EXP\_ERIMENT DESCRIPTION AND EVALUATION: HPC Workflow for Simulation and Optimization of Additive Manufacturing for Improving the Production of Gearboxes

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Consisting of original partners

<table>
<thead>
<tr>
<th>Institution</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraunhofer</td>
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<td>JOTNE EPM TECHNOLOGY AS</td>
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<td>UNOTT</td>
<td>THE UNIVERSITY OF NOTTINGHAM</td>
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<td>CONSULTORES DE AUTOMATIZACION Y ROBOTICA S.A.</td>
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<td>NUMECA</td>
<td>NUMERICAL MECHANICS APPLICATIONS INTERNATIONAL SA</td>
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<td>ITI</td>
<td>ITI GESELLSCHAFT FUR INGENIEURTECHNISCHE INFORMATIONSERARBEITUNG MBH</td>
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<td>Missler Software</td>
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<td>ARCTUR RACUNALNISKI INZENIRING DOO</td>
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<tr>
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<td>EUROPEAN SENSOR SYSTEMS SA</td>
</tr>
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<td>HELIC ELLINIKA OLOKIROMENA KYKLOMATA A.E.</td>
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<td>ATHENA RESEARCH AND INNOVATION CENTER IN INFORMATION COMMUNICATION &amp; KNOWLEDGE TECHNOLOGIES</td>
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<td>INT</td>
<td>INTROSYS-INTEGRATION FOR ROBOTIC SYSTEMS-INTEGRACAO DE SISTEMAS ROBOTICOS SA</td>
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<td>NABLADOT SL</td>
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<td>UNIVERSIDAD DE ZARAGOZA</td>
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<td>BARCELONA TECHNICAL CENTER SL</td>
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<td>CONSORCI DE SERVEIS UNIVERSITARIS DE CATALUNYA</td>
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<td>FICEP S.P.A.</td>
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<td>Powerkut Ltd., Coventry, UK</td>
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INO  Ingenieurburo fuer Numerische Optimierungsmethoden, Germany
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DHCAE  DHCAE-Tools GmbH, Germany
COTTES  COTTES Group, Spain
CYPE  CYPE SOFT, S.L., Spain
ITECAM  Centro tecnológico del metal de Castilla La Mancha, Spain
STT  STT Engineering & Systems, Spain
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**DOCUMENT HISTORY**

<table>
<thead>
<tr>
<th>Version</th>
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</tr>
</tbody>
</table>

1. Integers correspond to submitted versions
EXECUTIVE SUMMARY

Cycloidal gearboxes are a family of mechanisms characterised by high overload tolerance, high torsional stiffness, good reliability and very low backlash. This makes them particularly suitable for demanding applications that involve complex equipment (e.g. robots, space applications, and radars). The main bottleneck to the widespread use of cycloidal gearboxes in industrial automation and robotics is their production cost, since all parts must be manufactured with stringent geometrical and dimensional tolerances. The use of Additive Manufacturing (AM) would be a key breakthrough. Nevertheless, using AM techniques to manufacture high precision parts is a challenge and requires expensive trial-and-error procedures.

The numerical simulation of the process is a very promising approach to optimise the welding strategy. Both the thermal and the mechanical behaviour can be predicted, leading to an optimal manufacturing design. High Performance Computing (HPC) simulation tools capable of running these simulation routines, in a time that is compatible with the time to market of mechanical gearboxes developed by manufacturing SMEs, are of great importance. HPC is required for this experiment due to the long computing times and low accuracy of current simulations. A modest model of hundreds of thousands of cells takes about 10h on 16 processors.

Additive manufacturing simulations are challenging however, and commercial codes are far from providing the tools needed to “virtualise” the manufacturing process. On the other hand, the accurate simulation of these phenomena is extremely demanding from a computational point of view, especially with regard to the large number of time steps needed to perform a complete simulation of a product. The objective of the experiment is therefore the parallelisation and cloudification of a simulation tool to optimise AM to support the production of cycloidal gearboxes.

The use of HPC resources will be mandatory for SMEs aiming to improve the design process of AM if they are to obtain reliable simulations in an acceptable time and at an affordable cost. This implies simple access, through a friendly and secure environment and a clearly defined workflow, to HPC resources and simulation tools for AM SMEs in Europe who do not have the capacity to invest in their own HPC resources. As a result, SMEs will increase their usage of HPC services.

The use of HPC simulation tools can be seen as an enabling technology for the use of AM for manufacturing cycloidal gearbox parts and increasing the market share of these devices. This will allow the effective exploitation of AM for applications that until now could not be tackled while keeping production costs at a competitive level.

Each of the partners in the experiment benefits from several technical impacts. From the end user point of view the main technological impacts are directly linked to the improvement of the production process. This experiment has demonstrated the following:

- A reduction in simulation time by around 65% by making use of HPC resources through CloudFlow, which enables the use of AM in this context;
- AM subsequently allows the adoption of new solutions, such as printing the output shaft as a single piece which allows a 20% increase in torque density;
- Reduced waste materials (an average of over 30% was calculated for the given use case, with 66% reduction for the input shaft and 25% for the output shaft);
- Reduced time-to-market (by 30%, with a reduction of around two months from a typical six month period for the use case in this experiment);
- Increased competitiveness in the transmission systems industry for high tech applications;
• Introduction of a manufacturing technology that is off-limits in an industrial context, with State of the Art technologies.

CIMNE, as ISV of this experiment, benefits from the improvements of the services, with the following technical impacts from the experiment:

• Further advancement on the industrial applications of FEMPAR-AM, our large scale HPC scientific software tool tailored for AM;
• Becoming a reference as simulation software provider in AM;
• Experience gained in the use of the CloudFlow infrastructure as a means to provide software-as-a-service and specialised solutions;
• Building a community of users to explore exploitation routes;
• As a result of this, CIMNE expects a 20% increase in market share after one year, increasing to 50% after three years.

CSUC, the HPC provider, is extending their service portfolio and has specifically achieved the following:

• New knowledge acquisition through the project regarding visualisation tools and graphical nodes management, such as a remote visualisation integrated into a web browser;
• Implementation of Workflow edition (using the Workflow editor of the CloudFlow platform) and management tools in our HPC systems, accessible to the users with only a web browser;
• Implemented services that help the users to better understand the behaviour of their simulations;
• Remote desktop integration, which allows end users to perform pre- and post-processing stages of their workflow in the remote visualisation server, which implies that they do not need a high speed network connection to be able to download the outputs of the simulation (which can be very large);
• The estimated revenue for CSUC is €90,000 after one year and €180,000 after three years.

Using these developments, the end user is able to decrease the cost of cycloid gearbox by 30% thanks to AM and the numerical simulations. This comes from the reduction in production time and materials and allows production cost savings of a cycloidal gearbox from the current 10k€ to an estimated 7k€. This will mean selling an improved product at a lower price, while keeping the margin of profit at 35%. Moreover, the successful experiment allows the ISV to further advance the industrial applications of their large scale HPC scientific software tool, FEMPAR.

Also, considering that one of the short-term strategic objectives of CSUC is the offering of their HPC facilities to the industry, in particular increasing the usage of HPC resources by SMEs, this project is aligned with current working plans. The easy access to the CloudFlow Portal, with the only requirement being a web browser, may allow CSUC to implement a fast pay-per-use access to their HPC service. The remote visualisation service implemented can be included in the services portfolio that CSUC is offering as an HPC provider.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive summary</td>
<td>4</td>
</tr>
<tr>
<td>1 Description of the current (engineering and manufacturing) process (PU)</td>
<td>7</td>
</tr>
<tr>
<td>2 Description of the (engineering and manufacturing) process based on Cloud services (PU)</td>
<td>8</td>
</tr>
<tr>
<td>3 Lessons learned (PU)</td>
<td>12</td>
</tr>
<tr>
<td>4 Impact (PU)</td>
<td>13</td>
</tr>
<tr>
<td>5 Business model (CO)</td>
<td>17</td>
</tr>
<tr>
<td>6 Execution of the experiment (CO)</td>
<td>23</td>
</tr>
<tr>
<td>7 Recommendation to the CloudFlow infrastructure (CO)</td>
<td>28</td>
</tr>
<tr>
<td>8 Confidential information (CO)</td>
<td>29</td>
</tr>
<tr>
<td>9 Involved organisations</td>
<td>30</td>
</tr>
<tr>
<td>10 Appendix 1: User requirements and how they are met</td>
<td>31</td>
</tr>
<tr>
<td>11 Appendix 2: Usability evaluation</td>
<td>34</td>
</tr>
<tr>
<td>12 Appendix 3: Business model exploration concept</td>
<td>43</td>
</tr>
</tbody>
</table>
1 DESCRIPTION OF THE CURRENT (ENGINEERING AND MANUFACTURING) PROCESS (PU)

On average, the complete engineering and production of a cycloidal gearbox takes STAM about four to six months, depending on the design. This includes several steps and assumes that the collection of requirements has been done beforehand.

The first step is the generation of the cycloid profiles according to specifications, which requires engineering skills and tools and takes two to four weeks. After the profiles are detailed, multibody simulations have to be performed, to verify contact pressures on the profiles and perform corrections if needed. Moreover, this phase leads to the identification and integration of proper rolling bearings, and the realisation of technical drawings and of the CAM dataset. These steps usually require up to two months and are a necessary design phase that allows parts procurement to be performed, for which STAM has several suppliers. After parts are purchased and assembled, several tests have to be carried out so that the gearbox can be fine-tuned. These steps add up to a production time of about six months and a cost in terms of materials, parts and engineering work of about 10k€.

The current production process leads to a time to market which is largely dependent on the time-consuming production processes currently used for cycloidal gearboxes manufacture, such as Electrical Discharge Machining (EDM). Moreover, it is costly and inefficient in terms of material use. Current AM processes would reduce this time to production and material waste, but the high thermal gradients generated during such process would cause stresses and distortions in the material of the final part, thus affecting its performance due to the very strict geometric tolerances. A schematic representation of the current gearboxes production process is shown in Figure 1, highlighting the time, costs and FTE of each step.

![Figure 1. Current gearboxes production process](image)

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<thead>
<tr>
<th>Step</th>
<th>Time</th>
<th>Cost</th>
<th>FTE</th>
</tr>
</thead>
<tbody>
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<td>Cycloid Profiles Generation</td>
<td>0.5 months</td>
<td>1k€</td>
<td>1p. full time</td>
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<tr>
<td>MBS and integration of bearings</td>
<td>1.5 months</td>
<td>1.5k€</td>
<td>1p. full time</td>
</tr>
<tr>
<td>Preparation of CAM dataset</td>
<td>0.5 months</td>
<td>1k€</td>
<td>1p. full time</td>
</tr>
<tr>
<td>Parts procurement &amp; Prototyping</td>
<td>2 months</td>
<td>4.5k€</td>
<td>1p. full time and 1 p. 50%</td>
</tr>
<tr>
<td>Testing and Tuning</td>
<td>1.5 months</td>
<td>2k€</td>
<td>2pp. full time</td>
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</tbody>
</table>

FIGURE 1. CURRENT GEARBOXES PRODUCTION PROCESS
2 DESCRIPTION OF THE (ENGINEERING AND MANUFACTURING) PROCESS BASED ON CLOUD SERVICES (PU)

In the case of AM, to ensure that parts are produced according to the stringent geometrical tolerances, a proper simulation of the process is necessary, which can be very time consuming. The efficient use of HPC platforms could considerably reduce the simulation time, allowing for optimising the parts’ shapes (taking into account distortions and residual stresses). This is the motivation from the end user perspective for using the CloudFlow platform to efficiently simulate the metal AM production process and cut production time and cost, while maintaining or even increasing product quality.

As mentioned in the previous section, a gearbox producer may be willing to adopt AM as a new process to substantially decrease time to market and costs of their products. Introducing Cloud computing in the workflow changes the process as shown in Figure 2.

The main advantages of CloudFlow method compared to the traditional approach are the following:

- Subtractive Manufacturing does not allow for producing nearly every kind of shape with simple procedures and low costs, whereas with AM, the designer can include undercuts or other complex shapes;
- Thermal simulations help limit production costs and time, avoiding an approach completely based on trial-and-error and allowing for optimising the AM parameters to be used during the part production;
- AM helps the manufacturer to spare raw material and to be less time consuming than in the traditional method.

Referring to the workflow application, the AM simulations were chosen to be done via FEMPAR, a proprietary simulation software by CIMNE, which has been ‘cloudified’ and integrated into the CloudFlow infrastructure and adapted to be visualised remotely. A pre/post-processing application, GiD, is used to set the simulation parameters, import the geometries to be printed, and visualise the results of thermal simulations. Figure 3 shows the first step of the workflow, in which a web browser is used to connect to the service and select the desired experiment.
The second step of the workflow is the file chooser (Figure 4), which allows the user to select files from the uploaded folders containing: the geometries, mesh data (if already created), simulation data (if already completed) and scanning path information of the AM tool (.cli file).

The remote visualisation can then be accessed via login, and the GiD interface can be used to pre-process the simulation case; here the user can set the AM parameters, modify geometric aspects such as the surfaces and volumes composing the part to be printed, and set up and create the mesh.
FIGURE 5. PREPROCESSING

Figure 5 shows the user interface of GiD, with the geometry to be printed and its support. Figure 6 gives an overview of the definition of the parameters for the simulation task. In this case, the supports were modelled with an unstructured mesh to decrease the computational load, while the object has a structured mesh to increase the precision of the tessellation.

FIGURE 6. PROBLEM DEFINITION
After the experiment is set up and the simulation is running, GiD can also be used as a post-processing tool in order to visualise the results. In the case of the thermal simulation, the output is a field of temperatures within the printed geometry and its supports (Figure 7).

![CloudFlow Simulation](image)

**FIGURE 7. RESULTS VISUALISATION**

STAM, as the designer of the gearboxes and end users of the experiment, has found a 65% reduction of the simulation time (18.5 hours for the simulation of a single part on standard workstation vs. 5.5 hours for simulating the same part using HPC) thanks to the ‘cloudification’ of the software in the CloudFlow environment. This will allow for running a number of simulations in a reasonable time in the future, in order to find the optimal values for all the AM parameters, and to reach a one-trial manufacturing set up to maximise the time and cost reduction.

The time reduction and the possibility to manage all the different steps of the process from a single software interface improves the user-friendliness of the process. The possibility to run the workflow remotely from any internet connection node represents a further strength of the CloudFlow environment.

Referring to the technological breakthrough that the end user finds in using the CloudFlow Portal, the possibility to run a thermal simulation of a production process on multiple cores without physically owning a powerful computational infrastructure represents a significant advantage for state-of-the-art simulations. Moreover, the flexibility of the tool, with the possibility to choose between many different simulation problems within a unique environment will make the CloudFlow Portal a tool going beyond the state-of-the-art, increasing its overall effective use.
3 LESSONS LEARNED (PU)

The experiment, together with its technological and economic challenges and benefits led to an increased knowledge about the technologies involved for all the partners.

STAM, as end user, aimed to compare the state-of-the-art technologies and processes (namely, Subtractive Manufacturing steel working procedures) with the approach proposed to CloudFlow, the simulation of a “blown powder” Additive Manufacturing process. Thanks to this experiment, STAM obtained first-hand experience of the power of HPC computing in such simulations, with the main objective of achieving reliable thermal simulations of the manufacturing process of its cycloidal gearboxes in a much shorter time than by using a normal single core computer. Moreover, STAM learned that the needs arising from complex design and production processes and simulations are best targeted by giving the user total flexibility on the amount of resources to be used and other simulation parameters (e.g., the size of the mesh elements), allowing faster computations and providing customisable payment models, as in CloudFlow. Cloud technology opens new possibilities for the gearbox manufacturing industry, allowing the employment of AM, a methodology that was very limited until now due to the thermal gradients and mechanical distortions and stresses within the printed material. These were not acceptable with the very strict tolerances of such products. STAM, being active in several high-tech fields, also had a taste of the potential of HPC computing, which could be exploited in several design and production-related fields that occur daily, such as multi-body simulations of complex mechanisms.

For CIMNE, the ISV of the experiment, their major commitment is to provide fast and easy to use simulation software to their users. The simulation task targeted in this experiment was complex and challenging with respect to balancing these requirements. Cloud technology offers CIMNE and their simulation software FEMPAR new possibilities to hide complexity from the end user, thus, helping them to reach a good solution. It also allows providing end users with mechanisms to select the amount of resources to be used, according to their needs.

CSUC, the HPC provider, was mainly involved with the integration of CIMNE’s software in the platform and in the creation of workflows. The CloudFlow platform allowed the implementation of complex workflows that fit the needs of the users. The simplicity of the CloudFlow Portal increases the user productivity through the automation of tasks and the low requirements of only needing a web browser. The remote visualisation service, implemented in the CloudFlow Portal, enables the possibility to offer a remote visualisation for pre- and post-processing to the users.
4 IMPACT (PU)

The GEARBOXES experiment gave the participants several new skills and possibilities to be exploited in their future activities and businesses.

In particular STAM, as the end user of the experiment, will benefit from the CloudFlow environment and the developed workflow in their design activities. In fact, the design and optimisation procedure of the cycloidal gearboxes contains many challenges, especially in relation to the manufacturing of very complex shapes with very strict geometric tolerances. These complexities, together with the bottlenecks of traditional subtractive manufacturing techniques and the trial-and-error procedure used to optimise the product through long test campaigns, led to a time-to-market of up to six months for new models with production costs close to 10 k€.

Thanks to Additive Manufacturing and the thermal simulations tested within this experiment, the trial-and-error approach is likely to be eliminated, and the engineering/production time can be reduced to a couple of months. From the end user (mechanical designer and product manufacturer) point of view, this will imply a shorter time to market in the case of innovative product design with consequent competitive advantages and a reduction of the overall costs which are estimated to decrease to 7 k€ (a 30% reduction overall). This economic benefit can be achieved thanks to different factors:

- Firstly, the engineering time reduction;
- Secondly, the production time of the single item and the material saving thanks to AM;
- Finally, avoiding the trial-and-error approach for the optimisation which reduces the quantity of discarded parts during the quality control procedure.

Increased flexibility provided by AM will allow for opening new markets. Market expansion and new manufacturing opportunities will contribute to creating new jobs to support the growth brought by these opportunities. Existing resources will work to foster the follow-up activities of the project and allow STAM to use AM and simulation as the standard manufacturing workflow for cycloid gearboxes. Three years after the experiment completion it is expected to create three new jobs in the focus area of the experiment.

The typical customer of cycloidal gearboxes is an SME or Large Enterprise developing machines for industrial automation, robotics and space. The market size of such companies is estimated €600 million. One year after the experiment STAM aims at having 10 companies as customers in this market (approx. 0.015% of the market size), and three years after experiment completion STAM wants to triple their market share from 10 to 30 companies (approx. 0.05% of the market size). The type of product and associated service STAM provides in the field of cycloidal gearboxes is for special high-tech applications that cannot rely on series production suppliers. For this reason, each client usually requires the production of 1 to 2 gearboxes so we expect to sell roughly 12 to 15 gearboxes after one year and 35 to 40 after 3 years. STAM estimates the additional revenues of the company due to exploiting the experiment’s results to be €100,000 after one year and €320,000 after 3 years.

From STAM’s customers’ perspectives, cycloidal gearboxes are a key technology for a number of applications, since such devices allow them to obtain a high ratio between the input speed (e.g., an electric motor) and output (e.g., an end effector), which is translated into a high increase (20%) of the transmitted torque. Moreover, the high efficiency and compactness of cycloidal gearboxes make them suitable for some particular applications, such as aerospace and robotics, while the resistance to torque peaks and shocks makes them appealing for heavy industries such as wood working and steel
making. If AM is successfully adopted thanks to CF simulation, the customers of STAM will benefit from a higher product quality (*increased rated torque*), which is sold at a lower price (*cost savings*).

At the end of the experiment, the end user STAM has achieved the following **technical impact**:

- STAM now has the possibility to take into consideration AM as a possible manufacturing approach for gearboxes, since the experiment results have demonstrated that the simulation time can be reduced by around 65% (18.5 hours for the simulation of a single part on standard workstation vs. 5.5 hours for simulating the same part using HPC), thus the huge obstacle of long simulation time for the non-cloudified software is overcome. Even if 10-15 iterations of thermal simulation are needed, the target simulation time of 15 days is met on the basis of the demonstrated simulation time of the main parts (output shaft, input shaft and eccentrics) with a fine mesh.
- The scrap material reduction was calculated via CAD model, and which strongly depends from the shape of the object to be manufactured. Referring to the cycloidal gearbox parts (the case study), it was calculated that an average of over 30% of scrap material is saved (e.g., 66% for the input shaft, 25% for the output shaft).
- The torque density can be increased thanks to the AM approach, which allows the adoption of solutions such as printing the output shaft as one piece (Figure 8) – this would be too costly using traditional subtractive manufacturing techniques. Indeed, reinforced connection between the pin and the plate can be printed, and the transmittable torque increased by 20%. This result was calculated via analytical formulas, taking into account the connection radius and the pin section radius.
- The time-to-market of a new gearbox can be reduced by 30%: in the baseline situation, this time is around 6 months. The experiment showed how this can be reduced by 2 months, mainly thanks to the engineering workflow time reduction (avoiding the trial-and-error approach) and production time reduction through AM.

Summarising all the technical impacts, STAM can increase their competitiveness in the transmission systems industry for high tech applications due to the fact that they can become the number one source of mechanisms for special applications at a more affordable price in the cycloidal gearboxes market.

**FIGURE 8.** (LEFT) AM APPROACH WITH PRINTED PINS; (RIGHT) TRADITIONAL APPROACH, ASSEMBLED PINS

The above mentioned economic and technical benefits make the CloudFlow environment a key technology for an end user like STAM, since it allowed the company to start using AM as a new production process for its gearboxes, with very strict tolerances. Thanks to the lower costs and shorter time-to-market compared to the current situation, the market share of these devices can and will be increased.
CIMNE, as Independent Software Vendor, will be able to exploit a new service for its customers with a remotely accessible multi-core simulation of the emerging industrial process of Additive Manufacturing. This can allow their product (FEMPAR) to hold a reference position in the market of software simulations, reaching new market shares, in particular for high computational load applications. Moreover, a new potentially global community of FEMPAR users can be created, thanks to the remote user interface and software ‘cloudification’, so that technical feedback can be immediately collected for the future development of the code itself. The increased market share is expected to be 20% in the first year after the experiment and rise to 50% after 3 years. The expected total income is €14,000 for the first year and €64,000 on a 3-year perspective which is enough to cover the production and commercial related costs estimated in €12,000 for the first year (0,25 person) and €40,000 on a 3-year perspective.

CSUC, as HPC provider, will benefit from the lessons learned during this experiment, which are related in particular to the integration of the computing power of its infrastructure to a web-based environment, managing different software functionalities in a unique workflow. New technical skills about remote visualisation tools were also acquired by CSUC during the experiment. From an economic point of view, CSUC will benefit from the experiment activities and results. After the demonstration of AM multi-core simulation, CSUC will be able to develop a new HPC service for industrial customers, mainly SMEs, together with remote visualisation functionalities. These novel services in CSUC’s portfolio are expected to bring new customers to the company, who want to perform process simulations quicker than using desktop computers.

CSUC estimates the local (Catalonia) market size for the experiment results to be 10 customers one year after the project and 20 customers three years after the experiment, when (a) the market is more mature in terms of HPC simulation services usage and (b) developed tools have been improved through use by industrial customers. During those first stages the industrial customers will help to increase the usability of the platform, to make it easier for new customers who therefore will have fewer barriers to become users of HPC simulation services. After one year, CSUC estimates to gather 3 new companies (30% of the market) and grow up to 10 companies (50% of the market) after three years. The income (revenue) is estimated to be €90,000 after one year and €180,000 after three years: the envisioned income per customer at first stages is higher than on late stages, as the services need to be automated and so the cost will become more affordable (and attractive) for users. This will allow the creation of one additional job position after 3 years.

A Cloud-based infrastructure enables the development of more innovative and novel products:

□Strongly agree □Agree X Neutral □Disagree □Strongly Disagree

A Cloud-based infrastructure is a powerful tool that, depending on the application, can facilitate many phases of engineering workflows. However, this does not necessarily impact the novelty of the product.

A Cloud-based infrastructure enables more reliable and robust products:

□Strongly agree X Agree □Neutral □Disagree □Strongly Disagree

Cloud-based infrastructures enable the simulation of the production process of Metal Deposition (MD)-printed cycloidal gearboxes, making it more reliable and allowing the end user to benefit from this technology.
The integration of services on the Cloud within your development chain creates flexibility and production on demand:

X Strongly agree □ Agree □ Neutral □ Disagree □ Strongly Disagree

For this application, Cloud-based infrastructures minimised the problem of software licences and infrastructures, allowing greater flexibility in the design phase.

Services on the Cloud streamline and unclench the relevant processes:

X Strongly agree □ Agree □ Neutral □ Disagree □ Strongly Disagree

For this specific application, and also generally, Cloud services allow the users to be free from the infrastructures constraints of his system, and to focus on the relevant aspects of the engineering process.
5 BUSINESS MODEL (CO)

For the business model work developed for the GEARBOXES experiment the following methodology was implemented:

1. Analysis of the current vs. new Cloud-based business model for CIMNE as ISV, including definition of the exploration concepts.

2. Application of the Customer Development method (Section 5.2) for the theoretical Cloud-based business model validation in real scenarios, according to STAM’s feedback as end user of the software.


4. Definition of the revenue stream options for CIMNE associated with the new Cloud-based business model.

5. Analysis of the benefits obtained by an average end user under the Cloud software utilisation.

5.1 Business Model exploration concept

Figure 9 summarises the results of the work done with the software provider (CIMNE) involved in the GEARBOXES experiment in order to identify the Cloud-based specific business concepts. For that, the different blocks of the Osterwalder methodology for business model generation were reviewed step by step, obtaining the following main concepts, which were later tested during the Customer Development stage.

![Business Model Concept Diagram](image-url)

**FIGURE 9. BUSINESS MODEL CONCEPT**

The full Business Model report generated can be found in Appendix 3.
5.2 Customer Development

Following the Customer Development\(^2\) methodology, and with the purpose of assessing the Cloud-based business exploration concepts, the software provider worked with STAM as the testing end user, who provided real feedback about such proposed business concepts by answering a specifically designed questionnaire. A summary for the results obtained in the questionnaire is as follows:

Although not experienced yet, STAM gives a positive opinion about Cloud computing, but considers security to be a constraint unless it could somehow be assured in the service. STAM thinks that CIMNE’s software service might raise advantages when offered in a Cloud-based manner, and the impact (positive) would be higher in terms of lower price, higher computing power and service accessibility and usability. For STAM, the most valued aspects in the case of migrating to a Cloud-based software service are security assurance, quality of service, training and after-sales support. Finally, in such a scenario STAM would expect pay-per-use, licence subscription and flat rate as charging methods, in that order of preference.

5.3 Market and exploitation expectation

The following tables expose market research data concerning aspects such as customer segments, market size or clients, sales and income expectations for the Cloud-based exploitation intentions of CIMNE.

<table>
<thead>
<tr>
<th>INDICATOR</th>
<th>1 year perspective</th>
<th>3 years perspective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of proprietary applications/workflows in the Cloud</td>
<td>Quantify the number of applications or workflows with other solutions to be exploited in a Cloud based manner</td>
<td>1</td>
</tr>
<tr>
<td>Customer segment/niche</td>
<td>Define the type of customers to be addressed in terms of sector/industry, customer profile, customer size (SME, etc.)</td>
<td>AM engineering SMEs</td>
</tr>
<tr>
<td>Market size</td>
<td>Quantify approximately the global market size for that segment in terms of number of buyers potentially demanding the product/service</td>
<td>5</td>
</tr>
<tr>
<td>Number of clients</td>
<td>Quantify approximately the number of final users that will pay for the product/service</td>
<td>2</td>
</tr>
<tr>
<td>Market share</td>
<td>Quantify approximately the percentage (in terms of units or revenue) of the market segment addressed that will buy the product/service</td>
<td>20%</td>
</tr>
<tr>
<td>Number of new jobs created</td>
<td>Quantify approximately the number of jobs created as a consequence of the Cloud-based model</td>
<td>0</td>
</tr>
</tbody>
</table>

\(^2\) The Customer Development method was developed by Steve Blank and is based on the validation of a business model under the customer perspective, testing the customer reactions and opinions about some hypothesis previously established.
Clarifications:

- Although CIMNE developed FEMPAR-AM, a tool to simulate the AM process, the number of applications in the Cloud in a three year perspective could be increased to four, considering different types of parametric calculations.
- Even though the AM market is multi-billion in terms of market size, the customers considered by CIMNE in the table are companies or research centres buying simulation tools and not AM design or manufacture.

**TABLE 2. MARKET RESEARCH DATA BY ISV: EXPLOITATION ANALYSIS**

<table>
<thead>
<tr>
<th>INDICATOR</th>
<th>1 year perspective</th>
<th>3 years perspective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sales to existing clients</td>
<td>Quantify approximately the number of unitary sales of the Cloud-based product /service to already existing clients</td>
<td>2 month (flat) 2000 hours</td>
</tr>
<tr>
<td>Number of sales to new clients</td>
<td>Quantify approximately the number of unitary sales of the Cloud-based product /service to new clients</td>
<td>1000 hours</td>
</tr>
<tr>
<td>Average price</td>
<td>Define approximately the average price or prices of the Cloud-services to the previous clients</td>
<td>4000 €/month 2€/hour</td>
</tr>
<tr>
<td>Total income</td>
<td>Quantify the income derived from total sales</td>
<td>14000€</td>
</tr>
<tr>
<td>Production and commercial related costs</td>
<td>Quantify approximately the total costs raised from any type of activity associated to the Cloud-based business model</td>
<td>12000€</td>
</tr>
<tr>
<td>Payback</td>
<td>Estimate the period of time (normally expressed in years) required to recoup the funds expended in the investment or to reach the break-even point</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Clarifications:

- The simulations performed in the experiment took between 4 and 10 hours using 12 cores, which means between (around) 50 and 120 hours. Taking into account that the computational cost is quadratic with the problem size, solving a problem just two times bigger will result in four times more computing time. Therefore, 8000 hours would permit around 150 simulations of the smallest problem size considered by CIMNE. This number is divided by 4 each time the company considers a problem twice as big.
- The table shows average prices. CIMNE defined different rate plans during the business model development and the table shows an estimated average.

In terms of the charging models, in the specific case of CIMNE for the GEARBOXES experiment the two-stage approach will be as follows:

- In the CloudFlow Portal:
  CIMNE has basically followed the “on-demand” model. The cost of the application for the customer is 10 €/hour for the first core and 1 €/hour for additional cores.
Beyond CloudFlow:
CIMNE is interested in also implementing a monthly fee of 4000 € per user/month using up to 16 cores (as many hours as the user can require), and a package of 100 prepaid hours (first core) for 800 € + 1 €/core-hour for additional cores.

As end user of the GEARBOXES experiment, STAM predicts the following exploitation figures.

**TABLE 3. MARKET RESEARCH DATA BY END USER**

<table>
<thead>
<tr>
<th>INDICATOR</th>
<th>1 year perspective</th>
<th>3 years perspective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer segment/niche</td>
<td>Define the type of customers to be addressed in terms of sector/industry, customer profile, customer size (SME, etc.)</td>
<td>The typical customer of cycloidal gearboxes is a SME or LE developing machines for industrial automation. The customer type is not expected to change.</td>
</tr>
<tr>
<td>Market size</td>
<td>Quantify approximately the global market size for that segment in terms of number of buyers potentially demanding the product</td>
<td>about 600 Million Euros</td>
</tr>
<tr>
<td>Number of clients</td>
<td>Quantify approximately the number of final users that will pay for the product</td>
<td>10 companies</td>
</tr>
<tr>
<td>Market share</td>
<td>Quantify approximately the percentage (in terms of units or revenue) of the market segment addressed that will buy the product</td>
<td>0,015%</td>
</tr>
<tr>
<td>Company growth</td>
<td>Quantify approximately the number of new jobs created</td>
<td>0</td>
</tr>
<tr>
<td>Total income</td>
<td>Quantify the income derived from total sales</td>
<td>About 100 k€</td>
</tr>
</tbody>
</table>

Clarifications:

- STAM’s targeted market niche is high-performance gearboxes for custom applications, where huge international competitors are less likely to be competitive than their off-the-shelf solutions. For this reason, on average the product-to-customer ratio (and consequently the revenue per user, RPU) is around 1:1. It is expected, though, that with the increase in the number of clients some applications will require more than one gearbox, thus increasing the RPU.

Cycloidal gearboxes are a family of transmission systems capable of relatively high reduction ratios in compact sizes. This makes them suitable to be used for highly demanding equipment (robots, space applications, radars) especially in high-tech fields. The outcome of the experiments will allow STAM’s clients to enjoy the benefits of custom designed components, with improved mechanical properties (transmittable torque improved by 20%) and at competitive prices (ca. 10k€ per gearbox). Moreover, using simulation software will allow STAM to provide its clients an engineering service for the evaluation of innovative design concepts (e.g. using new materials and shapes) in a fast and reliable way.
5.4 End user benefits

In order to estimate the benefits of using this application in the Cloud and calculating the breakeven point of this solution, we need to quantify the costs to an end user of the application in the Cloud versus the costs they had to cover before using the Cloud.

From an average end user perspective, the following use case has been created in order to reflect the benefits obtained by such an end user based on the new Cloud software utilisation.

Calculation and comparison of costs

Assumption: We consider a 3-year timeframe and an average small customer making use of the software in an average manner (in terms of number of users and number of usages every year or month). In this simulation our small user consumes 2000 hours/year which would be 20 simulations of 100 hours. The learning curve, and consequently the time and effort needed to learn how to use GiD, are not affected by its ‘Cloudification’, so this factor has no impact on the end user benefits.

- Cost without using CF:

  It is assumed that the 20 simulations a year * 3 years = 60 simulations and around 6000 hours in total.

  | Software licencing               | = 150.000€ (3 years, including maintenance) |
  | Hardware cost                    | = Desk top PC                                 |
  | Total cost                       | = 150.000€ and the tasks could be completed in 250 days (2500€ per simulation or 25€ per hour) |

- Cost using CF:

  1 year = 20 simulations x 100 hours x 2€ /CPU hour = 4000€
  3 years = 4000*3 = 12000€
  1 year = 20 simulations x 100 hours x 0.1€ /CPU hour = 200€
  3 years = 200*3 = 600€

  Total cost = 12000 + 600
  = 12600 € and the task could be completed in 18 days (parallel simulation (up to 16 cores)) (210€ per simulation or 2,1€ per hour)

As it can be seen from these numbers, the Cloud solution brings two benefits:

1. Cost reduction 91% (traditional model 150000 versus 12600 Cloud model)
2. Time reduction 92%

Break-even point: The number of simulations in the period of 3 years (with an average of 100 hours per simulation) to see that the traditional model is cheaper than the Cloud model is 715 computations, meaning 239 computations a year or around 5 computations a week. So, if we consider an intensive customer of 5 or more computations a day then the traditional licence model is cheaper, while if the customer should launch less than 5 computations a day, then the Cloud model is cheaper for them.
Concerning the benefits for the customer we can detail them in the following table (3 years and 20 simulations a year):

### TABLE 4. COMPARISON TABLE: BEFORE/AFTER CLOUDFLOW

<table>
<thead>
<tr>
<th></th>
<th>Before CF</th>
<th>CF Experiment Cloud model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour costs for setup and/or training (if applicable)</td>
<td>Same as in CF</td>
<td>Same as before CF</td>
</tr>
<tr>
<td>Labour costs for simulation analysis (if applicable)</td>
<td>Same as in CF</td>
<td>Same as before CF</td>
</tr>
<tr>
<td>Software costs</td>
<td>150000 €</td>
<td>12000 €</td>
</tr>
<tr>
<td></td>
<td>Licence and maintenance</td>
<td>2 € per hour-core</td>
</tr>
<tr>
<td>Hardware costs</td>
<td>Desktop PC</td>
<td>600 €</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,10 € per hour-core</td>
</tr>
<tr>
<td>Total</td>
<td>150000 €</td>
<td>12600 €</td>
</tr>
<tr>
<td>Economic value Difference</td>
<td>-137400 €</td>
<td>-91 %</td>
</tr>
<tr>
<td>Time to complete the computing task</td>
<td>250 days</td>
<td>18 days</td>
</tr>
<tr>
<td></td>
<td>No parallel simulation</td>
<td>Parallel simulation (up to 16 cores)</td>
</tr>
</tbody>
</table>
To coordinate the experiment partners and monitor the progress, the experiment was broken down into seven main activities, each led by one of the partners. These activities and their timing is described in the Gantt chart in Figure 10.

### Activity Description

<table>
<thead>
<tr>
<th>Activity Description</th>
<th>Leader</th>
<th>Month Start</th>
<th>Month End</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1. User requirement analysis</td>
<td>STAM</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>A2. Collaboration with the CloudFlow Competence Center</td>
<td>CIMNE</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>A3. Integration with CloudFlow Infrastructure</td>
<td>CIMNE</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>A4. Intermediate reporting of results</td>
<td>STAM</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>A5. CloudFlow Implementation: Optimization in the cloud</td>
<td>CIMNE</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>A6. Final reporting of results</td>
<td>STAM</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>A7. Evaluation of experiments and business models</td>
<td>CFCC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 10. GANTT CHART OF THE EXPERIMENT**

In the following sub-sections, each of these activities will be described in detail, including the implementations and the developments that were carried out, as well as their outcomes.

### A1. User requirement analysis

This activity, led by STAM, was carried out to establish the functional needs of the end user of the experiment; eventually these functional requirements were translated into technical requirements for the simulation software (FEMPAR), its pre-processor and post-processor as well as for the CloudFlow Infrastructure. The starting point of the User Requirements Definition (URD) were the needs that drove STAM to look for HPC resources for the thermal simulation of the metal AM process as show in Figure 11.

**FIGURE 11. NEEDS THAT LED TO THE USE OF CLOUDFLOW PLATFORM**

The main, critical need that led to consideration of thermal simulation was the **negative effect that high thermal gradients** have on parts produced with metal AM. Moreover, the need that led to consideration of metal AM in the first place is the high cost and time to market associated with the EDM process, which is the manufacturing technique used nowadays to produce cycloid gearbox parts.
According to these first, very basic concepts, the initial requirements were as follows:

- Need to reduce time to market;
- Need to reduce material waste;
- Need to improve parts quality.

This first draft of needs was then further detailed and quantified and led to the first list of end user requirements.

Subsequently, these requirements were discussed with the ISV and the HPC provider to check their feasibility level and, most importantly, to translate them into technical requirements for the simulation software and for the HPC infrastructure. The final requirements defined by the experiment partners can be found in Appendix 1.

After defining the requirements of each partner and describing the method to measure their level of accomplishment, each requirement was given a feasibility level:

- **High**: it can be easily obtained within the experiment timeframe, resources and scope. Failure to comply with these requirements is not acceptable;
- **Med**: it might be achieved within the experiment timeframe, resources and scope if no criticalities arise. Failure to comply with these requirements shall be justified;
- **Low**: it represents a nice-to-have functionality but it is probably unachievable within the experiment timeframe, resources and scope.

**A2. Collaboration with the CloudFlow Competence Center**

This activity was ongoing throughout the duration of the experiment and consisted of the exchange of technical and functional information between the ISV and the CloudFlow Competence Center (CFCC). This was successfully carried out thanks to a Code Camp, the bi-weekly technical Telco’s and additional specific communications between partners. During the Code Camp in Kaiserslautern and the technical Telco’s, the technical work and the new developments for the CloudFlow Infrastructure at CSUC’s environment were decided. The main issues that were discussed within this activity were:

- The need for developing, by the CloudFlow System Design Group, improvements of the WFM to support loops, necessary for the optimisation service → This was accomplished by the CloudFlow System Design Group (CFSDG) and released during M9 (month 9 in the experiment timeline).
- Remote visualisation service, to provide pre-processing and post-processing of simulation tasks via remote visualisation → This was accomplished by CSUC in M7.

**A3. Integration with CloudFlow Infrastructure**

During the first 6 months of the experiment, CIMNE and CSUC designed a first version of the workflow to address STAM’s requirements and to launch complete simulations at CSUC’s HPC system. The aim of the design was to simplify as much as possible the interaction between the end user and FEMPAR. By using a visualisation service, the pre-processor GiD runs directly in the HPC environment, circumventing the need to transfer files.
Regarding the simulation software, GiD (building block B1 of software components) and FEMPAR were installed on the HPC machines. The installation of FEMPAR includes linking against the Intel MKL library which provides the interface to PARDISO, the sparse direct solver to be used to exploit CSUC’s HPC infrastructure. In September 2016, a first simulation of a very simple component running on CSUC’s HPC system was demonstrated by CIMNE to the experiment partners and to the project consortium at the project review meeting in Darmstadt.

After a first demonstration of the workflow, it was suggested to add functionality that would allow the user to input the number of cores to be used for the simulation and the queue type. This was done by CSUC and introduced as additional step to the workflow addressing the needed functionality as shown in Figure 13.

**A4. Intermediate reporting of results**

This activity was performed on time and consisted of the preparation of an intermediate results report as well as an intermediate demonstration. The deliverable was accepted during the review meeting held in M7 in Darmstadt (September 2016), where the state of the advancement of the experiment was presented and a simple simulation was shown.

**A5. CloudFlow Implementation: Optimisation in the Cloud**

This activity consisted of the joint efforts of the partners to optimise the simulation for the specific needs of the end user. In this phase STAM managed to convert the gearbox components that were selected for simulation into Common Layer Interface (CLI) files, which are needed as a simulation input. CLI is a universal format for the input of geometry data to model fabrication systems based on layer manufacturing technologies (LMT). It is suitable for systems using layer-wise photo-curing of resin, sintering or binding of powder, cutting of sheet material, solidification of molten material, and any other systems which build models on a layer-by-layer basis.
Its flexibility allows the format to be used for a wide range of applications, without loss of important information and without excluding data transfer between different applications. Due to this variety of possible applications, the syntax of these files could have several differences depending on the specific application and the application used to generate them. A slight syntax difference forced CIMNE, after analysing the files provided by STAM, to implement several changes in the code generating the scanning path and ultimately to allow STAM to use these files. These changes were developed, tested and eventually deployed end of October 2016 by CIMNE and CSUC. This allowed the partners to start testing and working on simulations with the real gearbox components, which were chosen and simulated with increasing complexity as shown in Figure 14.

The optimisation of printing parameters was deeply investigated but not deployed. This was partially due to additional implementations to make the reading of the CLI file more flexible. Moreover, in order to exploit loops and branches after their deployment, the release of the infrastructure on CSUC’s HPC servers would have needed an upgrade, at least temporarily compromising the system stability. The choice of running a simple optimisation loop within FEMPAR was discarded as it would have not exploited the advantages of the CF infrastructure. In order to address the user need for optimal parameter detection and exploit the benefits and power of HPC workflows, a parametric run was investigated, allowing the user to insert several values for production parameters (e.g. laser power and laser speed) before the simulation. A schematicisation of this approach is shown in Figure 15. This option was investigated and the implementations were started but not deployed.

A6. Final Reporting of Results

The results of the experiment as presented in this report were demonstrated during the final evaluation by the experiment end user, STAM. In the following, the main technical results of the experiment are described and compared to the experiment goals and requirements.

- The simulation software (FEMPAR) and the related pre/post-processing software (GiD) were integrated in the CloudFlow Infrastructure;
- The simulation software was then modified to comply with the files produced by the end user (this requirement was not included in the original list);
- The workflow for the management and running of the simulations was defined and implemented;
- Several components of the cycloidal gearbox were successfully simulated and analysed;
- The simulation of the main parts (output shaft, input shaft and eccentrics) with a fine mesh required less than 6 hours each. This means that even if 10-15 iterations of thermal simulation are needed, the target simulation time of 15 days is met;
- Analysing the parts printing process and comparing it to EDM, the difference in material waste was investigated; it was found that on average (weighted by parts volume) the material waste is reduced by 38%, as shown in Figure 16;

![Figure 16. WASTE MATERIAL SKETCH](image)

- Using additive manufacturing enables the manufacture of parts that normally would be produced as assemblies of single parts for economic reasons. For instance, the output shaft (shown in Figure 8) can be produced as a whole, which allows to use circular fillets and allows for an increase in transmittable torque of 20% (the increase in torque depends on the ratio between the pin diameter and the fillet radius, for this calculation a fillet radius of 0.75mm was considered).
7 RECOMMENDATION TO THE CLOUDFLOW INFRASTRUCTURE (CO)

Based on the experience from the experiment carried out, and from the end user’s point of view, the interface to design the workflow (Workflow Editor) is quite difficult to use by an inexperienced user. So, an end user will need the support of an expert. Time constraints in the industry are often tight. Any change that requires much time is crucial. Thus, a friendlier interface would be beneficial to allow the end user to create and edit workflows himself.

Regarding the implementation of the experiment, we have implemented the remote visualisation service as an application-like service. This service does not accept input or output parameters, which has been a problem in the workflow design because we need to set up the simulation using remote visualisation in an intermediate stage of the workflow, so we had to design a process to pass the CloudFlow service ID to the next stage.

Concerning usability issues, it would be very useful to have some more access to tools that allow to monitor asynchronous web services, for example to have access to some intermediate results of the job and to have an approximation to the time to get the job done. Closely related to this last point, it would be also very useful to have access to some e-mail notifications; that can inform the user when his job is finished.

---

3 This is possible as of April 2017.
8 CONFIDENTIAL INFORMATION (CO)

N/A
9 INVOLVED ORGANISATIONS

CIMNE employs some 150 scientists and engineers from different technical fields working in the development and application of numerical methods to a wide class of engineering problems. The research activities of CIMNE cover nonlinear analysis and safety studies of structures, adaptive meshing, shape optimisation in structural and fluid dynamics, computational fluid dynamics, multidisciplinary and multi-physics problems as well as the numerical simulation of metal forming processes for the manufacturing industry such as casting, welding, AM processes, among others.

STAM is an engineering and manufacturing firm providing turnkey solutions in the following sectors: automation & robotics, defence & security, aerospace, transports, energy. STAM has established partnerships with key players in the manufacturing industry: Faac, Kuka, CRF, OtoMelara, Comau and since 1997 is technological provider of the European Space Agency.

CSUC is a public consortium integrated by the Generalitat de Catalunya and ten Catalan universities. In 2000, it was recognised as a scientific and technical singular facility (ICTS) by the Ministry of Science and Innovation. CSUC manages e-infrastructures to serve the university and research communities.
# APPENDIX 1: USER REQUIREMENTS AND HOW THEY ARE MET

<table>
<thead>
<tr>
<th>Partner</th>
<th>Requirement</th>
<th>Success criteria</th>
<th>Measuring method</th>
<th>Feasibility</th>
<th>Achieved?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>End User – STAM</strong></td>
<td>Reduction of the engineering workflow duration</td>
<td>Development time is reduced by 20%</td>
<td>Comparison between the standard trial-and-error approach and the CloudFlow application</td>
<td>High</td>
<td>It has been calculated that development time would be reduced from 6 months to 4 months (33% time reduction). Achieved – with AM there is no need to cut away excess material. The material saving depends on the shape of the part, for example 66% for the input shaft, 25% for the output shaft. Overall an average of more than 30% reduction.</td>
</tr>
<tr>
<td></td>
<td>Material cost reduction through AM</td>
<td>Material waste is reduced by 30%</td>
<td>Calculation of the material amount through the CAD/CAM software</td>
<td>High</td>
<td>Achieved</td>
</tr>
<tr>
<td></td>
<td>Improvement of mechanical performances keeping the weight unchanged</td>
<td>Transmittable torque is increased by 15%</td>
<td>Comparison between baseline and optimised models through engineering formulas or FEM analysis (if needed)</td>
<td>Med</td>
<td>Calculated improvement of 20%.</td>
</tr>
<tr>
<td></td>
<td>Optimal AM parameters setting</td>
<td>The number of trials needed to manufacture a component is reduced by 80%</td>
<td>The average number of trials needed today to produce a part will be assessed. Thanks to the simulations, only one/two production attempts are needed. Would this be acceptable?</td>
<td>Med</td>
<td>This has not been assessed physically, but the reduction is still predicted, based on the assumption that AM uses a trial-and-error approach, which has now been replaced with simulation. It may be possible to obtain an estimate number of trials for comparison. An update will be given at the final review.</td>
</tr>
<tr>
<td>Partner</td>
<td>Requirement</td>
<td>Success criteria</td>
<td>Measuring method</td>
<td>Feasibility</td>
<td>Achieved?</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Improvement of the finished part quality</td>
<td>Modulus of distortion vectors in heat affected zone reduced by 20%</td>
<td>Comparison of baseline and CloudFlow simulations results.</td>
<td>Low – This requires coupling of mechanical problem and will be investigated if project duration allows</td>
<td>This has not yet been directly addressed (and was defined as low feasibility at the outset).</td>
</tr>
<tr>
<td></td>
<td>Residual stress minimisation</td>
<td>Volume affected by residual stress (non-zero stress tensor modulus) is reduced by 30%</td>
<td>Comparison of simulations results for non-optimised and optimised AM parameters set.</td>
<td>Low - This requires coupling of mechanical problem and will be investigated if project duration allows</td>
<td>As above</td>
</tr>
<tr>
<td></td>
<td>Simulation software to comply with files produced by the end user</td>
<td>The application can read simulation input files produced by the end user</td>
<td>Demonstration in evaluation</td>
<td>This was a new requirement that was identified during the project</td>
<td>Achieved</td>
</tr>
<tr>
<td>HPC Provider – CSUC</td>
<td>Add a new optimisation service to the service portfolio.</td>
<td>Different loops of the simulation are launched and the main parameter are optimised.</td>
<td>Demonstration of a user accessing and using the optimisation service during the evaluation</td>
<td>Med</td>
<td>Not done – there’s no optimisation loop</td>
</tr>
<tr>
<td>Partner</td>
<td>Requirement</td>
<td>Success criteria</td>
<td>Measuring method</td>
<td>Feasibility</td>
<td>Achieved?</td>
</tr>
<tr>
<td>------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td>---------------------------------------</td>
<td>-------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td></td>
<td>Integrate the remote visualisation service in different stages of the workflow.</td>
<td>The remote visualisation service is integrated in at least one stage of the final workflow.</td>
<td>Demonstration during the evaluation.</td>
<td>High</td>
<td>Achieved; the remote visualisation service suffers from some lag but is functional</td>
</tr>
<tr>
<td></td>
<td>Integrate GiD in the remote visualisation service</td>
<td>GiD is integrated to a specific remote visualisation service.</td>
<td>Demonstration during the evaluation.</td>
<td>High</td>
<td>Achieved</td>
</tr>
<tr>
<td>Software provider-CIMNE</td>
<td>Install FEMPAR in the HPC provider servers with appropriate optimisations</td>
<td>FEMPAR is successfully run when being called by the launcher service</td>
<td>Demonstration during the evaluation.</td>
<td>High</td>
<td>Achieved</td>
</tr>
<tr>
<td></td>
<td>Optimise FEMPAR to exploit HPC infrastructure</td>
<td>FEMPAR is able to execute many CPUs of the HPC hardware via multithreading</td>
<td>Demonstration during the evaluation.</td>
<td>High</td>
<td>Achieved</td>
</tr>
<tr>
<td></td>
<td>Reduction of simulation time</td>
<td>Simulation time is reduced by 50%</td>
<td>Comparison between the simulation time on standard offline tools and on the CloudFlow infrastructure</td>
<td>Med</td>
<td>Achieved</td>
</tr>
</tbody>
</table>
11 APPENDIX 2: USABILITY EVALUATION

11.1 Methodology and reporting

The following methods were used for the usability evaluation:

1) Heuristic evaluation in which two usability experts observed the software in use for a set of tasks;
2) “Think aloud” protocol in which the end user verbally described their process while performing the tasks;
3) An interview with the end user following the software demonstration to explore issues.

In this report, severities of the usability issues are estimated and recommendations to resolve them are proposed. Experiment leaders have been asked to provide response to these issues. The responses follow consultation with the appropriate partners for each issue (e.g. HPC provider or ISV). Some recommendations may require modification to the CloudFlow infrastructure that the ISV cannot resolve independently. Equally, some issues are not directly linked with CloudFlow, but nonetheless impact on the user experience when the whole process is considered. However, all recommendations are documented for future reference. It is recognised that it may not be possible to resolve each issue, and the suggestions are for guidance only. High severity items should be addressed as a priority.

Note that severity takes into account the number of users likely to be affected as well as the impact on the user’s experience. Thus, an issue that would lead to frustration among all users may be considered high severity, as well as an issue that may only affect a small proportion of users but could lead to discontinued use of the CloudFlow services may also be considered high severity.

11.2 Evaluation overview

Overview of user process

The user logs in to the CloudFlow Portal and selects the appropriate workflow. They then access the file selection screen and select the files for their job. Once the file is selected, a processing window appears, and then the remote visualisation tool is launched automatically with the file ready. The user must log in separately using credentials supplied by the HPC provider. The user pre-processes using the GiD interface, accessed remotely through the browser, adjust surfaces, and sets up the mesh. The job is sent to the Cloud for processing. After the job is finished, the user can return to the GiD interface to visualise the results.

Summary of usability evaluation

| Pros: |  |
• End user was able to use the software independently without the ISV being present.
• At any stage, the user can close the window and resume work without having to start the process from the beginning, which is helpful for remote visualisation work.
• The system facilitates collaborative work.
• The remote visualisation facility means that the work can be carried out on any device with a browser, which provides flexibility to the end user.

Cons:
• The end user has required additional support from the ISV to understand the process. User guidance is available but would greatly benefit from an overview of how to perform the whole process.
• There were a number of issues during the demonstration including time outs/crashes, and the system does not provide adequate feedback to help the user to diagnose the issue.
• New users would not understand the issues with overlapping surfaces, and the surface selection process is difficult.

11.3 Detail of usability issues

Issue 131.1: File selection screen organisation

Severity:
Low

Description:
Finding the appropriate files in the file selection screen is not easy and the screen is cluttered. It displays files and folders from multiple users, and the structure is unclear. With continued use this would become increasingly difficult to navigate as more files are uploaded.

Recommendations:
• For future versions, only files of the user who is currently logged in should be displayed.
Consider adding sorting options, filters, or a search tool to allow the user to more easily find the required file.

Response from experiment leader:
That will be implemented as required.

**Issue 131.2: Logging in to remote visualisation service**

**Severity:**
Medium

**Description:**
The user is required to log in separately to the remote visualisation service (Figure 18). This requires a second set of authentication details, provided separately by CSUC. Although the user was able to successfully log in during the evaluation, it was noted that they have previously had issues logging in at other sites. This may impact on other users whose organisations use security measures which may block access.

![Login Popup for NOVNC](image)

**FIGURE 18. LOGIN POPUP FOR NOVNC**

**Recommendations:**
- Ideally, the system should be able to log the user in automatically at this stage, after they have already logged in to CloudFlow.
- While it may not be possible to work around all firewalls etc. that may be in place at all companies, it would be helpful if there could be some on-screen help that alerts users to possible issues and helps to resolve them (e.g. instructions to allow access through the specified port).

Response from experiment leader:
This additional login step can be in principle easily avoided using the URL of the simplified VNC server, which allows for a direct connection without the authentication step. The problem in this situation is that the system can be accessed by any user without credentials on the platform so it could imply security issues.

Concerning the network configuration to be able to access visualisation service it is probably impossible to avoid that issue because it is mandatory to have a port available to access the service. CSUC will try to implement some warning message that informs the user about this information.

### Issue 131.3: Time out issues

**Severity:**
High

**Description:**
At several points during the demonstration, the user experienced time out problems which take them out of the Portal. This can cause significant frustration, particularly if in the middle of a complex task. Furthermore, there is only a generic error message which does not allow the user to understand what has happened, and they are likely to be unsure of the cause of the error. There were also other crashes in the demonstration with unidentified causes.

**Recommendations:**

- It is acknowledged that system timeouts may be beyond control. However, the system should **as a minimum** provide a clear error message explaining to the user that it has timed out, that their work has not been lost, and that they can log back in to the Portal to resume work.
- Ideally, the system should display an alert **before** timeout, for example a 30-second warning, in case the user is in the middle of a task.

**Response from experiment leader:**

CSUC is aware of that issue and is currently investigating if these timeouts are caused by the CloudFlow Portal or by the Workflow Manager. If it is something related to the CloudFlow Portal it should be easily solvable.

It is difficult to implement an alert before timeout because that problem occurs randomly, it can happen even if the user is actively working on the platform. This fact makes us think that is something related with the Workflow Manager version deployed at CSUC infrastructure.

### Issue 131.4: Problems with overlapping surfaces and selecting surfaces to delete

**Severity:**
High

Description:

During evaluation, significant time was spent on resolving issues with incorrectly connected surfaces. The process of selecting surfaces is cumbersome and time consuming, exacerbated by lag in the remote visualisation work. Error messages are shown, but they are unclear and the user still had difficulty in resolving the issue. Furthermore, if the user closes the error message (either unintentionally or to clear it out of the way of the working area), it does not seem to be possible to refer back to it (e.g. to check the line number affected) without repeating the error.

During the demonstration, the user selected incorrect surfaces several times, and at some points realised they had created new issues in attempting to resolve the original problem, for example by accidentally selecting and deleting multiple surfaces.

Note that this process was ultimately abandoned in the demonstration, after considerable effort to resolve the repeated errors, and we resumed the process using a previously saved example. The user has, however, been able to successfully complete it in the past.

Recommendations:

• Improve error messages to support the user in identifying and resolving errors. For example, the error may say that there is a problem with line 34, but it does not tell the user what to do; it would be better to warn the user that there are two surfaces in contact and explain that this will cause a problem, with instruction of how to resolve;
• Allow the user to refer back to error message information, or to otherwise diagnose the problem, even if the error window is closed;
• More clearly highlight problem areas (e.g. if the user does not have labels switched on, they don’t know what “line x” refers to);
- As selecting the correct item can be very difficult, consider automatic zooming when the user is selecting between two items that are very close together;
- Consider whether it may be possible to add intelligent selection of overlapping surfaces;
- Give an opportunity for confirmation when more than one surface is being deleted (e.g. “Delete 3 surfaces?” Y/N).

Response from experiment leader:

Problems of this kind are continuously addressed as a part of the development of GiD, the pre-processor developed by the ISV (CIMNE). All these recommendations will be transmitted to the GiD developing team and as future releases appear patching the version in the CloudFlow would solve the issue. In any case, it is important to stress that the issue severity depends on how good the original description of the geometry is.

Issue 131.5: Provide a clear overview of process and software functionality

Severity:
High

Description:

There is a GiD user manual (accessible under Help) which does provide instruction on how to perform the specific actions (e.g. how to delete a surface). However, it covers how to use the software, without giving an overview of the process. The user is given instruction about how to delete surfaces, but not why they might need to do this. A new user would not be aware of this. When the end user first encountered these issues, they required support of the ISV to understand them.

There are several points in the process where the user would be unsure of what to do unless they had been previously instructed. One example is in entering General Data (Figure 20), where for example they would not know which solver type to select. Another example is when the calculation has been sent to the Cloud, the user is asked to select a queue for the LSF parameters, but it is unclear what these options mean.
Furthermore, the software provides some very useful functionality that the end user had been previously unaware of and would not expect to find in the software, such as the Draw function which allows the user to visualise what they have done. An introduction to the software would help the user to get the most from the useful features it provides.

Recommendations:

- Provide an additional, introductory help guide that gives an overview of the process, shows the user how the software can be used, and highlights common issues such as overlapping surfaces and how to resolve them. This should be in addition to the existing help which gives instructions about how to perform tasks.
- Within the CloudFlow application, provide on-screen help/tooltips to explain user inputs, such as the queue dropdown.

Response from experiment leader:

The documentation of the package can be improved and the ISV is always working on that, as soon as it the investment can be afforded. In any case, we stress that for any simulation tool there is a background required to the user and there is an unavoidable learning process.

Issue 131.6: Unclear process information

Severity:

Low

Description:

When the user goes to start the Calculation process, the dialogue box in Figure 21 appears. The information message is unclear; the text “has finished” would lead the user to understand that it is complete, but in fact this only means it has been sent, so the text is slightly misleading. It is unclear what is happening now and what the user should do next.
Recommendations:

- Change the text to read “Process [name] has been sent. Please click “Next Step” above to continue to configure options.”

Response from experiment leader:

That will be changed as required.

**Issue 131.7: Lack of information about job duration**

**Severity:**

Medium

**Description:**

When the user submits the job to be processed, a screen appears telling them that it is currently executing (Figure 22), and stating which step it is processing (e.g. “5 of 8”). This process may take considerable time and there is no clear estimation given to the user, so they have no idea of how long they may have to wait.

**Recommendations:**

- If possible, provide an estimation of the time this job will take to execute;
- If it is not possible to give an estimation, advise the user that this process will take some time and notify them that they may close the window and check back later;
- Consider adding e-mail alerts to let the user know when the job is complete, so that they do not have to keep checking back frequently to see if it has completed yet.
Response from experiment leader:

In general, it is not possible to know how much time will be spent by an iterative simulation, it depends on the degree of accuracy desired and the number of iterations required to achieve convergence to the given criteria. E-mail alerts to inform the user when his job is done, can be easily implemented at batch manager level.

[From SDG]: The attached screenshot indicates a synchronous service that should finish before the HPC job starts (typically just a simple string manipulation). Other experiments executed in CloudFlow are able to produce progress information during simulation, though not necessarily accurate estimation of remaining time. A service can now request the infrastructure to send e-mail notifications.
APPENDIX 3: BUSINESS MODEL EXPLORATION CONCEPT

Information gathering for defining current Business Model of Companies

Project:

WP600 Coordinator:
11.4 Document Objective

This document is a questionnaire to be used to understand the current business model of the vendor companies involved in the CloudFlow Experiments. Answers to this template will help understand and analyse the basic lines of the current business model in place at each software vendor.

We will be using Osterwalder’s business model generation canvas as the basic framework to gather the most relevant information at each company. Consequently, in the next chapters we are proposing a number of direct questions in order to sketch a complete definition of the current business model.

11.5 Value proposition

11.5.1 Product name

Please provide the commercial name of your product (1 line maximum)

FEMPAR-AM

11.5.2 Most relevant technical characteristics

Please provide a very briefly description of the most relevant technical characteristics of the product. (5 lines maximum)

FEMPAR is a parallel hybrid OpenMP/MPI, object-oriented framework to perform Finite Element (FE) simulations of multi-physics problems. Several modules in FEMPAR permit to deal with a wide range of different physical phenomena (compressible/incompressible flows, electro-magnetism, etc.). The additive manufacturing FEMPAR module, FEMPAR-AM is a FE-based solver focused on the numerical simulation of coupled thermo-mechanical analysis.

11.5.3 Differential aspects in front of most important competitors

Please provide a very briefly description of the differential aspects (5 lines maximum)

FEMPAR is one of the few finite elements based multi-physics codes in the world that scales up to 500,000 cores. FEMPAR-AM is based on well-tested algorithms to simulate metal forming processes such as: metal casting (including pouring, solidification and cooling phases), welding (arc and Electron Beam technologies), Friction Stir Welding (FSW) and metal deposition (wire-feeding, powder-bed and blown-powder technologies).

11.6 Distribution

11.6.1 Distribution channels

Please describe very briefly the distribution channels you currently use to provide the product (5 lines maximum)

At a first stage and in the context of the project, the main distribution channel of FEMPAR-AM will be through the CloudFlow consortium, and through the FEMPAR repository and community of users, distributed as open source code, under the GNU GPL 3 licence, for all the other kind of applications. As we advance in the business model in the framework of the
CloudFlow platform, a dual-licensing scheme can be applied in order to permit FEMPAR-AM for commercial exploitation.

11.7 Marketing

Please briefly describe your advertising strategy and mechanisms (5 lines maximum)

The CloudFlow Portal will be an important tool to advertise FEMPAR-AM. Apart from that, we advertise FEMPAR through the usual academic activity, i.e. publications and participation in conferences and projects by FEMPAR developers. Also a well-structured webpage is currently under development. It will include tools for managing and receiving feedback from the user community, such as ailing lists, bug trackers, news, FAQs, etc.

11.8 Customer relationship

Please describe the way you currently interact with your clients. “We are interested to know if your product is a one-chance transaction, if it is a long relationship product, if you offer additional services, etc.” (10 lines maximum)

FEMPAR-AM is the first version of a simulation software resulting from the combination of the research code FEMPAR and specific AM formulations, having this experiment to explore exploitation routes, workflow and services, so at this moment STAM is our only customer and our “customer zero” to focus on. For the nature of the simulation service, it is clear that our aim is to provide a long term relationship product, with services such as development of client specific solutions (new AM modules), support and training, among others.

11.9 Customers

Please list the current customer segments your product is attending.

Our first customer segment is the kind of companies like STAM small companies needing occasional simulation services to improve the design of their products. The second customer segment is the research community to advance in R&D projects linked to AM technology (such as LEITAT, for example). Finally, our last customer segment is the marketplaces for simulation services, such as the CloudFlow, Ubecloud or Simscale, devoted to users of simulation services as a commodity, consulting companies, or software developers needing FEMPAR capabilities to offer client specific solutions.

11.10 Revenue stream

11.10.1 Incomes

Please list the current buying options (revenue families) you offer your clients, their main characteristics and their corresponding prices

<table>
<thead>
<tr>
<th>Buying option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SaaS and pay per use</td>
<td></td>
</tr>
<tr>
<td>Subscription models</td>
<td></td>
</tr>
</tbody>
</table>
11.11 Key resources

11.11.1 Personnel

Please give a brief description of the capacities and knowledge needed by the personnel involved in the creation and distribution of your product.

<table>
<thead>
<tr>
<th>Personnel profile</th>
<th>Description of their role</th>
<th>Number needed (approx.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhD in Computational Mechanics, expert on extreme scale computing</td>
<td>Design and implementation of new algorithms in FEMPAR.</td>
<td>0.4</td>
</tr>
<tr>
<td>PhD in Computer Science, expert on extreme scale computing</td>
<td>Design and implementation of new algorithms in FEMPAR.</td>
<td>1</td>
</tr>
<tr>
<td>Scientific software engineer</td>
<td>Development and maintenance of FEMPAR I/O capabilities and automatic installation and testing (CMake and CTest tools).</td>
<td>1</td>
</tr>
<tr>
<td>Project manager, expert in technology transfer and business models</td>
<td>Project management, market search, and interaction with potential private sector clients</td>
<td>0.2</td>
</tr>
</tbody>
</table>

11.12 Key activities

The most important activities in executing the company's value proposition. Please identify key activities per type (if any).

11.12.1 R&D

Please list the key activities (if any) involved in the research and development of your product (5 lines)

Our product is the result of R&D and therefore most of our efforts are concentrated here. We design and implement scalable algorithms for the numerical solution of partial differential equations. In particular FEMPAR is based on a domain decomposition strategy that has already been exploited as a multilevel solver but it also has potential to be exploited as a multiscale model, which is currently under investigation.

11.13 Distribution

Please list the key activities (if any) involved in the distribution of your product (5 lines)

At this stage, three distribution channels:
- Directly to STAM
- through the FEMPAR group of users (Open Source repository)
### 11.14 Key alliances

*Please indicate if you have currently any agreement or collaboration with other entity that acts as a provider, distributor, research...*

<table>
<thead>
<tr>
<th>Area*</th>
<th>Entity</th>
<th>Alliance description</th>
<th>Motivations for choosing this entity**</th>
<th>Benefits for your business***</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM simulation expert</td>
<td>Not defined</td>
<td>The aim is to help FEMPAR-AM to become the reference code for AM simulation.</td>
<td>N/A</td>
<td>Reduce time to market</td>
</tr>
<tr>
<td>HPC provider</td>
<td>Not defined</td>
<td>Provide computing infrastructure.</td>
<td>N/A</td>
<td>Not defined</td>
</tr>
<tr>
<td>Cloud services</td>
<td>Not defined</td>
<td>Provide remote simulation services.</td>
<td>N/A</td>
<td>Essential</td>
</tr>
<tr>
<td>Pre- and post-processing software</td>
<td>CIMNE</td>
<td>We use GiD a customisable pre and postprocessor developed by CIMNE.</td>
<td>Proximity, price.</td>
<td>Product improvement</td>
</tr>
<tr>
<td>Post-processing software</td>
<td>Paraview</td>
<td>FEMPAR provides an interface to analyse results using Paraview, an open source postprocessor.</td>
<td>Paraview is a widely used in HPC environments</td>
<td>Product improvement</td>
</tr>
</tbody>
</table>

*: I&D, Procurement, Production, Administration and management, Distribution, Marketing, After-sales / customer services  
**: Proximity, unique technology provider, price, etc...  
***: Cost reduction, reduce time to market, product improvement, indispensable, etc...
Figure 23. Business model concept