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PHABULOμS

Pilot-line providing highly advanced & robust manufacturing technology for optical free-form μ-structures

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= Deliverable D2.1 =

Data exchange format, loss-free, differentially modifiable

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Executive Summary

Deliverable "D2.1 – Data exchange format, loss-free, differentially modifiable" defines the framework to exchange data in the most reliable way that works for both customers and manufacturers within the PHABULOuS pilot line.

D2.1 proposes to define optical devices by a set of three (minimum) to four (maximum) files, including: 1) a CAD file, 2) a manufacturing report, 3) a "readme" metafile and, if available, when there are already manufactured samples, 4) a characterization report.

The "loss-free" definition adopted here applies to these files, and is purely geometrical: it requires all surfaces in files that are processed (change in CAD formats, change/simplification of models) along a project to not deviate from the initial ones by more than 50nm peak-to-valley, PV, when evaluated on a set of selected control points. The logic behind this value is based on the analysis of two different surface examples (asphere and free-form) where the impact of different ways of handling the data (different software packages, surface modelling, types of surface) has been studied.

This document also proposes a folder structure/file naming system that will enable the transfer and storage of secure data in a comprehensive and safe way. These folders will contain all the relevant information of the customer, project, content and date. Specifically, we propose the following folder naming:

CUSTOMERACRONYM_PROJECTNAME_CONTENT_YYYYMMDD

This document includes, at the end, a first draft of a proposal to set up the Design for Manufacturing/data healing tools that will support future customers in aligning with the PHABULOuS standard format.

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1. Introduction

The manufacturing of freeform optical microstructures is a complex process that involves several different steps (optical design, origination, replication, post-processing, integration and metrology/quality control) often accomplished by different manufacturers/suppliers.

On the one hand, the nominal shape of the optical components must be appropriately represented, i.e. described in a way that they can be stored and exchanged across the value chain without distortion or loss of information (i.e. in a "loss-free" way; see below) while ensuring accurate error traceability if/when appropriate. Failure to do this may result in non-negligible deviations in the manufactured components. Oftentimes, it is desirable that such representations can be controllably manipulated and do not contain redundant data.

On the other hand, real components always carry signatures of the process used to manufacture them. Indeed, as a result of manufacturing limitations, the shape of the real components (form, waviness and surface roughness) always deviates from the nominal (i.e. targeted) one. The acceptance range of such deviations (tolerances) need to be specified together with the nominal values. Moreover, including known manufacturing limitations in the representation facilitates the selection of the most appropriate manufacturing technologies and processes.

Finally, an appropriate representation ensures an optimum outcome from the metrology stage and ultimately a high quality of the delivered components.

"D2.1 – Data exchange format, loss-free, differentially modifiable" aims to define an efficient and robust context for such "loss-free" representation that works for both customers and manufacturers.

In PHABULOuS, the representation format of nominal freeform components is defined as "loss-free" if, after the required data exchange and manipulations along the chain, the resulting surface does not deviate from the initial one by more than 50nm peak-to-valley, PV, (this figure is discussed in Section 9) when evaluated on the selected control points (defined in Section 2.3). Therefore, loss-free for the PHABULOuS pilot line refers only to structural parameters, and not to optical performance.

The described data exchange format should be sustainable and be consistently used by (all the partners of) the PHABULOuS pilot line, also after project completion.

2. Exchanged data

The accurate description of an optical system must include the following aspects:

- For solutions comprising several parts, a full-solid 3D geometrical description of the assembly, including alignment tolerances and non-optical features, such as datum points, ejectors, material gates, to confirm these do not interfere with performance (Section 2.1).
- Full-solid 3D geometrical description of the different parts, including tolerances (Section 2.2).
- Definition of the control points (Section 2.3).
- Specification of the required surface finish (roughness) for all optical surfaces, including tolerances (Section 2.4).
- Description of the relevant material properties, with emphasis on the refractive index (Section 2.5).
- When surface coatings are requested, their locations, coating materials and thicknesses (Section 2.5).

2.1. Description of optical system (3D assembly)

The description of the entire set of parts in an optical train must use CAD models completed by an ICD (interface control drawing), in which the main dimensions and their relative positions are annotated with tolerances.

As discussed in the next section, there are different CAD formats that are well adapted to different types of designs.

2.2. Description of optical components (3D part geometry)

All the 3D parts within the 3D assembly must be described individually also using a CAD model and supporting ICDs that include the relevant dimensions and tolerances. Whenever possible, the optically active components must be described using analytical expressions. Approximated equations are acceptable providing they comply with the “loss-free” definition.

On the one hand, a set of (XYZ) control points laying on top of the optically active surfaces and ideally sampled over a well-defined grid allow manufacturers to make quality checks along the manufacturing process.

On the other hand, certain optical components may have surfaces with no optical function. However, these surfaces might serve other important purposes, such as mechanical or referential to e.g. enable a proper assembly into the complete system and may unintentionally contribute to the performance of the system. Both rough and polished surfaces are prone to produce unwanted stray light and hence must be carefully designed and manufactured.

In summary, all surfaces need to be completely described including their shape (form) as well as the manufacturing deviation tolerances, the materials and the required surface finish. Otherwise, the compliance of the manufactured systems with the customer specifications cannot be guaranteed. Surfaces can be effectively described using CAD models, ICDs and manufacturing reports and control points, as described below.

Neutral file exchange uses an intermediary neutral format to translate data between CAD systems. This method starts from a pre-processor embedded in the original CAD system, which generates the neutral file from the originating CAD format. The target CAD system post-processes the neutral file and converts it into the target native format. Some neutral formats are defined by standards organisations such as IGES and STEP while others are proprietary but still widely used and are regarded as quasi industry standards.

Table 1: Main information of neutral CAD formats.

	STEP	IGS	PARASOLID	STL
Year introduced	1994	1980	1989	1987
Last update	Continuously updated	1996	2016	None
Standard	ISO10303	ANSI	None	None
Representation	B-rep (precise) & Vis-rep (approx..)	B-rep (precise);	B-rep (precise)	Binary & ASCII
Organization	ISO and PDES Inc.	ANSI	Siemens	3D Systems

The best 4 neutral CAD file formats able to define optics comprising free-form surfaces are introduced in the table above. These are their main features.

<u>STP / STEP (File Extension: *.STEP, *.STP)</u>

STEP is the most widely used & accepted neutral CAD format today, therefore, making it a standard across multiple industries. Most CAD software supports importing & exporting STEP files, allowing it to be interoperable between different systems including CAM (computer-aided manufacturing), CAI (computer-aided inspection), and CAE (computer-aided engineering). Regarding mechanical CAD, there are three major STEP file formats:

- STEP AP203: Defines geometry, topology, and configuration management data of solid models for mechanical parts & assemblies.
- STEP AP214: Includes STEP AP203 features along with colors, layers, GD&T, and design intent.
- STEP AP242: Merges both STEP 203 & STEP 214 to introduce model-based definition (MBD) engineering.

IGS / IGES (File Extension: *.IGS, *.IGES)

IGES was the first neutral CAD format invented and deployed in the late 1970s/early 1980s. Although it is an old standard, technologically superseded by STEP & QIF, it is still widely supported and used.

IGES CAD format is mostly used to represent surface geometry (it can also represent solid models) and design work. It is often translated with gaps between surfaces, missing faces, and even surfaces with wrong orientations. Then, we recommend the use of STEP or QIF unless a tool for repairing faulty geometries is available.

PARASOLID (File Extension: *.X_T)

Parasolid format (currently owned by Siemens) is used by the geometric modelling kernel used in CAD, CAD exchange, CAM, CAE, and product visualization. It can represent wireframe, surface, solid, and general non-manifold models. Most Parasolid files migrate 3D solids and/or surface data. It is licensed and used in widespread CAD design software tools such as NX, SolidWorks, SolidEdge, MasterCAM, Onshape, and others.

STEREOLITHOGRAPHY STL (File Extention: *.stl)

In the field of 3D printing, the STL and OBJ are the most common formats. STL is much simpler and hence more widely used. Also, being smaller, STL files are preferred for sharing and publishing purposes.

There are a couple of aspects that make STL unique. Firstly, it is a tessellated format, which means that it approximates the surface of a 3D model using a series of interlocking triangles. This “triangular mesh” technique is the most common method used in 3D modelling.

Secondly, the resolution of STL files can be easily increased by just increasing the number of triangular planes used to represent the surface, albeit at the expense of increasing the file size. Nonetheless, even at the highest possible resolution, STL 3D models have lower fidelity than those using precise surface encoding (STEP, IGS, PARASOLID and even OBJ, for instance).

Table 2: Main advantages and disadvantages of the most common data formats used to represent 3D geometries.

	UPSIDES	**DOWNSIDES**
STP	Developed by ISO, a reputable organization. Mature file format. MBD-ready if using AP242	Big organization means slow to release new updates quickly.
IGS	Mature file format. Ubiquitously supported.	IGES does not support solid models, just surface geometry. IGES models typically contain a set of surfaces difficult to connect into a closed solid, owing to imperfections in the boundaries
PARASOLID	The internal modelling language used by lots of CAD and downstream software. Great CAD export option if you use NX or SolidWorks.	Not a standard data format. Uses some proprietary blend recipes, making some data inaccessible to non-Parasolid modelers.
STL	Small size files when triangles are large (limited number of triangles)	Imperfect description of smooth curved 3D objects, unless large files with tons of triangles are used

	Compatible with many CAD modelling software platforms Straightforward connection for 3D printing Raytracing is fast when triangles are large (e.g. for planar facets)	STL files are hard to modify Raytracing is very demanding/slow or not ray-traceable when triangles are small (increasing number of triangles)

2.3. Control points

Control points are a set of XYZ points which are defined in certain (critical) areas of the involved surfaces and that act as reference points for shape accuracy checks after each step. The control points should be defined carefully and cover:

- Main optically active surfaces. We suggest defining 5 points per lenslet, randomly spread and not less than 9 lenslets per FMLA (Freeform Microlens Array), at different locations. These locations must be selected depending on the design (whether it has symmetries or not, whether the lenslets shapes change radially or laterally).
- Non-optically-active surfaces which contain fiducial points or have reference and/or alignment functions.

Each time a CAD model is modified, either related to solid model operations, CAD changes or even CAD format changes, the pilot line will ensure that the deviation of the shape measure on the selected control points, is within the 50nm PV tolerance recommended above.

2.4. Surface finish

The term "surface roughness" refers to the deviations present in any real surface with respect to its nominal shape, excluding form and waviness. Although the transition between form, waviness and roughness deviations depends on the nature of the surface and the application, the latest always refers to the finest irregularities and is (almost) always an unwanted effect that arises from the inability to manufacture perfectly smooth finishes.

The final surface finish of optical components determines the amount of scattered light, hence impacting their optical performance. Surfaces demanding minimum scattering require a finish as glossy as possible, while others require a rather rough finish, to produce scattering in a controlled way (this is common in illumination) or to prevent stray light effects.

Amplitude parameters characterize the surface by averaging (in one way or another) the vertical deviations of the profile from the mean value. There are many different roughness parameters in use[1,2] with Ra (the arithmetic average) being the most common. However, it is defined for 1-dimensional tactile profilometry (i.e. scanning across a line), while surface roughness specifications are more reliable and do represent real surfaces more accurately when specified and measured on surfaces (i.e. areal). Recently, areal figures such as Sa and Sq (areal equivalents to Ra and Rq), but defined by deviations y_i throughout an entire surface are starting to prevail over the latter.

Although, areal figures (Sa, Sq, Ssk, Sku and others) have been standardized, it is currently not clear how widely they have been adopted by the optics community. As an example, in automotive applications and imaging applications, such as HELLA and LIM use cases, *Sa* should be <10nm typically. Due to its complex nature, "surface roughness" is specified, by averaging the measured heights of features above and below the mean surface level over certain "spatial wavelength range" given the in-plane separations of such height features.

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[1] *ISO 1302 addresses surface roughness. See more at https://www.iso.org/obp/ui/#iso:std:iso:1302:ed-*

[2] *ISO 25178-2 – Geometrical product specification (GPS), surface texture: areal, terms – definitions and texture parameters*

Both, the surface roughness and the spatial wavelength range depend strongly on the measuring equipment used (tactile profilometer, confocal microscope, interferometer, AFM, etc…), on the experimental conditions (field of view, resolution, number of measurements, contamination, etc.) and on the data processing (e.g. filtration). Therefore, "surface roughness" is a meaningful concept only when those aspects are clearly specified.

However, the PHABULOuS pilot line has not yet decided on the preferred metrology. This is currently being investigated and will be reported in D2.4.[3] In fact, different metrology may be selected for different freeform components, depending on their shapes, relevant dimensions and the application in question.

Therefore, we propose to hold the decision regarding surface roughness specification until these aspects have been clarified. The decision will we reported in D2.2. [4]

2.5. Materials and coatings

In order to support the pilot line customers, The PHABULOuS pilot line will, in the framework of WP2, prepare a set of libraries of available materials: Their relevant properties (optical, thermal, mechanical, etc.) will be described in a format compatible with the PHABULOuS preferred commercial simulation software packages (CODEV and LightTools).

In this way, the pilot line and its customers will be able to mutually align and confirm that the material set initially considered (in the design phase) will indeed be employed in the manufacturing phase. If the pilot line does not have access to a particular requested material, a valid alternative will be screened, agreed and selected.

Sometimes, the pilot line will need to consider special requirements due to e.g. legal regulations for material resistance (e.g. yellowing, temperature resistance, fire resistance…). If the pilot line does not have access to a particular requested material, a valid alternative will be screened, agreed and selected.

Regarding coatings and surfaces, where these should be applied, this should be clearly specified in the data exchange process. The customers and the pilot line will carefully investigate the expected performance of the coatings in free-form surfaces, carefully considering aspects such as for example, coating performance versus coating thickness, incident angle (of the light) and operating temperature as well as shelf and operational stability.

The PHABULOuS pilot line will prepare a set of libraries of their available materials, compatible with main software tools utilized by the pilot line (such as CODEV, Zemax, LightTools, Lucidshape, FRED…). This task is part of the "design tools" activity planned in WP2.

2.6. Characterization Methods and Workflows

The PHABULOuS pilot line will offer a wide range of metrology facilities featuring state of the art equipment and extensive know-how thus ensuring high-quality manufacturing. The metrology process will be tuned to the optical part being manufactured as well as to the selected manufacturing technologies and processes.

Ideally, the designs should be shared with the pilot line indicating the preferred metrology steps and equipment to ensure compliance with the specifications. Here, metrology refers to both **surface topology** (form, waviness and roughness) and to **optical properties** (transmittance, reflectance, have, optical efficacy, image quality, stray light, coloration, etc. – depending to the application in question).

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[3] *D2.4 – Initial characterization method and workflow datasheet (validated for 2 structures; proven for 5…1000µm structure size (on 10x10cm²). Initially planned in M12.*

[4] *D2.2 – Initial Best Practices design report and quantified manufacturing limitation including design models and software libraries. Initially planned in M12.*

The potential of the experimentally measured surface topologies is twofold. On the one hand, it enables the pilot line to quantify the manufacturing quality (by comparison with the nominal designs). On the other hand, it can be used to predict the optical performance of the manufactured components. This can be achieved using e.g. automatic image processing and/or optical simulation software tools (e.g. MATLAB, OriginPro, OpticalDesign, etc.).

The results from the characterization tests must therefore be saved in a format compatible with the software tools mentioned above. Text-based formats such as ASCII; comma separated values (.csv) are recommended for easy importing and manipulation.

To ensure correct referencing to samples and designs, the metadata must include, for each characterisation result file:

- The PHABULOuS unique sample/material ID and the individual sample-ID at the partner, executing the characterisation.
- The date/time of the measurement to keep full track of material history (so that potential ageing effects can be assessed if they influence measurement results).
- The measurement device and configuration, including information on lateral and vertical resolution (pixel resolution + optical resolution), field of view, and error bars in case of linescans (e.g. profilometry) or image data for areal measurements (e.g. WLI, optical microscopy, AFM, etc.).

The characterisation results will be reported to the PHABULOuS customers (as PDF documents) and will include all the here-mentioned meta-data except certain proprietary details about the configuration of the measurement devices.

Product-specific measurements, such as the measurement of photometric parameters, are carried out by the customer.

3. Beta proposal for data exchange within the pilot line

Here we propose a data exchange of one zip file or a folder (when companies don't accept compressed files) that includes the following files:

- **A CAD file** in a format selected by the customer and the pilot line: STEP, Parasolid are recommended for FMLAs comprising free-form mini lenses. Not all the solid modelling software packages (SolidWorks, Rhinoceros, CATIA…) can export/import any type of file format correctly, and the same applies to ray trace/optical design software (LightTools, Lucidshape, FRED, TracePro, CODEV, Zemax, etc.). Therefore, the CAD format must be carefully selected.

  The STL format may be preferable for certain geometries such as e.g. surfaces that can be accurately described as a set of plane triangles (providing they can be appropriately interpreted by the manufacturing equipment).

  Whenever possible, the models must include all the rounding and other special features linked to technological limitations of the pilot line. The compliance to the PHABULOuS format is the sole responsibility of the customer. However, the pilot line will support as appropriate (data healing step; see Section 5).

  Also, the final model must be free of interferences between non-optically active surfaces and design rays traveling through the solid, so that expected performance is preserved.

- A **manufacturing report**, including:

  - ICDs with PV form factor[5] (in this case, referred to each lenslet), tolerances[6], tip radii, draft angles, materials and coatings, description of holding features, maximum slopes.
  - List of control points (in mm).
  - Colored description of surface finish characteristics.
  - Analytical description of surfaces (if available and required by the pilot line).

  and, optionally:
  - Recommended measurements.
  - Description of feature "size"/dimensions. For example, for lens-like features, the maximum and minimum height and diameter (to facilitate the choice of the characterization tool).
  - Description of the unit cell for periodic arrays (to speed up the manufacturing process).
- After every manufacturing batch by the pilot line, the folder can also include files with **results of measurements** (see Section 2.6), that can be compared with the original designs to check whether each batch is compliant with the defined tolerances.

As an option, a ray tracing model file could be included in the data exchange, if the customers want the pilot line to check/review the performance of optical parts.

The recommended dimensional standard unit in the files above will be millimetres (mm), while angles should preferably be in degrees (°). In any case, customers and pilot lines should clearly specify the units.

4. Organization and storage of relevant information

The way technical information is organized and stored is an important aspect. For example, file names must be simple but nonetheless contain all the relevant information required to track back the origin of the file.

Specifically, the file name format needs to be consistent, sufficiently descriptive, and appropriately stored hence ensuring a quick search when needed. Setting up general rules is challenging since different naming formats work better for different types of data, projects, experiments, etc.

The preferred approach is to organize the files in folders named according to the comprising files. These folders will contain all the relevant information of the customer, project, content and date. Specifically, we propose the following folder naming format:

CUSTOMERACRONYM_PROJECTNAME_CONTENT_YYYYMMDD

Using this format facilitates chronological file sorting, even when the date has been reset in a copy-paste process.

For instance, **LIM_TRENZA_2MLADESIGN_20200601** folder and files contain the data corresponding to:

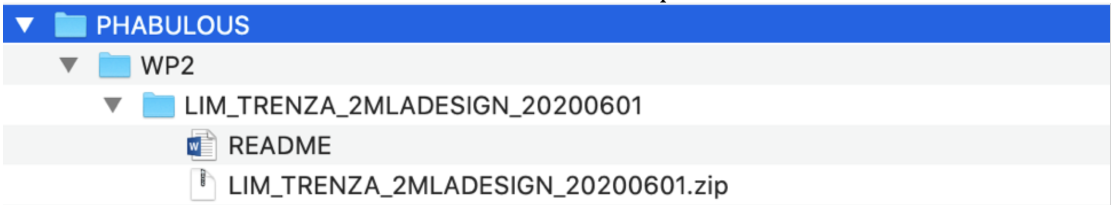
- Customer = LIMBAK
- Project = TRENZA
- Content = Two MLAs design
- Date = June 01 2020

[5] *Specifying form factor accuracy using PV is common in the industry but very imprecise. There are infinite types of surface deviations producing the same PV value which actually produce rather different performance. In general, Angular Deviations Frequency matter more than PV. Surface shape deviations (e.g. slopes) can be modelled by using Zernike polynomials placed over the surface to model surface deviations specified by the manufacturer. This topic will be distilled along the PHABULOuS pilot line*

[6] *Solid Works file format *.SLDPRT can contain annotations on tolerances. If customer uses this format, check tolerances are consistent with those specified in the ICDs*

In case more than one version of a design is exchanged along a day, the structure can be completed as follows **CUSTOMERACRONYM_PROJECTNAME_CONTENT_YYYYMMDD_V#,** in which case the example becomes **LIM_TRENZA_2MLADESIGN_20200601_V1, LIM_TRENZA_2MLADESIGN_20200601_V2, etc.**

The files and folder would look as follows in the computer.



Note the folder contains the zip file (see Section 3) and a very important readme.docx (or .txt) file with metadata information. We suggest the README.txt file in the directory contains information such as:

- Data name
- Author of the files
- Information contained in the files
- Modifications, compared to previous versions
- Recommended characterization methods and reference to characterization files (when available)
- Any other relevant information

In the example above, the README.txt will contain the information shown in Table 3.

Table 3: Information contained in the README file of the LIM_TRENZ_"MLADESIGN_20200601

DATA	LIM_TRENZA_2MLADESIGN_20200601_V2
AUTHOR	Rubén Mohedano, rmohedano@limbak.com, +34639627241
CONTENT	The files contain CAD model and manufacturing reports for the manufacturing of two free-form MLAs. The CAD models already include tip rounding as defined by manufacturers. These CAD files have been ray traced by customer and perform under specs, so customer and manufactured have agreed to manufacture the design as is.
MODIFICATIONS	Previous version of this design, LIM_TRENZA_2MLADESIGN_20200601_V1, had perfect knife edges, so these were not an accurate description of what could be manufactured
CHARACERTIZATION	Surfaces should be characterized using white light interferometry. After measurement of bottom and top MLAS, their alignment should be confirmed through data processing using as reference the datum points
OTHER COMMENTS	Materials, tolerances, form factor, surface finish and coatings are all described in the manufacturing report. In case something is not clear, please sync with Rubén Mohedano.

5. Design for manufacturing (DFM). Data check and healing

The input provided by the customer to the PHABULOuS pilot line may be incomplete and/or not compliant with the format described here. Moreover, optical systems and components often contain non-optical parts which are nonetheless essential for the manufacturing of the components themselves as well as for their subsequent integration in the system (blanks holding and processing, flanges, alignment marks, etc.). A mutual understanding between the customer and the pilot line with respect to these parts and their role/impact on the system is essential.

In order to support customers aligning with the PHABULOuS standard format, we will develop the following tools:

- Creating Solid models from raw data, such as cloud points or analytical expressions, to support customers unable to provide a proper closed solid in the recommended formats.
- Data healing recipes to a) locate corrupted and/or imperfect data on the files supplied by the customers (non-closed solids, wrinkles…) and b) reduce the size of the CAD files without losing accuracy.
- CAD accuracy checks to confirm that the CAD files used throughout the manufacturing process are consistent with the original CAD files supplied by the customer and sufficiently accurate. The PHABULOuS pilot line recommends the use of XYZ control points where the customer and the pilot line compare the Z values (height) corresponding to previously agreed XY coordinates.
- Algorithms to conveniently describe and implement known manufacturing limitations into customer's CAD models and to quantify the associated impact on performance.
- Designing/adding holding features with customer, compatible with their manufacturing needs (parts handling, material gates, parts ejection…) and their integration thereafter.
- Reviewing material alternatives with customers in terms of availability, performance and costs.

5.1. Adding manufacturing limitations to original CAD files

Under certain circumstances, the customer and the pilot line may agree to quickly assess the viability of the customer specifications. In this process, the provided CAD models will be differentially modified to account for manufacturing limitations and the resulting performance simulated and quantified against the initial specifications hence enabling both parts to de-risks decisions.

As mentioned, two circumstances need to be fulfilled for this purpose namely: a) the provided CAD model need to be differentially modifiable and b) the manufacturing limitations (for each step and technology) need to be known and appropriately described (i.e. in a CAD compatible form). The PHABULOuS pilot line will, in the framework of WP2, develop CAD routines with this objective.

Initially, the involved partners will screen existing software tools and develop macros, shortcuts, best practices and manuals to adapt them to the PHABULOuS manufacturing technologies. For example, DFMXpress,[7] a SolidWorks add-on, analyses CAD models for manufacturing, albeit only for "standard" fabrication technologies such as drilling, milling, turning and injection molding. When/if needed, the development of new tools will be attempted.

Below we provide a summary of the features that are often needed to model solids geometrically with maximum accuracy and which are relevant for PHABULOuS manufacturing technologies:

- Radii of curvature of tips and valleys
- Draft angles in vertical steps, relevant to e.g. identify de-molding issues.
- Material shrinkage (after UV replication).
- Surface roughness.
- Tolerances (X-Y-Z lens units shifts).
- Full colour/spectral analysis (including materials and light sources).

6. Conclusion

Handling data of complex FMLA devices in an efficient and safe way is not straightforward. In order to make sure the final optics manufactured comply with customer goals requires suitable manufacturing technologies but also the proper framework assuring no relevant information is lost in tasks involving data exchange.

[7] https://www.solidsolutions.co.uk/solidworks/3d-cad/features/dfmxpress.aspx

The consortium has discussed the experience of different partners regarding data exchange: types of CAD files, definition of special features in the surfaces, tolerances, control points…. After compiling their results and ideas, this deliverable gathers a series of guidelines (and recommendations) to avoid project failures linked to an improper handling of data within the PHABULOuS pilot line, but also when the pilot line interacts with customers.

These guidelines are not unique and fixed: rather, the goal of PHABULOuS is improving them along the project so at the end an optimal data exchange context has been established to support the ultimate objective of this H2020 action, which is the sustainability of the PHABULOuS pilot lines in the future.

7. Degree of progress

The deliverable is 100% fulfilled.

8. Dissemination level

The Deliverable D2.1 “Data exchange format, loss-free, differentially modifiable” is public and therefore it will be available to download on the project’s website on demand.

9. Appendix I. Analysis of CAD files fidelity

We have compared different CAD files formats and different CAD software tools with respect to the accuracy in describing surfaces. For this purpose, we used two examples: an aspherical rotationally symmetric shape and a radically free-form surface.

Starting from STEP solids, native solid works (*.sldprt), Parasolid (*.x_t) and STL files were saved and exchanged between SolidWorks, Rhinoceros and SpaceClaim. A set of control points (in specific XY coordinates) were evaluated in all the new solids (upon closing the software and re-opening it again, importing the previously saved files). The Z values of the evaluations were compared with the Z values expected from the analytical description of the surfaces. Both, the aspheric and the free-form examples yielded the same conclusions:

- Parasolid and STEP formats created by SolidWorks accurately match the native SolidWorks format for the design of aspheres and free-forms.

- When creating the optical surface curve from an equation, SolidWorks is only accurate up to 43nm RMS and 121nm PV. A better approach is calculating a number of points (to be determined in each case) calculated with the equation, import these into SW and create a NURBS surface through the points. This yields accuracies in the range 0.39nm RMS and 1.3nm PV in aspheres and 7nm RMS and 23nm PV in free-forms (as confirmed by CSEM and LIMBAK, see Figures 1 and 2).

- STL files can be created with a good accuracy (but worse than the other three formats, i.e. 62nm RMS and 150nm PV error) within SolidWorks, but file size is large at around 1MB per 1mm radius lens (for an MLA, the file size will quickly increase to 1GB or more).

- No difference was found in the way SolidWorks and SpaceClaim import and interpret STEP and STL formats.

- Parasolid files are the lightest of all tested 3D drawing formats, and yield the same accuracy.

Based on the obtained results, we recommend 50nm PV as the deviation limit for loss-free CAD files. It is important to be careful when generating the CAD files and, in case the control points evaluation does not lead to accuracies below 50nm PV, find the root cause and try to model the surfaces using a different approach; for example, using an optimal set of points, with an intelligent sampling able to follow the free-form surfaces accurately.

X - mm	TRUE - mm	Y - mm (SW Native)		Δ(nm)	
		(Solid directly from the equation)	(solid by XYZ points)	(Solid directly from the equation)	(solid by XYZ points)
0,00	0,000000E+00	0,000000E+00	0,000000E+00	0,000000	0,000000
0,20	2,302408E-02	2,307200E-02	2,302479E-02	47,921357	0,711357
0,40	9,418666E-02	9,419000E-02	9,418714E-02	3,340808	0,480808
0,60	2,205567E-01	2,204980E-01	2,205568E-01	-58,729659	0,030341
0,80	4,178501E-01	4,177770E-01	4,178496E-01	-73,059878	-0,439878
1,00	7,252236E-01	7,252240E-01	7,252236E-01	0,406404	-0,003596
			RMS (nm)	43,00	**0,39**
			p-v (nm)	120,98	**1,15**

Equation parameters	
ROC	0,875
K	-0,5
A4	0,01
A6	-0,005
A8	0,001

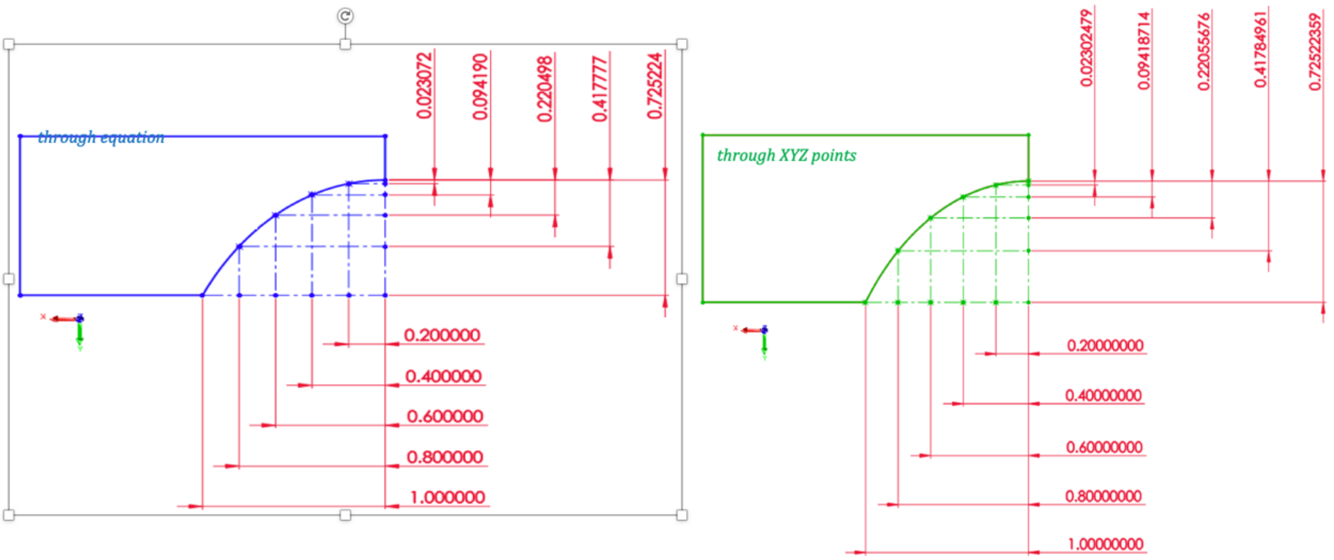


Figure 1: Analysis of aspheres, by UPMT and CSEM. All CAD files, generated from the equation directly, are equally accurate, down to 43nm RMS, when compared to the original analytical description of the asphere. The accuracy increases to 0.39nm RMS when the CAD files are based on a set of 100 points directly generated from the equation and imported into SW (green figures).

LIM free-form test				
x	y	$z_{polynomial}$	z_{stp}	difference $z_{polynomial} - z_{CAD\ files}$ (nm)
0,0000000000	16,4147574956	17,3009719879	17,3009711900	-0,7979000003
0,0000000000	19,1375130695	21,3214914195	21,3214899200	-1,4994999979
0,0000000000	21,8590157091	25,6476431662	25,6476416900	-1,4762000013
0,0000000000	24,5968961330	30,5766140738	30,5766139800	-0,0937999971
4,9575219434	18,9892880590	21,8509792479	21,8509833300	4,0820999985
4,4315988369	21,6688348632	26,0217597343	26,0217627800	3,0456999980
3,6026171086	24,4705163578	30,7834122563	30,7834122100	-0,0462999985
8,4429094126	21,2522356225	27,0822617550	27,0822429900	-18,7650000001
			RMS	**6,9204435110**
			PV	**22,8470999986**

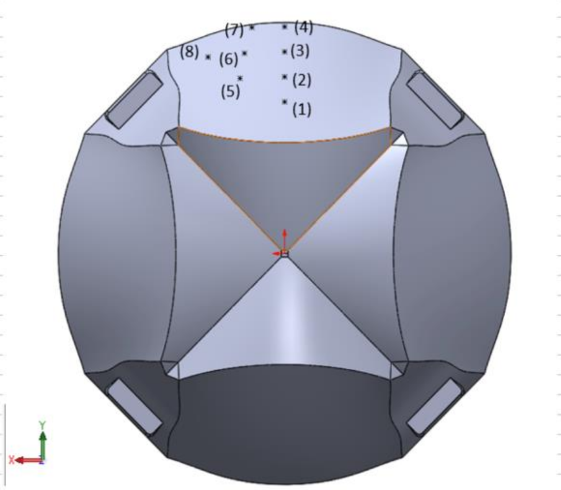


Figure 2: Analysis of a free-form surface by LIMBAK. All CAD files are equally accurate, down to 6.92nm RMS, when compared to polynomial approximation of the free-form surface.