TERRIFIC
Enhancing Interoperability

SEVENTH FRAMEWORK PROGRAMME

Deliverable D5.4:

Progress of the validation process

Task T5.1:

Validation use cases and scenarios

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Executive Summary

This document contains deliverable D5.4 of the TERRIFIC FoF STREP Project. Deliverable D5.4 is a Technical Report of the progress of the validation of isogeometry in engineering by the four TERRIFIC use cases. It is the second report in a series of three and summarizes intermediate results.

All four industrial cases have already progressed their implementations to a degree that allows comparisons of traditional engineering methods contra those based on TERRIFIC methods and tools. The results are encouraging; isogeometric applications are even in their prototype-like state equal in functionality and often more efficient.

More of the measurements of key performance indicators need to be quantitative instead of only qualitative to be convincing arguments for vendors to upgrade their commercial tools. The final deliverable of this task will to address this issue at the end of the TERRIFIC project period.

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1 Introduction

This report summarizes the current status of the project's validation process for the application of isogeometry. In a joint effort a methodology has been identified and described in D5.2 that allows measuring the usefulness of isogeometric technology for the four TERRIFIC industrial use cases. The basic goal has been to enable comparison of cost, time and resources to take advantage of isogeometric technology and its benefits. This methodology has been tried out and evaluated since.

The schedule of WP5 validation activities is presented in Figure 1, below.

				MS3	MS4			MS5	MS6
month	12	15	18	21	24	27	30	33	36
1 - Car Dip Paint Simulation				initial	▨			final	▨
2 - Future Railway Technology					initial	▨		final	▨
3 - Aircraft Parts					initial	▨		final	▨
4 - Isogeometric Machining					initial	▨		final	▨
Reported in deliverables:					D5.4				D5.6

Figure 1: Schedule of validation activities

The current state of validation depends on the availability of IGA technology, which – according to the project plan and D6.2 [10] – is as follows:

- MS3 after month 21: Positive assessment of the first extension of the TERRIFIC Isogeometric Toolkit.
- MS4 after month 24: Sufficient progress in the four application work packages; Conversion tool for STEP-files available; Progress of validation checked; Updated dissemination and use plan available.

Table 1, below, provides details of the relation between IGA tools and use cases, that is, both which tools will be provided by which use case and – especially important for validation - which tools are needed by them. Interesting observations could already be gathered with the current state of the tool set for this month 24 milestone and are reported in this document. The rightmost column shows, however, also that some of the required tools first become available right now or even within the coming half year. The validation activity will, therefore, continue to explore new scenarios.

Table 1: Industry case dependencies on new technology

Industry case	Tool provided	When	Tool needed	When
1 - Car Dip Paint Simulation	Surface segmentation	month 6		

Industry case	Tool provided	When	Tool needed	When
1 - Car Dip Paint Simulation	Basic functionality for triangular meshes	month 6/12		
1 - Car Dip Paint Simulation	Flow volume segmentation	month 18		
1 - Car Dip Paint Simulation	Volume segmentation	month 33		
1 - Car Dip Paint Simulation			Spline surface from triangulation	month 6
1 - Car Dip Paint Simulation			Volume from boundary surfaces	month 6
2 - Future Railway Technology	Surface segmentation	month 6		
2 - Future Railway Technology	Solver for linear elasticity	month 12		
2 - Future Railway Technology	Solver for nonlinear elasticity	month 24		
2 - Future Railway Technology	Sensitivity computations	month 24		
2 - Future Railway Technology	Solver for harmonic balance method	month 33		
2 - Future Railway Technology			Change parameterization of trivariate NURBS models	month 6
2 - Future Railway Technology			Visualization tools	month 6
2 - Future Railway Technology			STEP and IGES import	month 6/12

Industry case	Tool provided	When	Tool needed	When
2 - Future Railway Technology			Create isogeometric model from CAD input	month 12
3 - Aircraft Parts	Solver for 3D linear elasticity	month 24		
3 - Aircraft Parts	Solver for 3D Navier Stokes	month 24		
3 - Aircraft Parts			Volume from boundary surfaces	month 6
3 - Aircraft Parts			Isogeometric linear elasticity solver	month 6
3 - Aircraft Parts			Evaluate B-spline basis functions, 2D and 3D	month 6
3 - Aircraft Parts			Read untrimmed NURBS surfaces from IGES	month 6
3 - Aircraft Parts			Create isogeometric model from CAD input	month 12
4 - Isogeometric Machining	Transform a collection of trimmed patches to one non-trimmed one, 2D	month 24	Solver of sparse linear systems, fitting tools for B-Spline surfaces.	month 6

Industry case	**Tool provided**	**When**	**Tool needed**	**When**
4 - Isogeometric Machining	Compute self intersection points of offset curves and surfaces	month 24	Represent and evaluate trimmed parametric surfaces supporting the faces of IGES models - Subdivision solver for implicit surfaces.	Month 6 - month 24
4 - Isogeometric Machining	Compute silhouette curves and regions defined by silhouette curves	month 33	Compute silhouette curves on faces - Subdivision solver for regions defined by boundary and implicit curves.	Month 24 – month 33
4 - Isogeometric Machining	Connection of a plugin with TopSolid framework	month 24	Wrapping of C++ classes into C#.	Month 24

The usefulness of IGA for industry could be proven already at this stage; experiences are reported in chapters 2.1, 2.2, 2.3 and 2.4 for all four industry cases respectively. An analysis of the results is given in chapter 3 including proposals for refinements of the current methodology.

2 Industrial use case validations

The following sub-sections describe the activities of the individual use cases to validate their use of isogeometric representations.

Where validation KPIs were already weighed in importance for a use case and rated for their usefulness the following scales were applied:

Weights of importance:

- 0 - No interest

- 1 - Improvement appreciated
- 2 - Improvement is an important selling point for the technology
- 3 - Crucial

Grades of usefulness:

- 6 - Satisfactory
- 7 – Applicable/useful
- 8 - Appreciated
- 9 - Good
- 10 – Ideal .

2.1 Case 1: Automotive - Dip paint simulation for car bodies and frames

2.1.1 Introduction

We want to explain a dip paint simulation by using triangulated solids as the underlying surface describing format of the object to be simulated. The triangulated solid and some input parameters of the paint bath of an entire car body while dipping through the bath need to be sufficient to perform a dip paint simulation. This dip paint simulation needs to detect all non- and badly painted areas caused by gas bubbles. Additionally, another result of the dip paint simulation is the status of residual liquid, once the entire car body has emerged from the bath. The goal is to reduce the liquid carry over from one bath into the next one or into the oven.

2.1.2 Flow Volumes

In order to perform the dip paint simulation WP1 has developed a decomposition of the 3 - Dimensional space in so-named Flow Volumes. The flow volumes are the maximal subsets of the free volume which are bounded only by horizontal planes on top and bottom and by triangles of the triangulated solid with the property that every horizontal slice of the flow volume is connected. The latter property makes them especially useful for dip paint simulation since it guarantees a unique filling level within each flow volume.

2.1.3 Flow Paths

Another important question in the simulation of a dip coating process arises: If a certain flow volume is filled up, which other flow volumes will be filled next? Here the liquid will often flow or drop through several other flow volumes until it reaches a local minimum. Which flow volumes exactly are influenced if one flow volume starts overflowing cannot be determined from the volume graph. The flow volumes have to be organized into a graph which encodes the adjacency relationship between neighboring volumes. For instance, if a flow volume is filled with liquid, then the liquid will start to fill up one of the neighboring flow volumes, and it is important to know which one will be filled up first. It is also important to detect whether these so-named flow-paths end in neighboring flow volumes or continue flowing unless no lower flow volume can be found anymore.

2.1.4 Perform the Simulation

At this stage all developed sub–algorithms need to be connected to one piece. This so-called dip paint simulation will be able to compute the air and liquid behavior when an entire car body is riding through the paint tank – see Figure 2 as illustration for one of the many paint shop possibilities.

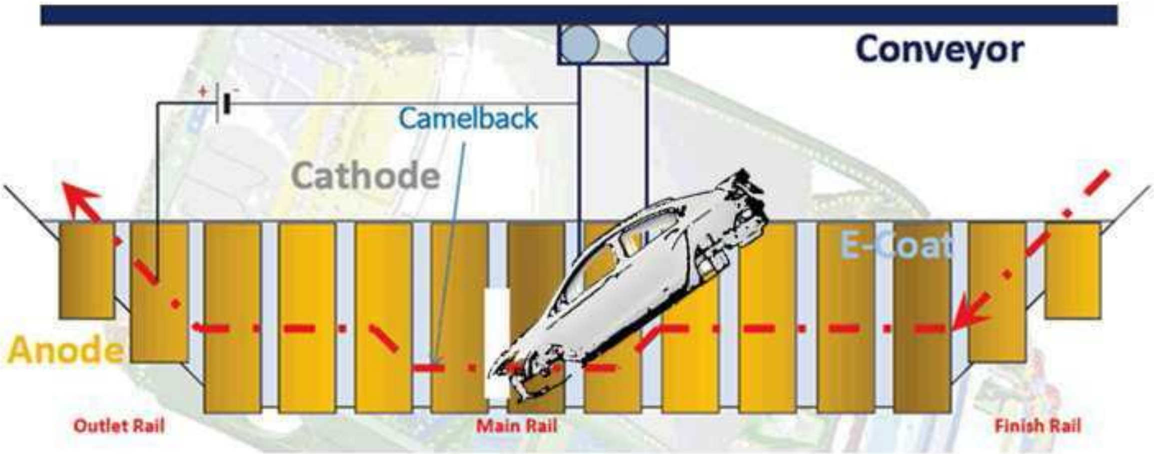


Figure 2: This Figure illustrates the path of an entire car body while it moves through the paint tank.

2.1.5 Validation Process

In cooperation with General Motors, more precisely, with Adam Opel GmbH, a validation cube has been designed and constructed to analyze different results. The validation cube – see Figure 3 and Figure 4 – has been dipped in and out of a small tank. A transparent test cube has been built to visualize the water distribution after fill/drain. The total interior volume is 4.88 liter. Each compartment is connected with a hole to the neighboring compartment. Two holes to the outside exist for fluid access or drainage. The hole diameter is 0.02m. The outer dimensions are 0.2×0.2×0.2m.

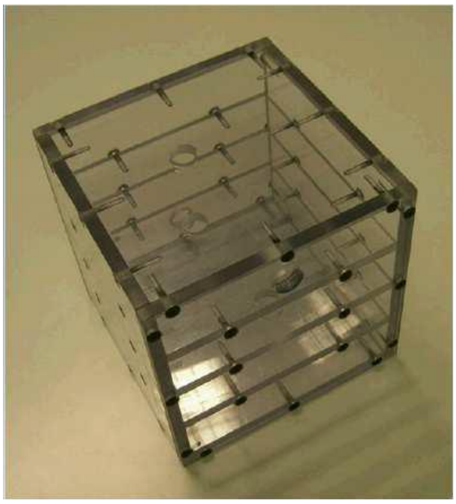
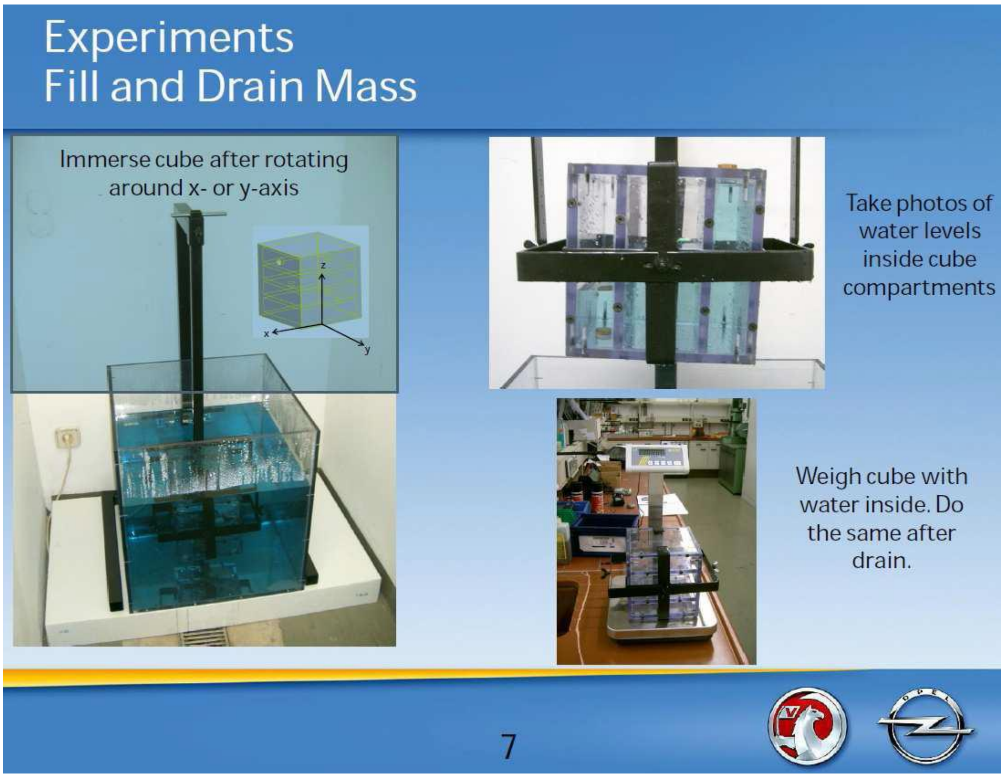


Figure 3: Validation cube

Tests have been performed by using the following methods:

- Reality
- Hydrodynamic Case i.e., CFD (Computation Fluid Dynamics) simulation
- Hydrostatic Case i.e., the old version of ALSIM
- Hydrostatic Case i.e., the new version of ALSIM developed within the ″Terrific″ project.



Experiments
Fill and Drain Mass

Immerse cube after rotating around x- or y-axis

Take photos of water levels inside cube compartments

Weigh cube with water inside. Do the same after drain.

Figure 4: This description was made by Opel Germany.

In Figure 5 one can see the three different positions of the validation cube which have been analyzed when completely dipped in and after dipping out. For getting the result after dipping in, the two holes to the outside have been closed after dipping in. To determine the result after dipping out, the holes have been opened again.

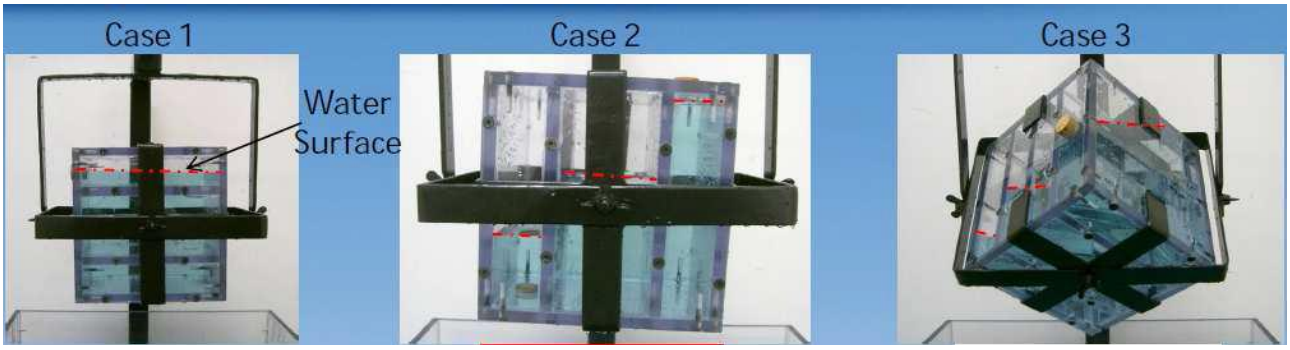


Figure 5: This Figure illustrates three different angle positions of the validation cube and the status of the remaining water after dipping in.

Figure 6 and Figure 7 illustrate the different results. The horizontal axis points out the experiment number, corresponding to the three cases seen in Figure 5. The vertical axis shows in Figure 6 the drain mass [%Total] and in Figure 7 the fill mass [%Total].

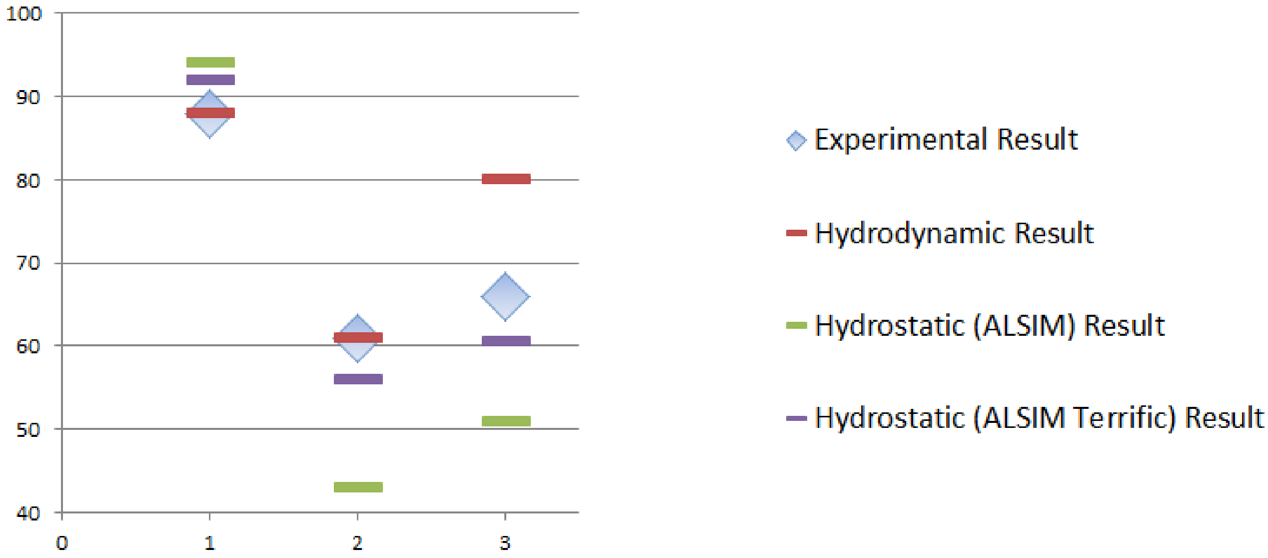


Figure 6: The different fill results of the three cases after dipping in.

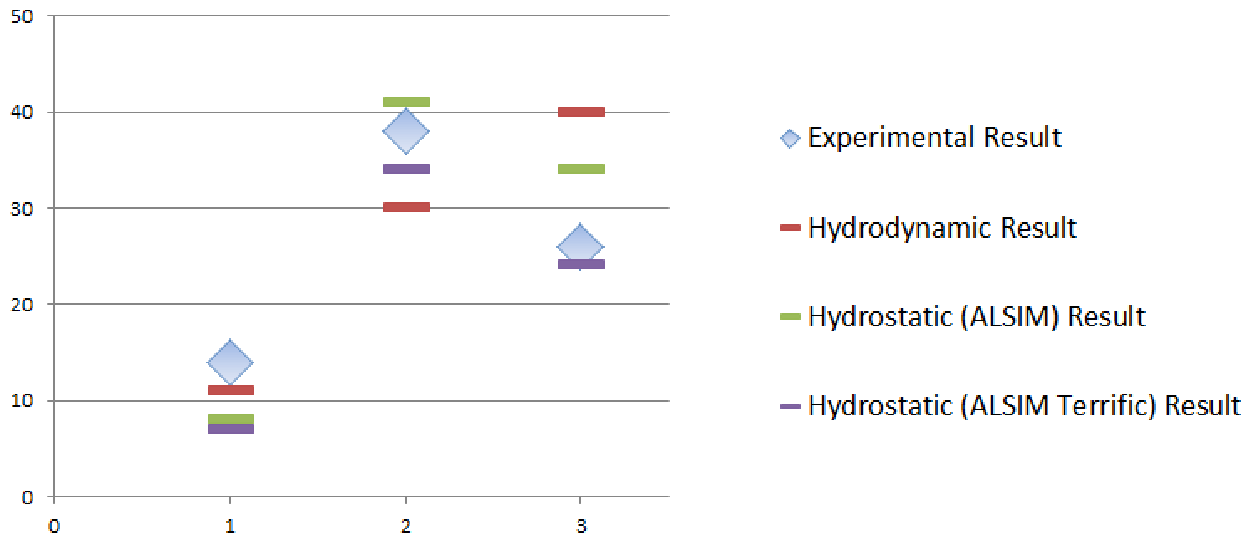


Figure 7: The different fill results of the three cases after dipping out.

2.1.6 Conclusion

With respect to the examples validated by General Motors the results of WP1 within Terrific will lead to huge enhancements in the performance of the dip paint simulation. The results will get more exact than the current version of ALSIM and in some cases the exactness of the results will be even better than existing CFD simulations can compute.

This evaluation leads to the following KPI measurements.

Table 2: KPI measurements dip painting

Key Performance Indicator	Value	Current Process	IGA
Simulation accuracy / precision in predictions	3	7	9
Simulation processing time	3	6	10

More detailed information can be seen in the Deliverable 1.3 [11] of WP1.

2.2 Case 2: Railway - Isogeometric simulation in railway technology

2.2.1 Introduction

The main goals of WP2 “Isogeometric railway technology” are to develop isogeometric methods for shape optimization and nonlinear frequency analysis. As intermediate step, the development of an isogeometric finite element solver for the linear elasticity problem of structural mechanics on multi-patch geometries has been defined and implemented for D2.3.

As part of the validation process of Case 2, we can so far compare the simulation process based on our isogeometric structural mechanics solver with the process based on currently available commercial tools and evaluate the results according to the methodology and performance indicators introduced in D5.2.

Since the *TERRIFIC part* serves as an advanced, common demonstrator of the whole process from CAD model, over isogeometric analysis-suitable volume parameterization (see Figure 8) to isogeometric structural analysis and manufacturing, we use it for validation here. For this advanced part with a complicated geometry featuring indents and beveled edges, we show results of isogeometric finite element analysis and validate them in comparison to commercial FEM software ANSYS® Mechanical.

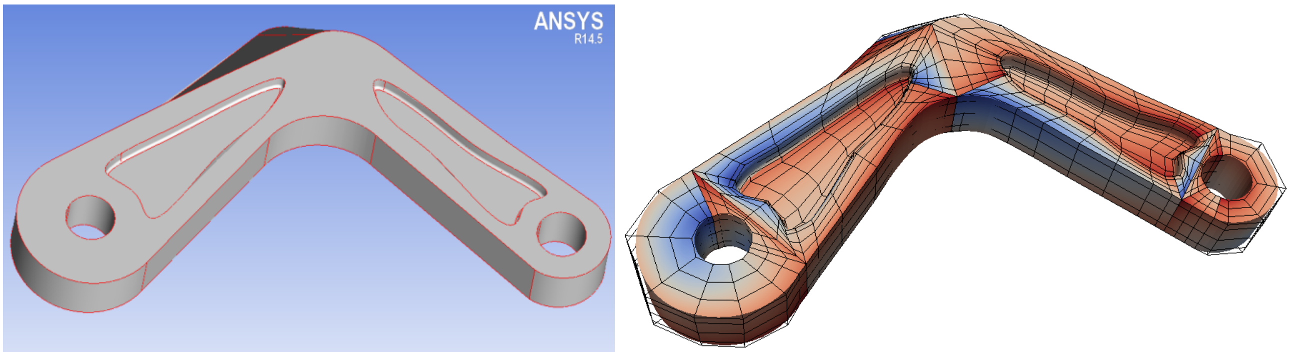


Figure 8: NURBS surface model of the TERRIFIC demonstrator part from CAD (left). Isogeometric analysis-suitable parameterization, consisting of 15 trivariate NURBS patches. Mesh of control points and actual geometry are displayed (colored by parameterization) (right).

2.2.2 Validation Process

Validation Setting

As described above, we solve the linear elasticity equation on a multi-patch NURBS parameterization in 3D (see Figure 8). Since the part is manufactured by project partner INRIA from the aluminum alloy AU 4 G, we have to consider the following material parameters:

$$E = 74\ GPa, \quad \nu = 0.33, \quad \rho = 2800\ kg/m^3.$$

The center-to-center distance of the two holes is 229 mm and the weight of the whole part is 1.30 kg. For the static computations the inner surfaces of the left hole on the Figures is subject to a Neumann surface load with

$$f = (20,-14,0)\ N/mm^2$$

and the inner right hole is fixed by zero-Dirichlet boundary conditions.

For isogeometric finite element analysis (IGA), the volume parameterization was generated by Work Package 6 (see Figure 8) and consists of 15 B-Spline volume patches with degree 3 in all directions with a total of 2,484 control points. For analysis we have a total of 9,174 degrees of freedom after refinement of solution spaces, including coupling conditions of the patches.

In the preprocessing step within ANSYS®, a mesh of 104,602 quadratic tetrahedral elements with 144,744 nodes was automatically generated from the original CAD geometry.

Note that the number of degrees of freedom in the ANSYS® (FEM) mesh is roughly 50 times higher than in the isogeometric parameterization we used, but the mesh was auto-generated and not fine-tuned regarding computational accuracy.

Validation Results

The results of the analysis, displacements and von Mises stress are visualized in Figure 9 and Figure 10 for our isogeometric solver and ANSYS® respectively. Considering the boundary conditions, the shape of the displaced part and the peak of the stress distribution occurring at the bending look reasonable. The maximum displacement is *7.0 mm* for both IGA and FEM, the general stress distributions match very well and the stress maxima are also very close with *680.7 MPa* for IGA and *666.8 MPa* for FEM.

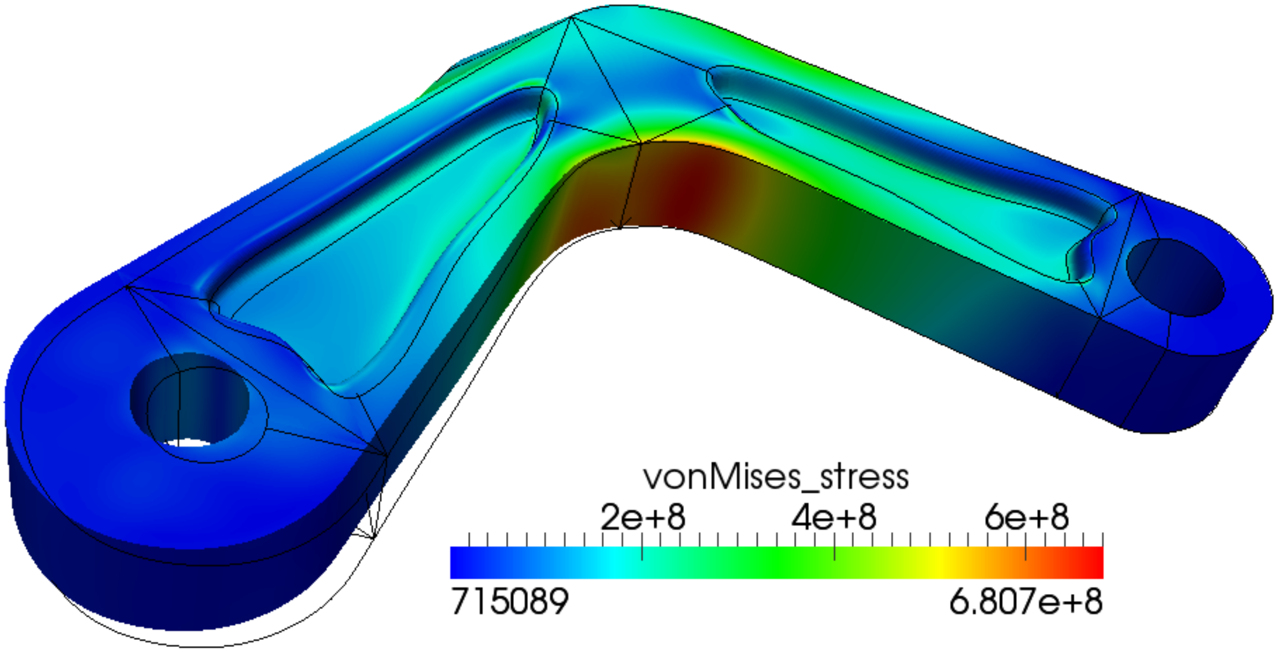


Figure 9: Isogeometric result of displaced demonstrator, colored by von Mises stress in [Pa]. Stress peak occurs near the bending.

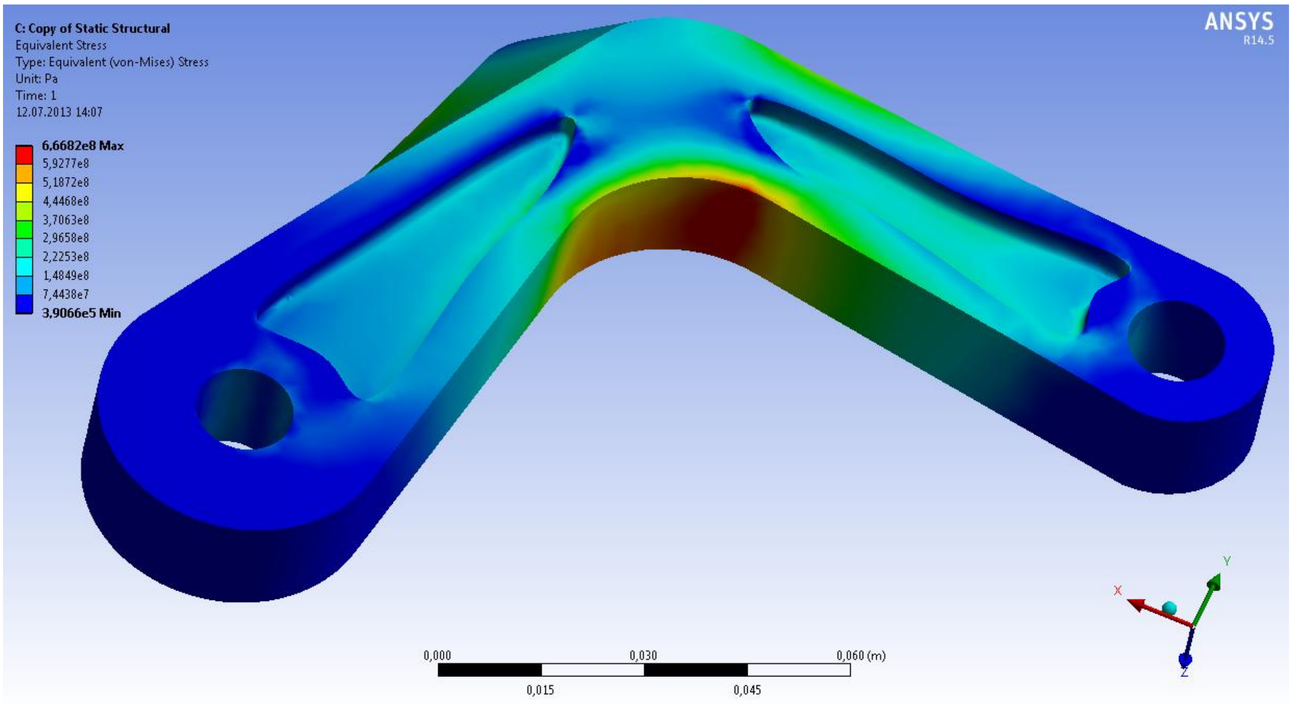


Figure 10: ANSYS® analysis result of displaced demonstrator, colored by von Mises stress in [Pa]. Stress distribution and peak values match isogeometric results in Figure 9 very well.

Taking a closer look at the stress distributions in Figure 9 and Figure 10, one can see discontinuities of stress, which cannot be avoided when enforcing a continuous displacement field over patch interfaces only in IGA, but also unphysical high stress values. These stress peaks occur for both IGA and FEM at certain geometrical features where the geometry is (almost) singular. It is still up to future work to try to improve the isogeometric model in order to avoid singular points of the parameterization and also improve postprocessing by finding means to circumvent the evaluation at singular points. Even though the FEM mesh is already very fine there, it suffers from the near singular parameterization as well, since some tetrahedrals have small angles and concave edges.

Furthermore we have also solved the corresponding eigenvalue problem for the zero-Dirichlet boundary condition of the right hole and determined the eigenfrequencies listed in Table 3. Here we find a very good correspondence of the results of our isogeometric solver with the ones obtained by ANSYS®. The deviation of corresponding eigenfrequencies is less than 0.5% and thus very small.

Table 3: First 6 eigenfrequencies fk of TERRIFIC demonstrator computed with IGA and FEM. Results match very well and deviation between IGA and FEM is very small.

k	**1**	**2**	**3**	**4**	**5**	**6**
f_k [Hz] (IGA)	220.4	357.5	735.7	1223.2	2133.1	3337.9
f_k [Hz] (FEM)	219.5	356.4	732.3	1221.2	2127.8	3340.0
Deviation [%]	0.42	0.31	0.46	0.16	0.25	0.06

To sum up, with the computations carried out by the commercial FEM software ANSYS®, we have validated our isogeometric finite element solver for a complex industrial multi-patch geometry, i.e. the TERRIFIC part. We could notice that both computations lead to a very good agreement of results for linear static and eigenfrequency analysis, even though the number of degrees of freedom used for IGA was significantly smaller than in FEM.

2.2.3 Evaluation of Key Performance Indicators (KPI)

In D5.2 a number of Key Performance Indicators was defined in order to describe the features that affect the feasibility of the current process using commercially available tools (FEM) and the isogeometric analysis process (IGA). In Table 4 we have summarized the evaluation of the relevant KPIs for the validation of our isogeometric structural solver against commercial software such as ANSYS®. The importance of the KPI is weighted with a value between 0 and 3 and the grades for FEM and IGA are assigned from 6 to 10.

In *accuracy and simplicity of the description of geometries* IGA outperforms FEM, because it is possible to exactly represent the geometries designed within CAD software by the functional description with NURBS in isogeometric analysis, while for FEM an approximation with tetrahedral elements has to be generated.

The *meshing effort* within the current process is quite high and can be very time-consuming, however there are automated mesh generators available simplifying the process. For IGA a (multi-patch) volume parameterization has to be generated from an original CAD surface description, which is not a trivial process and still under research.

Even for a high number of degrees of freedom (DOF), *computational time* of commercial FEM solvers like ANSYS® is pretty fast, since the software has been under development and codes optimized for decades. Thus it is clear that our research code cannot yet cope with them.

Due to the higher smoothness of the functions employed in IGA compared to the piecewise continuous element-wise representation in FEM, *simulation accuracy* is higher for same number of DOFs.

As mentioned before, the product maturity of commercially available software is much higher than of our research software and thus it is *easier to use* from an end-user point of view.

Table 4: Key performance indicators evaluation: Comparison of current process (FEM) with isogeometric analysis process (IGA).

Key Performance Indicator	Value	FEM	IGA
Accuracy in the description of geometries	2	6	9
Simplicity in the description of geometries	2	6	9
Meshing effort	2	7	7
Computation time	3	9	7
Simulation accuracy / precision in predictions	3	7	10
Ease of use	1	9	6

Our evaluation of KPIs shows a pretty balanced picture for the comparison of standard and isogeometric methods. Isogeometric analysis has clear benefits compared to classical FEM, but obviously the currently available research software cannot yet be as mature as the commercial tools.

2.3 Case 3: Aeronautics - Isogeometric approaches for typical aircraft parts

2.3.1 Introduction

The basic goal of WP5 is to compare aspects of functionality, cost, time, quality and resources of current simulation processes with the same aspects for processes where isogeometric technology is applied. In order to do so in use case 3 we first focused on a thermal problem solved on a pneumatic pipe. The same problem will be solved with both the current industrial process and the IGA (isogeometric analysis) approach. A quantitative comparison regarding key performance indicators was performed. The thermal model problem can be considered as a subset of the actual industrial benchmark problems, the delivery of which is scheduled at month 36. Besides its simplicity this model problem holds the basic features of both the current simulation process, and the new process introduced with IGA. This is the reason why this problem is useful in quantifying the key performance indicators listed below. This use case report is divided into the model problem formulation and the description of the validation process. Results and key performances indicators description and evaluation conclude this section.

2.3.2 Model Problem Formulation

The model problem is a thermal problem defined on the pneumatic pipe geometry. The temperature diffusion for still air is modeled by the well known Fourier’s equation:

$$\begin{aligned} -\lambda\Delta u = f \quad & \text{in } \Omega, \\ u = 300 \quad & \text{on } \partial\Omega \end{aligned}$$

The parameter values are specified for air; their values and units are displayed in Table 5. The thermal source f is considered uniformly distributed over the domain. The problem is then completed with Dirichelet boundary conditions.

Table 5: Physical parameters for the thermal problem

Parameter	Symbol	Value	Units
thermal conductivity	λ	0.026	W/(m K)
thermal source	f	10	W/m3
temperature	u	unknown	K

2.3.3 Validation Process

Validation Setting

In this section we define the validation process. The model problem defined at the previous section will be solved with the current approach and the new Isogeometric approach. The following paragraphs will briefly describe both the current approach and the new Isogeometric one.

- *Current approach*: this approach is based on finite volumes discretization of the differential operators describing the physical problem. The software used to perform this analysis is STAR-CCM++.
- *Isogeomteric approach*: in this approach the native geometry shape functions are used as basis functions for the variational problem corresponding to the strong form presented at the previous section.

In both cases we set up a second order accurate solver.

Validation Results

Figure 11 presents the results for the analysis of the model problem using both the current approach (right column) and the new isogeometric approach (left column). The snapshots present the solution for different meshes. In both cases the spatial refinement is stopped when satisfactory accuracy is reached.

These results show that the isogeometric approach converges with a considerably smaller number of cells. This advantage drastically decreases the number of shape functions needed for the description of the domain and the numerical convergence of the method. These achievements will be listed together with Key Performance Indicators (KPI) at the next section.

Isogeometric Approach *Current Approach*

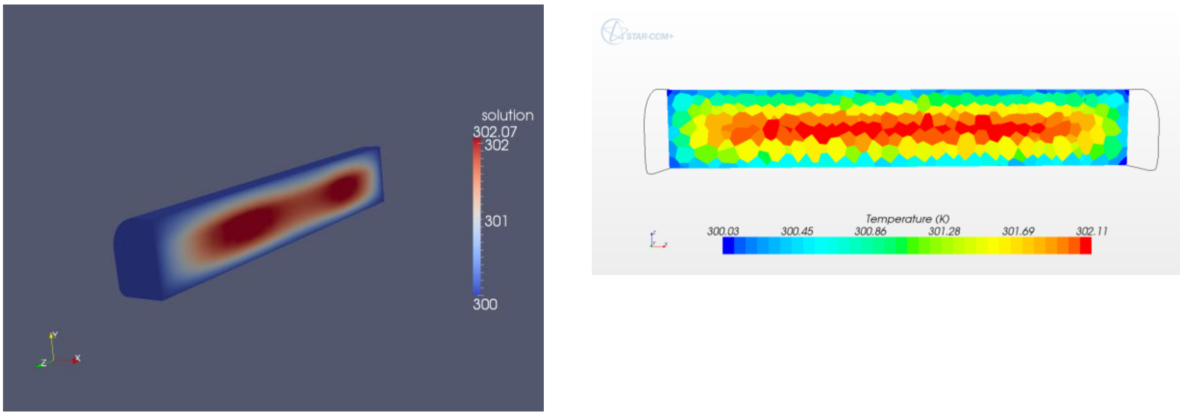


Figure 1a: 96 cells. ***Figure 1b:*** 3,614 cells.

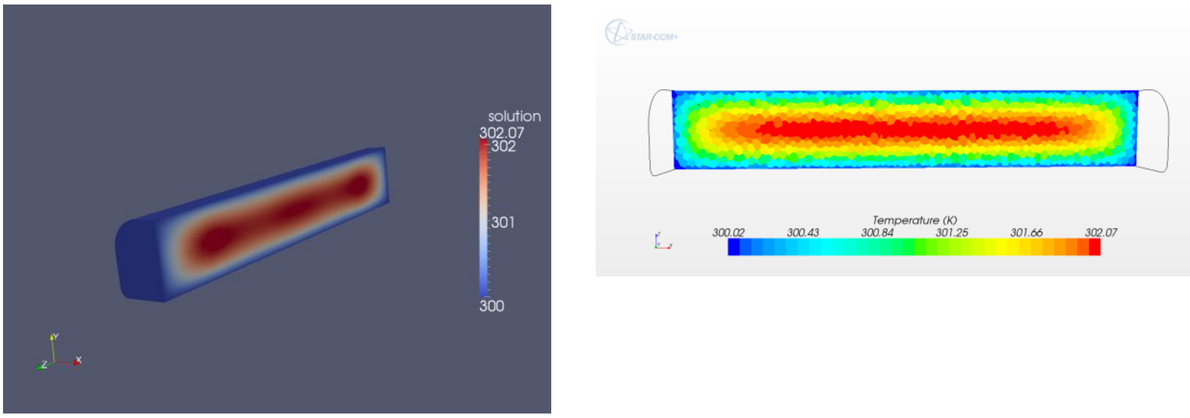


Figure 1c: 288 cells. ***Figure 1d:*** 29,811 cells.

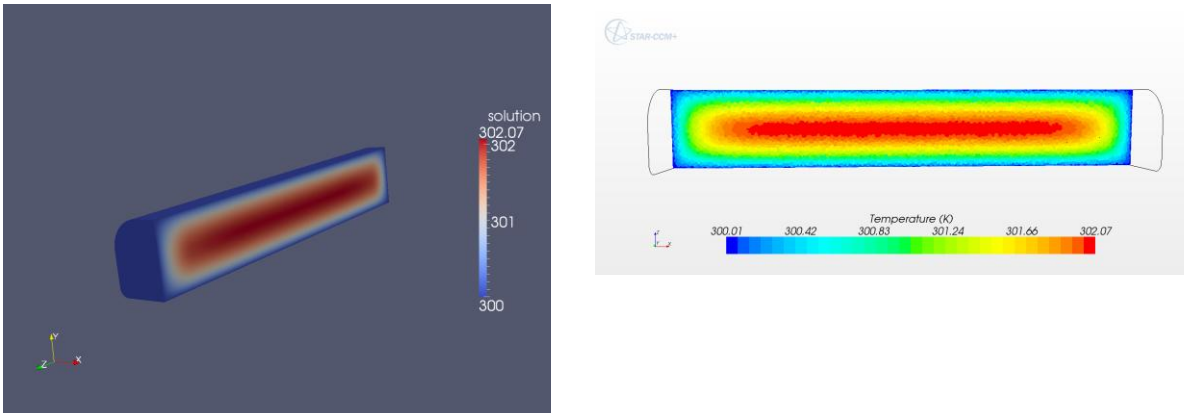


Figure 1e: 1,573 cells. ***Figure 1f:*** 124,695 cells.

Figure 11: Convergence for current and isogeometric approach

2.3.4 Definition and Evaluation of Key Performance Indicators (KPI)

Key Performance Indicators describe the features that affect the feasibility of the current process and the IGA process. Their definitions follow in the subsequent lines. The quantitative evaluation of the KPIs is provided in Table 6. The experiments showed a considerable difference in the number of cells required for the analysis of a model; this number is much smaller – and, thus, significantly better - for IGA than for traditional methods. This benefit could not be captured by one of the originally specified KPIs; a new one is, therefore, proposed (see in the following list and item #9 in Table 8).

Exactness of the geometry. Isogeometric analysis provides the capability of exactly representing the solution domain.

CAD import operations. In the current process, given a CAD representation of the geometry, this has to be processed in order to be imported into the numerical solver. IGA takes advantage of using natively the shape functions of the CAD data.

Meshing operations. The imported geometry needs then to be discretized depending on the master element definition. In IGA the meshing operations are substituted by natural operations on native geometry shape functions. These operations include knot refinement and degree elevation.

Number of shape functions to reproduce the discretized geometry. In the current process the original geometry is discretized to fit the discrete solution space. In the isogeometric approach the solution space includes the geometrical representation of the domain. This results in a far smaller number of shape functions that describe the domain.

Number of degrees of freedom at convergence. Once the problem is set up a sequence of refining processes takes place until convergence is achieved, see the sequence of results from figure 1a to 1f. With the isogeometric approach convergence is achieved involving a smaller number of cells. This results in a smaller number of unknowns for a given accuracy.

User interfaces. User interfaces set up the environment where the analysts perform their simulations. The current process can rely on graphical interfaces, the IGA approach requires to be implemented in native c++11. On one hand graphical interfaces simplify the model implementation. On the other hand graphical interfaces hide numerical details of the method to the user, resulting in a weaker control of results.

Table 6: Key performance indicators evaluation, grades are assigned from 6 to 10

Key Performance Indicator	Value	Current Process	IGA
Exactness of the geometry.	2	6	10
CAD import operations.	1	6	8
Meshing operations.	2	8	9
Number of shape functions to reproduce the discretized geometry.	2	6	10
Number of cells of freedom at convergence.	3	6	9
User interfaces.	1	7	6

2.4 Case 4: Computer-Aided Manufacturing - Isogeometric machining tools

2.4.1 Introduction

The basic goal of WP4 is to compare aspects of functionality, cost, time, quality and resources of current machining processes with the same aspects for processes where isogeometric technology is applied.

Machining tools are used to transform a digital model such as a collection of B-spline patches that defines the boundary of a solid into a real object to be manufactured. The precise control of these machining tools is a critical issue, on which the quality of the resulting products heavily depends.

To evaluate the practical behaviour of algorithms studied in this project, we have embedded them into the TopSolid CAD software in order to test them in an industrial context. The objective of the work developed during this second year of TERRIFIC is to settle down the framework, which allows us to test the implementation of methods of WP4 (and potentially of the other work packages) inside the TopSolid software developed by Missler.

2.4.1.1 The problems

During this second year, we focused on the Isoparametrization of multiple patches for path planning of milling tools.

This first problem consists of simplifying a geometric representation of a surface composed of several patches into a single one, made of one B-Spline surface. The purpose of this transformation is to construct a parametric surface, the isoparametric curves of which can be used to drive the cutting tool.

Since the TERRIFIC part serves as an advanced, common demonstrator of the whole process from CAD model, over isogeometric analysis-suitable volume parameterization to isogeometric structural analysis and manufacturing, we use it for validation here. For this advanced part with a complicated geometry that features discontinuities between faces, we show results of the isogeometric parametrization, which provides a single surface, and validate them in comparison to the basic patches of surfaces found in the commercial TopSolid software package.

2.4.1.2 Embedding dedicated code into CAD software

The algorithms developed by INRIA have been further improved towards integration into TopSolid. To embed an external functionality into given software, the following issues have been covered:

1. Make the two pieces of software communicate.
2. Transform data structures of one software into the data structure of the other software.
3. Bind the external functionalities to new functions in the given software.

2.4.2 Validation Results

The following steps have been conducted after the initial completion of the integration of INRIA’s algorithms into TopSolid.

The demonstrator part, initially provided as a STEP file, has been treated inside TopSolid, using the isogeometric parameterization algorithms of INRIA.

As initial results, the quality of the resulting surface looks a lot better, when using existing analysis and comparison tools of TopSolid, as shown in Figure 12, below.

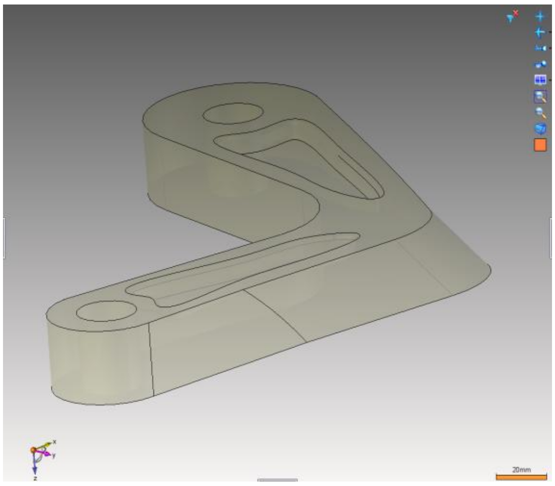


Figure 12: Initial definition of the demonstrator part (STEP data)

2.4.2.1 Definition of the working area

We are going to treat the following area that is indicated below in blue.

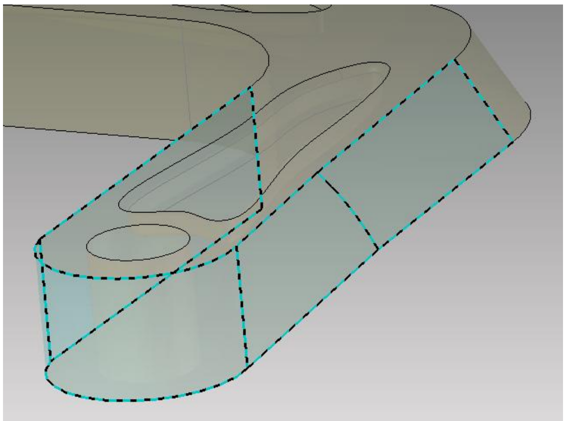


Figure 13: Tool working area definition

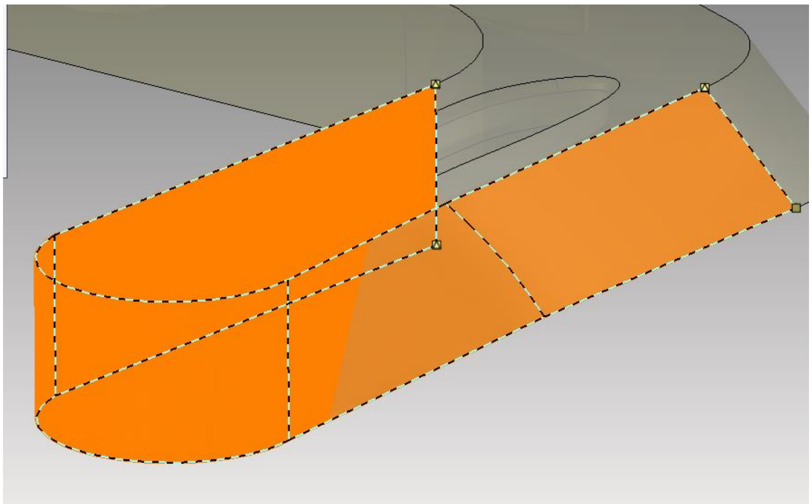
The analysis focused on the curvature, on the reflection lines, on the isoparametric lines and on the distance between the computed surface and the initial one.

It is important to notice that the selected area is composed of simple supporting surfaces such as planes and cylinders, so that dedicated re-parameterization techniques could have been employed here to compute a single B-spline surface from the boundary curves of these patches.

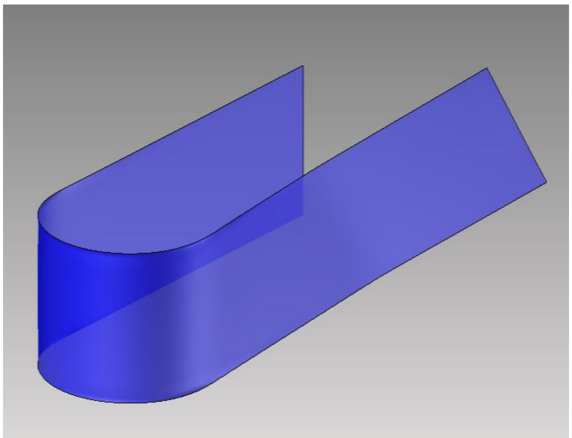
2.4.2.2 Results

After several trials, a mesh size of 1mm was retained towards optimal results:

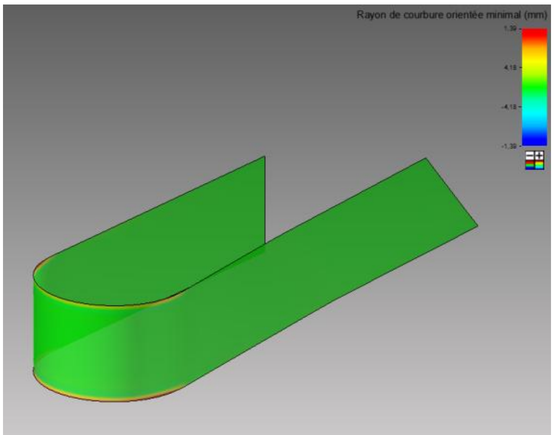
CPU time: 5 min 15 s, which is rather long.



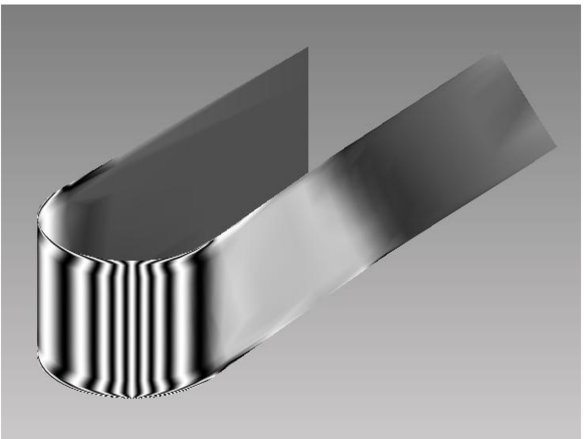
Computed surface:



Curvature analysis:

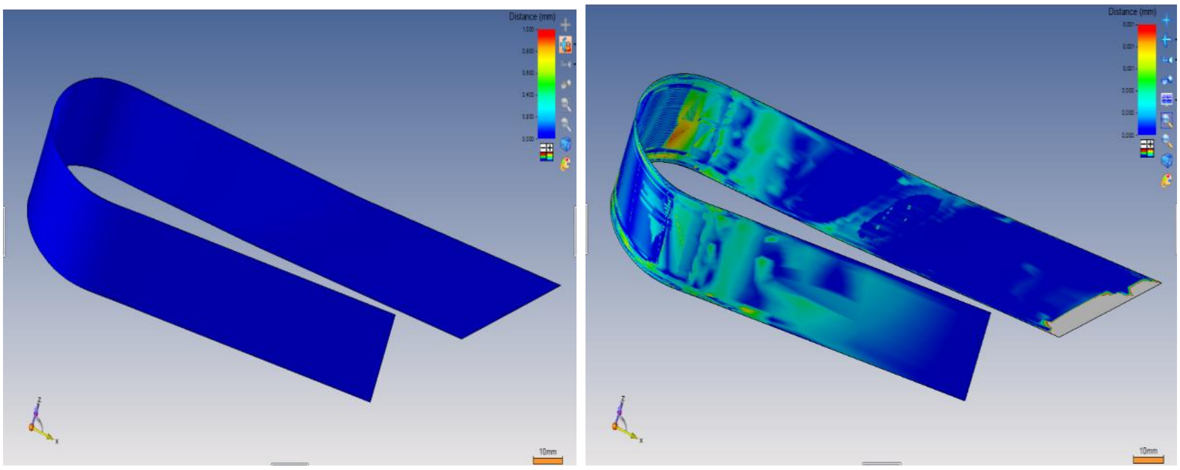


Some distortion appears on the border:



I

Geometric gap (scale 1mm & 1 μm):



The curvature is still more important on the boundary of the surface. The computation time is significant. The geometric precision is almost perfect, i.e., in the order of a micron.

With a realistic rendering effect, we observe that there is no continuity of the light, before replacement of the patch collection:

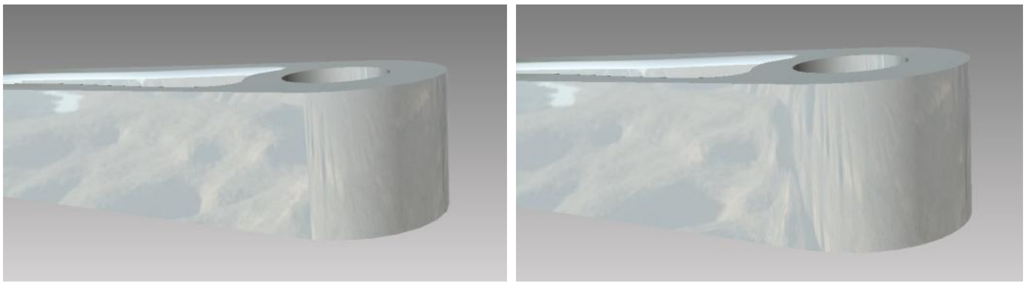


Figure 14: Rendered images of the test part

After replacement (right image), the light reflection is perfectly continuous.

This has influence on the control of machining tools, as illustrated below:

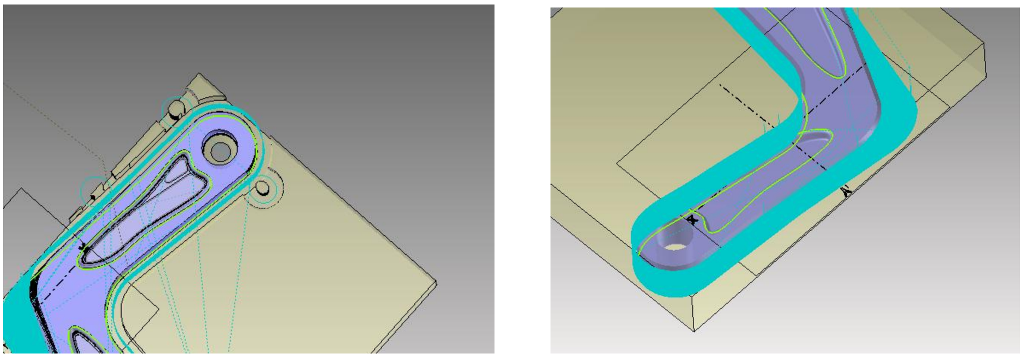


Figure 15: Test part machining model with (left) and without (right) issues

On the left image, there are tangency problems and the tool path of the cutting tool projected on the initial surface is not “smooth”. This implies unnecessary external loops of the cutting tool that are visible on the above picture (potential collision of the tool with the part; the tool might brake).

The simplification of the surface made the loops disappear (right image) which results in a better quality on the machined part and in a safer tool path (in terms of clashes, collisions of the tool with the part).

Figure 16: Final part after machining

2.4.3 Key Performance Indicators (KPI)

The quantitative evaluation of the KPIs for industry case 4 is provided in Table 7.

Table 7: Key performance indicators evaluation: Comparison of current process (TopSolid machining) with isogeometric analysis process (IGA)

Key Performance Indicator	Value	Current	IGA
Accuracy in the description of geometries	2	6	9
Simplicity in the description of geometries	2	6	9
Computation time	3	N/A	6
Tool path generation	3	8	10
Ease of use	2	9	9

Comments on this table:

Accuracy in the description of geometries: the new algorithms bring much better continuity on the surfaces, which leads to better quality for machining.

Simplicity in the description of geometries: the process is much more automated which relieves the user of manual interactions.

Computation time: Such algorithm is not available in the present TopSolid software and we would think that calculation time is not important. However, this is today on the market a prevalent criterion for selecting a machining package among others.

Tool path generation: the quality of the generated path is close to the optimal that one can imagine.

Ease of use: no change, as this issue is ruled by the TopSolid User’s Interface. It is however an important issue.

2.4.4 Conclusion

Our evaluation of KPIs shows a pretty balanced picture for the comparison of standard and isogeometric methods. Isogeometric algorithms have clear benefits compared to classical tool path production.

Many more test cases have to be realized towards bringing this approach to a quality, reliability and confidence level of a standard commercial package.

3 Analysis of initial validation results

The initial validations have been analyzed to conclude with corrective actions. The main question for this Task 5.1 is whether we need to revise the initially defined process and the identified KPIs. The objective of the task is to provide convincing arguments for industry in general and for engineering software vendors in particular. The commercial players need to be convinced to invest into the resource consuming effort of replacing or at least enhancing some of their core technology. Therefore, not only does isogeometry need to have significant advantages, but TERRIFIC needs to show them in figures.

3.1 Key performance indicators review

The results reported from the use cases are collected in the summary Table 8, below. The types of KPIs have been harmonized into the ones defined in Deliverable 5.2, see [9], whenever the here reported semantics matched the originally intended meaning. Else new KPIs were introduced. The table is sorted to list in subsequent rows measurements of the same KPI by different use cases.

The columns of this table have the following meaning:

KPI	: name of a key performance indicator
Case	: identifier of a TERRIFIC industrial use case
Weight	: importance of a KPI to a use case
CT	: rating of the current technology option for a KPI
IGA	: rating of the isogeometric analysis option for a KPI
New	: if a cell has the value "x", this KPI was not defined in D5.2 [9]
Comment	: remark concerning this KPI or this use case.

Table 8: KPI measurements summary

Id	KPI	Case	Weight	CT	IGA	New	Comment
1	Accuracy of geometries	2	2	6	9		
1	Accuracy of geometries	3	2	6	10		
1	Accuracy of geometries	4	2	6	9		
2	Availability of standards						
3	Computation time	2	3	9	7		

Id	KPI	Case	Weight	CT	IGA	New	Comment
3	Computation time	4	3	NA	6		
4	Cost of commercialization						
5	Ease of use	2	1	9	6		
5	Ease of use	3	1	7	6		
5	Ease of use	4	2	9	9		
6	Effort for analysis design round-trip	3	1	6	8		Is called "*CAD import operations*" in case 3.
7	Integration into existing industry case environment						
8	Meshing effort	2	2	7	7		
8	Meshing effort	3	2	8	9		
9	Number of cells of freedom at convergence	3	3	6	9	x	Can this be merged with one of the existing ones?
-	Number of conversions between data and geometry formats						Will be merged with "Effort for analysis design round-trip".

Id	KPI	Case	Weight	CT	IGA	New	Comment
10	Product maturity	2					research code cannot yet cope with commercial FEM; "improve the isogeometric model in order to avoid singular points of the parameterization" "improve postprocessing by finding means to circumvent the evaluation at singular points"
11	Simplicity of geometries	2	2	6	9		
11	Simplicity of geometries	3	2	6	10		Is called "*Number of shape functions to reproduce the discretized geometry*" in case 3.
11	Simplicity of geometries	4	2	6	9		
12	Simulation accuracy / precision in predictions	1	3	7	9		Expect "results will get more exact than the current version of ALSIM and in some cases the exactness of the results will be even better than existing CFD simulations"
12	Simulation accuracy / precision in predictions	2	3	7	10		

Id	KPI	Case	Weight	CT	IGA	New	Comment
13	Simulation processing time	1	3	6	10		Expect "huge enhancements in the performance of the dip paint simulation".
14	Software sustainability						
	Tool path generation	4	3	8	10	x	
15	Training effort						

3.2 Analysis of measurements

The summary of the four industry cases in Table 8 shows some interesting trends:

a) IGA is applicable to industrial tasks, even at this still prototype-like stage, and its functionality is comparable to current technology, even though this has been developed over many decades.

b) Different KPIs are weighed the highest (3) by the different use cases, except for "Computation time", which is generally important. In all these three different cases ("Simulation accuracy", "Number of cells of freedom", "Tool path generation") IGA is clearly better than current technology, that is, two to three grades. Thus, IGA has a great potential, and not only in a single domain, but in different application areas.

c) Computation time is a serious issue and should be among the next ones to be addressed in the industrialization of IGA.

d) KPIs with relevance to industrial use, that is, beyond the pure technical evaluation of IGA, could not be measured, yet. The TERRIFIC scenarios are probably much closer to R&D than to operational use. In addition, IGA is not available, yet in the same commercial setting as current technology.

3.3 Corrective actions

The use of KPIs serves the purpose of evaluating IGA technology against current or traditional technology. The KPI set initially identified will be revised for the final measurements at the end of the project:

- The operation oriented ones, such as "Software sustainability" may be removed. It can be expected that the two technologies will not differ much in those.

- Some technological KPIs may be added, like the ones tagged as "new" in the above summary table. It seems that it is the technological benefits that make IGA superior to current solutions.
- Current measurements are just indications that one of the technologies is superior. Some industry cases have in addition provided concrete figures in their descriptions above. More of such figures are required, and they need to be connected to commercial KPIs. These shall enable commercial considerations, such as return of investment, to convince decision makers of end users and of vendors. Examples of such KPIs are the above "Simulation processing time", "Effort for analysis design round-trip" and "Meshing effort". Quantitative measures for those and similar ones need to become available towards the end of TERRIFIC.

3.4 Validation process and time line

Validation activities will continue as new tools in WP6 enable extended use case scenarios. New test data will be applied in more realistic workflows.

The final results of the validation activities will be summarized in D5.6, Final validation of the project results, which is due in month 36.

4 Conclusion

The process of validating the industrial cases and specifically their use of isogeometric analysis (IGA) is on track. This report contains initial evaluations for all four use cases. Several of the key performance indicators that were identified in D5.2 [9] could be applied to compare the usefulness of current technology with IGA. Especially for those indicators that the industrial partners consider most important IGA is clearly superior to what is in operation today.

The validation effort will continue for one more year and will finally be concluded in report D5.6 . The scope of measurements will increase as new tools and new test data become available. As industry else and especially engineering software vendors need to be convinced to include IGA in their products TERRIFIC must show not only qualitative results, but quantitative measurements of the benefits of IGA. Focus shall, thus, be on providing commercial KPIs in addition to the already satisfactory technical KPIs.

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