Deliverable D 5.1

Report on the technical specification for 3D printed physical visualisation tools for crossings

Project acronym:	XCROSS
Starting date:	01/10/2024
Duration (in months):	30
Call (part) identifier:	HORIZON-ER-JU-2023-EXPLR-04
Grant agreement no:	101178744
Due date of deliverable:	28-02-2025
Actual submission date:	19-03-2025
Responsible/Author:	Xabier Pérez Ferrero
Dissemination level:	PU
Status:	Version 1

Reviewed: yes

This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No101178744.

Document history		
Revision	*Date*	*Description*
1	21-02-2025	Draft issue
2	19-03-2025	Revised Version
3	28-03-2025	Final Version

Report contributors		
Name	*Beneficiary Short Name*	*Details of contribution*
Xabier Pérez Ferrero	AIMEN	Main author
Angie Lamprea	University of Leeds	Reviewer
Chonlatis Charoenwong	University of Leeds	Reviewer
Ivan Shevtsov	ProRail	Reviewer
Ali Aksu	RET	Reviewer
Valeri Markine	University of Delft	Reviewer

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Executive Summary

This deliverable summarises a technical specification that will serve as a start point for the development of a 3D printed physical visualisation tool that aims to improve railway crossings maintenance operations, allowing a more precise and faster way to evaluate crossing's profiles wear level and quality of onsite repair works executed by the railway maintenance team.

First, an overview of the current methodology for railway crossings physical assessment of wear and repair quality along the used tooling is presented, including the requirements that the tooling must fulfil to cope with the operational constraints of the repair process. This is of special relevance to define the conditions that the 3D printed tooling must undergo, and to stablish a set of requirements needed to select the appropriate additive manufacturing technology and material to be employed in the manufacturing process.

Secondly, a section presenting the different existing additive manufacturing technologies suitable for the manufacturing of 3D printed physical visualisation tools is explained, assessing their pros and cons to select the most adequate AM technique to produce WP5 demonstrator. The design of such demonstrator is then introduced, proposing two different approaches to determine the one that better satisfies the target functionality for railway crossing wear and quality repair assessment by the repair team operators, along with a product viability study that analyses the necessary key points that must be addressed to ensure a successful product adoption by the railway sector.

A third section focused on determining the most suitable thermoplastic 3D printing polymer is then presented. The operational requirements that must be satisfied by the 3D printing material are listed, as well as the technical requirements that a 3D printer must gather to successfully produce the proposed component.

Finally, a set of use conditions and guidelines is defined for the visualisation tooling that intends to be manufactured as to ensure correct and successful crossings wear and quality of repair assessment.

A complete roadmap to secure WP5 successful outcome has been defined, covering all the stages from the problem understanding and use case definition, covering the product development and technical specification including its production strategy as well as a study of product viability to guarantee successful adoption after project activities are over, together with a set of operation instructions for the newly proposed 3D printed physical visualisation tools.

Abbreviations and Acronyms

Abbreviation / Acronym	Description
WP	Work Package
S&C	Switches and crossings
LCC	Life Cycle Cost
AR	Augmented reality
AM	Additive Manufacturing
LFAM	Large Format Additive Manufacturing
FGF	Fused Granulate Fabrication
IR	Infrared
FFF	Fused Filament Fabrication
CF	Carbon fibre
GF	Glass fibre
TDS	Technical Data Sheet
DEM	Demonstrator
PEI	Polyetherimide
PA	Polyamide
PC	Polycarbonate
SLS	Selective laser sintering
SLA	Stereolithography
DLP	Digital light processing
MJF	Multi Jet Fusion
PPS	Polyphenylene sulfide
PEKK	Polyetherketoneketone
LM-PAEK	Low melt polyaryletherketone
PEEK	Polyether ether ketone
TPI	Thermoplastic Polyimide
HTN	High temperature nylon
Tg	Glass transition temperature
CTE	Coefficient of thermal expansion

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1 Background

XCROSS aims to develop a radical, technology-driven asset management methodology for railway crossings. The main objectives of the project are:

- Significantly reduce lifecycle costs by minimizing the number and scope of maintenance interventions performed on crossings.
- Significantly reduce in-service disruptions (e.g. delay minutes) due to fewer actionable track crossing surface defects and associated failures.
- Improve the usable lifespan of crossings by providing crossing maintainers with data-driven tools to guide them regarding where and how to maintain crossings.
- Provide infrastructure managers for the first time with a data-driven, low-cost path to the implementation of preventative maintenance at crossings.
- Significantly reducing crossing asset inspection time compared to traditional visual methods.

The present document constitutes the Deliverable D5.1 "Report on the technical specification for 3D printed physical visualisation tools for crossings" in the framework of the XCROSS project (HORIZON-ER-JU-2023-EXPLR-04), task 5.1 of Work Package 5. This deliverable presents the current manual crossings repair scenario, repair intervention assessment and the steps required to bring the crossings back to its original status according to the specific standards. Rail wear and deformation assessment by manual tooling is studied to propose a new tooling manufactured by 3D printing and to introduce a novel profile verification methodology. The tools that XCROSS WP5 activities aim to improve will be applied in both preventive and corrective maintenance by revamping the current way of quantifying crossing deviations and help repair teams to bring the crossings back to their optimum status, reducing current deviations after repair. An overview of suitable Additive Manufacturing technologies and 3D printing materials is presented, together with several design approaches for the 3D printed physical visualisation tools, that account for the technical and operational requirements of current crossings repair protocols with the intent of establishing a technical specification for the manufacture and operation of the newly proposed 3D printed profile verification tooling.

2 Objective/Aim

This document has been prepared to address the objectives of task 5.1 from Work Package 5 (WP5). This document is the first one of two report deliverables from WP5 (Deliverable D 5.1).

Task 5.1 aims to define a technical specification to develop a 3D printed physical visualisation tooling for crossings. To meet the objectives of Task 5.1, this document is organised in 4 main sections:

- Section 3: Presents the target Use Case and current issues that WP5 development aims to address. Working conditions and operational constraints are summarised. D2.1 has served as a input source for the development of this section.
- Section 4: Defines the proposed approach based in additive manufacturing, by resuming the available AM technologies, setting the approach to design the tooling, how it will be manufactured and stablishes guidelines to ensure its viability and implementation in railway repair activities.
- Section 5: Introduces the additive manufacturing material, proposing several candidates to manufacture the demonstrator and the rationale behind.
- Section 6: Sets the guidelines that must be followed to ensure successful use of the tooling to be developed.

The technical specification defined in D5.1 will pave the way for the following project activities:

- **WP5, Task 5.2**: Design and manufacturing of a mounting frame and integration with the digital twin (M4-M22).
- **WP5, Task 5.3:** Development and optimisation of the manufacturing strategy for the slice component of the visualisation tool for guiding crossing interventions (M4-M22).
- **WP5, Task 5.4:** 3D printing process development for the manufacturing of preliminary representative coupons (M5-M18).
- **WP5, Task 5.5:** Production of the slice prototypes for the visualisation tool (M18-M27).
    - Deliverable 5.3: Report on the 3D printed slices prototypes as one of the major components of the physical visualisation tool.
    - Deliverable 5.3 (DEM): Physical prototypes of the 3D printed slices as one of the major components of the visualisation tool.
- **WP8, Task 8.2:** Laboratory testing of field demonstrators (M18-M20)
- **WP8, Task 8.3**: Field demonstrators (M21-M29).
- **WP 8, Task 8.4:** Analysis of demonstrator data and validation (M18-30).
    - Deliverable 8.1: Report on the requirements for physical crossing inspection demonstrators.
    - Deliverable 8.2 (DEM): Report on the analysis of crossing demonstrator test results.

The conclusions of this deliverable should not be assumed as fixed, understanding this report as an initial approach to the scope of WP5 whose contents can evolve and be enriched in subsequent reports as the project progresses.

3 Use case definition

Railway crossings degrade significantly faster than plain tracks, which results in highly expensive corrective actions and maintenance that also affect daily operation of rail-based transport. XCROSS project will develop a series of techniques to minimise the consequences of wear and deformation inflicted on rail crossings by the constant transit of railway carriages. An example of such rail crossings is depicted on Figure 1.

Figure 1. Rail crossing example where maintenance work will be performed. Image courtesy of RET.

Among the several technologies developed in XCROSS to overcome such concern, WP5 refers to the improvement of corrective maintenance actions that intend to bring back to operational condition the worn crossings. Currently, the reconditioning procedure followed implies grinding degraded locations to later add material by welding. The operator achieves the near-original shape of the repaired rail by smoothing out the surface with subsequent grinding operations with the help of manual gauges and rulers. Such manual procedure is very costly due to its complexity and time required, which mostly relies on operator experience, and the end-shape of the rail is not always as intended, resulting in deviations from 2-3mm, being the target of maximum 1mm deviation. To achieve this target, the current standard for measuring and verification of the manual repair works include gauges and templates as shown in Figure 2. When placed on top of the rail, the gaps between the gauges and the rail profile indicate the areas where material needs to be added by welding. A detailed description of this procedure is explained in D2.1 under section 5.3.1 (Rolling surface geometry inspection).

Figure 2. Current manual gauges and templates used for manual verification of manual repair works. Image courtesy of ProRail and RET.

Tasks from WP5 focus on creating a physical visualisation tool to aid maintenance teams working on crossings, which aims to improve the currently used gauges or templates when used as a complement to the augmented reality app that is going to be developed under WP6 and also to help to the current repair procedures where significant grinding and welding is applied. The new visualisation tool that is going to be developed under this work package will be a modular tool manufactured by 3D printing, which will allow to gauge several locations at the same time, providing a more accurate and quick interpretation of the wear and deformation level from the rail profiles by letting the operator asses several types of defect along the crossing at the same time and with a common reference frame.

The new maintenance approach and tooling aims to reduce the deviation from rail optimum shape target and the time required for the repair interventions by reducing the complexity of the whole process, thanks to a more robust methodology for wear and deformation assessment of rails. The developed physical visualisation tooling will serve both preventive maintenance (evaluation of wear) and corrective maintenance (verification of repair quality) operations.

3.1 Description of use case

XCROSS project activities focus on railways intersection switches. Figure 3 shows a scheme of a railway intersection, where the crossing is circled in red. The central area of the crossing where rails converge at a thin section called “frog” or “nose” and its adjacent profiles is the part of the crossing which is subjected to the largest amount of wear inflicted by the train wheels.

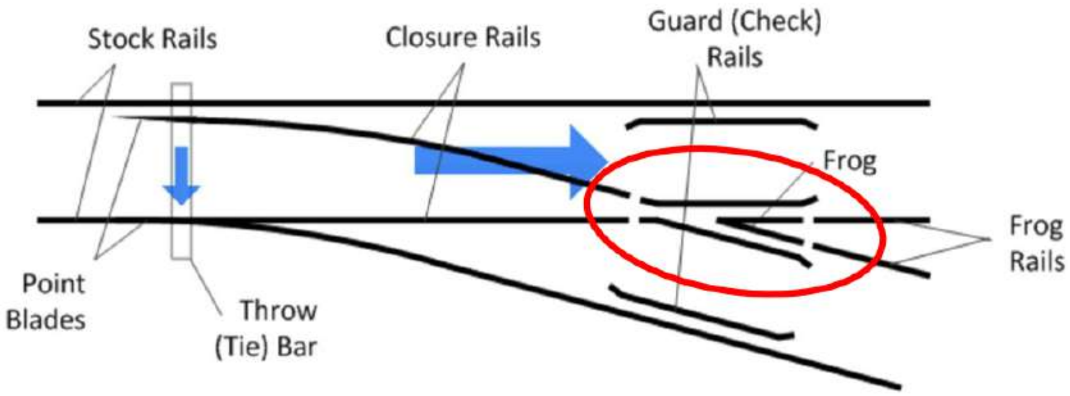

Figure 3. Railway intersection diagram. Crossing area is circled in red. Image courtesy of RET.

Figure 4 illustrates the central area of the crossing that tend to suffer the largest degradation and where repair efforts are maximum.

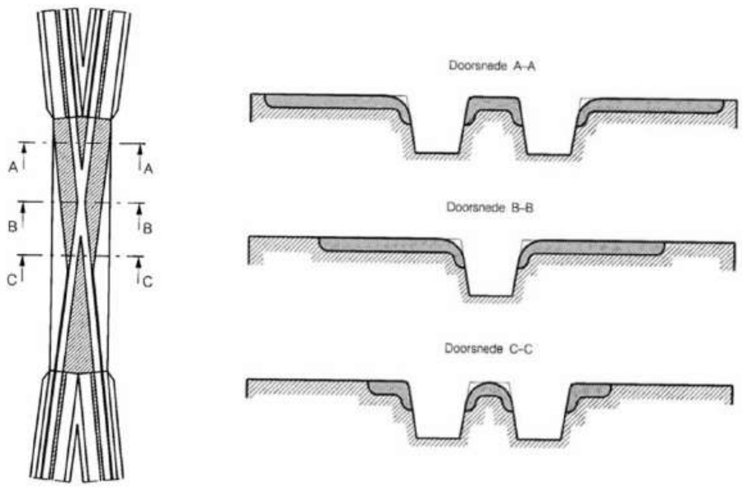

Figure 4. Crossing sections of special relevance which are more subject to wear. Image courtesy of RET.

Due to the large level of wear that crossings experience, manual repair work is required to bring back them to a functional status. A team of two persons is required to perform the repair operations, which involve manual assessment of wear, grinding, welding and verification of profile surface after repair. This process is complex and delicate since it requires a lot of manual work and experienced welders. Full depiction of the repair process is illustrated on Figure 5.

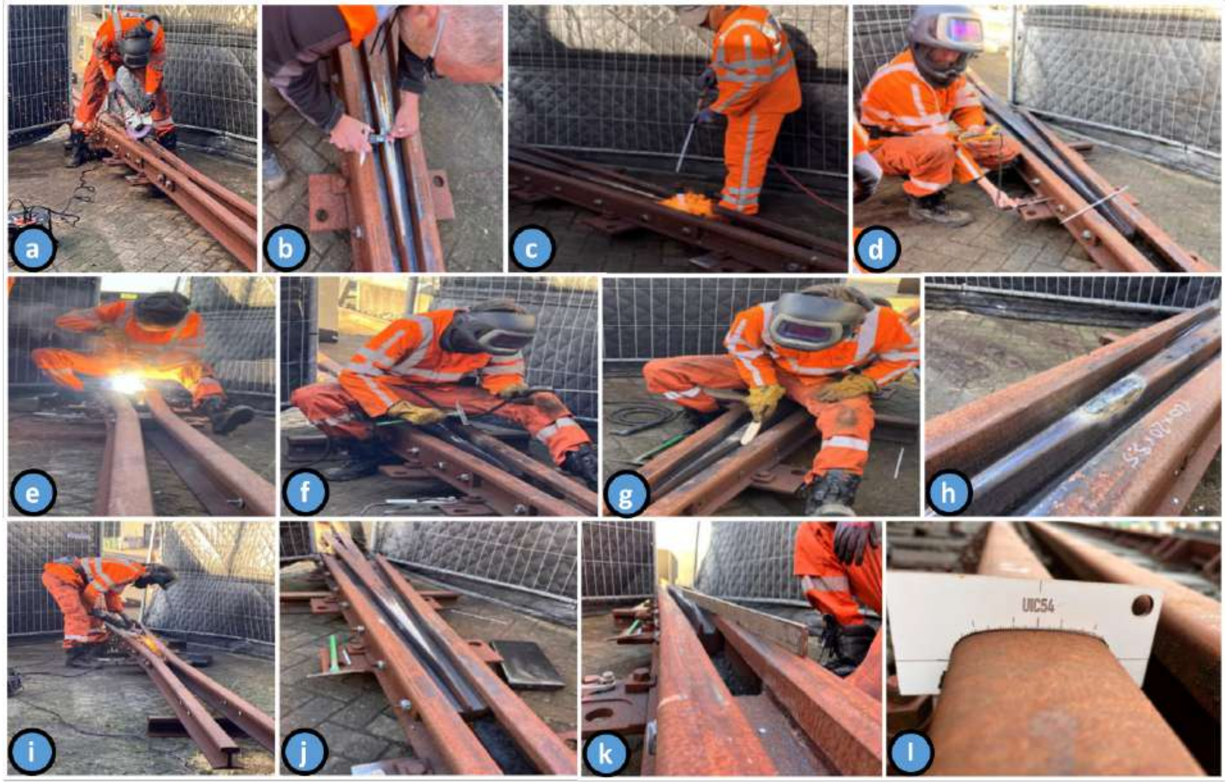

Figure 5. Manual repair process of crossing during repair technical workshop held at RET training centre. Image courtesy of RET.

Currently assessment of crossing wear is performed using MiniProf [1] wear evaluation device (Figure 6). This system is used before the repair team is deployed to carry out the repair works. MiniProf [1] assesess the wear level at intervals of 50mm along the rail profile, as can be seen on the 3D scan of railway crossing on Figure 7, further information about this inspection system is found in D2.1 under section 5.3.1.2. Once the repair team performs the repair, rail surface status is inspected prior and after the repair process by means of manual gauges and rulers.

Profile template gauges are used to assess profile contour. These are placed over the rail (step l from Figure 5) and moved forward and backward to spot contour deviations due to lack or excess material. Straight edge of profile is measured using 1m ruler (step k from Figure 5) and deviation must be contained within <1mm over 1m length. Operations of adding material by welding and removing excess by grinding take place iteratively until profile deviation is contained within 1mm. Manual repairing procedure is fully detailed in D2.1 under section 5.4.1.

Figure 6. MiniProf [1]profile wear assessment device inspecting wear at nose section.

XCROSS activities in WP5 intend to develop a new physical visualisation tool that improve the current methodology of repair teams which rely on individual gauges like the ones shown in Figure 2 by creating a modular tool that will be capable of assessing both profile contour and straightness of crossing surfaces simultaneously at different locations taking as a reference the sections at which MiniProf [1] system surveys the wear level as shown in Figure 7. The new methodology intends to reduce the time required and the complexity of the repair process and also aims to reduce the profile deviation after repair in at least 0,5mm from the intended shape with respect to current procedure.

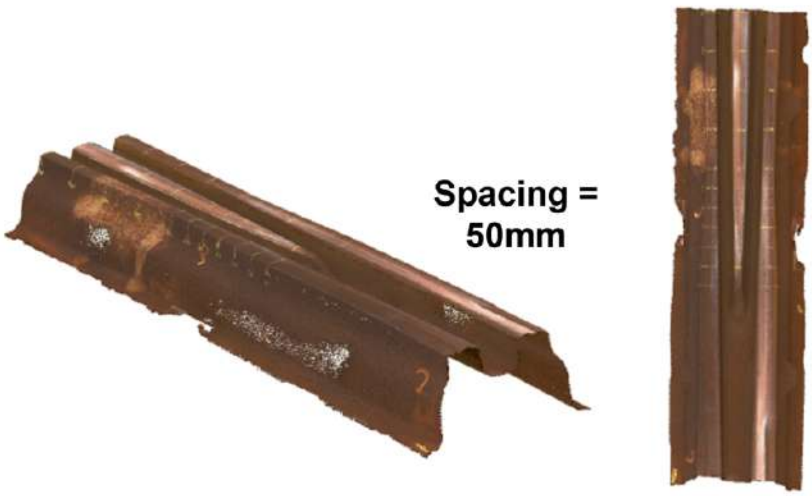

Figure 7. Spacing between measurements with MiniProf [1] at crossing 3D scanning. 3D scanning image obtained during repair technical workshop held at RET training centre. Image courtesy of University of Leeds (UoL).

3.2 Operational requirements

The operational requirements that the 3D printed tooling must comply with in a standard measuring and verification operation of railway crossing reconditioning process have been gathered by means of a technical workshop carried out at RET facilities in the Netherlands, where railway operators explained the repair process step by step. Such requirements are summarised below:

- **Maximum allowable wear for railway operation:** 3-5mm vertical deviation and straight edge measurement tolerance: ≤ 1 mm over 1 metre.
- **Measurement accuracy:** Current methodology allows to measure up to 0.2mm deviations.
- **Maximum profile deviation after repair target:** 1mm (currently achieved by welders), aiming to reduce to 0.5mm.
- **Spacing between measurements:** Measuring templates must be spaced at least 50mm in the nose area, considering up to 25mm if possible on the most critical section. Behind the nose (300mm from the nose end) verification points can be spaced up to 100mm.
- **Visibility of defects:** Deviations from rail with respect to 3D printed gauge must be easily spotted. If the developed tooling makes harder to visualise the worn sections that need to be repaired, adoption of the proposed approach and tooling will not be successful.
- **Simplicity and repeatability:** Tooling operation must be simple and repeatable. Any new tooling that requires extra complexity at the time of placing the tooling over the rails and introduces the possibility of obtaining non repeatable measurements if the tooling allow variabilities at the time of positioning will induce the risk of sub-optimal repairs.
- **Lightweight:** tooling must be easily carried by a single person. Weight of developed measuring tool must not suppose an impediment for verification operations. Weight target to be contained under 10kg.
- **Robustness and durability:** Tooling must endure standard operations that current tooling is subjected to. If developed tooling fails to do so, adoption of it will not be successful.
- **Modularity:** Switches can vary from older to newer versions and between rail manufacturers. Developed tooling must allow easily swap of measuring templates in order to adapt the handheld structure to the switch to be repaired. Operators must have different templates that can be mounted at the required position of the handheld structure depending on the situation.
- **Methodology:** Current method for profile checking is done by moving templates back and forth over the profile. New tool should aim to not only maintain current methodology that welders know but to improve it. Handheld structure must allow easy displacement of templates, which will enable verification of intermediate areas between the defined template spacing along the structure. Additionally, vertical displacement or damping of templates must also be considered to account for positive deviations on the profile surface (e.g. excess material after repair).

3.3 Operational constraints

During the technical workshop held at RET Netherlands, railway welders have contributed stating the operational constraints present in the current repair process:

- **Low light conditions**: Crossing repairs are usually carried out at night. The 3D printed measuring templates must allow easy visualisation. Bright color or fluorescent paint and/or reflective agent coatings will be tested to coat the 3D printed prototype templates to improve visualisation at night when used artificial lighting.
- **Weather agents:** Crossings are repaired in situ, this means that repairs can take place in cold, humid, sunny or rainy conditions if required. Because of this, the developed tooling must be designed using materials that can endure harsh climate conditions.
- **Temperature:** Welding and grinding processes rise rail surface temperature. Protocol stablishes that verifications of geometry can only be performed with rail surface temperature at 50ºC, however due to time constraints this temperature can be significantly higher. 3D printed measuring templates must be manufactured in temperature resistant material. Important to define highest temperature window as it will affect 3D printing material selection.
- **Time constrains:** Total current repair time is around 2h to 2h 30min, from which time required for manual measurement and marking is around 30min. Proposed tooling must not increase this time.
- **Personnel available**: Railway repair team is composed of two persons. The repair tool must be carried and operated by only one person, hence the tool to be developed must be light and manoeuvrable enough.

4 Additive manufacturing technologies and product development

Nowadays there are many additive manufacturing technologies, each of them aimed to different material, resolution needed, production process characteristics etc. Such variety of technologies allows to select the most suitable one to produce components 100% tailored to their use case.

Among the several AM technologies capable of processing polymer composites below are presented some of the most well-stablished nowadays:

- **Fused Filament Fabrication (FFF):** The most popular 3D printing technique. A thermoplastic filament is extruded through a heated nozzle and deposited on a build platform, optionally heated to improve adhesion to build surface. The molten filament is deposited layer by layer following a CAM program. Deposited layers fuse together as the melted plastic quickly solidifies, creating thus a 3D object. Presented in small to large format and different motion platforms like cartesian or robotic systems. Manufactured parts are of anisotropic nature, presenting higher mechanical properties along the deposited layer than across the stacked layers.
- **Fused Granulate Fabrication (FGF):** Same methodology than FFF technology but the material comes in granulated or pelletised format instead of filament and the printhead is based on a

extrusion screw system. Used on larger format or when resolution is not relevant and faster manufacturing times are required. Same anisotropic process nature as FFF.

- **Resin (SLA and DLP)**: Resin 3D printers using the SLA (Stereolithography) or DLP (Digital light processing) technologies are based on the photopolymerization process: thermosetting resin contained in the 3D printer tank is cured (hardened) by a light source (laser or projector) to form the object, layer by layer. Resin 3D printers use liquid resin as the 3D printing material, versus plastic filament for extrusion 3D printers. Resin based materials allow the manufacturing of extremely detailed parts, usually of small format, and the mechanical properties are generally limited when compared to thermoplastic materials, nonetheless mechanical properties are considered isotropic.
- **Powder (SLS and MJF)**: The main types of polymeric powder bed fusion printers are SLS (Selective Laser Sintering) and MJF (MultiJet Fusion). In both processes, parts are built by thermally fusing (or sintering) polymer powder particles layer-by-layer. The materials used in both MJF and SLS are thermoplastic polymers (usually limited to Nylon) that come in a granular form. Parts produced by both processes can achieve high level of detail and are more isotropic than parts produced by FFF or FGF.

Given the use case defined in section 3 and its requirements, the most interesting AM technologies for the manufacturing of the 3D printed visualisation tools are FFF and FGF technologies, which can process a wider range of thermoplastic composites due to their process versatility, present the largest range of materials available when compared to other AM technologies and their popularity and wide adoption across different countries makes them accessible and affordable technologies. A broader discussion between FFF and FGF technology selection taking into account additional aspects such as tool design, life cycle cost, and product viability aspects is presented in the following points under section 4.

4.1 Additive manufacturing techniques

AIMEN counts with several AM based thermoplastic composites processing platforms, primarily depending on the scale of the parts intended to be manufactured. On this section the thermoplastic composite AM platforms available at AIMEN are presented.

<u>**FFF Desktop based additive manufacturing**</u>

AIMEN counts with a 3NTR A2V4 (Figure 8) high temperature desktop 3D printer for processing of high-performance filaments which is capable of printing large parts in polymers such as PC, PPS, PEI, PEKK, LM-PAEK etc.

This machine features a triple extruder printing head, which allows multi-material printing and fabrication of complex geometries using support structures made of water-soluble materials. An example of manufactured components can be seen on Figure 9.

A heated platform and heated chamber allow the control of ambient temperature, which is a compulsory requirement when using high temperature materials that usually need to be kept at glass transition temperature (Tg) during the 3D printing process to ensure adequate layer bonding strength and prevent thermal gradients that otherwise would suppose non-uniform cooling and lead to contraction of layers, originating thermally induced stresses that accumulate along the layer stacking process leading to part deformation defect known as "warping" in the 3D printing technology, which can suppose failure of the process.

Printing Specifications	A2
Printer Technology	FFF
Number of Extruders	2 or 3
Maximum X-Y Axis Speed	300mm/sec — 11.8"/sec
Maximum Z Axis Speed	2mm/sec — .08"/sec
Maximum Extruders Speed	43mm/sec — 1.7"/sec
Build Envelope - W x D x H[1]	600 x 325 x 500mm 23.6 x 12.7 x 19.6"
Positioning Precision - X-Y	11 Microns — .000433"
Positioning Precision - Z	5 Microns — .0002"
Positioning Precision - Extruders	9 Microns
Filament Diameter	2.85mm +/- .1mm
Standard Nozzle Diameter[2]	.4mm — .01575"
Max Extruder Temperature[3]	430°C — 806°F
Maximum Heated Bed Temp[4]	160°C — 320°F
Max Heated Chamber Temp[1]	90°C — 194°F
Minimum Layer Thickness	50 Microns — .00197"

Figure 8. 3NTR A2V4 desktop FFF 3D printer. [2]

Desktop FFF 3D printing is used when small to medium size neat-shape parts with high level of detail or tolerance are required. Desktop 3D printing process can take longer manufacturing time but the achieved level of detail ensures no required postprocessing. Desktop 3D printers can also work autonomously and unsupervised as production machines, with low level of human interaction.

Figure 9. Example of precision components manufactured at AIMEN using PC-CF composite filament from 3DXTECH® [3].

Material availability on FFF desktop 3D printers is the largest. There is a huge variety of thermoplastic filaments, each of them tailored for a specific application.

Robot based FFF and FGF additive manufacturing

AIMEN features a Large Format Additive Manufacturing (LFAM) cell (Figure 10), which is a thermoplastic extrusion AM facility composed of a FANUC [4] robotic platform with 9 total motion axes and high-end 3D printing equipment. This AM robot platform can be equipped both with FFF (Fused Filament Fabrication) or FGF (Fused Granulate Fabrication) printheads depending on the use case.

The available FGF extrusion AM equipment is composed of a CEAD's 3D printing ecosystem, featuring an E25 printhead [5] capable of depositing up to 10Kg/h of thermoplastic material at a maximum temperature of 400ºC to 3D print high performance polymers. This printhead can produce layers from 0.5mm up to 9mm height and from 3mm to 30mm bead width. The manufacturing printbed is a tailored 3x1.2m static buildplate which can be heated up to 140ºC. Additionally, there is a second dynamic circular printbed of 1.2m diameter, also heated up to 140ºC which is fitted to the 2-axis FANUC positioner.

Figure 10. LFAM robot cell with FGF equipment from CEAD B.V [5].

FANUC's R-2000iC / 125L [4] robot allows manufacturing parts up to 1.8 metres in height. This large format setup is generally used to manufacture extra-large parts at high deposition rates with low level of detail. Manufacturing process is monitored by means of thermal cameras as can be observed in the manufacturing process observed in Figure 11. Manufacturable geometries are constrained by the pellet-based extrusion system and when high level of detail and tolerances are required, a second post processing operation is needed, as depicted on Figure 12.

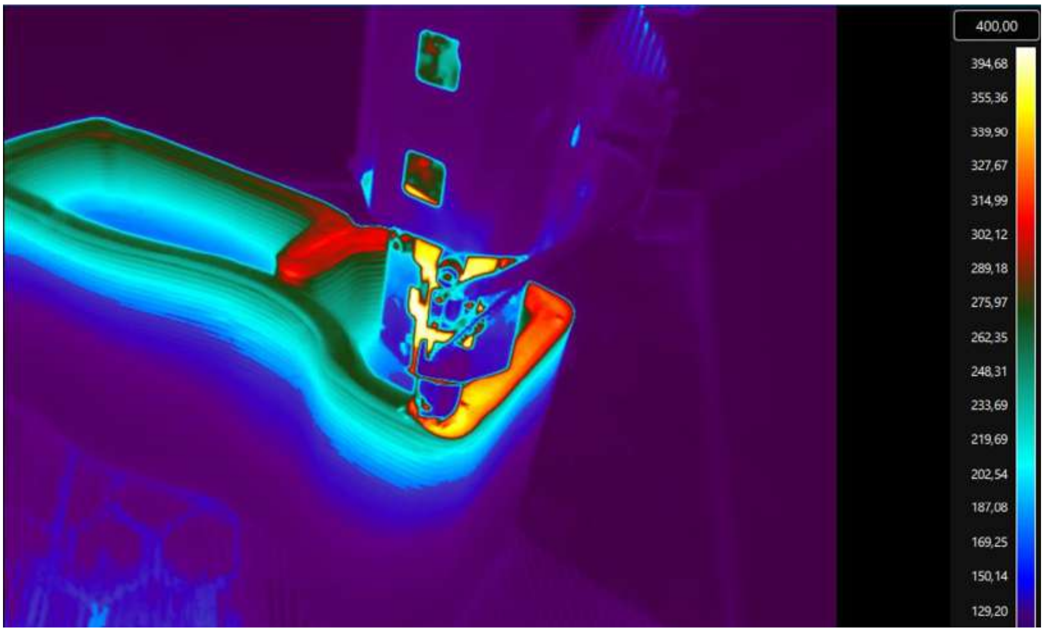

Figure 11. FGF process monitorisation with thermal camera.

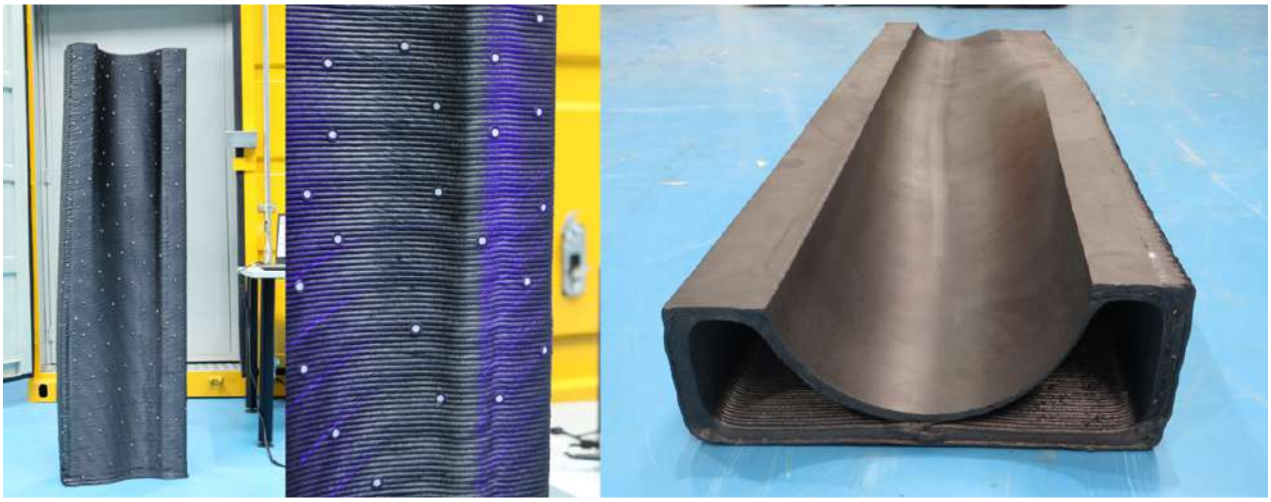

Figure 12. Example of large format FGF mould manufactured at AIMEN with FGF CEAD equipment using PEI-CF material. Left images display "as printed" condition and right image shows part after precision machining to achieve final part geometry.

LFAM FGF additive manufacturing materials are specially formulated thermoplastic composites, generally tailored with very low CTEs and high fibre load to prevent part deformation due to the impossibility of high ambient temperature control like on enclosed desktop 3D printers. This turns into a lower range of specific compounds.

The FFF extrusion AM equipment is composed of a DYZE DESIGN Typhoon extruder [6] printhead (Figure 13) capable of depositing up to 1Kg/h of thermoplastic material at a maximum temperature of 450ºC to 3D print high performance polymers. This printhead can produce layers from 0.5mm up to 2mm height and bead width from 0.6mm to 5mm using 2.85mm filament, an example of the manufacturing process is shown on Figure 14. The Typhoon printhead at AIMEN is equipped with an IR heater to increase substrate layer temperature during material deposition and increase layer-to-layer adhesion when manufacturing large parts.

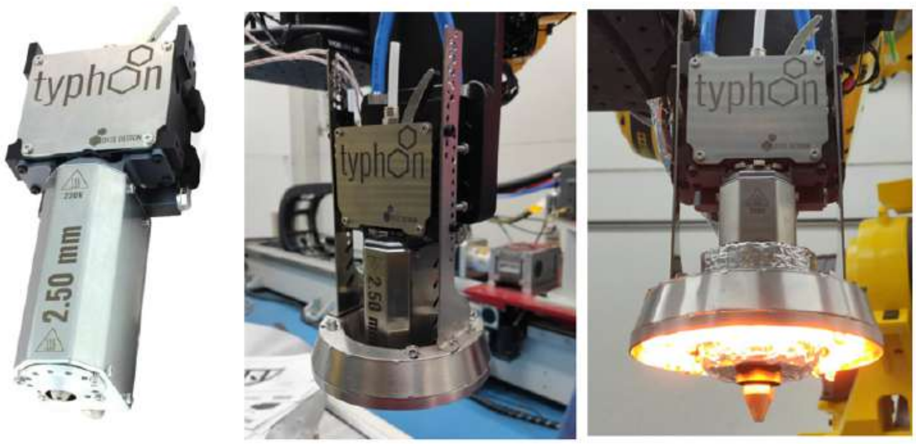

Figure 13. Typhoon [6] FFF printhead and IR heater retrofit at AIMEN.

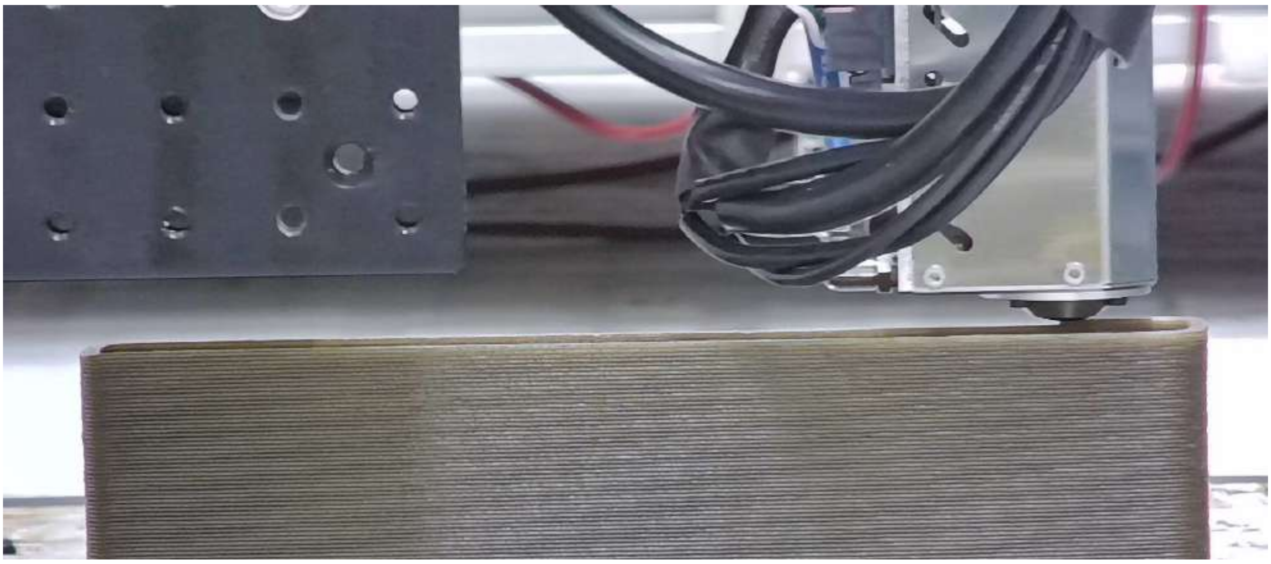

Figure 14. Manufacturing process using Typhoon [6] FFF printhead.

Typhoon printhead is generally used to manufacture medium size components at intermediate and high level of detail and faster deposition ratios than conventional desktop 3D printers like the examples presented on Figure 15, and also taking advantage of the alternative deposition strategies that a robot platform allows such as non-planar deposition. Machining can be requested if higher level of detail or tolerance is required at localised areas, e.g. surfaces interfacing with other components.

Figure 15. Example of medium format parts manufactured with FFF Typhoon printhead at AIMEN using PA composite material. Central image displays cross section to appreciate resolution of printed layers of 1mm height.

Typhoon printhead works with the same type of filament than desktop 3D printers use, however it is important to highlight that due to the open atmosphere nature of the robot-based process, some of the high-end polymers that require stable high ambient temperature during the 3D printing process will not be successfully printed. This process is not as constrained as pure pellet based LFAM AM or FGF but it is still more restrictive than desktop filament 3D printing in terms of compatible materials and manufacturable geometries.

4.2 Measuring tool design approach

The 3D printed physical visualisation tool to be developed under WP5 design activities will be composed of the following main elements:

- **Handheld structure:** Carries the measuring templates and allows user to transport and locate over crossing profiles.
- **Measuring templates:** 3D printed components that allow visualisation of profile deformation and wear.

The handheld structure will be made of aluminium profiles and standard fastening components to allow fitting the subcomponents such as handle or connection elements to fix the measuring templates.

For the measuring elements, two different approaches have been considered:

- Single piece: a single element manufactured in one go will be fitted to the handheld structure. This element will be a continuous structure. Cutaways must be machined to let the user view through the continuous element once place over the crossing. Large format AM is the most suitable AM technology for its production, however a subsequent machining operation to achieve required tolerances is required. Since it is a continuous element, there is a lot of material implied and heavy weight is expected. If component is damaged at any location, there won't be repair possibility. An schematic of this approach is shown below on Figure 16.

Figure 16. Continuous 3D scanned surface used as example for single piece measuring element.

- Modular elements: several 3D printed measuring templates are fitted to the handheld structure as per the example shown in Figure 17. It is possible to locate the measuring templates at the desired spacing, for example matching with measurement locations gauged by MiniProf [1] device or at locations prescribed by particular regulations of the railway company. Additionally, quick replacements of the measuring templates would ensure continuous operation if any of them results damaged during operation. Since the measuring templates are individual, the handheld structure design can allow them to slide forward and backwards over the rail surface as the repair staff currently do with the verification 2D gauges. Additionally, vertical displacement can also be considered in the design in such a way that if there is a dip on the profile, or the presence of excess material after the repair, the 3D printed slices will move upwards or downwards to accommodate for the type of defect. If all the slices are perfectly aligned in the vertical axis, it is also possible to validate straight edge of profile verification. Manufacturing method for 3D printed slices can be desktop FFF 3D printer or FFF robot manufacturing. Desktop 3D printers allow to print hollow structures with a defined percentage of infill lattice structure, which produce robust yet lightweight components.

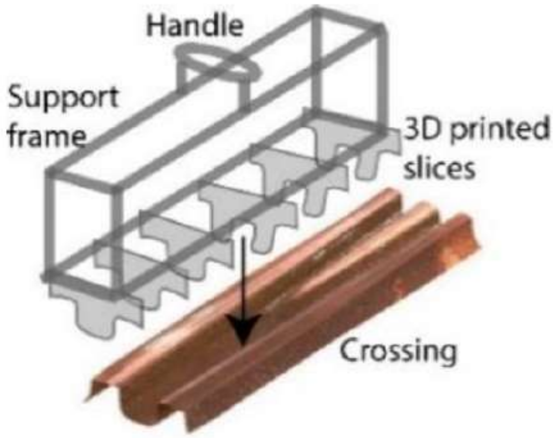

Figure 17. Schematic of modular tooling approach: handheld structure fits several 3D printed measuring templates.

From the two design approaches presented the modular tool approach is considered as the most flexible and viable, since it allows a clearer and faster visualisation of rail defects than the single piece approach, presents a much more reduced weight, and allows assessment of profile contour and straight edge deviation simultaneously. Moreover, quick onsite replacement of damaged measuring templates or reusability of handheld structure that allows onsite tool adaptation to different crossings maintaining the main structure is possible unlike on the single element approach.

4.3 Product viability

XCROSS demonstrator from WP5 aims to develop a new methodology in onsite maintenance profile verifications by means of a new type of modular visualisation tool. The resulting product intent is to be introduced in the rail maintenance operations and for that the most important aspect is that contractors can see an improvement with respect to their current verification procedure in order to willingly adopt it.

However, even if the design and functionality of the product is successful, adoption will not be possible if the production logistics of the visualisation tooling are not optimised and realistically achievable to satisfy the demand of the sector.

There are many different types of rail crossings not only across the different railway-based transports but also across the different railway companies in European countries. To be able to deal with the large quantity of crossings present in the railway sector, a universal approach that can adapt to the different scenarios is proposed.

A list of key points to ensure product viability has been compiled and is presented below:

- **Universal crossings database.** A crossings database with optimised profile geometry must be developed for each railway-based transport. Each crossing should include the set of measuring templates models that are required to mount on the universal handheld structure and allow complete crossing profiles verification.

- **Availability of production technology.** Production technology selected must be available locally to allow fast response when new measuring templates are required.
- **Accessibility of production technology.** Production will not be successful if highly specialised personnel is required to manufacture the 3D printable visualisation tools. Selected additive manufacturing technology must be as much accessible and universal as possible in a way that local 3D printing companies can produce tooling if they're supplied with the dataset of production files, and also maintenance contractors can consider to acquire 3D printers that would allow themselves to produce 3D printed tooling by average level technicians.
- **Production files availability**. European-wide crossings database will store universal manufacturing files, composed of CAD models and general 3D printing process parameters in universal formats.
- **Universality of designs across several manufacturing technologies**. If for any reason the proposed additive manufacturing technology is not available, the tooling design should ideally be compatible with alternative manufacturing technologies with minor tweaking such as metal based additive manufacturing or even conventional metal machining.
- **Simplicity of design**. Both the design of the tooling and the AM based technology proposed for the tooling production must be as simple and minimalist as possible, so non-specialised staff from any company or country will be able to reproduce the tooling without having to contact an expert team.
- **Availability of materials.** Proposed materials for 3D printing of tooling must be common and easily sourced, high performance materials with limited supply chain will not be considered.
- **Processability of materials.** High-end materials that require very specific and complex to operate 3D printers will not favour quick turnarounds, hence only materials which are processable but average professional 3D printers will be considered.
- **Manufacturing in one-go.** To ensure quick supply of measuring templates and keep manufacturing cost as low as possible, the manufacturing process much be simplified as much as possible. This favour technologies capable of producing the final product in one-go without requiring subsequent post processing technologies.
- **Circularity of materials.** Components manufactured in thermoplastic materials can be reprocessed again after their end of life. Worn out, damaged parts or simply components that are not anymore used after the purpose they have been manufactured for is no longer required can be shredded and melted to turn them again into filament in an extrusion machine to 3D print any other component.

4.4 Selection of additive manufacturing technology

This section aims to select one of the additive manufacturing technologies available at AIMEN that were presented on section 4.1.

The design approach presented on section 4.2 that aims to recreate an easily manufacturable 3D printed tooling that ensures good mechanical properties and low impact of inherent 3D printing process anisotropy. The design proposes the manufacturing of individual measuring templates that fit into the suggested modular approach that ensures compatibility across different crossings and follows the currently stablished verification procedure, improving it instead of introducing a new methodology. Individual measuring templates size is suitable for FFF desktop 3D printer and robotic filament 3D printing. However, only desktop 3D printing can achieve the required resolution and tolerances without adding additional post processing operations.

Product viability key points reunited in section 4.3 remark the importance of having accessible technology that is easily operated by technicians with standard level of specialisation. Nowadays more companies across different sectors have incorporated desktop 3D printers to their capabilities not only for production but also for having onsite capabilities of creating on demand components to allow fast inhouse repairs or solutions to their daily challenges. This fact is a proof of how present and accessible desktop 3D printers in modern companies across the world are. Desktop 3D printers can also operate unsupervised once the manufacturing process have been optimised and tested to be reliable, which supposes that the technicians in charge can dedicate their time to work on other matters.

Robotic platforms like the one present at AIMEN are one of its kind, large investment and unique solutions, being the LFAM robot cell at AIMEN the only one of such characteristics in Spain. 3D printing equipment is partly tailored to the robot carrying it and the software solution utilised to create the manufacturing path planning programs is a tailored solution developed for AIMEN's robot cell. A multidisciplinary team of technicians with knowledge of material science and robotics is required to operate the LFAM cell, implying a minimum of two technicians and one full day for robot cell and manufacturing program preparation plus another day for the production process which must be supervised at every moment because of safety regulation about robots. Each robot manufacturer utilises their own robot programming language, which results in tailored software not compatible with robots from different brands or non-robotic platforms. Energy consumption of robotic platforms is several orders of magnitude larger than electrical consumption of desktop 3D printers that can be connected at standard electrical network without requiring high energy triphasic input.

Because of the above points, AIMEN's proposal to select the most suitable additive manufacturing technology is desktop FFF 3D printers, which fulfil best the business case and project requirements. Nonetheless, a high precision robotic platform using Dyze's Typhoon filament extruder will also be investigated in the project activities for comparison of manufacturing process and back-to-back business case assessment.

5 Material selection for demonstrator

The material utilised in combination with the FFF additive manufacturing technology proposed in section 4.4. comes in the form of thermoplastic filament. This is a standardised format in 1.75mm and 2.85mm depending on the machine type.

Not every polymer is suitable for a layer-by-layer deposition process due to the uneven cooling of the layers. 3D printing polymers are tailored to the process having generally low coefficient of thermal expansion to prevent thermal deformations during the manufacturing process. Reinforcement short fibres are also usually found in concentrations ranging generally from 10% to 30%.

FFF 3D printing materials are available in a vast variety of matrix and reinforcement combinations. Thermoplastic composite materials main advantage is the possibility to tailor their formulation to satisfy as much as possible final product's requirements. This section aims to propose a list of materials that ensure both a successful FFF additive manufacturing process compatible with the geometry to be manufactured and are technically compliant with the product use case targeted requirements.

5.1 Material requirements

To define the material requirements, focus will be first on defining the minimum technical requirements that the material must satisfy, for which product operational requirements defined in section 3.2 are considered. Secondly, 3D printer requirements that production machine must reunite to successfully process technical 3D printing filaments are described under manufacturing requirements section.

5.1.1 Technical requirements

The technical requirements that the 3D printing material must satisfy based on operational requirements from section 3.2 are listed below:

- **Temperature resistance**: Verification protocol indicates verification must be done with rail surface temperature at 50ºC, but this can be higher if welders don't follow protocol. At least 100ºC must be withstand by the 3D printing tooling. To ensure no deformations occur, polymer must comply with minimum heat deflection temperature under load (ISO 75) of around 120ºC.
- **Impact resistance:** 3D printed tooling must be robust enough to withstand impact against metal rails or ballast if dropped. Material must be rigid enough but not brittle. Preference for amorphous type polymers reinforced with carbon or glass fibres.
- **Wear resistance:** 3D printed tooling must resist wear caused by sliding of templates over rail surface.
- **Weather and chemical resistance:** Selected polymer must be capable of enduring harsh climate conditions such as humid weather, UV radiation, rainwater, oils and debris from repair process.
- **Format:** 3D printing material must come in filament format of 1.75mm or 2.85mm +- 0.05mm diameter to be compatible with high resolution FFF 3D printers. Spool material must be capable of enduring at least 90ºC to allow compulsory drying process before 3D printing.

5.1.2 Manufacturing requirements

3D printing polymers that satisfy the technical requirements listed under section 5.1.2 demand a general set of requirements from a manufacturing point of view. This set of requirements is aimed to define the 3D printer characteristics that must be reunited by the machines used to produce the 3D printed tooling ensuring the minimum quality required. The purpose of this section is to create a machine specification that will allow production of 3D printed tooling to 3rd parties across different countries.

Minimum 3D printer technical requirements for production of 3D printed tooling:

- Manufacturing tolerance of +-0.1mm
- Antiabrassive nozzles of 0.6mm diameter compatible with reinforcement fibres (carbon or glass fibres).
- Melt temperature between 280 to 330ºC (depending on polymer)
- Heated buildplate up to 120ºC.
- Actively heated enclosed chamber capable of ensuring at least 80ºC ambient temperature.
- Specific heatplate adhesives (PA adhesive or PC adhesive) or compatible surface (e.g. texturized PEI)
- Build area of around 40x40x20cm XYZ (will be revisited after design of templates is completed)
- Slicing software capable to replicate additive manufacturing process developed in XCROSS.

5.2 FFF materials suitable candidates

This section is aimed to define a list of materials that comply with the technical requirements stated in section 5.1.1 and with the operation conditions from section 3.2. This list will not only serve to select the final material within XCROSS project, but also to provide compatible alternatives for 3rd party manufactures across several countries if the specific compound selected for XCROSS project is not possible to source. The compounds listed below are manufactured by 3DXTECH® [3], which has both USA and EU distributors. Base compounds are also listed to allow 3rd parties to find alternative manufacturers. AIMEN has decided to use compounds from 3DXTECH® due to the very good experience and reliability over the years that its products have granted along several past research projects related to FFF additive manufacturing.

- CarbonX PC-CF
- CarbonX ezPC-CF
- CarbonX HTN-CF
- CarbonX PA6-CF
- CarbonX PA12-CF
- FibreX PA6-GF30
- FibreX PA12-GF30

The previously proposed materials are categorised as high-performance engineering grade polymers, with estimated prices ranging from 46€ to 116€ per standard 500gr spool. Ultra performance grade polymers usually reserved for aerospace grade application that exceed required characteristics by XCROSS business case. Such materials are as PEEK, PEKK, LM-PAEK, TPI, or PEI and have not been taken into account because of limited their availability, expensive price that would not suit the business case (500gr spool starting at 200€), and requiring industrial grade high temperature 3D printers that are very costly to operate, require highly qualified personnel, and are not easily available on every location.

A summary of main characteristics from the proposed materials can be seen in

	Composition		Mechanical properties					Thermal properties		
Material	Matrix	Reinforcement fibre	Tensile strenght, Break (MPa)	Tensile Modulus (Mpa)	Tensile elongation, Break (%)	Flexural Strenght (Mpa)	Flexural Modulus (Mpa)	Glass Transition Temperature (Tg, ºC)	Deflection temperature at 0,45 MPa	Cost € (500gr)
CarbonX PC-CF	PC	Carbon (20%)	70	6200	2	90	5890	143	135	88
CarbonX ezPC-CF	ezPC	Carbon (20%)	73	6980	2,1	85	6540	127	119	88
CarbonX PA6-CF	PA6	Carbon (20%)	63	3800	3	84	3750	70	147	38
CarbonX PA12-CF	PA12	Carbon (20%)	72	8000	2,1	90	7900	158	150	88
Fibrex PA6-GF30	PA6	Glass (30%)	62,8	4261	6	72	3600	70	186	37
Fibrex PA12-GF30	PA12	Glass (30%)	82	7800	4,5	94	7550	158	150	65
CarbonX HTN-CF	PPA	Carbon (20%)	87	8200	1,9	95	7895	125	240	116

Table 1. Comparison of proposed 3D printing materials. Complete material technical datasheets can be found in Appendix A.

	Composition		Mechanical properties					Thermal properties		
Material	Matrix	Reinforcement fibre	Tensile strenght, Break (MPa)	Tensile Modulus (Mpa)	Tensile elongation, Break (%)	Flexural Strenght (Mpa)	Flexural Modulus (Mpa)	Glass Transition Temperature (Tg, ºC)	Deflection temperature at 0,45 MPa	Cost € (500gr)
CarbonX PC-CF	PC	Carbon (20%)	70	6200	2	90	5890	143	135	88
CarbonX ezPC-CF	ezPC	Carbon (20%)	73	6980	2,1	85	6540	127	119	88
CarbonX PA6-CF	PA6	Carbon (20%)	63	3800	3	84	3750	70	147	38
CarbonX PA12-CF	PA12	Carbon (20%)	72	8000	2,1	90	7900	158	150	88
Fibrex PA6-GF30	PA6	Glass (30%)	62,8	4261	6	72	3600	70	186	37
Fibrex PA12-GF30	PA12	Glass (30%)	82	7800	4,5	94	7550	158	150	65
CarbonX HTN-CF	PPA	Carbon (20%)	87	8200	1,9	95	7895	125	240	116

Table 1. Comparison of proposed 3D printing materials. Data courtesy from 3DXTECH [3].

5.3 Preliminary selection of FFF material

Taking into consideration the technical requirements of the 3D printed visualisation tool to be manufactured and the listed materials from previous point that reunite such requirements, the three most suitable candidates have been proposed to undergo future material testing along WP5 activities that will result in the selection of the definitive material for the manufacturing of the 3D printed visualisation tool.

Aside from the technical requirements, manufacturing requirements, material availability, and product viability have been also considered to satisfy a competitive business case that can guarantee the development's continuity and adoption after project activities end.

The proposed candidates are:

1. FibreX PA6-GF30
2. Fibrex PA12-GF30
3. CarbonX PC-CF (alternatively CarbonX ezPC-CF depending on stock)
4. CarbonX HTN-CF (Contingency solution if extra high temperature resistance is required)

Fibrex PA6-GF30 is proposed as the first candidate because of the elevated temperature resistance it possess (186ºC) that is considered the driving characteristic at the time of material selection because of the operational requirements explained in section 3.2. Glass fibre reinforcement improves impact absorption capacities, which is aligned with product robustness requirements.

However, PA6 is known for its hygroscopic characteristics, that needs to be taken into consideration and studied further along the project, since if the tooling is operated in a repeated manner under heavy rain conditions, humidity can eventually degrade the tooling over time. Climatic chamber testing is available at AIMEN to study the influence of humidity over material properties. It is considered that due to having the lowest price of all the proposed materials it is still worth to study its viability despite its hygroscopicity, as it will greatly improve the economic business case for a future product adoption.

As a second candidate, Fibrex PA12-GF30, a Polyamide-12 based polymer is proposed due to its lower moisture absorption when compared to PA6. Glass fibre reinforcement is again favoured over carbon fibre due to its better impact resistance. Temperature resistance (150ºC) is slightly lower than that of the first candidate, but still sufficient to deal with operational requirements (minimum temperature resistance of 100ºC).

CarbonX PC-CF is an allrounder carbon fibre reinforced polymer with a very well-balanced set of characteristics, easy printability and average cost. This material has proven its suitability for robust outdoor applications since long time ago, it is for example used to produce automotive bumpers. Its temperature resistance up to 135ºC also makes it suitable to endure rail temperature during the verification process.

Lastly and only as a contingency plan if the previously proposed materials fail the practical test degrading because of excessive rail temperature, an extremely high temperature resistant material, CarbonX HTN-CF nylon will be considered. Note that this material cost is several times larger than that of the main candidates and it is not easily sourced. This material should only be considered if all of the other candidates fail to demonstrate endurance against profile temperature.

Future project activities will characterise the proposed materials and manufacture a few measuring templates from each material to undergo measuring trials over a crossing repair process in order to acquire practical information before manufacturing the complete demonstrator in the definitive material.

6 3D printed physical visualisation tools use conditions

Since the developed measuring tooling will be composed of different materials and will rather be an assembly of multiple tools and components than a single tool, several use conditions must be considered to ensure correct use from railway operators and allow it to produce results as intended by design. A list of basic use conditions is presented below:

- **Temperature of rail:** Official verification protocol stablishes that rail temperature at measuring time must not exceed 50ºC. However it has been noted that welders sometimes check rail at even 200ºC. PC-CF polymer proposed to manufacture measuring templates starts deforming after 120ºC, therefore maximum temperature at verification should not exceed 100ºC. If this is not possible to ensure, polymers with higher performance should be considered, which must be taken into account in the business case of the product due to its higher price.
- **Keep out of fire sources:** If templates are nearby or subjected to fire sources (e.g. torch used to preheat rail or grinding/welding debris) they can melt or even burn. Tooling must be placed at a safe distance from fire sources when not in use or protected by the appropriate means.
- **Be gentle:** physical verification tooling will be composed of multiple elements assembled together. Even though if the components are designed and manufactured as robust as possible, it should be treated as gently as common sense demands when using any precision verification tool presenting adjustable components. This means transporting it in an adequate protective case and not dropping or abusing it, failure to do so can end up in components having free play between them or being damaged, resulting in incorrect measurements.
- **Store clean and dry:** Tooling materials will be resistant to wear, chemical and climate agents, however and because tooling will be an assembly of several components, it must be store clean and dry after use. Dust or dirt particles can get into moving components and affect its optimal operation. Air blowing of dirt and regular maintenance with standard lubricants like WD40 that protect against corrosion, allow displace of moisture and enable smooth gliding of moving parts is advised.

This set of use conditions is of preliminary nature and will be further detailed as the tooling design evolves and matures in the future activities of WP5, where a full set of operation instructions will be defined.

7 Conclusions

The objective of WP5 is constituted by proposing a new methodology to improve crossings wear and repair works quality assessment that introduces a new 3D printed visualisation tooling which allows to quantify profile deviations in a more precise and complete way. For that, the first task (T5.1) of the work package comprises the development of a technical specification for the physical visualisation tool demonstrator to assist asset management quality assurance, which has been outlined into this deliverable D5.1. The strategy followed to define a technical specification for the proposed 3D printed tooling has consisted in assessing the use case and its constraints to set the criteria to create a design that satisfies all the identified technical requirements, the selection of the right additive manufacturing technology together with the most suitable thermoplastic composite that can endure the working conditions of a repair operation, for which a set of operational considerations is defined.

First section analyses in detail the use case that concerns the activities from WP5, explaining the type of railway crossing that is going to serve as demonstration platform. The current repair procedure has been defined, and operational conditions and constraints that will affect the development of the 3D printed physical visualisation tooling presented. Current manual verification methodology pre and post repair has also been studied, detailing the steps involved in the repair process and exposing the limitations of the current tooling consisting on 2D gauges, rulers and MiniProf [1] device. The types of profile shape deviations assessed by such measuring elements have been studied in order to include them as items that the 3D printed visualisation tooling should be able to quantify.

Next, an overview of the different existing composite additive manufacturing technologies is presented and the most suitable ones for the manufacturing of the visualisation elements are identified. The available additive manufacturing platforms at AIMEN based on such technologies are described and two design approaches compatible with the available equipment are proposed: a single element approach and a multielement modular approach, deeming the later more adequate as it allows simultaneous quantification of all the defect types that are currently verified with the 2D gauges used by the repair team. FFF additive manufacturing technique has been proposed as the most suitable one to produce the demonstrator, based on the rationale explained during the design approach and an additional section regarding product viability, which summarises the main keypoints that are advised to follow to ensure the effectiveness and adoption by the sector of the to be developed 3D printed physical visualisation tool after project completion.

Following to the selection of the manufacturing technology, a section dedicated to determining the most suitable 3D printing materials is presented, summarising the technical requirements that must be reunited and listing the most appropriate ones for the manufacturing of the 3D printed tooling together with their main attributes. By taking into account the operational requirements and constraints from sections 3.2 and 3.3 and also the product viability considerations under section 4.3, three material candidates and a fourth one as contingency backup are selected. These candidates will undergo several testing activities along subtask 5.3 in order to select the final material choice.

Finally, a preliminary list of use conditions and instructions that is advised to follow at the time of performing crossings wear and repair measurement assessment with the proposed 3D printed crossing profiles verification tooling is advised to follow so as to guarantee that its functionality is optimum as per design.

A thorough study about the use case problematic has been conducted, giving as a result a proposal for the additive manufacturing technology to be employed together with the most suitable design approach that satisfies operational requirements and constraints, along with several 3D printing materials which reunite the technical requirements that the 3D printed tooling must gather. Additionally, a product viability study based on the railway sector adoption perspective and a set of guidelines for successful operation of the proposed 3D printed tooling are advised.

The mentioned contents complete the technical specification document for the 3D printed physical visualisation tooling and allow to initiate more detailed work with regards to the tooling design, material testing, manufacturing trials with the available AM technologies at AIMEN and the fabrication of 3D printed tooling prototypes to commence physical testing over the real crossing use case available at RET facilities. Following to this deliverable, WP5 subtasks described in section 2 are ready to kick off.

The contents and conclusions drafted from this report should be considered as a starting point for the activities of WP5 and are likely to evolve and be enrichened as project activities progress and new feedback from other WPs is apported.

8 References

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Appendix A – Material TDS

3DXTECH Advanced Materials

TDS Rev 3.0

Technical Data Sheet: CarbonX™ Carbon Fiber Polycarbonate 3D Printing Filament

Physical Properties	Standard	Unit	Typical Value
Density	ISO 1183	g/cc	1.36

Mechanical Properties	Standard	Unit	Typical Value
Tensile Strength, Break	ISO 527	MPa	70
Tensile Modulus	ISO 527	MPa	6200
Tensile Elongation, Break	ISO 527	%	2
Flexural Strength	ISO 178	MPa	90
Flexural Modulus	ISO 178	MPa	5890

Thermal Properties	Standard	Unit	Typical Value
Glass Transition Temperature (Tg)	DSC	°C	143
Deflection Temperature at 0.45 MPa (66psi)	ISO 75	°C	135

Electrical Property	Standard	Unit	Typical Value
Surface Resistance	ASTM D257	Ohm/sq	$>10^9$

Printed Specimen Conditions
Printer: Open Source FDM/FFF
Nozzle: 0.4mm
Layer Height: 0.25mm
Infill: 100%, +/- 45°
Extrusion Temp: 300°C
Bed Temp: 140°C
Specimen Orientation: XY Flat

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TDS Rev 1.0

Technical Data Sheet: CarbonX™ Carbon Fiber ezPC Polycarbonate 3D Printing Filament

Physical Properties	Standard	Unit	Typical Value
Density	ISO 1183	g/cc	1.36

Mechanical Properties	Standard	Unit	Typical Value
Tensile Strength, Break	ISO 527	MPa	73
Tensile Modulus	ISO 527	MPa	6980
Tensile Elongation, Break	ISO 527	%	2.1
Flexural Strength	ISO 178	MPa	85
Flexural Modulus	ISO 178	MPa	6540

Thermal Properties	Standard	Unit	Typical Value
Glass Transition Temperature (Tg)	DSC	°C	127
Deflection Temperature at 0.45 MPa (66psi)	ISO 75	°C	119

Electrical Property	Standard	Unit	Typical Value
Surface Resistance	ASTM D257	Ohm/sq	$>10^9$

Printed Specimen Conditions
Printer: Open Source FDM/FFF
Nozzle: 0.4mm
Layer Height: 0.25mm
Infill: 100%, +/- 45°
Extrusion Temp: 275°C
Bed Temp: 95°C
Specimen Orientation: XY Flat

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3DXTECH Additive Manufacturing

Tech Data Sheet
Rev 1.0

CarbonX™ Carbon Fiber Nylon 12 (PA12) 3D Filament

Physical Properties	Standard	Unit	Typical Value
Density	ISO 1183	g/cc	1.16

Mechanical Properties	Standard	Unit	Typical Value
Tensile Strength, Break	ISO 527	MPa	72
Tensile Modulus	ISO 527	MPa	8000
Tensile Elongation, Break	ISO 527	%	2.1
Flexural Strength	ISO 178	MPa	90
Flexural Modulus	ISO 178	MPa	7900

Thermal Properties	Standard	Unit	Typical Value
Glass Transition Temperature (Tg)	DSC	°C	158
Deflection Temperature at 0.45 MPa (66psi)	ISO 75	°C	150

Electrical Property	Standard	Unit	Typical Value
Surface Resistance	ASTM D257	Ohm/sq	$>10^8$

Printed Specimen Conditions
Printer: Open Source FDM/FFF
Nozzle: 0.4mm
Layer Height: 0.25mm
Infill: 100%, +/- 45°
Extrusion Temp: 285°C
Bed Temp: 110°C
Specimen Orientation: XY Flat

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TDS Rev 3.0

Technical Data Sheet: CarbonX™ Carbon Fiber Nylon (Gen3) 3D Printing Filament

Physical Properties	Standard	Unit	Typical Value
Density	ISO 1183	g/cc	1.17

Mechanical Properties	Standard	Unit	Typical Value
Tensile Strength, Break	ISO 527	MPa	63
Tensile Modulus	ISO 527	MPa	3800
Tensile Elongation, Break	ISO 527	%	3
Flexural Strength	ISO 178	MPa	84
Flexural Modulus	ISO 178	MPa	3750

Thermal Properties	Standard	Unit	Typical Value
Glass Transition Temperature (Tg)	DSC	°C	70
Deflection Temperature at 0.45 MPa (66psi)	ISO 75	°C	147

Electrical Property	Standard	Unit	Typical Value
Surface Resistance	ASTM D257	Ohm/sq	$>10^9$

Printed Specimen Conditions
Printer: Open Source FDM/FFF
Nozzle: 0.4mm
Layer Height: 0.25mm
Infill: 100%, +/- 45°
Extrusion Temp: 275°C
Bed Temp: 80°C
Specimen Orientation: XY Flat

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Tech Data Sheet
Rev 1.0

FibreX™ Glass Fiber Reinforced Nylon 12 [PA12+GF30]

Physical Properties	Standard	Unit	Typical Value
Density	ISO 1183	g/cc	1.23

Mechanical Properties	Standard	Unit	Typical Value
Tensile Strength, Break	ISO 527	MPa	82
Tensile Modulus	ISO 527	MPa	7800
Tensile Elongation, Break	ISO 527	%	4.5
Flexural Strength	ISO 178	MPa	94
Flexural Modulus	ISO 178	MPa	7550

Thermal Properties	Standard	Unit	Typical Value
Glass Transition Temperature (Tg)	DSC	°C	158
Deflection Temperature at 0.45 MPa (66psi)	ISO 75	°C	150

Electrical Property	Standard	Unit	Typical Value
Surface Resistance	ASTM D257	Ohm/sq	$>10^{13}$

Printed Specimen Conditions
Printer: Open Source FDM/FFF
Nozzle: 0.4mm
Layer Height: 0.25mm
Infill: 100%, +/- 45°
Extrusion Temp: 285°C
Bed Temp: 110°C
Specimen Orientation: XY Flat

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TDS Rev 1.0

Technical Data Sheet: AmideX™ PA6-GF30 Glass Fiber Nylon 3D Printing Filament

Physical Properties	Standard	Unit	Typical Value
Density	ISO 1183	g/cc	1.35

Mechanical Properties	Standard	Unit	Typical Value
Tensile Strength, Break	ISO 527	MPa	62.8
Tensile Modulus	ISO 527	MPa	4261
Tensile Elongation, Break	ISO 527	%	6
Flexural Strength	ISO 178	MPa	72
Flexural Modulus	ISO 178	MPa	3600

Thermal Properties	Standard	Unit	Typical Value
Glass Transition Temperature (Tg)	DSC	°C	70
Deflection Temperature at 0.45 MPa (66psi)	ISO 75	°C	186

Electrical Property	Standard	Unit	Typical Value
Surface Resistance	ASTM D257	Ohm/sq	>10^9

Printed Specimen Conditions
Printer: Gearbox™ HT2
Nozzle: 0.4mm
Layer Height: 0.25mm
Infill: 100%, +/- 45°
Extrusion Temp: 265°C
Bed Temp: 70°C
Specimen Orientation: XY Flat

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Disclaimer: The technical data contained on this data sheet is furnished without charge or obligation and accepted at the recipient's sole risk. This data should not be used to establish specifications limits or used alone as the basis of design. The data provided is not intended to substitute any testing that may be required to determine fitness for any specific use.

Tech Data Sheet
Rev 2.0

CarbonX™ Carbon Fiber High Temp Nylon (HTN) 3D Filament

Physical Properties	Standard	Unit	Typical Value
Density	ISO 1183	g/cc	1.24

Mechanical Properties	Standard	Unit	Typical Value
Tensile Strength, Break	ISO 527	MPa	87
Tensile Modulus	ISO 527	MPa	8200
Tensile Elongation, Break	ISO 527	%	1.9
Flexural Strength	ISO 178	MPa	95
Flexural Modulus	ISO 178	MPa	7895

Thermal Properties	Standard	Unit	Typical Value
Glass Transition Temperature (Tg)	DSC	°C	125
Deflection Temperature at 0.45 MPa (66psi)	ISO 75	°C	240
Melt Temperature (Tm)	DSC	°C	265

Electrical Property	Standard	Unit	Typical Value
Surface Resistance	ASTM D257	Ohm/sq	$>10^9$

Printed Specimen Conditions
Printer: Open Source FDM/FFF
Nozzle: 0.4mm
Layer Height: 0.25mm
Infill: 100%, +/- 45°
Extrusion Temp: 295°C
Bed Temp: 130°C
Specimen Orientation: XY Flat

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