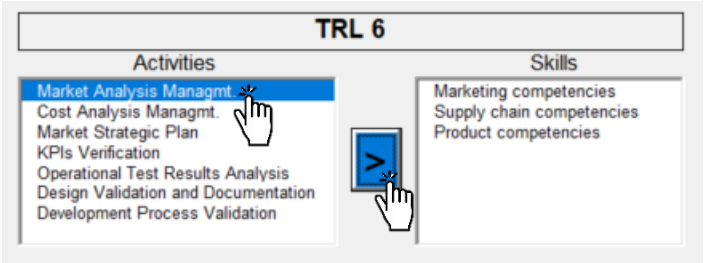
2.2.4 Skills

The last part of the report corresponds to the skills assessment section. Whenever a TRL assessment, the user can select the "START SKILLS ANALYSIS" button to open the window.





The skills window is organized by TRL. In each one, the are to boxes, the left one where for the activities and the right for the skills. Only the activities that are related to undone or in progress requirements will appear. To show the skills, the user must select an activity first and the select the “>” button.



2.2.5 Reset

Finally, the last action the user can do is the clear the whole report by pressing the “RESET REPORT” button. By pressing it, it will clear the table of versions and requirements status and the all the TRL requirements will ungroup.

3 Algorithm and Interactions Description

The assessment process was developed using VBA User Forms. In particular, 64 of them:

1. 3 for the starting questions and assessment information: UserForm01 to UserForm03
2. 59 for each of TRL requirements questions: UserForm_1 to UserForm_59
3. 1 for the assessment ending and to make the backend calculations: UserForm_60
4. 1 for skills analysis windows: UserForm_61

Every user form represents a way to interact with the tool, therefore the concept was to create a path in the theoretical assessment process on how the user will interact with the tool. Information, data and checkpoints are shown by the visual form where you can put details or make a choice.

The high-level algorithm used is the represented in the figure below:

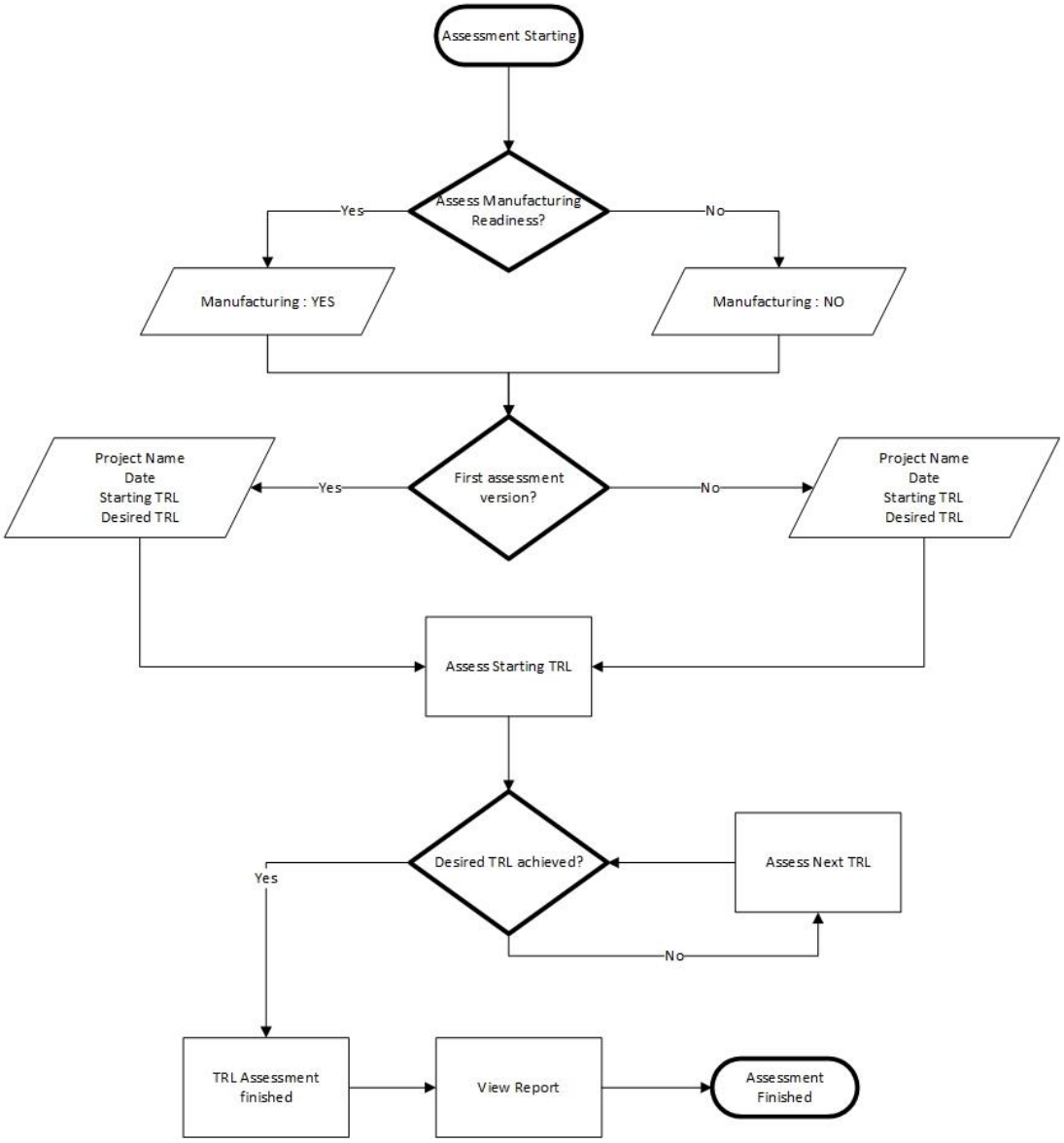


Figure 3-1 Tool's High-Level Algorithm

In particular, the interaction among the users and the user forms and how the data flows between spreadsheets is shown in the diagram below:

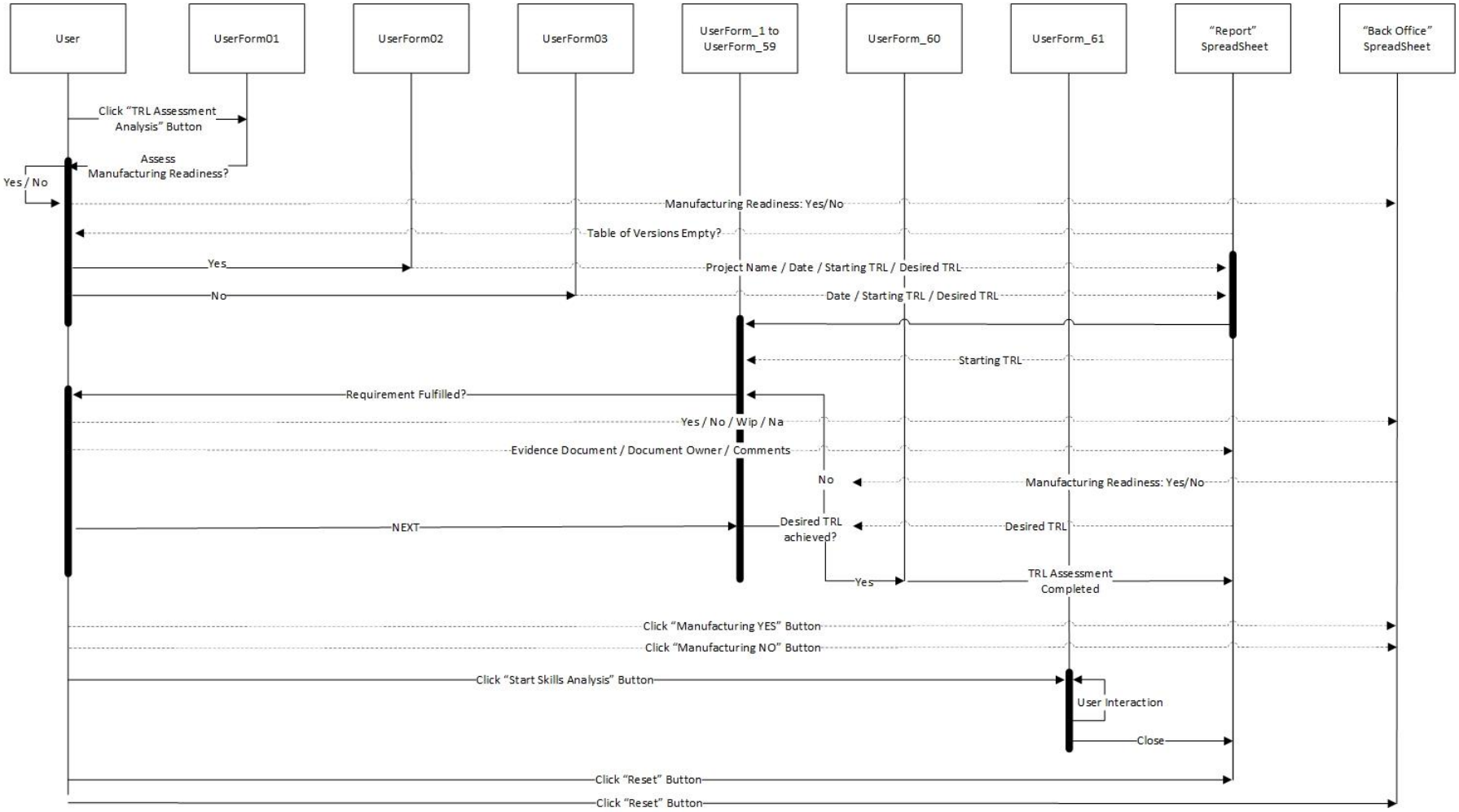


Figure 3-2 Tool Interactions Diagram

Finally, the competition percentage for a particular TRL has been calculated the following formula:

$$TRL_i\% = \frac{1 * NR_{i,YES} + 0.5 * NR_{i,WIP}}{NR_{i,YES} + NR_{i,NO} + NR_{i,WIP}}$$

Where $NR_{i,m}$ represents the Number of Requirements for the TRL = "*i*" with a status of "*m*" that can be: YES, NO, WIP (Work in Progress) or NA (Not Applicable).

4 Tool's Backend

In this section, the backend structure and some VBA code will be explained in case the user would like to extend the tool's capabilities or to change some of the current ones.

4.1 Database

The main structure of the tool's database, which is in the "Back Office" tab, consists of a table for TRL requirements from TRL 1 to 9, a table with the activities and a table for the skills. It is important to note that a requirement could have more than one activity to be satisfied and one activity could have more than one skill to be performed, as it is shown in the figure below:

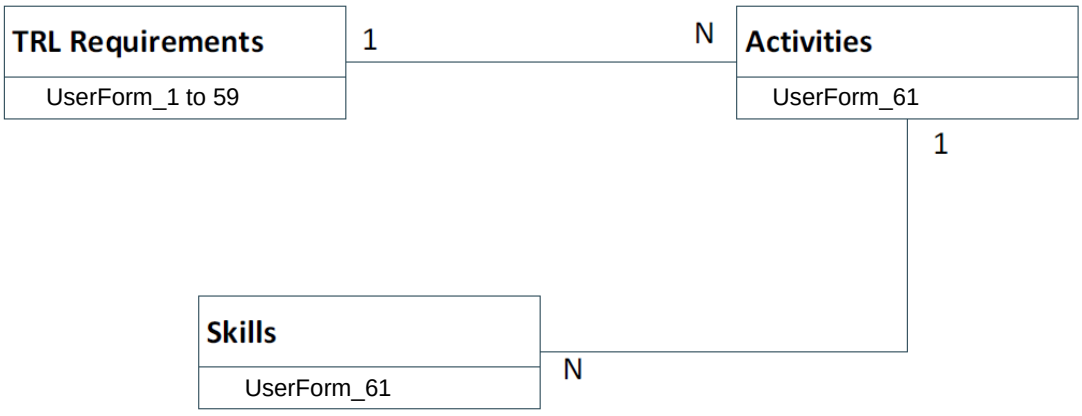


Figure 4-1 Entity-Relation Diagram

Therefore, user forms' language is linked to a specific cell reference. If a description is modified, it is not necessary to modify anything in the language because the cell reference will remain the same, differently speech is for adding or removing requirements, activities, or skills.

Moreover, the "Back Office" sheet has complementary tables and variables:

- A cell that contains whether the assessment includes Manufacturing Readiness or not (YES or NO).
- A table used by the UserForm_61 to know which activity is selected
- A couple of tables to calculate the % achieved at each TRL

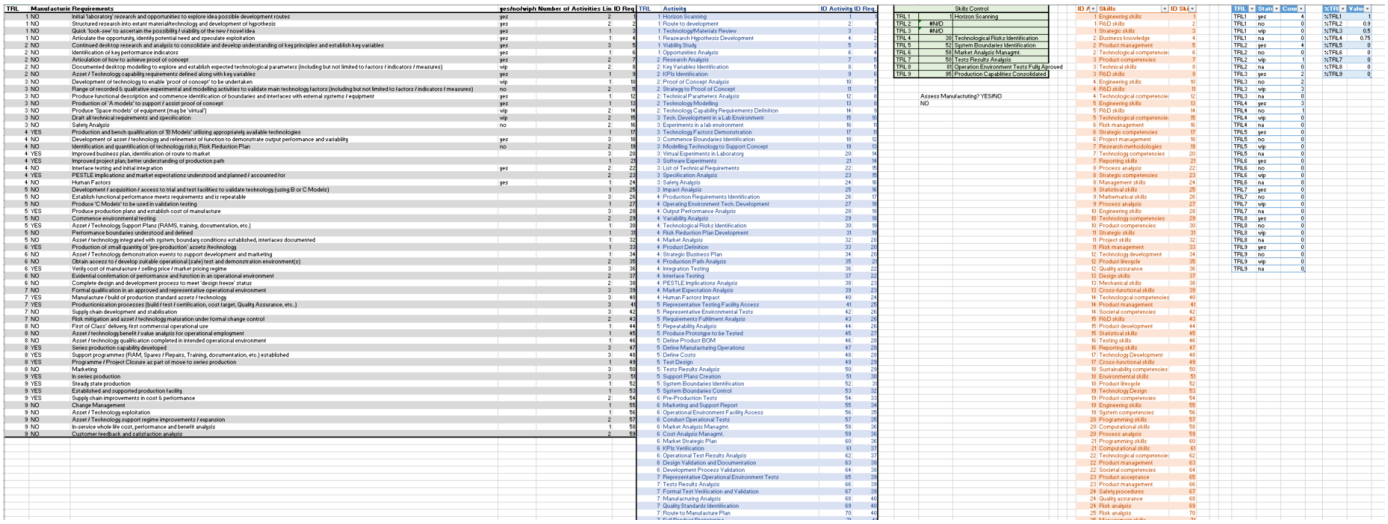


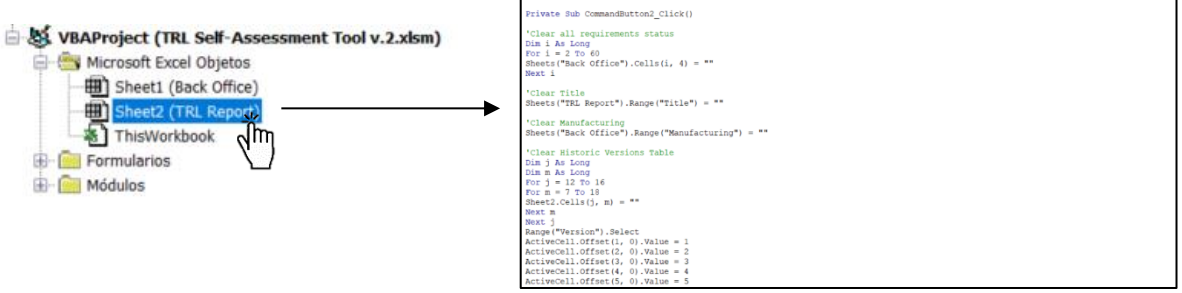
Figure 4-2 Snapshot of Back Office sheet

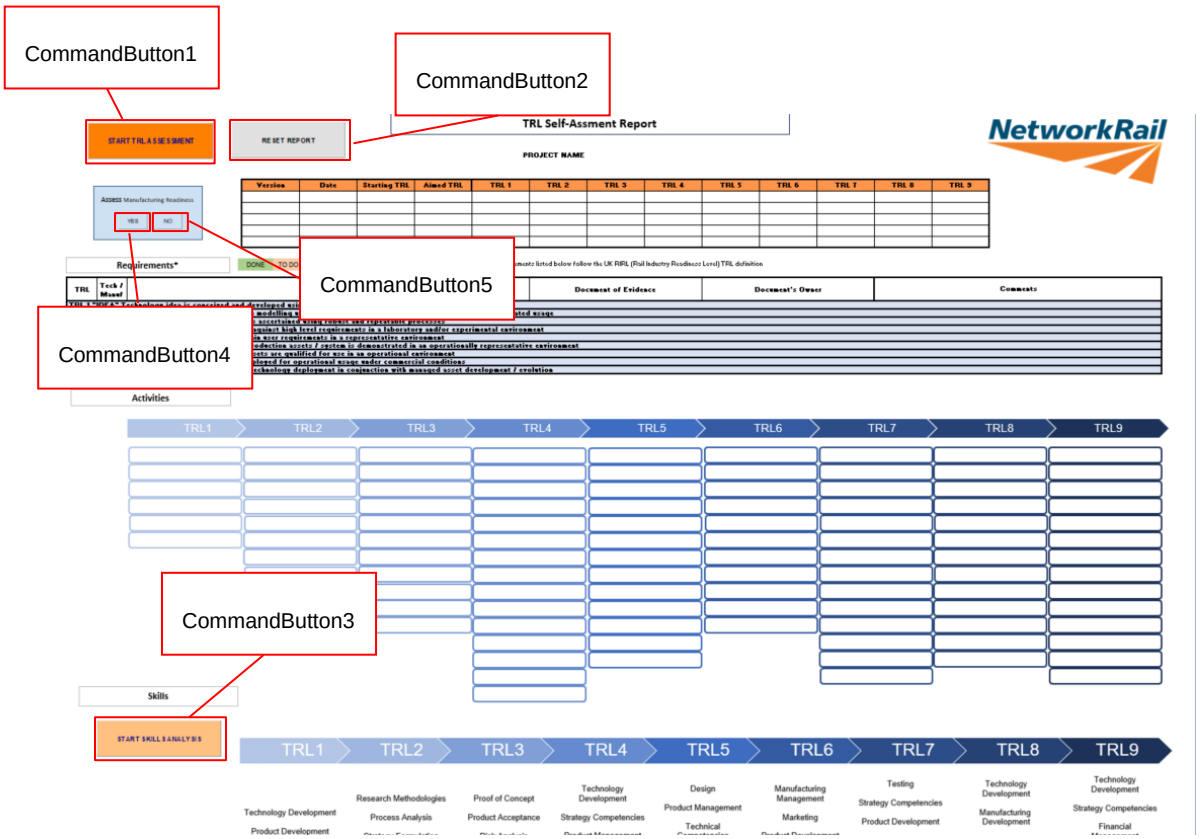
4.2 Visual Basic for Applications

The tool has been developed and coded using Visual Basic for Applications (VBA). The code is mainly split between the TRL Report sheet and the User Forms. Coding Best Practices have been followed like adding comments to understand the code, using self-understandable variable names or use global reference that even if the cells are moved on the sheets, the reference will still be linked.

4.2.1 TRL Report Sheet

In the TRL Report section, the actions after clicking the different buttons have been programmed. This window only has the different sub-routines for the 5 different buttons.





As shown in the previous figure, 5 different buttons can be selected, therefore 5 sub-routines “on click” have been coded to run each time a button is pressed.

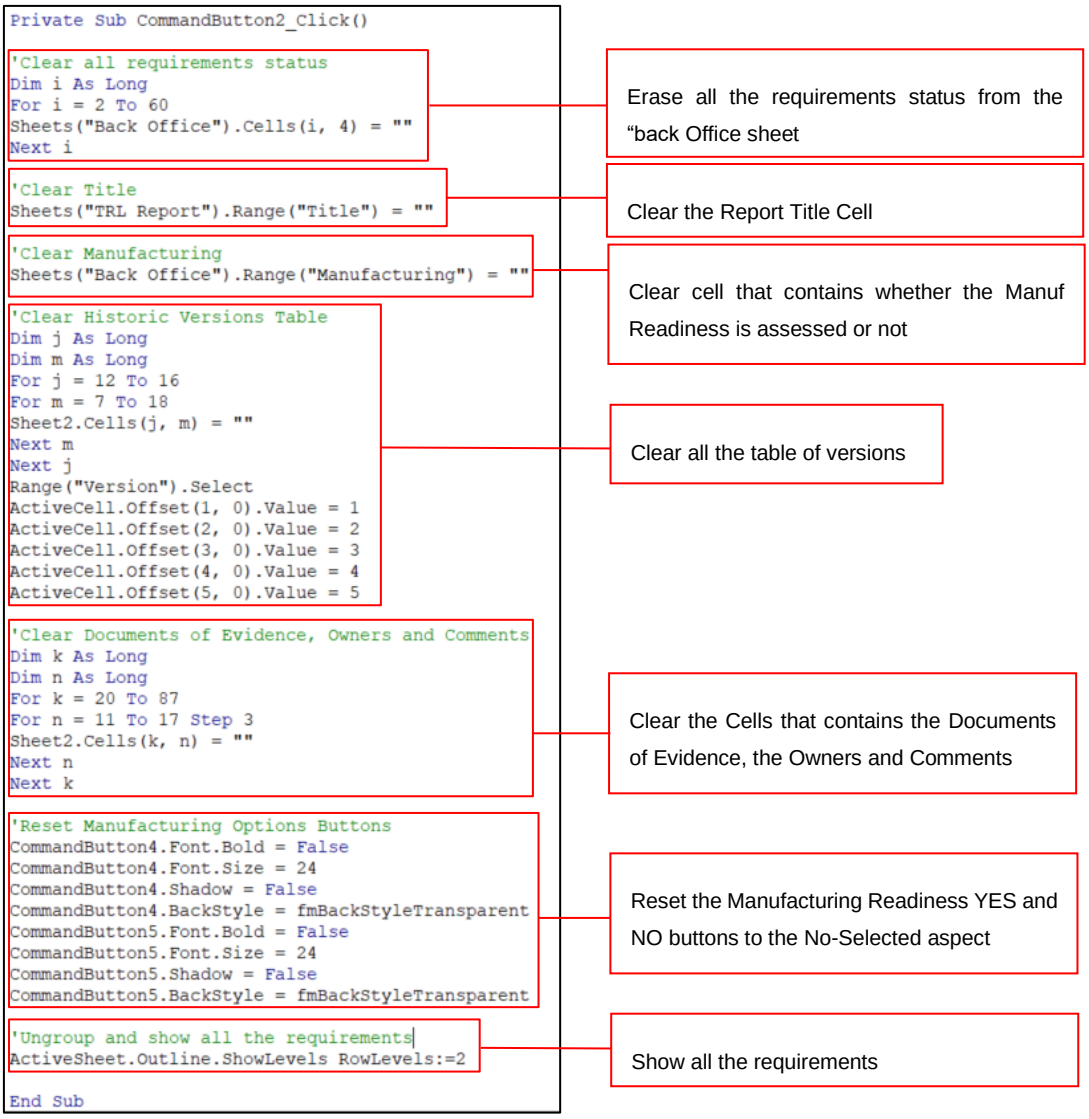
- CommandButton1_Click()

```
Private Sub CommandButton1_Click()

UserForm01.Show

End Sub
```

By selecting this button, the TRL assessment will start, therefore the UserForm01 will be shown

- CommandButton2_Click()

By selecting the reset button, the report will be cleared, and everything will be erased. In particular:



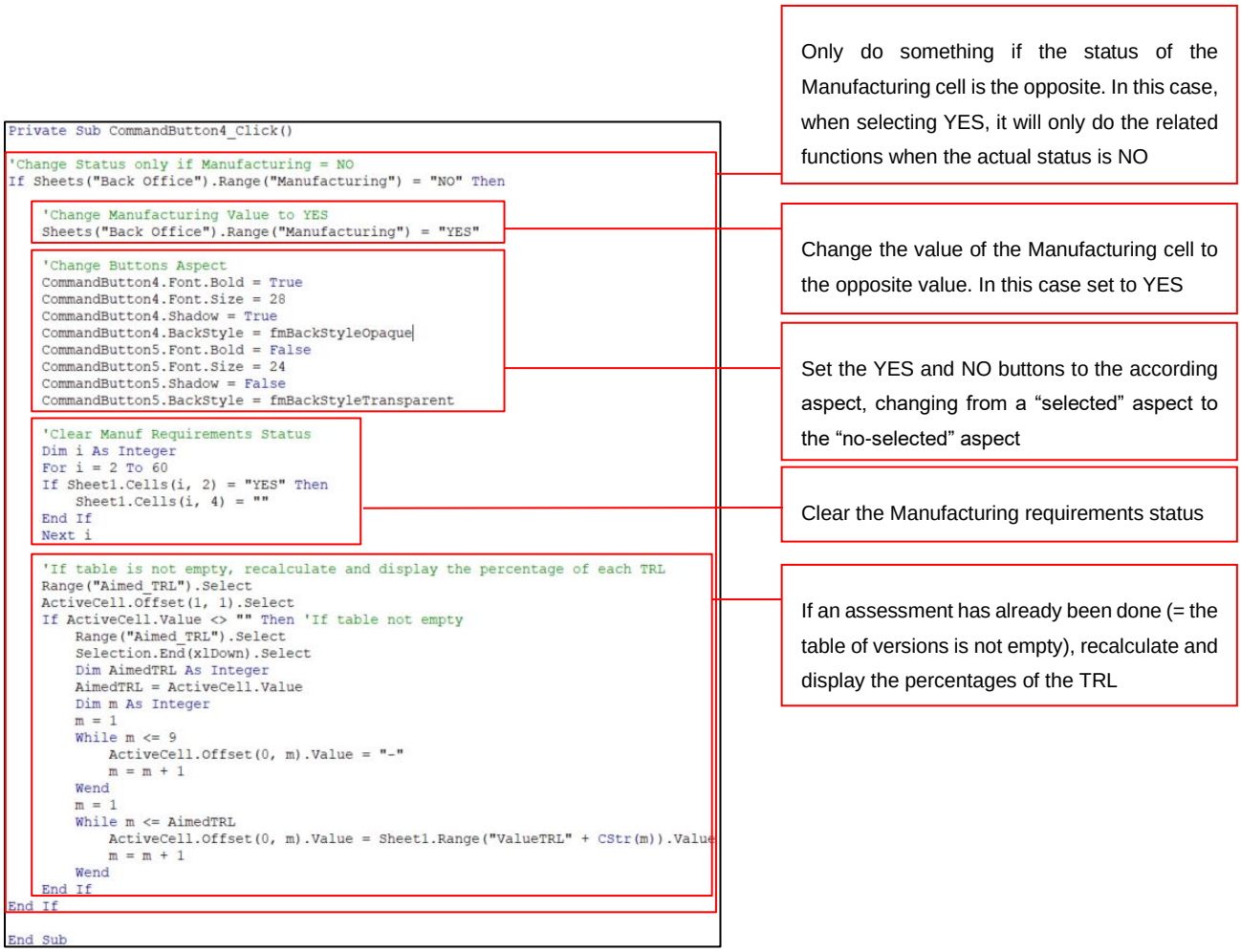
- CommandButton3_Click()

```
Private Sub CommandButton3_Click()

UserForm_61.Show

End Sub
```

By selecting this button, the Skills analysis will start and therefore the UserForm_61 will be shown

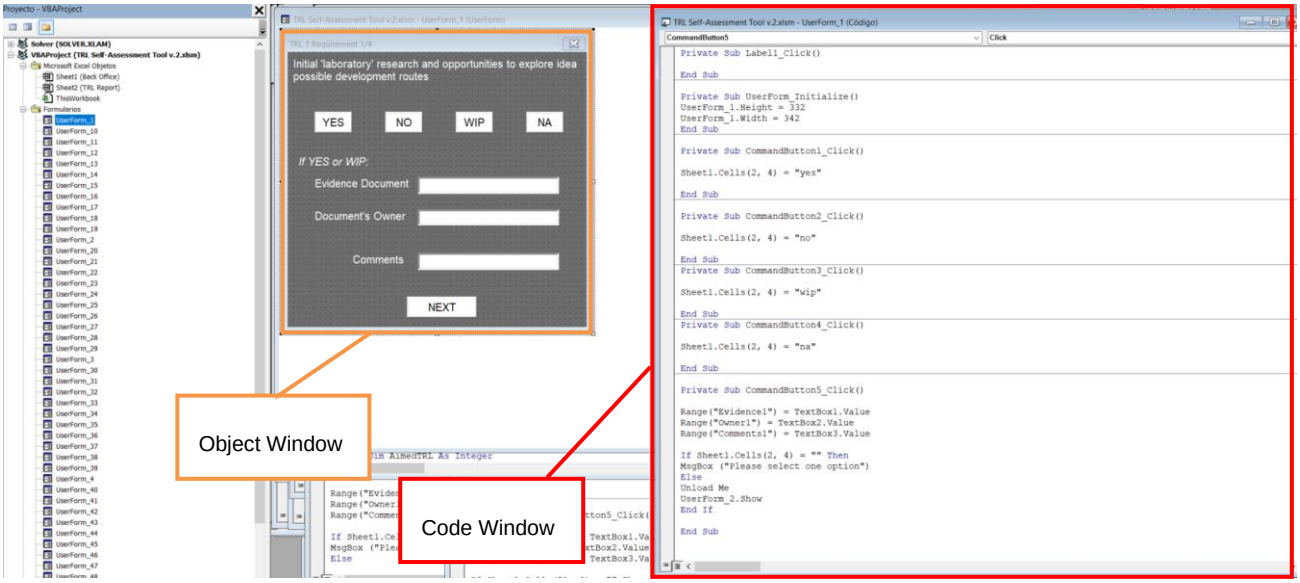
- CommandButton4_Click() and CommandButton5_Click()

These buttons correspond to the YES and NO buttons of Manufacturing Readiness. Only the CommandButton4_Click() sub-routine is explained as the code follow the same approach for both.



4.2.2 User Forms

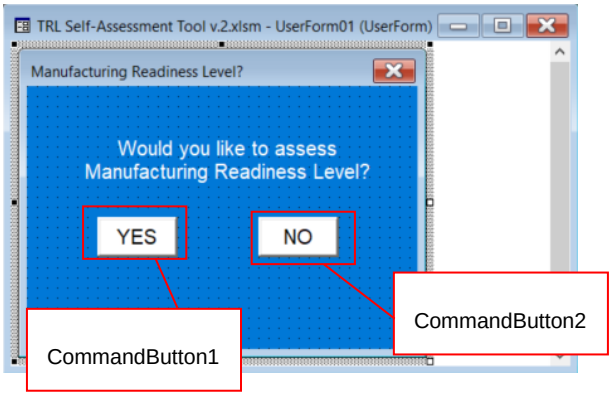
The User Forms have 2 different windows to be addressed, whether is the “Object” or the “Code”. The Object is where all the Labels, TextBox, ListBox, CommandButtons and others are arranged and what the user will see. On the other side, the Code window is where actions are programmed.



5 main different types of User Form can be defined:

4.2.2.1 UserForm01

Object Window:



Code Window:

```
Private Sub UserForm_Initialize()
UserForm01.Height = 185
UserForm01.Width = 240
End Sub
```

Routine that is runs when the Form is opened. Used to define a fixed size due to problem found when the screen resolution changes. This has been done in every Form and won't be explained again.

CommandButton1_Click() and CommandButton2_Click() are equivalent and just CommandButton1_Click() is explained.

```
Private Sub CommandButton1_Click()
'Change Buttons Aspect
Sheet2.CommandButton4.Font.Bold = True
Sheet2.CommandButton4.Font.Size = 28
Sheet2.CommandButton4.Shadow = True
Sheet2.CommandButton4.BackStyle = fmBackStyleOpaque
Sheet2.CommandButton5.Font.Bold = False
Sheet2.CommandButton5.Font.Size = 24
Sheet2.CommandButton5.Shadow = False
Sheet2.CommandButton5.BackStyle = fmBackStyleTransparent

'Set Manufacturing Cell to YES
Sheet1.Range("Manufacturing") = "YES"
Unload Me

'Select which next UserFOrm to display
Range("Date").Select
ActiveCell.Offset(1, 0).Select
If ActiveCell.Value = "" Then 'If table of versions empty
    UserForm02.Show
Else:
    UserForm03.Show
End If

End Sub
```

Set the Manufacturing YES and NO buttons to the according aspect, changing from a “selected” aspect to the “no-selected” aspect

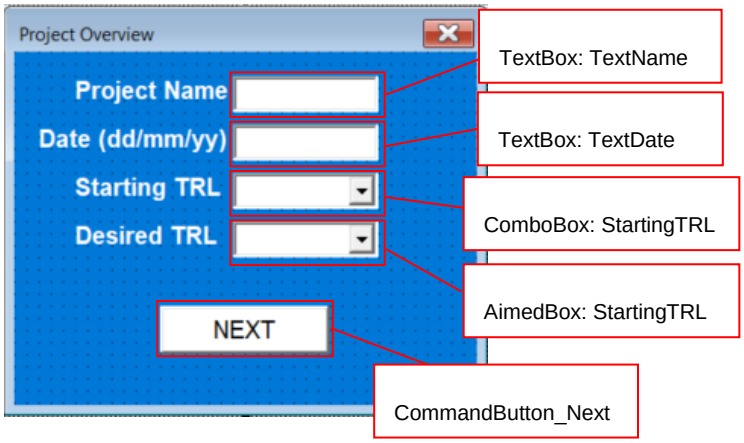
Set the Manufacturing Cell value to YES. In CommandButton2_Click() is set to NO and the Manuf. Requirements status to Not Applicable

If it is the first assessment version (=table is empty), display UserForm02, otherwise UserForm03

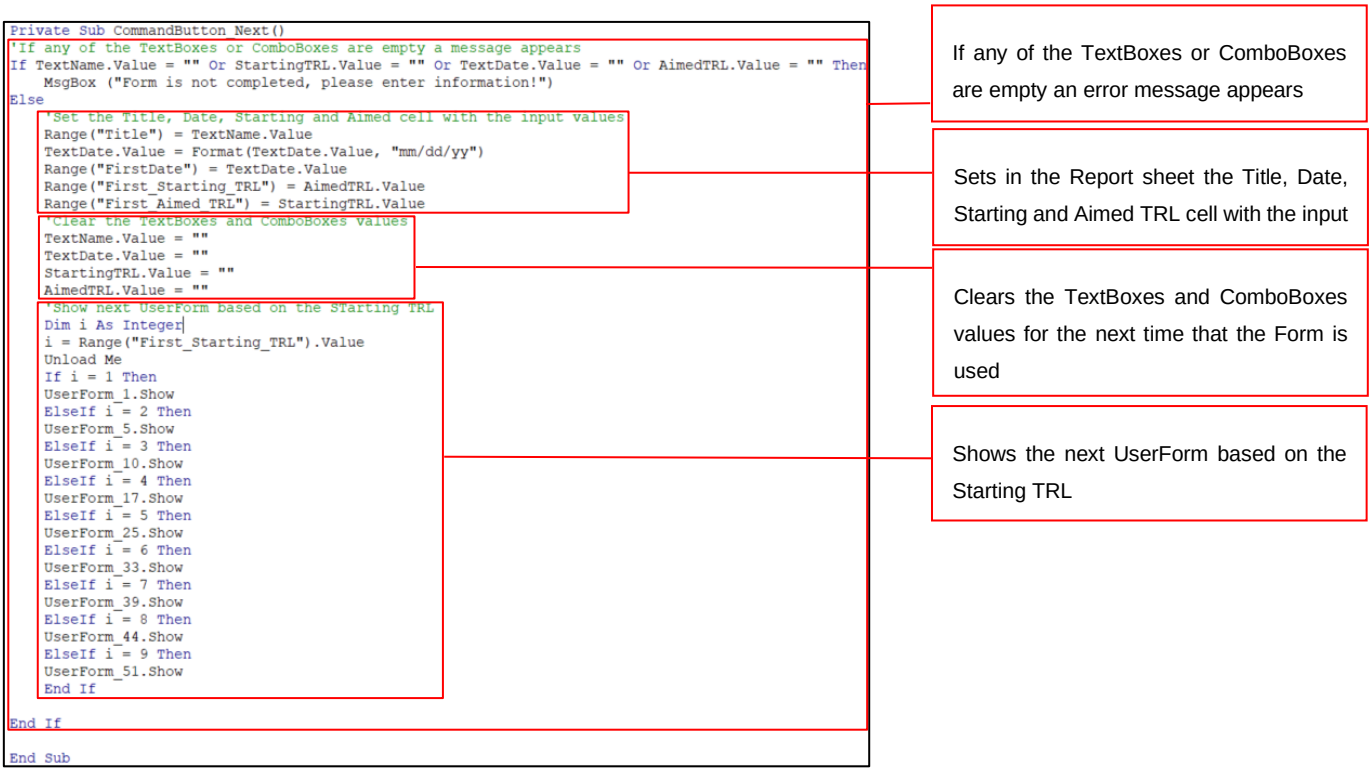
4.2.2.2 UserForm02 and UserFrom03

Both UserForm02 and UserForm03 are similar. The only difference is that UserForm03 do not ask for the Project Name because it a newer evaluation version of the same project.

Object Window:



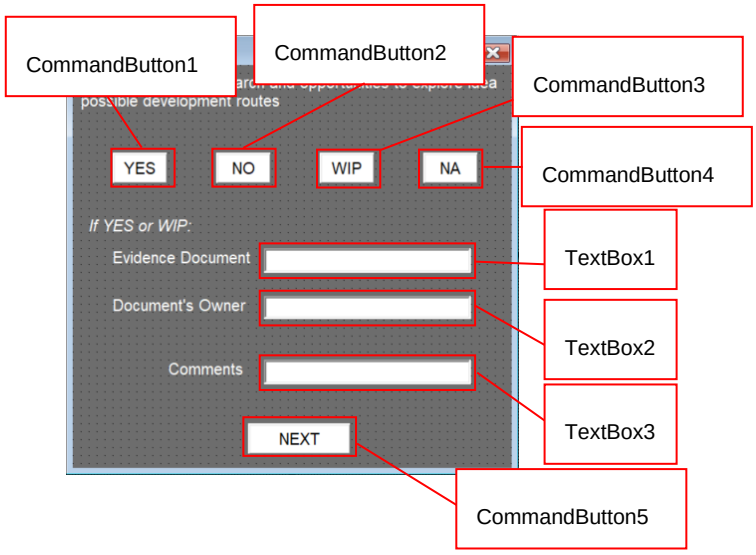
Code Window:



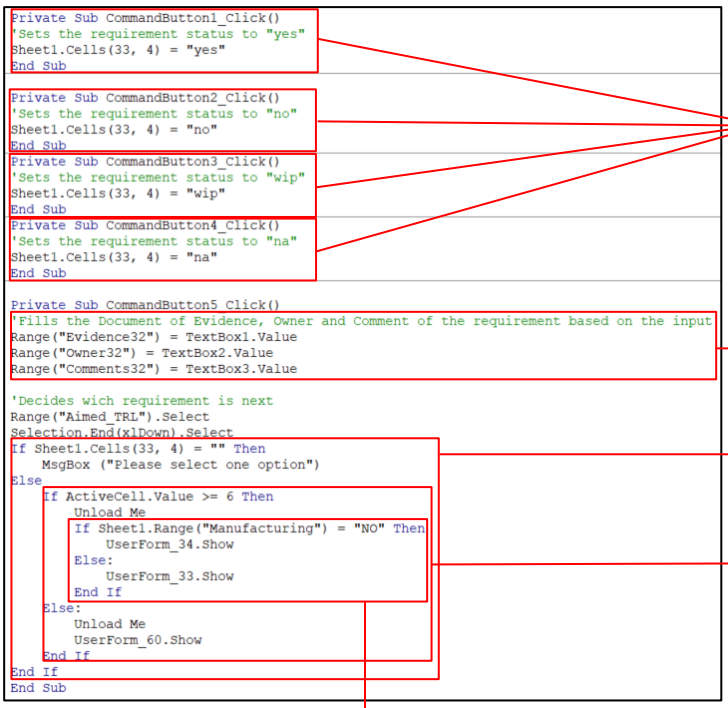
4.2.2.3 UserForm_1 to UserForm_59

These User Forms are where the user set if the requirements have been achieved or not, are in progress or does not apply. The Object Window look the same for all, with 5 buttons and 3 boxes where the user can add back up evidences and comments. The code is similar for all of them with 2 things that may vary. The UserForm_32 has been selected because it contains the 2 differentiating components.

Object Window:



Code Window:



```
Private Sub CommandButton1_Click()
'Sets the requirement status to "yes"
Sheet1.Cells(33, 4) = "yes"
End Sub

Private Sub CommandButton2_Click()
'Sets the requirement status to "no"
Sheet1.Cells(33, 4) = "no"
End Sub
Private Sub CommandButton3_Click()
'Sets the requirement status to "wip"
Sheet1.Cells(33, 4) = "wip"
End Sub
Private Sub CommandButton4_Click()
'Sets the requirement status to "na"
Sheet1.Cells(33, 4) = "na"
End Sub

Private Sub CommandButton5_Click()
'Fills the Document of Evidence, Owner and Comment of the requirement based on the input
Range("Evidence32") = TextBox1.Value
Range("Owner32") = TextBox2.Value
Range("Comments32") = TextBox3.Value

'Decides wich requirement is next
Range("Aimed_TRL").Select
Selection.End(xlDown).Select
If Sheet1.Cells(33, 4) = "" Then
    MsgBox ("Please select one option")
Else
    If ActiveCell.Value >= 6 Then
        Unload Me
        If Sheet1.Range("Manufacturing") = "NO" Then
            UserForm_34.Show
        Else:
            UserForm_33.Show
        End If
    Else:
        Unload Me
        UserForm_60.Show
    End If
End If
End Sub
```

Depending on which button the user selects for the requirement, either the requirement has been done (“yes”), not done (“no”), is in progress (“wip”) or the requirement is not applicable (“na”), the requirements status cell in the “Back Office” sheet is filled

Fills the cells in the Report sheet of the requirement Document of Evidence, Owner and Comment of the requirement based on the input

Error message if any of the above requirements status has been selected

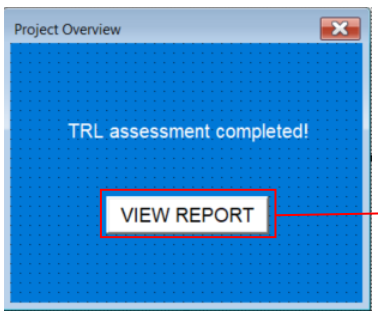
For the requirements that are the last TRL requirements (like in this case, last require for TRL 5) it checks whether the Aimed TRL is to choose whether to show the next requirement or finish the assessment (UserForm_60)

For the requirements that precedes Manufacturing requirements, it cheeks if the Manufacturing Readiness was considered or not, to know which UserForm showing next

4.2.2.4 UserForm_60

This User Form indicates that the TRL Assessment is completed. When clicking in the button, the report will appear, and some backend calculations and display features will take place.

Object Window:



CommandButton1

Code Window:

```
Private Sub CommandButton1_Click()
'TRL < Starting TRL assumed completed
Dim LastRequirRows As Variant
LastRequirRows = Array(0, 5, 10, 17, 25, 33, 39, 44, 51)
Range("Starting_TRL").Select
Selection.End(xlDown).Select
If ActiveCell.Value > 1 Then
    Dim r As Integer
    r = 2
    While r <= LastRequirRows(ActiveCell.Value - 1)
        Sheet1.Cells(r, 4) = "yes"
        r = r + 1
    Wend
End If
'Calculate and display the percentage of each TRL
Range("Aimed_TRL").Select
Selection.End(xlDown).Select
Dim AimedTRL As Integer
AimedTRL = ActiveCell.Value
Dim m As Integer
m = 1
While m <= 9
    ActiveCell.Offset(0, m).Value = "-"
    m = m + 1
Wend

m = 1
While m <= AimedTRL
    ActiveCell.Offset(0, m).Value = Range("ValueTRL" + CStr(m)).Value
    m = m + 1
Wend
'Hide Rows TRL not desired
Dim TRLRows As Variant
TRLRows = Array("21:24", "26:30", "32:38", "40:47", "49:56", "58:63", "65:69", "71:77", "79:87")
Range("Starting_TRL").Select
Selection.End(xlDown).Select
If ActiveCell.Value > 1 Then
    Dim i As Integer
    i = 0
    While i < (ActiveCell.Value - 1)
        Rows(TRLRows(i)).Hidden = True
        i = i + 1
    Wend
End If
Range("Aimed_TRL").Select
Selection.End(xlDown).Select
If ActiveCell.Value < 9 Then
    Dim j As Integer
    j = 8
    While j >= ActiveCell.Value
        Rows(TRLRows(j)).Hidden = True
        j = j - 1
    Wend
End If
Unload Me
End Sub
```

When the starting TRL is different from 1, the lower TRLs are supposed achieved and all their requirements status are set to “yes”, so the %TRL will be then 100%

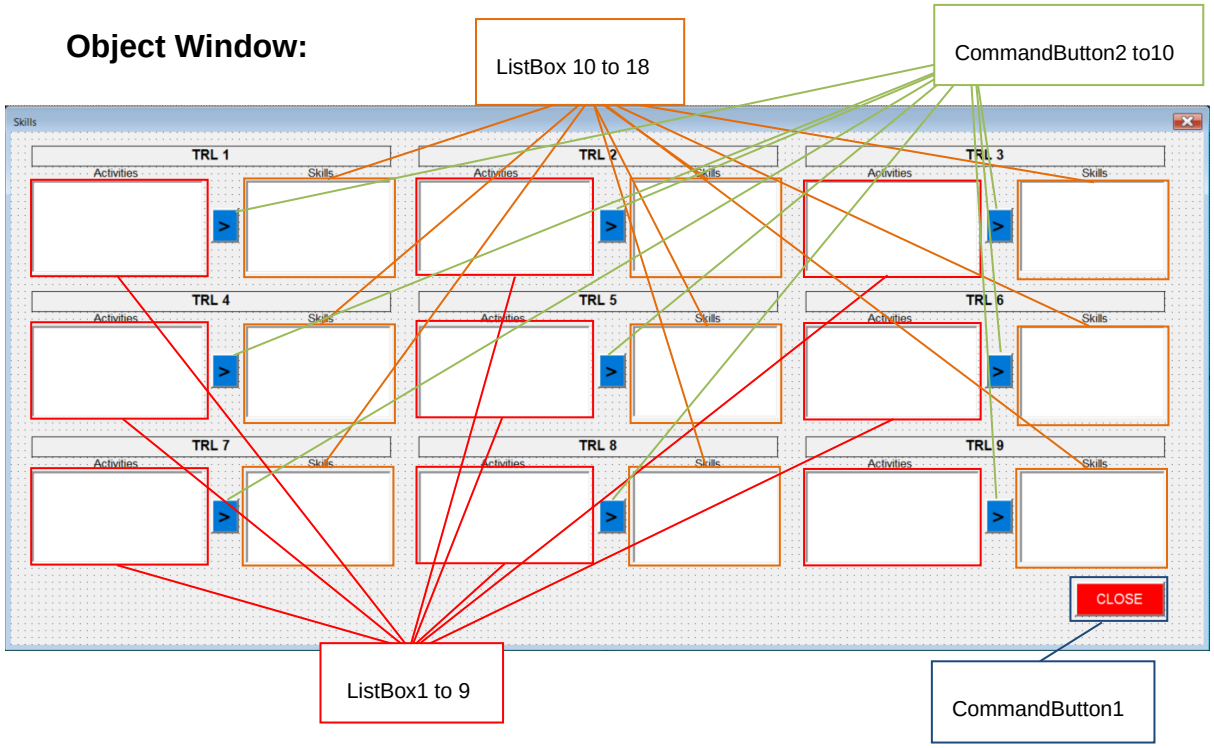
It displays the % of TRL of each level. For those TRL higher that the desired/aimed TRL It will display “-“ and for lower ones, it will display the value that is calculated in the “Back Office” sheet.

The requirements from the TRL that are not assess are hidden. For this purpose, an array defines the rows for each TRL.

4.2.2.5 UserForm_61

This User Form is used to display the skills that correspond to each requirement not fulfilled or in progress.

Object Window:



Code Window:

```
Private Sub UserForm_Initialize()

UserForm_61.Height = 473
UserForm_61.Width = 1046

Dim i As Long
Dim j As Long
Dim k As Long

UserForm_61.ListBox1.Clear
UserForm_61.ListBox2.Clear
UserForm_61.ListBox3.Clear
UserForm_61.ListBox4.Clear
UserForm_61.ListBox5.Clear
UserForm_61.ListBox6.Clear
UserForm_61.ListBox7.Clear
UserForm_61.ListBox8.Clear
UserForm_61.ListBox9.Clear

For i = 2 To 60 'counter for requirements
    k = Sheet1.Cells(i, 1).Value 'k gets the value of the TRL
    If Sheet1.Cells(i, 4) = "no" Or Sheet1.Cells(i, 4) = "wip" Then
        For j = 2 To 107 'counter for activities
            If Sheet1.Cells(i, 6).Value = Sheet1.Cells(j, 10).Value Then
                If k = 1 Then
                    UserForm_61.ListBox1.AddItem Sheet1.Cells(j, 8).Value
                ElseIf k = 2 Then
                    UserForm_61.ListBox2.AddItem Sheet1.Cells(j, 8).Value
                ElseIf k = 3 Then
                    UserForm_61.ListBox3.AddItem Sheet1.Cells(j, 8).Value
                ElseIf k = 4 Then
                    UserForm_61.ListBox4.AddItem Sheet1.Cells(j, 8).Value
                ElseIf k = 5 Then
                    UserForm_61.ListBox5.AddItem Sheet1.Cells(j, 8).Value
                ElseIf k = 6 Then
                    UserForm_61.ListBox6.AddItem Sheet1.Cells(j, 8).Value
                ElseIf k = 7 Then
                    UserForm_61.ListBox7.AddItem Sheet1.Cells(j, 8).Value
                ElseIf k = 8 Then
                    UserForm_61.ListBox8.AddItem Sheet1.Cells(j, 8).Value
                ElseIf k = 9 Then
                    UserForm_61.ListBox9.AddItem Sheet1.Cells(j, 8).Value
                End If
            End If
        Next j
  End If
Next i


End Sub
```

Clear the ListBoxes from the previous analysis

Fill the 9 Activities ListBoxes with the requirements with “no” or “wip” status

9 different routines CommandButton#_Click() (#: 2 to 10) with the same code structure. Just CommandButton2_Click() is explained

```
Private Sub CommandButton2_Click()
UserForm_61.ListBox10.Clear
If UserForm_61.ListBox1.ListIndex = -1 Then
    MsgBox ("Please select one TRL 1 Activity")
Else
    Sheet1.Range("N2").Value = UserForm_61.ListBox1.Value
    Dim i As Long
    For i = 2 To ([TableSkill].Rows.Count + 1)
        If Sheet1.Cells(i, 18).Value = Sheet1.Cells(2, 13).Value Then
            UserForm_61.ListBox10.AddItem Sheet1.Cells(i, 19).Value
        End If
    Next i
End If

End Sub
```

Clear the Skills ListBox from the previous analysis

MessageBox in case any Activity is selected, to avoid error message

Set the Activity name in a specific cell to then get the Activity ID

Based on the Activity ID, fill the Skill ListBox with the related skills

```
Private Sub CommandButton1_Click()

Unload Me

End Sub
```

Close the Form whenever the “CLOSE” button is pressed