Large-scale EXecution for Industry & Society

Deliverable D9.7

Impact on Productivity and Business Process Improvement in Aeronautics

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GLOSSARY

ACRONYM	DESCRIPTION
BD	Big Data
CAE	Computer-aided Engineering
CFD	Computational fluid dynamics
CPU	Central processing unit
DOE	Design of experiments
FV	Finite Volume
GPU	Graphics processing unit
HPC	High performance computing
HW	Hardware
IT	Information Technology
KPI	Key Performance Indicator
LP	Low-pressure
MPI	Message Passing Interface
OpenMP	Open Multiprocessing
RANS	Reynolds Averaged Navier Stokes
SFC	Specific Fuel Consumption
SME	Small and medium-sized enterprise
SPH	Smoothed-particle hydrodynamics
SW	Software
URANS	Unsteady Reynolds Averaged Navier Stokes

WP	Work Package

TABLE OF PARTNERS

ACRONYM	PARTNER
Avio Aero	GE AVIO SRL
Atos	BULL SAS
AWI	ALFRED WEGENER INSTITUT HELMHOLTZ ZENTRUM FUR POLAR UND MEERESFORSCHUNG
BLABS	BAYNCORE LABS LIMITED
CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
CIMA	CENTRO INTERNAZIONALE IN MONITORAGGIO AMBIENTALE - FONDAZIONE CIMA
CYC	CYCLOPS LABS GMBH
ECMWF	EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS
EURAXENT	MARC DERQUENNES
GFZ	HELMHOLTZ ZENTRUM POTSDAM DEUTSCHESGEOFORSCHUNGSZENTRUM GFZ
ICHEC	NATIONAL UNIVERSITY OF IRELAND GALWAY / Irish Centre for High-End Computing
IT4I	VYSOKA SKOLA BANSKA - TECHNICKA UNIVERZITA OSTRAVA / IT4Innovations National Supercomputing Centre
ITHACA	ASSOCIAZIONE ITHACA
LINKS	FONDAZIONE LINKS / ISTITUTO SUPERIORE MARIO BOELLA ISMB
LRZ	BAYERISCHE AKADEMIE DER WISSENSCHAFTEN / Leibniz Rechenzentrum der BAdW
NUM	NUMTECH
O24	OUTPOST 24 FRANCE
TESEO	TESEO SPA TECNOLOGIE E SISTEMI ELETTRONICI ED OTTICI

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EXECUTIVE SUMMARY

The LEXIS (Large scale EXecution for Industry & Society) Project is building an advanced engineering platform at the confluence of HPC, Cloud and Big Data (BD) which will leverage large scale geographically distributed resources from existing HPC infrastructure, employ Big Data Analytics solutions and augment them with Cloud services. This project relies on three large scale pilots in industrial and scientific sectors (Aeronautics, Earthquake and Tsunami, Weather and Climate) to validate and deploy its technology and infrastructure improvements, assigning to each pilot its own work package. One of the targets of this validation is the analysis of how the adoption of the state-of-the-art HPC/Cloud/BD technologies deployed in LEXIS may positively influence the productivity and produce remarkable enhancements in the business processes involved in the three considered large-scale pilots. Impacts on the targeted sectors are the focus of Work Package 9 (WP9), that this deliverable is framed within. More specifically, this deliverable illustrates the impacts on engineering productivity and the improvements on the engineering business process deriving from the implementation in LEXIS of the Aeronautics Large-scale Pilot, that relies on the advanced SW technologies developed in Work Package 5 (WP5 - Aeronautics Large-scale Pilot) and HPC/Cloud/BD platforms and techniques designed in WP2 (LEXIS Requirements Definition and Architecture Design) along with WP3 (Data system and data management) and WP4 (Orchestration and cloud services).

The aim of the Aeronautics Large-scale Pilot led by Avio Aero in LEXIS is to significantly improve the feasibility and exploitation of advanced Computer-Aided Engineering (CAE) numerical modelling capabilities able to predict the fluid-dynamic behaviour of aircraft engine critical components. From both a digital technology and business perspective, a marked step change is thus envisaged: faster and more accurate CAE analyses that exploit newly deployed HW/SW resources in an innovative cross-converged HPC/Cloud/BD environment enabling the implementation of greatly improved or newly designed Computational fluid dynamics (CFD)-based engineering methodologies. To meet this ambitious objective in WP5, the industrial applicability of the LEXIS advanced engineering platform is under investigation through two aeronautical engineering case studies:

- The “Turbomachinery Use Case” regarding a turbomachinery configuration,
- The “Rotating Parts Use Case” referring to rotating parts representing gearboxes,

both designed to examine complex fluid dynamic behaviour in aeronautical engine critical components. With a specific look at their differences, Turbomachinery Use Case, that is based on CPU-demanding, data-intensive and time-consuming unsteady CFD simulations of a LP (low-pressure) turbine, mainly aims to reduce as much as possible the running time of the adopted CFD application solver to calculate faster all the engineering variables of interest, such as pressure, density, momentum or stagnation energy of the turbomachinery flow field. Instead, Rotating Parts Use Case, which is built on sophisticated CFD simulations aimed at studying complex flow fields in mechanical parts rotating at high speed in a multi-phase mixture (air/oil), is focused on supporting the execution of the used CFD application solver and optimizing its set-up with the final target of predicting key phenomena involved in the rolling gears, like wind-age effects and resistant torques both impacting on mechanical efficiency and power transmission levels of gearboxes. Looking to the wider scenario of Aeronautics in Europe, the methods developed and the innovations pursued within WP5 in LEXIS can be adopted from other companies in the aeronautical domain, like European jet engine manufacturers and their OEMs, allowing them to facilitate a significant increase of productivity and a relevant amelioration in engineering analysis processes, besides the opportunity to benefit from the usage of very advanced HPC/Cloud/BD platforms.

In this context, the present document D9.7 is intended to illustrate the impacts on the productivity and the business process improvements resulting from the implementation in LEXIS of the two above-mentioned aeronautical engineering case studies included in WP5.

Position of the deliverable in the whole project context

This deliverable is the result of dedicated activities in WP5 that, carried out in the context of the following tasks:

- Task 5.1 - HW/SW Integration Requirements,
- Task 5.2 - Turbomachinery Use Case Set-up and Run,
- Task 5.3 – Rotating Parts Use Case Set-up and Run,

Task 5.4 Final Validation Assessment, has a precise relation with the impact strategy of the LEXIS project developed in WP9 and its related task:

- Task 9.4 Productivity and Business Process Improvement on targeted Large-scale Pilot, Replication, Innovation and IPR Management.

More specifically, such activities have been aimed to assess both the impacts on the productivity and the business process improvements that may be derived from the execution of the LEXIS Aeronautics Large-scale Pilot.

This Aeronautics Large-scale Pilot relies on CPU-intensive and time-consuming CAE simulations targeted to examine the complex fluid dynamic behaviour of LP turbines and gearboxes respectively through the Turbomachinery Use Case and the Rotating Parts Use Case, that are the two aeronautical engineering case studies included in LEXIS WP5. The complexity and difficulty in the development of such large-scale test beds arise out of obligation to combine the specification of the used SW application with the proper HW technologies and configurations aiming at the optimal mapping on the HW/SW infrastructure of the computing system used to execute it. Once fully implemented the most suitable HW/SW infrastructural layer, the deployment of the two above-mentioned aeronautical engineering case studies may be able to determine some positive impacts on the engineering productivity and notable improvements on the engineering business process based on faster and more accurate CAE analyses that have been carried out in the considered use cases.

Focusing on the presentation of such impacts and enhancements on the targeted aeronautical sector, Avio Aero is singly responsible for writing this deliverable without any direct contributions from the other LEXIS partners.

From a contractual standpoint, this report document has to be delivered at the end of M36.

Description of the deliverable

The main purpose of this document is to illustrate the expected increase in the engineering productivity and the improvements on the CAE business process related to the CFD investigations involved in the deployment in LEXIS of the Aeronautics Large-scale pilot, after summarizing the main targets and the status of the Turbomachinery Use Case and the Rotating Parts Use Case that this pilot is built on.

The discussion of the above-mentioned impacts and enhancements will be focused on the increase in productivity and the improvement in the CAE process involved in the two considered use cases, ending in the assessment of the impacts from the adoption of the state-of-the-art technologies used in LEXIS on those.

To conclude, some final remarks summarizing the main outcomes from the analysis of impacts on productivity and business processes improvements, that have been identified in the proposed Aeronautics pilot, and reporting potential future developments, as well as mentioning the relationship with the general impacts stated in the LEXIS grant agreement, will be provided.

1 INTRODUCTION

Aviation manufacturers and their OEMs face enormous challenges to design, test and build their products on-time and on-budget. They are tasked with engineering products of the highest technical complexity which also must meet the strictest safety and performance requirements. Quite simply: There is no room for error.

To succeed, aeronautical engineers need to heavily rely on CAE technology to gain accuracy, to save time and to reduce design cycles. Generally speaking, CAE involves the use of advanced HW/SW solutions to improve product design and resolve engineering problems for a wide range of industries, not limited to aeronautics. This can include simulation, optimisation and validation of products and processes, covering the entire engineering process from design to testing and the planning of manufacturing.

Framed in this context, the Aeronautics Large-scale pilot implemented in LEXIS intended to exploit sophisticated CAE software solutions coupled with next-generation HPC/Cloud/BD technologies to enable and validate innovative and faster investigation strategies for the design and optimization of critical aircraft engine's components. This pilot relies on long-running HW-intensive CAE simulations aimed to examine the complex fluid dynamic behaviour of LP turbines and gearboxes through the two aeronautical engineering case studies included in LEXIS WP5, the Turbomachinery Use Case and the Rotating Parts Use Case, respectively. The achievement of the target values for the Key Performance Indicators (KPIs) identified for the two above-mentioned case studies is supposed to have some positive impacts and business process enhancements in the considered aeronautical industrial sector in terms of increase in productivity and CAE process improvement.

In this deliverable the description of the impacts on the productivity and the business process improvements that are linked and consequent to the implementation of the Aeronautics Large-scale Pilot in LEXIS is provided. In detail, after the introductory part, this deliverable includes 3 main sections:

- 2 - The Aeronautics pilot: targets and status,
- 3 - Impact on productivity and business process improvement in the Aeronautics pilot,
- 4 - Summary.

Section 2 summarizes the targets and the main results of the Turbomachinery Use Case and the Rotating Parts Use Case that the Aeronautics Large-scale Pilot relies on and have been widely discussed in Deliverables D5.5 [1] and D5.4 [2].

Section 3 illustrates the improvements on the engineering business process and the effects of the increase of engineering productivity that may be derived from the implementation of the two considered use cases, together with the impacts resulting from the adoption of the state-of-the-art digital technologies made available in LEXIS.

Finally, Section 4 will highlight the final remarks of this deliverable.

2 THE AERONAUTICS PILOT: MAIN TARGETS AND RESULTS

The reduction of the polluting emissions of aircraft engines is a key requirement for the aeronautic industry. Significant efforts are underway to design the next generation of green propulsors and, within this scenario, the turbomachinery modules and gearboxes for aircraft engines typically must comply with a variety of, sometimes conflicting, requirements. In this engineering context, the design optimization is key factor to define a competitive product and demands the adoption of HW-intensive and time-consuming CAE simulations based on sophisticated numerical solvers. The use of reliable and sophisticated prediction methods supports the detailed investigation and comprehension of the involved physical phenomena through the adoption or development of innovative computing technologies. On the other hand, as much as the level of accuracy of the prediction methodologies is increased, the higher is the computational cost and the duration of the CAE analyses, that could become incompatible with the industrial needs in Aeronautics.

The Aeronautics Large-scale Pilot aims to significantly enhance the feasibility and exploitation of advanced CAE numerical modelling capabilities able to predict the fluid-dynamic behaviour of aircraft engine critical components. To meet this ambitious objective, the industrial applicability of the next-generation HPC/Cloud/BD management technologies available or newly developed in LEXIS has been investigated through the deployment and the assessment of sophisticated numerical solvers within the two aeronautical engineering case studies included in the Aeronautics Large-scale Pilot, a turbomachinery application (the “Turbomachinery Use Case”) and a mechanical rotating parts’ one (the “Rotating Parts Use Case”).

A description of the main objectives and results of the research and development activities targeted to the deployment of the Turbomachinery Use Case and the Rotating Parts Use Case is hereafter reported. Please refer to the Deliverables D5.5 [1] and D5.4 [2] for a more extensive discussion.

2.1 THE TURBOMACHINERY USE CASE

Avio Aero is at the forefront of developing new innovative aeronautic design technologies. These technologies are transforming the design and production of aeronautical components and modules for next generation greener and quieter engines. Critical component of aeronautical engines are the turbine modules, where accurate prediction of flow physics has been and is nowadays the subject of intensive research to achieve better engines’ efficiency, stability and operability.

By leveraging the LEXIS technologies, Avio Aero has produced a significant change in the computer-aided engineering processes supporting the design of its turbomachinery products: less time-consuming HW/SW coupling, opening the doors to the “real-time” design approach. The Turbomachinery Use Case mainly targeted to drastically reduce the execution time of CFD investigations of the turbomachinery flow field in aeronautical turbines from 30 days to a few ones. The adoption of solely CPU-based HPC platforms in the early stages of the LEXIS project has made it possible to achieve a value of running time only slightly better than the one measured in the Avio Aero production environment, so this was only a preliminary step to set the baseline with which to compare the reduced execution time potentially obtainable through GPU-accelerated computing solutions.

The CFD investigations considered in the Turbomachinery Use Case have involved the use of TRAF [3] code, a CFD solver developed by the University of Florence that is designed to help turbomachinery designers solve steady/unsteady 3D Reynolds-averaged Navier-Stokes (RANS) equations in the Finite Volume (FV) formulation on multi-block structured grids.

Starting from the production version of the TRAF application, that is suitable to run on pure CPU-based HPC infrastructures, the LEXIS project has allowed Avio Aero to carry out some development activities for porting the solver to GPU-accelerated computing platforms in order to dramatically decrease the execution time: the 5x speed-up was a real severe challenging target. From a business perspective, this means faster availability of technical information that engineers can use in the optimization process of any turbomachinery design they are committed to do.

The primary KPI used to measure the achievement of the above stated goal is the so-called “speed-up”, defined by the following ratio:

$$S = \frac{\Delta t_{CPU}}{\Delta t_{GPU}},$$

where the numerator represents the computational time of a given simulation running on a CPU-based architecture, while the denominator is the computational time of the same simulation running on a GPU-equipped platform. This ratio is clearly strongly dependant on the choice of the two simulation set-ups being compared. This point has been largely discussed in Deliverable D5.5 [1].

The latest optimized version of the TRAF code -version 2021- was tested on the Barbora HPC cluster [4] at IT4I with an industrial test case, that is depicted in Figure 1.

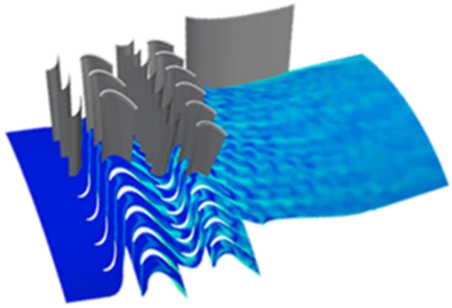

Figure 1: Two-stage turbine case with rear struts simulated by TRAF code in the CPU-to-GPU code porting framework

In this case study, the baseline calculation was performed by 108 MPI processes on 108 CPU cores, using the minimum number of HPC nodes at Barbora, that is N=3, needed to meet the memory requirements of the computational model with no GPU acceleration. A second set-up doubled the number of used CPU cores (216 on 2xN=6 nodes), by activating 2 OpenMP threads per MPI process, while still using the same number of MPI processes (108), again without GPU acceleration. The average net computational time per simulation step was measured for the two solely CPU-based set-ups: the effect of the CPU scalability on the reduction of the computation time was less than linear, showing for the speed-up a value of only 1.73x compared to a number of nodes twice higher.

The best configuration tested on Barbora for the GPU-accelerated calculation, instead, employed 16 GPUs on 4 GPU-accelerated nodes, by running 16 MPI processes (one MPI process on each GPU) with no OpenMP-based parallelization. The measurement of the average net computational time per simulation step was again performed, revealing that the increase of the speed-up is more than linear with the GPU acceleration. Compared to the baseline on CPUs, in this case the number of computing nodes has increased only by one and the target value of at least 5x for the speed-up has been successfully exceeded, resulting in 7.04x.

Table 1 summarizes all these details illustrating for each of the three above-mentioned set-ups the used number of computing nodes, MPI/OpenMP processes, HW resources and measured computational time and related speed-up.

NUMBER OF NODES	MPI PROCESSES × OpenMP THREADS	HARDWARE RESOURCES	NET TIME PER STEP [s]	SPEED-UP
N=3	108 × 1	108 CPU cores	689.4	(baseline)
2 × N	108 × 2	216 CPU cores	399.0	1.73x
N+1	16 × 1	16 GPUs	97.98	7.04x

Table 1 Industrial test case on Barbora: performance figures of the CPU-based computation set-ups and the GPU-accelerated one

In order to further optimize the GPU-accelerated solution, other improvement and testing activities have been carried out on new Karolina HPC cluster [5], equipped with higher-performance GPUs over the prior generation available at Barbora (NVIDIA A100 vs V100), activating also the OpenMP parallelization and providing even better achievements. Table 2 summarizes these achievements in terms of measured computational time and related speed-up on Karolina, besides including the details about the number of used computing nodes and GPUs. For further technical details please refer to Deliverable D5.4 [2]. More specifically, a value above 5x for the speed-up has been obtained even on just one Karolina computing node mounting 8 GPUs: the achieved value was 6.23x. So, compared to the GPU-enabled set-up at Barbora, that was based on 4 GPU-accelerated computing nodes, the solution at Karolina has leveraged one GPU-accelerated computing node only. This, besides going beyond the initial target in terms of running time reduction, proved to be also the most beneficial one from a cost perspective, as extensively reported and demonstrated in Deliverable D5.4 [2]. Table 2 also exhibits , by exploiting up to 32 GPUs, that the maximum achieved speed-up has been 21.4x, representing this a very great achievement for Avio Aero. Indeed, from the 1-node to the 4-node configuration, going through the intermediate ones based on 2 and 3 nodes, the detected improvement for the speed-up revealed to be quasi-linear on Karolina, showing in these 4 cases both technical and cost effectiveness compared not only to the baseline but also to other two computational set-ups on Barbora listed in the Table 1.

NUMBER OF NODES	HARDWARE RESOURCES	NET TIME PER STEP [s]	SPEED-UP
1	8 GPUs	110.6	6.23x
2	16 GPUs	56.66	12.2x
3	24 GPUs	44.14	15.6x
4	32 GPUs	32.22	21.4x

Table 2 Industrial test case on Karolina: performance figures of the best performing GPU-accelerated set-ups with 1, 2, 3 and 4 nodes

The above-mentioned strong improvements in the execution of TRAF numerical code, that is a critical part of the entire Turbomachinery design process, will allow to gain important benefits in terms of productivity (see Section 3.2.1) and to raise the quality level of new potential Avio Aero products' portfolio (see Section 3.1.1).

2.2 THE ROTATING PARTS USE CASE

Through the Rotating Parts Use Case in the LEXIS project, Avio Aero aims to develop enablers supporting the digital (r)evolution being applied to the design and development of gearboxes, that are a key product within the Avio Aero business.

The main goal here is supporting the traditional gearbox design approach, based on correlations, expertise and legacy data, with a completely new CFD numerical method capable of quickly and reliably validating the industrial solutions that Avio Aero is going to insert in the next-generation gearboxes. Checking the general behaviour of the air-oil mixture, its distribution, the scavenging capabilities as well as keeping the resistant torque levels under control are the most important issues to be addressed during the design and analysis phases. For this reason, securing the accuracy and reliability of the numerical solver underlying the above-mentioned CFD investigations is the top priority.

The challenge presented by the Rotating Parts Use Case is to predict and simulate, with increasing accuracy, the flow field operating inside aeronautic gearboxes where the combination of jet lubrication and high tangential speeds precludes the possibility of neglecting the interactions between liquid and gaseous phase.

The simulation of these phenomena typically requires a large amount of computing resources and takes considerable running time. In this context, the commercial solver Altair nanoFluidX™ [6] has been used. This is a new-generation Smoothed-particle Hydrodynamic (SPH) solver used to predict free-surface or multiphase flow behaviour in the presence of complex moving geometries or extreme flow deformation (sloshing and mixing). It is optimized for use on graphics processing units (GPUs), ensuring minimal turn-around time.

In the LEXIS project, nanoFluidX® has been widely and successfully tested in different conditions so as both to provide a high quality of analysis and to minimize the computational time as much as possible, as broadly discussed in Deliverables D5.5 [1] and D5.4 [2]. These two drivers mixed together have proven to be a key factor to improve business productivity and to pave the way for assuring performance and reliability in the design of next-generation aeronautical gearboxes. Several rotating parts geometries with increasing complexity have been adopted and effectively simulated here. The most representative one, the ultimate one very close to real industrial products, is shown in Figure 2.

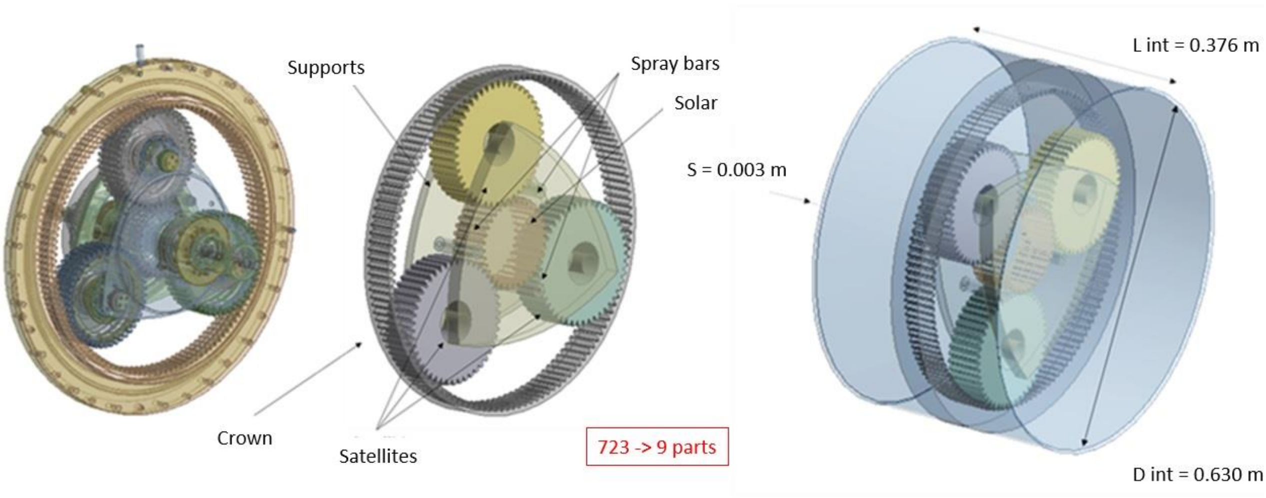

Figure 2: Enoval Planetary gearbox model used to test/optimize nanoFluidX® capabilities

The CFD investigations carried out in the Rotating Parts Use Case based on nanoFluidX® have allowed Avio Aero to obtain remarkable benefits in terms of running time reduction, resulting from the adoption of a SPH method that provides gearbox designers with the ability to investigate the multiphase fluid-dynamic behaviour of high-speed gearboxes faster than using traditional FV CFD approaches. Moreover, in Deliverable D5.5 [1], it has been argued that this newly developed CFD methodology is supposed to provide important gains in mechanical efficiency and gearbox sizing optimization, so potentially leading to increase the design quality of next-generation aeronautical rotating parts products.

3 IMPACT ON BUSINESS PROCESS IMPROVEMENT AND PRODUCTIVITY IN THE AERONAUTICS PILOT

Simulating complex geometries or phenomena such as the ones in aeronautics can be difficult even with modern computers as it requires a large amount of computing power required by sophisticated numerical solvers and delivered by advanced IT infrastructures. So, uniting engineering simulations based on sophisticated numerical solvers and state-of-the-art HPC platforms allows CAE in Aeronautics to enable innovative and faster investigation strategies for the design and optimization of critical aircraft engine’s components. Besides introducing newly designed CFD solvers able to accelerate the execution of the CAE simulations involved in the presented use cases, the deployment of the Aeronautics industrial pilot in LEXIS has revealed considerable advantages in terms of:

- Improvements in the CAE processes underlying the two considered use cases,
- Increase in productivity,
- Impacts coming from the adoption of the state-of-the-art HPC technologies available in LEXIS,

that will be described in the three following Subsections 3.1, 3.2 and 3.3, respectively.

3.1 CAE PROCESS IMPROVEMENT

Aeronautics is one of the most tightly controlled and regulated markets in the world. With a long design and production process, high safety standards, and a multitude of engineering requirements necessary to achieve optimal performance, any solution that can shorten the process while yielding higher-quality outcomes has the potential to deliver huge savings in design and production costs.

CAE simulations accomplish this by providing design analysis early in the production process, eliminating designs that fail simulation tests, and reducing the number of designs that must undergo expensive prototype testing.

One of the main advantages of CAE is that it only takes a few hours compared to several days or even weeks to build and test physical prototypes. Of course, a physical prototype will usually be required at some point, but CAE greatly reduces the amount of these that are required. The use of CAE and the subsequent reduced requirement for physical prototypes saves on product development costs and time, while ensuring improved product quality.

A competitive CAE engineering team in today's aeronautical industries has to make excellent use of the technological tools available in order to:

- Speed up as much as possible the most critical and time-consuming CAE process steps involved in the design workflows,
- Enhance the remote visualisation features to quickly and effectively display data and simulation results,
- Implement in the CAE design workflows newly designed engineering methodologies at the leading edge of numerical technology.

In this context, the Turbomachinery Use Case mainly targeted to reduce from months to days the computational time of the most time-consuming CAE process step included in the underlying CFD workflow. The industrial goal here was to reduce the running time of the adopted CFD solver by a factor of at least 5x, by exploiting GPU acceleration. Moreover, such use case aimed to implement some remote visualisation techniques to efficiently display the simulation results interactively in real-time, besides also providing users with the option of non-interactive automated visualisation of the results and a viewing feature for the live monitoring of the application process status.

On the other hand, the Rotating Parts Use Case intended to deploy a newly designed CFD-based engineering methodology allowing to define the proper accuracy of the physics-driven CAE modelling while minimizing the required computing time in the underlying CFD workflow. In addition, the deployment of the HW-intensive pre-processing phase included in the application workflow was also part of the goals of the Rotating parts Use Case implementation.

The following Sections 3.1.1 and 3.1.2 will describe the above-mentioned improvements in the CAE processes respectively for the Turbomachinery Use Case and the Rotating Parts Use Case.

3.1.1 Turbomachinery Use Case

CAE is used to both design and support the engineering process for a product, allowing tests and simulations to be performed without the need for a physical prototype. The most frequently used CAE simulation analysis techniques include finite element analysis (FEA), computational fluid dynamics (CFD), thermal analysis, multibody dynamics (MBD), durability and optimization.

The Aeronautics Turbomachinery Use Case discussed here relies on CFD investigations that, as in any typical CAE analysis, involves pre-processing, solving and post-processing steps. Figure 3 provides a high-level overview of the CFD workflow deployed in the Turbomachinery Use Case, illustrating the tasks of the above-mentioned steps and the CAE application solver used in the computational phase.

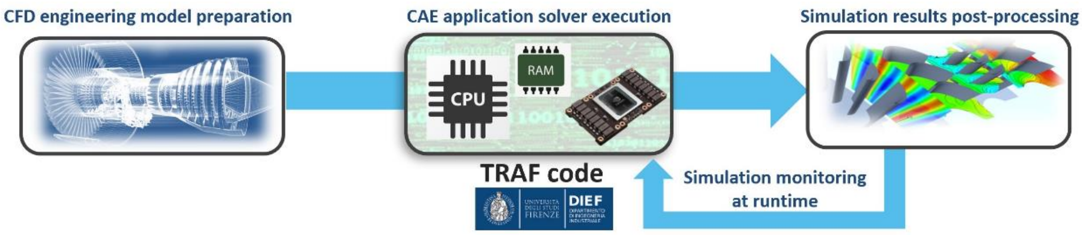

Figure 3 Application workflow of the CFD simulations in the LEXIS Aeronautics Turbomachinery Use Case

The pre-processing stage is out of the scope of the LEXIS project and is performed locally on the workstation of the end users, while the strongly HPC-demanding and time-consuming computational phase, based on the TRAF code, has been drastically enhanced in LEXIS thanks to the advanced capabilities provided in terms of state-of-the-art supercomputing centres, SW enhancements and HW/SW systems integration.

The last consolidated version of TRAF currently running in the Avio Aero IT production environment relies on a hybrid MPI/multi-platform shared-memory parallel computational model and runs on solely CPU-based HPC resources [7, 8]. In order to try to reduce as much as possible the duration of the computational phase, first of all extensive scalability and performance tests have been performed on the solely CPU-release of TRAF code running on pure CPU-based resources at the two LEXIS supercomputing partners, IT4I and LRZ. This has not proven sufficient to meet the industrial target of reduction of TRAF running time by at least a factor 5x, so a newly designed GPU-enabled release of the code has been developed, deployed and tested on the GPU-accelerated HPC resources provided by IT4I, the Barbora and Karolina HPC clusters. Through the best GPU-accelerated solution deployed on Barbora based on 16 GPUs NVIDIA V100, a speed-up of 7.04x has been obtained compared to the baseline executed on solely CPU-based computing nodes at Barbora, as argued in Deliverable D5.4 [2] and reported in Table 3. After deploying TRAF also on Karolina, the so implemented GPU-accelerated solutions revealed, always compared to the baseline, a speed-up of 6.23x and 21.4x as summarized in Figure 3 and also widely reported in Deliverable D5.4 [2]. In the first case, the execution performance has been optimized from a joint technical/cost perspective by adopting only 8 GPUs NVIDIA A100, instead in the case of 21.4x the HW acceleration has been maximized by using 32 GPUs NVIDIA A100 while still saving execution costs towards the baseline. So, in addition to the impressive reduction of the running time, the improvement of the computational phase involved also the running costs, but this will be better described in Section 3.2.1.

HPC SOLUTION	HPC CLUSTER	HARDWARE RESOURCES	SPEED-UP
3 pure-CPU nodes	Barbora	108 CPU cores	(baseline)
4 GPU-accelerated nodes	Barbora	16 GPUs NVIDIA V100	7.04x
1 GPU-accelerated node	Karolina	8 GPUs NVIDIA A100	6.23x
4 GPU-accelerated nodes	Karolina	32 GPUs NVIDIA A100	21.4x

Table 3 Speed-up of the computational phase vs used HPC resources

Besides the improvement of the computational phase, in the CAE process underlying the Turbomachinery Use Case the post-processing of simulation results and the on-line monitoring of the simulation status have been enhanced as well. More specifically, as regards the post-processing phase, the advantage of the remote visualisation option that has been enabled on LEXIS lies in the elimination of the need to move huge amounts of TRAF-based simulation data from the HPC infrastructure to the local workstations. Moreover, in addition to the ability to visualise the results of TRAF-based simulations interactively in real-time, users were allowed to benefit from the option of non-interactive visualisation of results, which can be used both for the calculation itself and for straightforward comparison of individual calculation variants. On the other side, referring to the on-line monitoring of the TRAF simulation status implemented in LEXIS, the possibility of accessing the current state of a workflow execution in a quick, easy and visual manner has been assessed as very useful and effective from the involved CAE analysts because it ensures that long-running simulations, even if drastically accelerated, are executing properly.

Finally, as complementary work included in the optimization of the computational phase, the possibility, implemented here in LEXIS, of recovering TRAF application from the last computed state has contributed to further improve the CAE process robustness for the Turbomachinery Use Case. This brings an effective use of the employed computational resources, as well as may allow Avio Aero, in the case of any unexpected system maintenance or failure, to save some money while executing long-running TRAF simulation jobs. Depending on the type of the turbine to be analysed, the objective of the investigation and the speed of convergence of the simulation, it would be very difficult to provide a standardized value for the execution time of long-running simulation, however in general the most time-consuming computing jobs may last 1-2 solar months by running TRAF on pure-CPU HPC systems such as the baseline in Table 3, while it may take now up to 1-2 business weeks on GPU-accelerated systems (such as a single GPU-accelerated node at Karolina) with the newly developed GPU-enabled TRAF release. Therefore, considering the case of a GPU-enabled TRAF simulation lasting 2 business weeks, the implemented checkpointing mechanism, being able to save intermediate simulation results, may allow -if set on a 3-day basis for example- to lose only up to approximately 20% of the costs of the core-hours employed by the computations, if any unexpected system maintenance or failure may occur between 2 checkpointing mechanisms. Without checkpointing or before its implementation in LEXIS, the economic loss due to a system maintenance or failure occurring at the end (or just before) the computation could also be up to 100% of the costs incurred by the needed core-hours.

Leveraging all the improvements obtained in the TRAF-based CAE process underlying the Turbomachinery Use Case, the turbine design system methodology at Avio Aero is now in the position to be effectively revised including the three main steps illustrated in Figure 4. Firstly, a set of turbine blading geometries are selected and the related URANS CFD simulations target to predict the turbomachinery flow field making use of the enhanced GPU-accelerated computational phase based on the solver TRAF. Once population of results has been created, also working in different operating conditions, a meta-model has to be built based on some AI techniques to be newly introduced here. This will finally allow designers to select the optimum candidate fully fitting the design requirements.

WORKFLOW WITH THREE STEPS

INITIAL POPULATION, META-MODEL BUILD, OPTIMUM CANDIDATE SELECTION

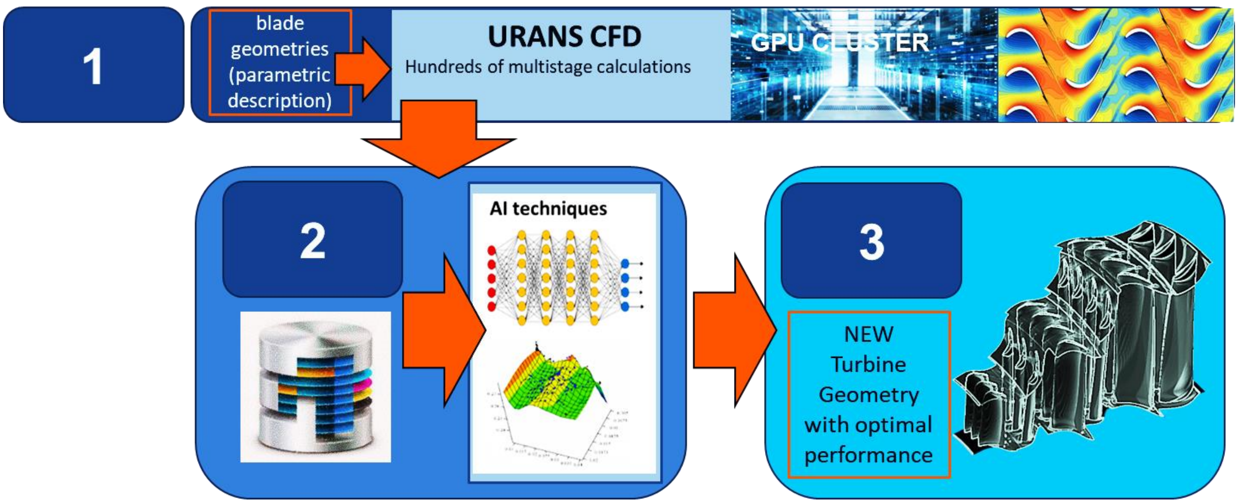

Figure 4 Optimization process using URANS SW based on GPU-equipped computing platform

3.1.2 Rotating Parts Use Case

The basic CAE process for the rotating parts CFD simulations is shown in Figure 5.

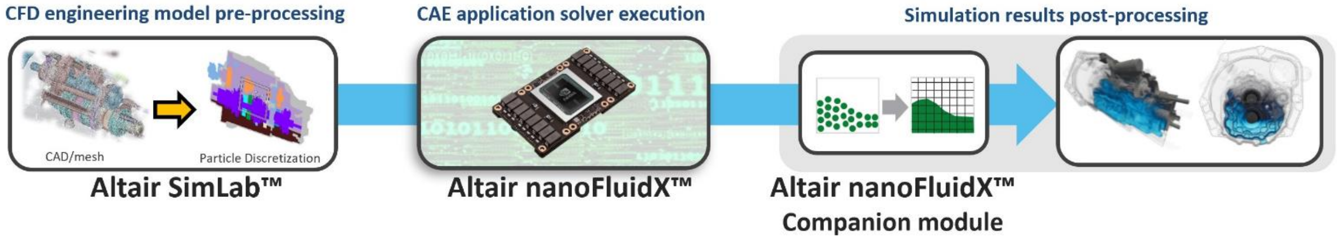

Figure 5 Application workflow of the CFD simulations in the LEXIS Aeronautics Rotating Parts Use Case

Compared to the original version presented in 2019 at the beginning of the LEXIS project, this high-level workflow has remained practically unchanged, but some significant improvements have been introduced specifically in:

- The pre-processing phase, with the more user-friendly GUI provided by the newly released version of Altair SimLab® [9],
- The solver itself, whose execution has been reduced of more than 20% thanks to specific software set-ups matured in the three years of development (tests have been carried out with same reference code). In addition, the use of the advanced GPUs NVIDIA A100 available on the newly introduced Karolina HPC cluster has accelerated convergence of numerical solutions. Running time of nanoFluidX® simulations has been furtherly reduced of circa 40% but all these enhancements have been partially vanished due to the need of assuring reliable solutions by imposing a high granularity in the particles' diameter used to simulate the complex phenomena occurring in the gearbox domain.
- The post-processing phase, which has benefited from important developments in the nanoFluidX®-companion module. The latest post-processing tool version significantly speeds up the workflow while providing unique insights to the simulation data. In addition, after three years of development pursued in the LEXIS project, several scripts/excel macros have been created to ease the computational output data reduction.

The whole set of the before mentioned improvements has led globally to save almost 40% versus the "2019" equivalent simulation time. All these improvements have been possible thanks to both the advanced HPC resources made available in LEXIS and the work that Avio Aero and the LEXIS partners involved in WP5 have performed to integrate the HW and SW technologies adopted in this use case. More specifically, once this newly designed application workflow -that is applicable for the simulation of the multiphase fluid-dynamic behaviour of high-speed gearboxes- has been implemented on the LEXIS platform, the human labour of the WP5 partners has allowed to benefit Avio Aero from the best results in the SW execution, aiming to remove any limitations encountered in terms of performance and to enable the scalability of the used CFD solver.

Another key result achieved in LEXIS after three years of research and development activities is the high reliability/robustness of the implemented numerical process, on the basis of which, as a follow-up step, a new workflow for the Design of Experiments (DOE) in gearboxes engineering is intended to be deployed and more widely tested, able to generate CFD-driven solutions more performant than mechanical solutions generated by traditional approaches pursued up to now. More specifically, the implementation of this DOE workflow, that can benefit from the increased accuracy and the reduced running time introduced by the newly adopted numerical solver, is enabled by the adoption of a SPH-based simulation method which turned out to be faster than the traditionally adopted FV CFD approach. Some details about the mentioned DOE, that is depicted in Figure 6, are illustrated hereafter.

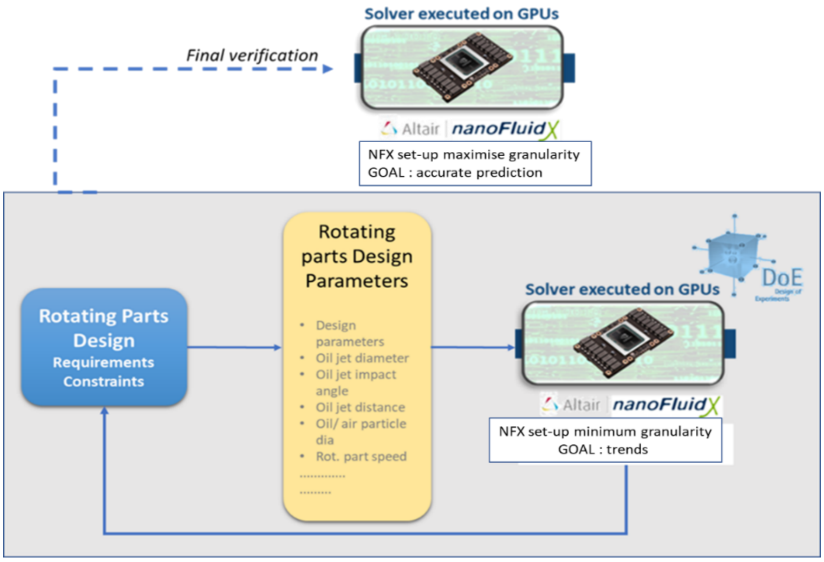

Figure 6 Design of Experiments (DOE) for gearboxes engineering

Firstly, traditional set-up of requirements for a new gearbox and its related constraints covering safety, performance and durability aspects will be defined. Afterwards, several nanoFluidX simulations will be launched to investigate effects of different parameters (like oil jet diameter, oil jet impact angle, oil jet distance from the rotating wheel, different wheel speed). Particles' granularity will be fixed at the minimum value assessed in the LEXIS validation phase to get quick, even if low, accurate answers. Target here is to get trends and derivatives of parameters versus performance. Final validation of gearbox design will be carried out by selecting particles' diameters sufficiently small, in line with the previously defined best practices. In this case the goal will be to get accurate and reliable performance data.

The just described Design of Experiments technique will be the preliminary step before assessing the rotating parts design by a more complex optimization procedure, similarly to the approach illustrated for the Turbomachinery Use Case in the previous paragraph. The unique difference between these two fundamental aeronautical products (turbines and gearboxes) is the maturity level of CFD application software, that is much more consolidated in turbomachinery products after some decades of usage and evolution.

3.2 INCREASE IN PRODUCTIVITY

After having described the considerable improvements in the CAE processes underlying the Turbomachinery Use Case and the Rotating Parts Use Case in the previous paragraph, this section will now illustrate the increase in productivity resulting from the implementation of the two considered engineering use cases. More specifically, for the Turbomachinery Use Case, the increased productivity of the Avio Aero engineering team is directly enabled by the drastic reduction in the running time of the CFD solver that the turbomachinery flow field simulations discussed here rely on, because faster engineering analyses help to reduce the amount of time it takes to design a new turbomachinery. Another enabler to further increase the productivity is the reduction of the costs needed to run the CFD simulations included in the Turbomachinery Use Case, made possible by the implemented GPU-accelerated computing solution that is both less time-consuming and cheaper than the solely CPU-based one. On the other hand, with regard to the Rotating Parts Use Case, the improvements in terms of productivity derive from the ability to define the proper accuracy of the physics-driven CFD modelling while minimizing the computing time required from the newly adopted CFD application solver. Also in this case, less time-consuming engineering analyses allow the Avio Aero Engineering team to reduce the time to market of newly designed aeronautical products, thus resulting in the increase of productivity.

3.2.1 Turbomachinery Use Case

The execution performance of TRAF has been remarkably improved through the GPU-enabled version of the solver with respect to its pure CPU-based production release.

The significant speed-up factor achieved implies some competitive advantages, the main being that advanced numerical analyses can now be run in reasonable timeframes, compatible with design iterations, allowing CAE analysts to get quicker valuable engineering insights with a level of detail that is not guaranteed by simpler approaches. Furthermore, such achievements are of great interest not only for the Aerodynamics, but also for other disciplines (e.g., Aeromechanics, Aeroacoustics etc.), therefore the resulting beneficial impact is widespread. These results can be incorporated into a revised and so enhanced turbomachinery design approach, that, based on faster engineering analyses, allows the Avio Aero Engineering team to improve its productivity, to reduce time to market of newly designed turbomachinery products and to finally rise the product competitiveness.

Another important outcome of this research activity is the simulation cost reduction coming from the adoption of the GPU acceleration in the CFD investigations underlying the Turbomachinery Use Case. An appropriate and well-structured cost analysis has been carried out to measure the impact of the accelerated platforms compared to traditional CPU-based ones by combining the computational time reduction on one hand, and the higher costs of GPU-equipped HPC systems on the other hand. Results are clearly dependent on the specific characteristics of the adopted computational platforms, but the Turbomachinery Use Case revealed that the use of GPU-enabled numerical tools for CFD can not only provide a productivity gain in terms of increased number of analyses within a specific time frame. The adoption of GPU-accelerated CFD solvers could be also beneficial from a cost perspective, because the Turbomachinery Use Case implemented in LEXIS demonstrated that the higher usage costs of the adopted GPU-equipped HPC solutions is more than counterbalanced by the resulting reduction in the running time of the executed CFD simulations.

In Deliverable D5.4 [2], a benefit/cost index has been defined to quantify these advantages according to the following formula:

$$Benefit/cost\ index = \frac{computational\ speedup}{cost\ increase\ factor},$$

where the $computational\ speedup$ is the ratio of the execution time on a pure CPU-based HPC system (baseline) to an accelerated platform, while the $cost\ increase\ factor$ is the ratio of costs between the accelerated computational system and the solely CPU-based one.

Table 4 summarizes the values of the benefit/cost index for the computational set-ups already illustrated in the previous Section 3.1.1. The best value of this index, that is 2.02, was achieved with the set-up of one GPU-accelerated node at Karolina, which resulted in a 6.23x speed-up compared to the baseline on 3 pure-CPU nodes at Barbora. However, even the best set-up in terms of running time reduction, having a 21.4x speed-up and leveraging 4 GPU-accelerated nodes at Karolina, resulted in a cost reduction index equal to 1.74, which is not too worse than the best value. Nevertheless, with the same number of GPU-accelerated computational nodes, this computational set-up at Karolina proved to be better than the one on Barbora according to both the speed-up and the benefit/cost index, being able to count on a higher number of more powerful GPUs at Karolina. In fact, the 4 GPU-accelerated nodes at Karolina have allowed to achieve a value of 1.74 for the benefit/cost index, which is greater than the one achieved through the same number of GPU-accelerated nodes on Barbora.

HPC SOLUTION	HPC CLUSTER	SPEED-UP	BENEFIT/COST INDEX
3 pure-CPU nodes	Barbora	(baseline)	(baseline)
4 GPU-accelerated nodes	Barbora	7.04x	1.43
1 GPU-accelerated node	Karolina	6.23x	**2.02**
4 GPU-accelerated nodes	Karolina	21.4x	1.74

Table 4 Benefit/cost index and speed-up of the GPU accelerated solutions compared to the baseline on a pure-CPU computation set-up

Consequently and to sum up, in cost model that directly relates the rental price of the computational resources allocated on the operated supercomputers to the actual hourly usage of the computing nodes, the cost reduction highlighted here coming from the GPU acceleration allows the company to save precious money that may be invested in research and development activities aimed to further accelerate the execution of the discussed CFD simulations and, so, to additionally increase the engineering productivity.

3.2.2 Rotating Parts Use Case

One of the key driver of the Rotating Parts Use Case is the optimization of the balancing between nanoFluidX accuracy and running time in the application solver execution phase. Key steps of optimization are summarized in the following points:

- Firstly, a preliminary activity has been set to understand how the nanoFluidX® software is operating and only later aimed to increase, thanks to a comparison with basic experiments, results' accuracy by lowering the particles' diameter. Figure 7 shows the two basic test articles investigated.

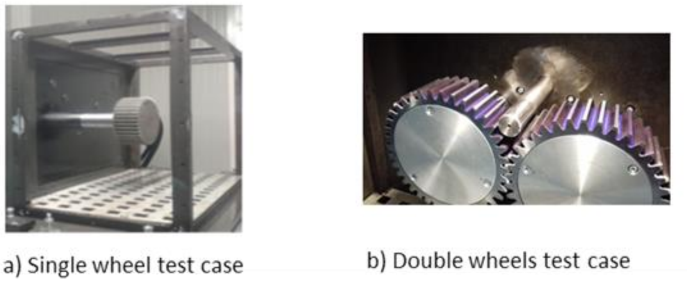

Figure 7 Rotating parts test cases used for the validation

- The ultimate version of the nanoFluidX-based CFD methodology (delivered in 2021 and tested to simulate Enoval test case shown in Figure 8) has finally incorporated some improvements in terms of flexibility and modelling simplification and considerable advantages in the matter of solver execution acceleration, this last point in particular strongly enabled from running on the advanced GPUs NVIDIA A100 available on the newly introduced Karolina HPC cluster.

Figure 8 Enoval Planetary gearbox test case

Besides the optimization of simulation execution, looking at the end-to-end CAE workflow underlying the Rotating Parts Use Case that includes the enhanced stages of model preparation and results‘ post-processing as well, the resulting improvements in terms of productivity have led to save almost 40% of 2019 overall simulation time in spite of higher accuracy guaranteed by very large amount of small-diameter particles. Moreover, another aspect of paramount importance in relation to the increase in productivity is that, at the end of the LEXIS project, Avio Aero can count on a modern, reliable, fast enough CAE design approach capable of supporting and sustaining the large know-how acquired over several decades of work in the aeronautical market. Thanks to this new approach, faster engineering analyses in the design of gearboxes allows the Avio Aero Engineering team to improve its productivity and to reduce time to market of newly designed aeronautical rotating parts products, so finally increasing the product competitiveness.

3.3 IMPACTS FROM THE ADOPTION OF STATE-OF-THE-ART HW/SW TECHNOLOGIES

The adoption of state-of-the-art digital technologies, including both sophisticated numerical solvers and advanced HPC platforms, experienced in LEXIS for the deployment of the Turbomachinery Use Case and the Rotating Parts Use Case, has allowed Avio Aero to derive some positive impacts from the implementation of two discussed engineering case studies.

Referring to the Turbomachinery Use Case, the acceleration of the TRAF solver on GPU-equipped HPC architectures clearly showed some benefits that may be obtained in the engineering design process through the newly adopted GPU-accelerated strategy. The most apparent benefit is represented by the speed-up, which quantifies how faster the simulations may become thanks to the GPU-accelerated computing, with respect to the execution on traditional CPU-based platforms. By drastically reducing the running time of CFD simulations on LP turbines, the newly introduced GPU-accelerated HPC clusters (as Barbora and Karolina at IT4I) allow the Avio Aero Engineering team to increase the number of design iterations per unit time and/or produce more accurate results within acceptable times in the turbomachinery design by using more complex physical models. Depending on the type of the turbine to be analysed, the objective of the investigation and the speed of convergence of the simulation, the number of design iterations may be highly variable, however it should be considered here that, based on a factor of 6.23x, which is the best obtained speed-up from a joint technical/cost perspective, now six design iterations can be performed at the same time as only one was previously performed.

These advantages open the door the new possibilities of engineering analyses in Turbomachinery, not only related to fluid-dynamics, but also to aero-elastic and acoustic problems impacting, besides performance, aero-engines safety and environmental aspects. In this context, Avio Aero Engineering team has also evaluated that, covering the big variety of turbine applications, the expected number of GPUs involved in the numerical simulations can range from 16 units (simpler test cases, low stages number) to more than 100 ones, when complete LP turbine modules have to be investigated.

Another added value is the possibility of substituting steady solvers (where time is not taken into account and performance parameters are based on averaged fluid flow quantities) with unsteady ones that, thanks to the GPU acceleration, are becoming attractive and really applicable in every-day industrial workscope. In this way, unsteady effects, previously neglected, can be now considered to produce more physics-based and accurate performance results able to get more marked improvements in the thermodynamic LP turbine module efficiency.

Currently, expected benefits should be around 0.3% in terms of engine Specific Fuel Consumption (SFC) reduction. This figure has been confirmed by some preliminary Avio Aero analyses carried out on legacy engines (with confidentiality issues), already operating on the market, comparing numerical solutions with/without the application of the novel internal design procedure which benefits from both GPU technology and the ability to use more accurate, physics-based unsteady codes.

On the other hand, with regard to the Rotating Parts Use Case, the main obtained impact resulting from the adoption of state-of-the-art digital technologies has been the implementation of a newly designed CFD-based engineering methodology. This novel engineering approach has allowed the Avio Aero Engineering team both to define the proper accuracy of the physics-driven CFD modelling and to minimize the required computing time in the investigation of multiphase fluid-dynamic behaviour of high-speed gearboxes cooled with an oil-jet system. Thanks to the recently launched Karolina HPC cluster, the simulation time needed to analyse complex flow fields in gearboxes for aircraft applications proved to be inside one day, so fully matching the industrial needs related to the design verification. Moreover, the access to recent and powerful hardware technology on Karolina HPC cluster, not limited to the compute nodes but including also the visualization ones, made possible the successful deployment of the HW-intensive pre-processing phase included in the application workflow of the Rotating Parts Use Case. So, looking at the overall CAE workflow underlying the Rotating Parts Use Case, it can be undoubtedly said that the advanced computational capabilities available on Karolina together with the Altair tools nanoFluidX® and SimLab® gave a strong contribution to speed up the CFD analysis process on aeronautical rotating parts supporting the digital (r)evolution being applied to the design and development of gearboxes. The newly introduced engineering procedure is expected to provide, besides assuring standard safety aspects, important gains in mechanical efficiency and gearbox sizing optimization. Consequent weight savings are expected to range among 1.00-3.00 [kg] acting to reduce aero-engine SFC from -0.3% to -0.1 %. The former value refers to a short-range aircraft while the latter one is for a long-range aircraft mission.

4 SUMMARY

In this deliverable, the impacts on business processes improvements and productivity that have been clearly identified after the implementation in LEXIS of the two aeronautical engineering case studies included in WP5, the Turbomachinery Use Case and the Rotating Parts Use Case, have been presented. The deployment of such industrial test cases has revealed very remarkable impacts in terms of improvements in the CAE processes underlying the two considered use cases, increase in productivity and positive implications coming from the usage of the state-of-the-art HW/SW technologies available in LEXIS.

For the Turbomachinery Use Case, the improvement of the CAE process consisted in the wide optimization of the computational phase, mainly aiming to drastically reduce the duration of the running time for the TRAF-based CFD jobs involved in the use case and, then, also targeting the implementation of a check-pointing mechanism to recover the TRAF application from the last computed state in the case of any unexpected system maintenance or failure. Besides the improvement of the computational phase, some enhancements of the post-processing phase (for the visualization of simulation results) and the on-line monitoring phase (for the display of the simulation status) have been also made and quickly mentioned here. Getting back on the optimization of the computational phase, the impressive speed-up factor achieved through the GPU acceleration may allow the Avio Aero engineering team to benefit from some remarkable competitive advantages, being that advanced numerical analyses not only can now be run in reasonable timeframes compatible with design iterations, but they can be executed also in more cost-effective way based on the newly released GPU-accelerated version of the TRAF solver. Thus, after having described how accelerated and cheaper investigation strategies have been enabled here, it was finally stressed that embracing and exploiting the state-of-the-art HW/SW technologies made available in LEXIS can open the door the new possibilities of engineering analyses in Turbomachinery, not only related to fluid-dynamics, but also to aero-elastic and acoustic problems impacting, besides performance, aero-engines safety and environmental aspects. Moreover, the possibility of replacing steady solvers with unsteady ones that, thanks to the GPU acceleration, can support more physics-based, accurate and faster CFD simulations in turbomachinery, is also made possible from the adoption of the advanced digital technologies successfully experienced in the Turbomachinery Use Case in LEXIS. From a digital technology and business perspective, this is a very remarkable achievement paving the way for other research opportunities in the future: less time-consuming computational analyses that exploit newly designed, improved and/or tightly coupled HW/SW components seem to have the ability to open the doors to the "real-time" design approach for the engineering of turbines. The next research and development activities in this direction may be focused on further accelerating the execution of the discussed CFD simulations by exploring other HW-acceleration technologies, by adopting other CFD solvers or by changing the HPC paradigm such as experiencing Quantum Computing.

On the other hand, with regard to the Rotating Parts Use Case, the improvement of the underlying CAE process, that has involved not only the computational and post-processing phases but also the pre-processing one, has allowed the Avio Aero engineering team to save almost 40% in the overall simulation time compared to the original version of the CAE application workflow presented in 2019 at the beginning of the LEXIS project. Moreover, it has been highlighted that, based on the reliability/robustness of the implemented numerical process, this newly improved engineering workflow is able to generate CFD-driven solutions that are more performant than the mechanical ones generated by traditional approaches pursued up to now. More specifically, the ultimate version of the newly designed CFD methodology, that is based on the GPU-accelerated CFD solver Altair nanoFluidX®, has incorporated some significant improvements in terms of flexibility and modelling simplification and considerable advantages in the matter of solver execution acceleration thanks to the advanced computational capabilities made available in LEXIS. Thus, the Avio Aero Engineering team can now leverage a modern and reliable CAE design approach capable of supporting faster engineering analyses in the design of gearboxes, with a clearly resulting benefit in terms of increase of productivity. Therefore, the adoption of state-of-the-art HW/SW technologies provided by LEXIS gave a strong contribution in the Rotating Parts Use Case to speed up the CFD analysis process on aeronautical rotating parts supporting the digital (r)evolution being applied to the design and development of gearboxes. Besides accelerating the underlying CFD analysis process through newly introduced CAE tools compared to the traditionally used one, the definition of the proper accuracy for the adopted physics-driven CFD model has been part of the main goals in the Rotating Parts Use Case. In the future, the definition of the optimization canvas, including the parameterization of different geometrical components, the choice of the best optimization algorithms and the selection of the most appropriate SW execution engine/orchestrator, will be the objective of the next research and developments activities.

As an ultimate outcome from all impacts discussed here, it has been also mentioned that some benefits in terms of reduction in the engine SFC are also envisaged.

Finally, it should be noted that the impacts on productivity and business process improvements in Aeronautics that have been examined here are closely related to the first three of general impacts stated in the LEXIS grant agreement (ID: 825532) preparation document (part B) and summarized in Figure 9:

Impact 1: *Demonstrated increase of innovation and productivity in the main target sector of the Large Scale Pilot Action;*

Impact 2: *Increase of market share of Big Data technology providers if implemented commercially within the main target sector of the Large Scale Pilot Action;*

Impact 3: *Effective integration of HPC/BD/Cloud technologies in the main target sector(s) of the Large Scale Action, resulting into integrated value chains and efficient business processes of the participating organizations;*

Figure 9 Impacts 1, 2 and 3 included in the LEXIS grant agreement (ID: 825532) preparation document (part B)

Particularly, the innovations -described in Section 3.1- that have been introduced while improving the CAE process underlying the two presented use cases and the increase in productivity -treated in Section 3.2- deriving from the achieved improvements are undoubtedly included in the “Impact 1“ (see Figure 9) and clearly represent a key enabler for the “Impact 2“, while the impacts from the adoption of state-of-the-art HW/SW technologies -discussed in Section 3.3- are evidently related and fully aligned to the “Impact 3”.

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