PROJECT FINAL REPORT

Grant Agreement number: N°NMP3-SL-2009-233524

Project acronym: SIMUGLASS

Project title: DEVELOPMENT OF A SYNERGISTIC COMPUTATIONAL TOOL FOR MATERIAL MODELING, PROCESS SIMULATION AND OPTIMIZATION OF OPTICAL GLASS MOLDING

Funding Scheme: Collaborative project

Period covered: from 2010.01.01 to 2013.12.31

Name of the scientific representative of the project's co-ordinator[1], Title and Organisation:

Dr. Olaf Dambon, FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V

Tel: +49 (0)241 8904 233

Fax: +49 (0)241 8904 6233

E-mail: olaf.dambon@ipt.fraunhofer.de

Project website[1] address: www.simuglass.com

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

1. Executive summary

For the high-volume production of complex optical components out of glass, such as aspheres or structured surfaces, glass moulding is a powerful and economically viable technology. Against the conventional glass optics fabrication consisting of grinding and polishing, glass moulding is a replicative technology using high-precision moulds with which glass components are deformed above transition temperature. But even though the precision glass moulding process has already been applied for many years in an industrial environment, the step for the fabrication of the necessary moulds is still very time-consuming and expensive. One reason for this is the fact that during the cooling step the glass optic shrinks. The shrinkage size has to be measured experimentally which finally leads to a re-machining of the mould. By applying this strategy, the final shape of the mould is generated in an iterative way. This labour-intensive strategy has to be applied once the glass geometry or the glass type is changed. An elegant way to avoid these iteration loops would be the deployment of finite element (FE) simulations based on computational modelling of the material properties to understand and finally to predict the shrinkage behaviour of the glass, which would lead to a more efficient mould manufacturing and a more economic precision glass moulding process.

SimuGlass is a Collaborative Project between European and India and aims at significantly enhancing the competitiveness of the European optical industry for the direct replicative production of complex optical components via collaborative development of a powerful synergistic computational FEM-tool for the precision glass moulding Technology. Achieved significant results are:

Definition and specification of moulding processes

Based on the in-house moulding technology, the isothermal moulding process and the non-isothermal moulding process were defined for industry partners respectively. Scientific analysis was carried out on the relevant thermal, mechanical, rheological and optical glass material properties and their dependency on the moulding process parameters (forming velocity, temperature, force and time).

Glass material property measurement

A range of selected material properties including emissivity, density, elasticity, thermal expansion coefficient, viscosity, viscoelasticity and friction coefficient were experimentally determined. The experimental measurement approaches were standardized.

Numerical modelling of glass moulding process

Computational modelling of the glass moulding process was carried out, including the radiative heating and viscous flow of glass and the thermal and mechanical properties of other relevant components (moulding tool, cooling concept, vacuum chamber and so on).

Development of simulation software tool

A simulation software tool was developed based on client-server concept by Java RCP and RMI technology. Simulation tasks can be generated by the FE-Client at the user side, and sent to the FE-Server through network. The FE-server can automatically execute the simulation task send results back to the client. This innovative approach realizes the integration of computational resources and the reduction of costs for the user.

Validation

The developed FEM-tool was validated by defined demonstrators, which were produced in the real moulding environment on industrial glass moulding machines. Simulation and experiment results were comparable, and the difference in between were in accepted tolerance. After compensation approach, the shrinkage error was significantly reduced according to simulation results.

2. Summary description of project context and objectives

Project Objectives

The overall goal of the SimuGlass project is to develop a powerful synergistic computational FEM-software tool for optical glass moulding processes. Based on this ambitious goal, the following scientific and technological objectives have to be realized:

- Scientific analysis of the relevant thermal, mechanical, rheological and optical glass material properties and their dependence on the moulding parameters (forming velocity, temperature, force, etc.);
- Development of powerful computational material models able to describe and predict glass material behaviour;
- Implementation of the developed glass material models into a computational framework based on Finite Element Modelling (FEM);
- Computational modelling of the glass moulding process and the thermal and mechanical properties of other relevant components (moulding tool, cooling concept, vacuum chamber and so on);
- Validation of the developed FEM-tool in real glass moulding experiments on an industrial glass moulding machine for theoretical model optimization.

These objectives finally lead to the development of a computational-based FEM-tool, in which the complex behaviour of the glass material during the moulding process is implemented. The basis for the development is the multidisciplinary approach between European and Indian researchers, which is essential for the material understanding.

All objectives stated above are realizable within the project duration. At the end of the project, the understanding of modelling of glass material during the moulding process is enhanced and integrated in an FEM-tool. Based on this gained new knowledge, the computational modelling of glass material behaviour will be integrated into real production processes. An industrial use of the tool can be assumed.

Project Context

In order to realize above mentioned project objectives, the following difficulties concerning the computational modelling of the glass properties as well as the process of precision glass moulding can be pointed out:

- Available simulation software, such as ANSYS or ABAQUS, does not provide glass material models that are accurate enough;
- Up to date, there are still lacks of computational modelling glass material behaviour in dependence of temperature and force. Furthermore, general standardized implementation methods for newly developed material models in an FEM-environment do not exist;
- Powerful material models covering the whole cycle of glass moulding from room temperature up to the process-relevant softening point are not available;
- Glass material properties relevant for precision glass moulding are only partly available. In addition, standardized determination methods of material properties are not available;
- A holistic consideration and quantitative computational modelling of the whole precision glass moulding process does not exist.

Based on these topics, an innovative approach of the proposal is the development of a generalized simulation tool covering the whole cycle of glass moulding from room temperature up to the process-relevant softening point incl. newly developed glass material models. In this holistic approach, furthermore, standardization procedures will be generated and qualified. These are the following:

- Generation of a standard implementation method for the newly developed material model or model combination in the selected FEM simulation environment, by means of user programmable features;
- Generation of a standard determination method of the material properties corresponding to the developed material model or model combinations.

Since current FEM-models and simulation tools as well as glass material models cover only parts of the process and value chain, respectively, in SimuGlass the whole process chain including its characteristics is considered (Figure 2-1).

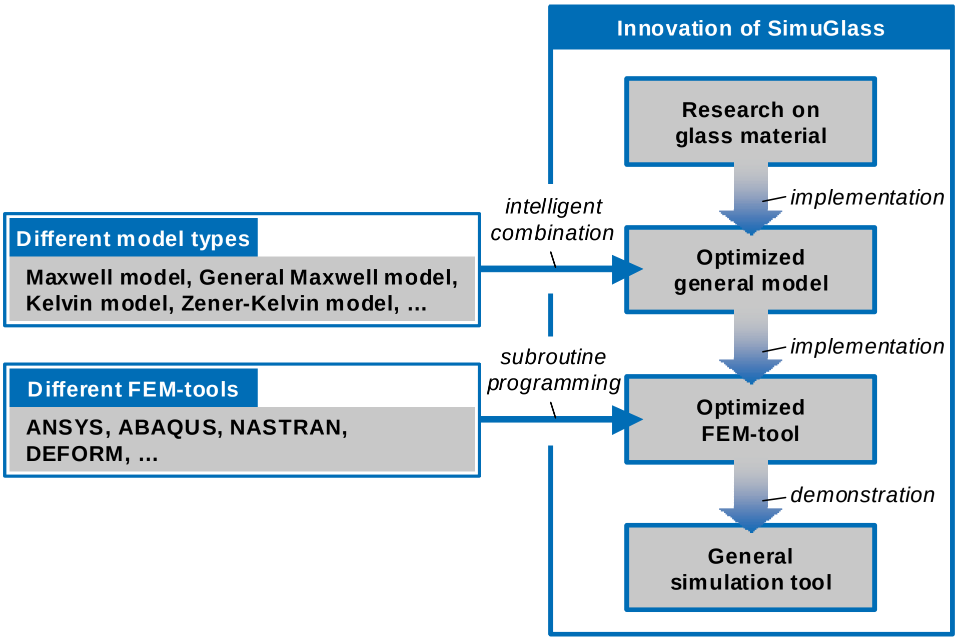


Figure 2-1: Innovative approach of SimuGlass

By developing such a tool, the efficiency of the entire process chain for precision glass moulding will be increased. The time-consuming iteration steps after moulding in order to determine the shrinkage size can be eliminated. This size will be determined in the simulation and considered in advance in an adapted mould design. Furthermore, due to the gained knowledge concerning glass material behaviour as well as the newly developed material models, the moulding process itself can be improves. By simulating the process, optimal process parameters can be identified more quickly. Hence, time- and cost-consuming pre-tests before industrial production can be reduced.

By realizing the goals of SimuGlass, both the optics industry in high-wage countries as well as in emerging countries will be strengthened. The integrative approach of SimuGlass revolutionized the fabrication of optical components – from current labour-intensive manual work to modern simulation-tool based automated production.

Since SimuGlass is a Collaborative Project between European India, the definition of work plan was based on a balanced effort between the two consortia in Europe and India with two different, but complementary foci. Since in Europe, the technology of glass moulding is being established, the focus of the European consortium is on the glass material processing and process modelling. Against this, the Indian consortium focuses more on material modelling and model implementation into a computational environment. Nevertheless, all partners of the two consortia are involved into each other's work packages in order to guarantee a sufficient information flow (Figure 2-2).

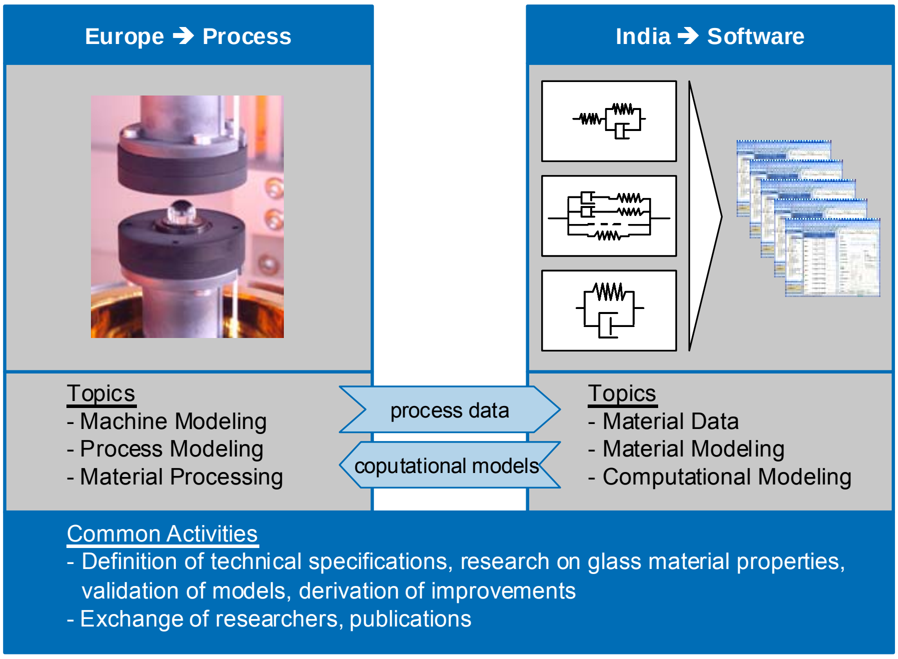


Figure 2-2: Overall strategy of SimuGlass project

The implementation strategy of SimuGlass is an integrated and holistic approach that results from the considered process chain with the individual process steps and the resulting key aspects of development:

- Holistic, since it considers all relevant elements of the value chain (research on glass material, computational material modelling, process modelling and demonstration and validation);
- Integrated, since it particularly includes the interactions among each other as well as the consistency.

Figure 2-3 demonstrated the principal setup of the solution approach. To the left, the value chain that will be considered in SimuGlass is shown. In the middle, the expected research outcome is illustrated. And to the right, the involved partners are shown.

The industrial partners Kaleido and EcoGlass represent typical end-users of the moulding technology in Europe. While Kaleido focuses more on the moulding of high-precision components (e.g. optics for mobile phones), EcoGlass concentrates more on the manufacturing of medium precision optics (e.g. illumination optics for the automotive sector). The Indian SME, BELMC is engaged in precision optics for strategic and commercial users in India. Due to their participation, a transfer of the SimuGlass development into industrial practice is assured.

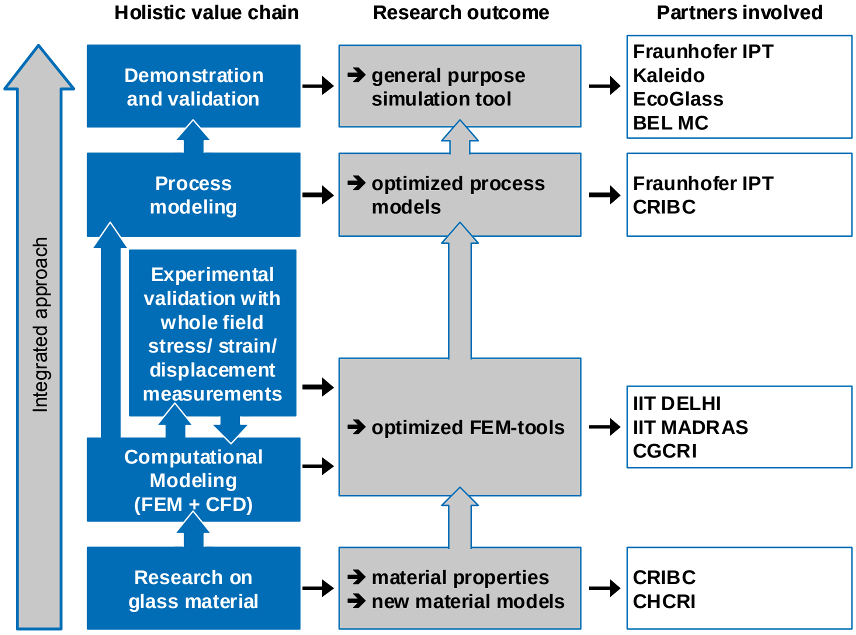


Figure 2-3: Overall strategy of the work plan

3. Description of the main S&T results/foregrounds

The main achievements of the project are reported per work package, in following pages. Detailed scientific results can be found from referenced deliverables. All achieved deliverables and milestones are also presented at the end of each work package.

WP1: DEFINITION OF SPECIFICATIONS

Leader: KAL

Participants: IPT, CRIBC, KAL, ECOG, IITD, IITM, CGCRI, BELMC

The objective of WP1 is to define relevant, application-related specifications of precision glass moulding system as boundary condition for the software selection, model building and verification. The main achievements of this work package are:

Kaleido moulding process

The moulding process in EcoGlass is done automatically on an electrical moulding machine, which is a typical isothermal moulding process due to the synchronized temperature change of glass and moulds (Figure 3-1).

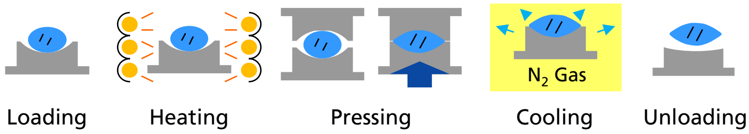


Figure 3-1: EcoGlass moulding concept

Moulding tool

The general diameter of the moulds is between 50 and 150 mm, depending on the size of the final product. Binder-less tungsten carbide is used as substrate materials for mould manufacturing. And DLC coating is applied on the manufactured moulds.

Glass

Glass discs with different diameters and thicknesses are used for different size of the final product. Glass composition is determined by requirements of the final product. Soda-lime-silica low-Tg glass is mainly used by Kaleido: D-ZK2 from the manufacturer CDGM was used for SimuGlass Project.

Process

Several steps of the moulding process were defined and shown in Figure 3-4. At the beginning of the cycle, the moulds together with the glass preform are heated up to the moulding temperature with the help of the flushed nitrogen gas, then the temperature of whole system is homogenized inside the nitrogen gas atmosphere. After that, the glass preform is pressed to the desired form by the moulds, followed with the holding process in which the glass part is cooled down together with moulds by blowing nitrogen gas, till the glass reaches around Tg. Then the upper mould is opened and the glass is quickly cooled to around 200°C, and then taken out of the moulding machine for natural cooling down to room temperature.

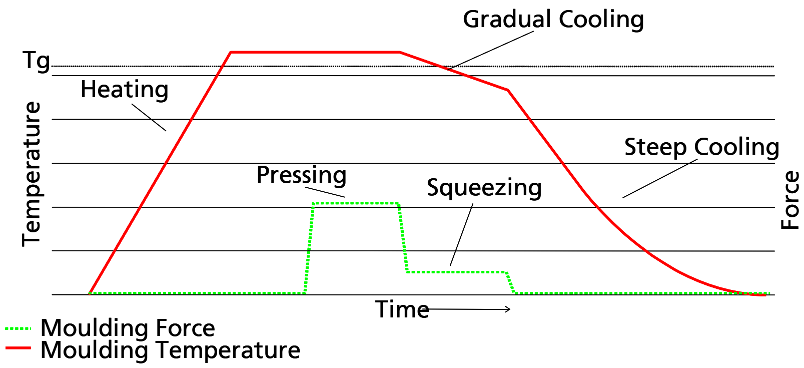


Figure 3-2: Sketch of Kaleido moulding process

EcoGlass moulding process

The moulding process in EcoGlass is done manually on pneumatic presses with one cavity, which is a typical non-isothermal moulding process due to the initial temperature difference between glass and mould (Figure 3-3).

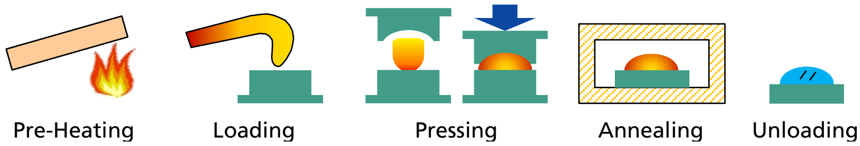


Figure 3-3: EcoGlass moulding concept

Moulding tool

The general diameter of the tooling is between 10 and 100mm, depending on the size of the final product. Stainless steel with a content of nickel and chromium is used for tooling manufacturing.

Glass

Glass rods with different diameters are used for different size of the final product. Glass composition is determined by requirements of the final product. Two main glass compositions are used by EcoGlass: soda-lime-silica glass and borosilicate glass. LIBA glass, which is manufactured by Preciosa Ornela, was used for SimuGlass Project.

Process

Several steps of the moulding process were defined Figure 3-4. At the beginning of the cycle, the top and bottom part of the tooling are separated. After the hot glass rod is put into contact with the bottom tooling, top part of the tooling moves down and a glass blank is created between the top and bottom tooling. The glass blank can be removed after the top tooling moves up, and placed into annealing chamber for determined cooling cycle to release internal stress. At the beginning of the moulding cycle, the temperature of the glass rod can be up to 200°C higher than the tool, which works generally in the temperature range from 400 to 600°C. Once they are put in contact, glass temperature is decreasing and tooling temperature is increasing. Glass temperature will continuously decreases in the annealing chamber after the moulding cycle is finished.

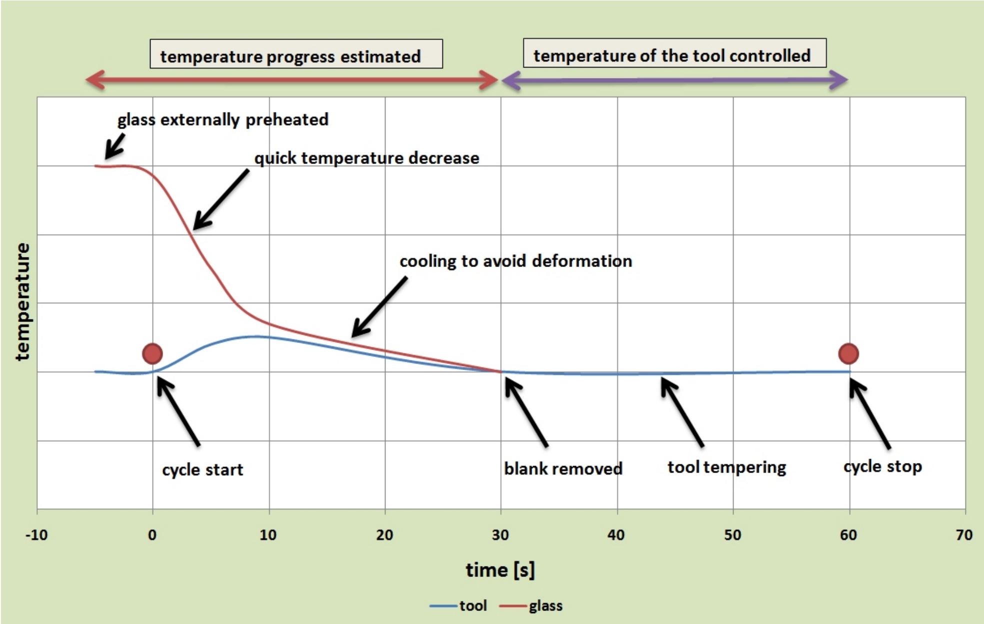


Figure 3-4: Sketch of EcoGlass moulding process

Achieved Deliverables and Milestones

Deliverable No.	Deliverable Description
D1	Specification of moulding tasks, evaluation criterion, moulding environment, mould design, mould materials and properties and possible glass pre-form geometries as boundary conditions for the further work packages

Milestone No.	Milestone Description
M1	Creation of general boundary conditions for the following research on glass property

WP2: DETERMINATION OF INFLUENCE FACTORS

Leader: CRIBC

Participants: IPT, CRIBC, KAL, ECOG, CGCRI

The objective of WP2 is to determine the influence factors for the shrinkage error via systematic analysis of the glass material properties and glass mould process. The main achievements of this work package are:

Analysis of influence factors

Both demonstrated moulding processes from Kaleido and EcoGlass were systematically analysed to find out the influence factors for the shrinkage error. Both moulding processes were simplified and considered as similar thermo-mechanical phenomena which could be carefully divided into a thermal- and a mechanical analysis system in the physical prospect of view. A schematic of such prospective view is shown in Figure 3-5.

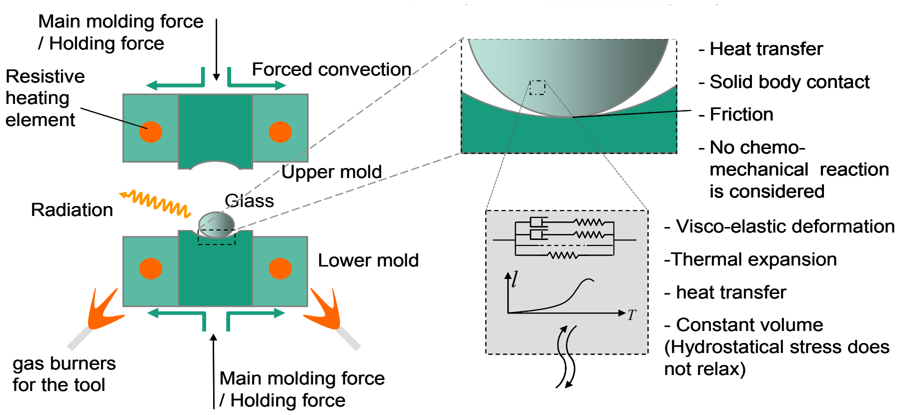


Figure 3-5: Schematic of the physical system of both moulding processes

To further analysis the exact influence factors within all involved physical effects in the system, the factors were subdivided into two groups, namely factors inside the solid body and factors in the surface interaction on the solid body surface. These two subgroups were concretized as the material properties of the solid body and the related process parameters with respect to the solid body surface interaction boundaries. Based on this criterion, relevant glass material properties and process parameters were selected for the further study:

- Material properties: chemical composition, density, elasticity, thermal expansion coefficient, viscosity, viscoelasticity and friction coefficient.
- Process parameters: moulding temperature, pressing force, holding force and cooling speed.

Constitutive model of glass material

A systematic study of available constitutive models for viscoelastic materials was carried out, since the glass material behaves as a viscoelastic material at the moulding temperature of both moulding processes. All applicable constitutive models for glass materials were listed and sorted based on literature studies (Figure 3-6).

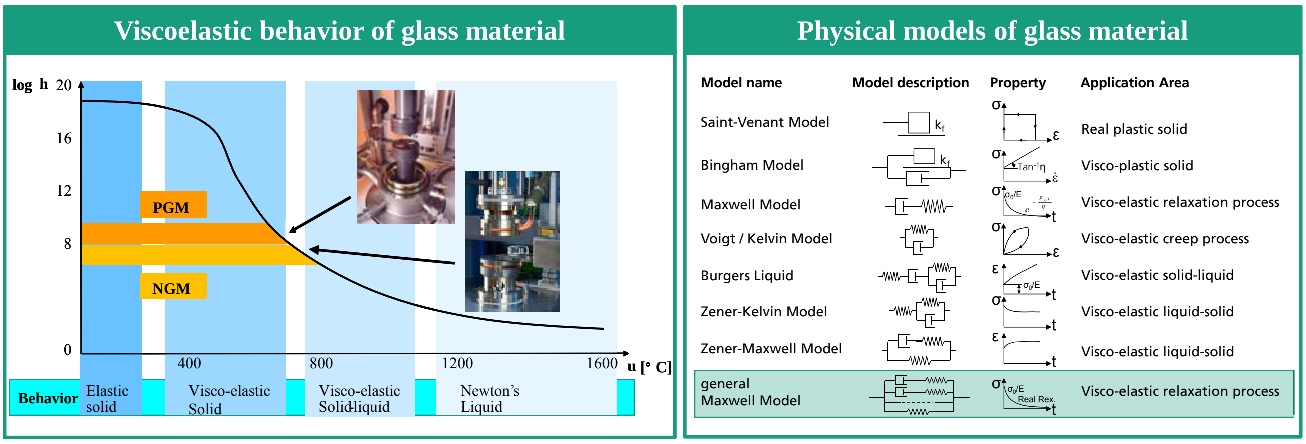


Figure 3-6: Applicable material constitutive models of glass material for both moulding processes

These models were further studied by comparing their respective predictions with experimental results. A generalized Maxwell model was finally selected as the suitable constitutive model for glass in the moulding processes covered here, considering the balance between accuracy and implementation possibility in a FEM code. In parallel, the Williams-Landel-Ferry shift function was chosen to take into account the glass thermo-rheological-simplicity.

In conclusion, most important influence factors on the final shrinkage error of moulded glass lens are determined and listed below:

- Thermal expansion coefficient
- Stress relaxation
- Holding force
- Moulding temperature
- Cooling speed

Achieved Deliverables and Milestones

Deliverable No.	Deliverable Description
D2	Specification of material properties which have influence on the final shrinkage error
D3	Theoretical models to describe the characteristic of the involved glass material properties
D4	Specification of influencing factors in the moulding environment on the final shrinkage error, and their influence behaviour

Milestone No.	Milestone Description
M2	Specification of influencing factors for the shrinkage error and their theoretical model

WP3: DETERMINATION OF GLASS MATERIAL PROPERTIES

Leader: CRIBC
Participants: CRIBC, KAL, ECOG

The objective of WP3 is to experimentally determine glass material properties. Prior to this characterization, a limited number of glass grades of interest was selected. The main achievements of this work package are:

Selection of glass grades

Having used as main criterion the interest of the industrial partners, five glass grades were selected and prioritized.

- Priority level 1 P-SK 57 (Schott) and LB 2000 (Preciosa) ;
- Priority level 1' D-ZK2 (CDGM) ;
- Priority level 2 SF 57 (Schott) and N-FK51A (Schott).

Standardisation of measurement method of glass material properties

Based on the identification of relevant properties performed in WP2, a range of characteristics of the retained glasses, including chemical composition, density, elasticity, thermal expansion coefficient, viscosity, viscoelasticity and friction coefficient were experimentally determined. The standardized experimental measurement approaches are reported in the following pages.

Chemical Composition

The chemical composition of each glass has been determined by XRF analyses for the main oxides and by ICP analyses for trace elements. The glass compositions are given in the following table.

Table 3-1: Glass composition

Oxyde (%)	P-SK57	LB 2000	D-ZK2	SF57
SiO_2	43.12	68.31	45.65	27.21
Al_2O_3	4.01	0.791	5.05	0.0038
B_2O_3	14.02	0.128	10.02	0
Na_2O	2.77	10.38	0.318	0.407
K_2O	0.021	5.59	1.8	0.564
Li_2O	6.3	0	8.1	0
CaO	0.05	5.55	0.061	0.014
MgO	0.003	0.424	0.01	0.002
BaO	24.75	4.62	20.2	0
MnO	0	0.001	0	0
ZnO	3.48	3.06	4.95	0.005
SrO	0.79	0.019	0.047	0

Oxyde (%)	P-SK57	LB 2000	D-ZK2	SF57
PbO	0	0	0	71.47
Fe_2O_3	0.002	0.016	0.005	0.001
Cr_2O_3	0.001	0	0	0
La_2O_3	0	0	3.52	0
As_2O_3	0.041	0	0	0.191
Sb_2O_3	0.233	0.597	0.109	0
TiO_2	0.211	0.069	0.016	0.0008
ZrO_2	0		0.107	0.0007
P_2O_5	0	0.003	0	0
SO_3	0	0.035	0.07	0.005
Fluor	0.008	0.5	0	0
Total	99.81	100.093	100.033	99.8743

The PSK-57, LB 2000 and D-ZK2 are glasses with high silica content. PSK-57 and D-ZK2 glasses show a high bore content whereas LB 2000 is characterized by high soda content. The SF57 differs forms the three others: it has a high lead content.

Density

The densities are determined geometrically from bar samples of typical dimensions 50 x 5 x 3 mm³. Typical values are reported graphically below.

Figure 3-7: Geometrical density values of three of the selected glasses

Elasticity

The elastic modulus of the available glass samples has been measured at room temperature using the impulse excitation technique (IET). Rectangular bar-shaped specimens of nominal dimensions 50 x 4 x 3 mm³ were machined by diamond grinding out of the glass blanks received so as to guarantee a correct parallelism between their faces. The room temperature tests were conducted according to the provisions of EN 843-2. The specimens were supported on wires located at the nodes of the first bending mode or first torsional mode, and struck a light blow. The resulting vibration acoustic signal was captured by a microphone and analysed using the Resonance Frequency and Damping Analyser (RFDA, IMCE, Diepenbeek, Belgium). A minimum of 10 frequency values were determined for each vibration mode and the elastic properties were calculated from these average vibration frequencies according to EN 843-2. The obtained elastic properties are presented in the table below and compared with supplier's data (in red).

Table 3-2: Young's modulus, shear modulus and Poisson's ratio

	P-SK57	D-ZK2	LB2000
E (GPa)	90.8 93	89.4 82.2	70.3 90.44
G (GPa)	36.4 37	36.1 36.4	28.8 -
ν	0.24 0.25	0.24 0.24	0.22 -

Thermal Expansion Coefficient
The thermal expansion coefficient has been measured using an Adamel push-rod dilatometer. The samples were bars 50 x 5 x 4 mm³. Two heating rates have been investigated, namely 1.6°C/min and 5.0°C/min. The experimental curves are analysed according to ISO 7884-8. The push rod dilatometer is constituted of a sensor linked to an alumina rod which is in contact with the glass sample. The whole is then placed into a furnace and heated with a given rate from room temperature. When the glass starts to soften, the alumina rod tends to indent (penetrate) the glass. The measurement is automatically stopped at this stage. The recorded dimensional changes with temperature are corrected afterwards for the thermal expansion of the rod and quartz support. The obtained curve allows the assessment of the transition and softening points, T_g and T_s respectively, and the determination of the thermal expansion coefficients (α) at the "solid" and "liquid state" corresponding to the slope of the linear part of the dilatometric curve below and above T_g respectively. As an example, the behaviour of the D-ZK2 is shown below as well as its characteristic temperatures when running the test under a heating rate of 5°C/min

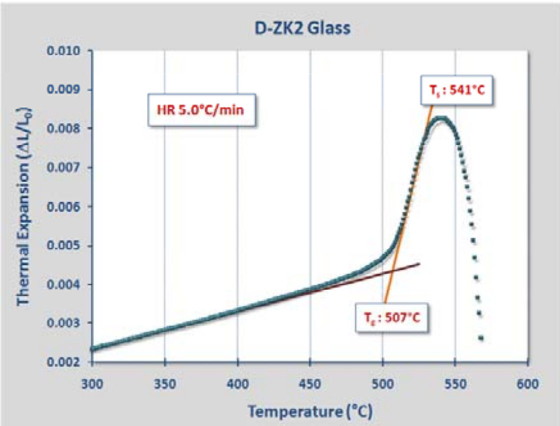
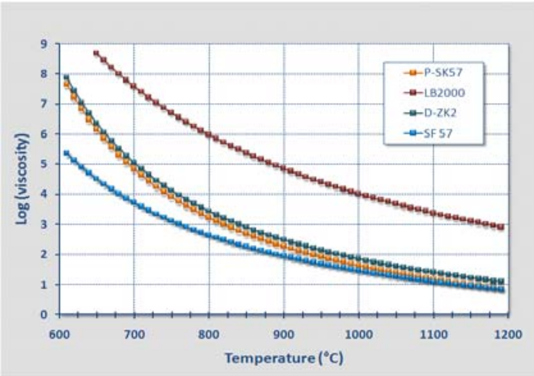


Figure 3-8: Tg and Ts values for D-ZK2 glass in the case of HR=5°C/min

Viscosity
Hot temperature glass viscosity is measured with a Haake viscosimeter using a coaxial cylinder measurement system. A platinum rod is immersed into the molten glass (~50g) contained in a platinum cylindrical crucible. The platinum rod is linked to a rotor allowing its rotation at a given rotation speed whereas the platinum crucible is fixed. This system allows the glass to flow between the immersed part of platinum rod and the crucible surface in contact with the glass. A sensor enables to measure the torque needed to keep a constant rotation speed and thereby, the shear stress in the glass. Taking into account the geometry of the cell, this stress is related to the glass viscosity at the test temperature by the following relation:

$$\log\eta = \frac{\tau}{D}\times 1048$$

with D the rotation speed of the rotor. The temperature range for this equipment varies between 800°C and 1400°C and the viscosity is measured from the highest temperature to the lowest in order to have the best thermal homogenization inside the sample. For each temperature, the shear stresses are measured at 3 shear rates and the resulting viscosity is calculated. The pooled data from 3 individual runs are then fitted according to the VFT equation. A comparison of the viscous behaviour of 4 glasses is shown below.



Viscosity Points	P-SK57	LB 2000	D-ZK2	SF57
10^4	744	1002	758	680
$10^{7.6}$	593 611	682 699	616	519 540
10^{13}	494 535	526	490 538	391 462
$10^{14.5}$	523	498	456 525	450

Figure 3-9: Viscous behaviour of the selected glasses and Characteristic temperature points derived from the VFT fitted rheological behaviour

The use of the fitted equations outside the experimentally covered temperature range, e.g. to predict the viscosity below the glass transition temperature is however not straightforward; significant discrepancies are observed between the calculated viscosity points (i.e. temperatures corresponding to 104, 107.6, 1013 and 1014.5) and those reported by the suppliers.

However, a similar behaviour is observed for the P-SK57 and D-ZK2 grades whereas the rheological behaviour of the LB2000 and SF57 glasses differs significantly. The former is obviously more viscous over the whole temperature range tested, the latter being apparently less viscous in the low temperature range (i.e. below 900°C). Owing to fluor volatilization and corresponding continuous composition change, it has not been possible to determine the viscosity curve of the N-FK51A grade.

Viscoelasticity

The viscoelasticity of glass material, which was described mathematically in Prony-Series, was measured by 4-point-benting-relaxation test. A glass bar with 70*20*5mm in geometry was bended in Toshiba moulding machine (Figure 3-10).

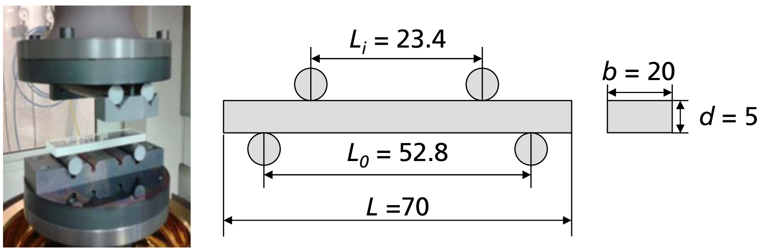
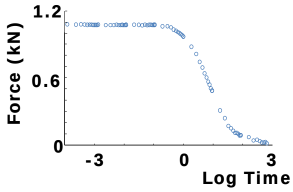


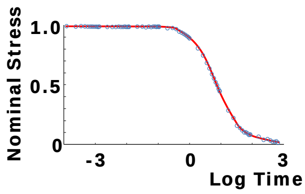
Figure 3-10: Experimental setup design of ring-compression test

The glass bar and 4-point-bending-mould was firstly heated up to a temperature around Tg. Then the upper moulding tool was pressed on the glass bar, until a small displacement was generate. The position of the moulding tool was held, while the reaction force was recorded at 10^5 Hz sample rate.

The measured force was transferred to the stress by means of 4-point-bending equation, and nominalized. The curve of nominal stress was fitted by 6-terms Prony-Series by the MATLAB programming (Figure 3-11).



$$\sigma_{max} = \frac{3(L_0 - L_i)}{2bd^2} F$$



$$G(t) = G_\infty + G_0 \sum_{i=1}^{n} \alpha_i e^{-\frac{t}{\tau_i}}$$

Figure 3-11: The measured reaction force and curve fitting on nominal stress

Friction Coefficient

The friction coefficient between glass and mould material was measured by ring-compression test. A glass ring with 8mm in height, 12 mm in inner diameter and 24mm in outer diameter was pressed by a pair of flat moulds on a standard moulding machine (Figure 3-12).

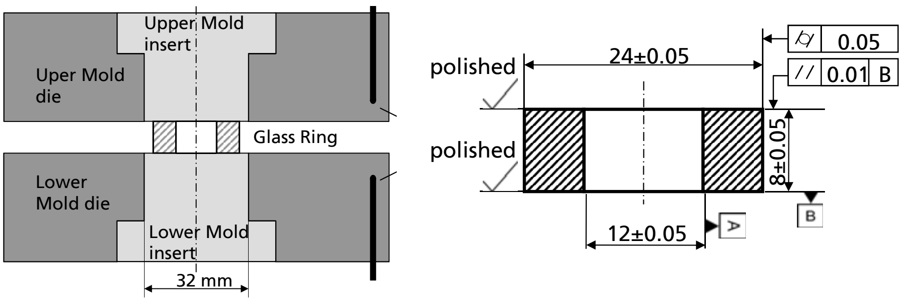


Figure 3-12: Experimental setup design of ring-compression test

The glass ring and moulds were firstly heated up to the moulding temperature. Then the glass ring was pressed to reach different height reduction. The reduction of the inner diameter of glass ring was measured for each height reduction. In parallel, a FEM simulation was carried out under the same test environment with different friction coefficients, in order to generate a standard "height reduction"-"inner diameter reduction"-"friction coefficient" diagram (Figure 3-13). The measured "height reduction"-"inner diameter reduction" curve from ring-compression test was compared with this standard diagram, so that the fiction coefficient was determined.

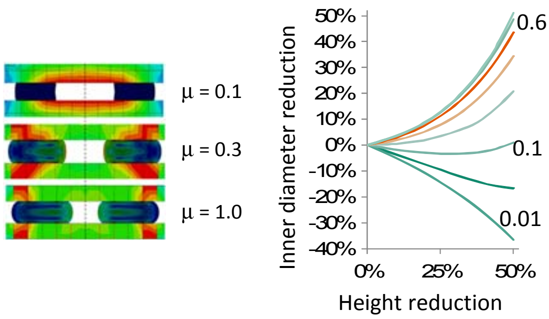


Figure 3-13: Standard "height reduction"-"inner diameter reduction"-"friction coefficient" diagram by Simulation

At the end, the format of "standard material property sheet" was defined (Figure 3-14). So that the measurement results of glass material properties can be directly used for FEM simulation. The detailed measurement results of all selected glass types can be found in relevant deliverables.

Thermal Expansion	
α [1/K]	Temp [°C]
9.61E-06	20
9.61E-06	505
9.92E-06	510
1.45E-05	600
1.82E-05	700
2.10E-05	800
2.31E-05	900
2.48E-05	1000

Prony Series (505°C)	
G_i	τ_i
0.001	8.40E-07
0.001	0.000294
0.002887	0.294
0.4259	1.59
0.4811	6.9
0.088112	139.88

WLF Shift Function		
Tr	C_1	C_2
505	15.7	274.8

Young's Modulus	Poisson's Ratio
E [GPa]	ν
70.3	0.221

Heat Capacity
C [J/(kgK)]
740

Conductivity
k [W/(mK)]
0.61

Density
ρ [kg/m^3]
2580

Figure 3-14: Example "standard material property sheet" (glass type: LB2000)

Achieved Deliverables and Milestones

Deliverable No.	Deliverable Description
D5	Determination of all necessary material properties for selected glass material according to the developed theoretical model

Milestone No.	Milestone Description
M3	Complete data sheet including the relevant material properties of glass

WP4: ANALYSIS OF INTEGRATION METHODS TO THE FEM SOFTWARE TOOLS

Leader: IITD

Participants: IPT, KAL, ECOG, IITD, IITM, CGCRI

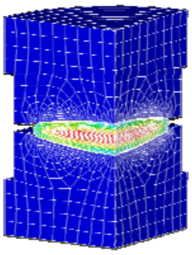
The objective of WP4 is to determine suitable integration methods to the FEM software tools for glass moulding process. The main achievements of this work package are:

Selection of FEM platforms

Selection of FEM platform was carried out among available commercial software, such as NASTRAN, ABAQUS, ANSYS, MSC.MARC and so on, on which the simulation of glass moulding process should be carried out. Finally, ABAQUS and ANASYS were selected due to the selection criteria:

- Thermo-structural coupling analysis
- Big deformation
- Nonlinear material property
- Thermo-rheological behaviour

A simulation of double-concave lens pressing was carried out on ANSYS and ABAQUS respectively. Comparable simulation accuracy was observed, but there was a big difference on the computation time. ABAQUS was obviously faster than ANSYS due to the supporting of direct-coupling method for thermo-structural analysis. Finally, ABAQUS was selected as the optimum FEM platform for further development.



Max. Form Error at Radius = 11 mm

Max. Form Error	Upper Surface	Lower Surface
ANSYS	3.1 µm	3.4 µm
ABAQUS	3.7 µm	3.7 µm

Coupling Methods

	Coupling Methods
ANSYS	Indirect coupling
ABAQUS	Direct coupling

Computation Time

Computation Time	Computation Time	Configuration
ANSYS	90 min	Xeon E5450 64Bit 3GHz 2-Processor 6-Kernel 6GB
ABAQUS	20 min	Xeon E5450 64Bit 3GHz 2-Processor 6-Kernel 6GB

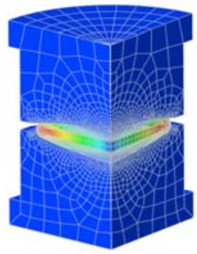


Figure 3-15: Comparison between ANSYS and ABAQUS on double-concave lens pressing

Study on test models

4 test models were defined to verify the integration method of numerical modelling on ABAQUS:

- Cylinder compression test to verify the integration of viscoelasticity material property;
- Thermal expansion test to verify the integration of heat expansion coefficient;
- Sandwich heat transfer test to verify the integration of contact heat conductance;
- Cooling test to verify the integration of convection coefficient.

Cylinder compression test

Because simulation error was occurred and model improvement was carried out, this test model will be reported in WP5.

Thermal expansion test

Because simulation error was occurred and model improvement was carried out, this test model will be reported in WP5.

Sandwich heat transfer test

Sandwich heat transfer test was carried out to verify the integration of contact heat conductance. The schema of experiment set up is shown in Figure 3-16. A piece of reference glass material B270 was placed between two pieces of another reference material from the Corning™ glass Pyrex ® 7740, designed as 3 cylindrical glass block (Ø45 x H15 mm) stacked above the other. The isolation material Dotherm® 1100 from the company DO-THERMTM GmbH Germany, which has a very low thermal conductivity of 0.10 W/(m•K) at 100 °C, was used to avoid heat loss of the system, in order to increase the measurement accuracy.

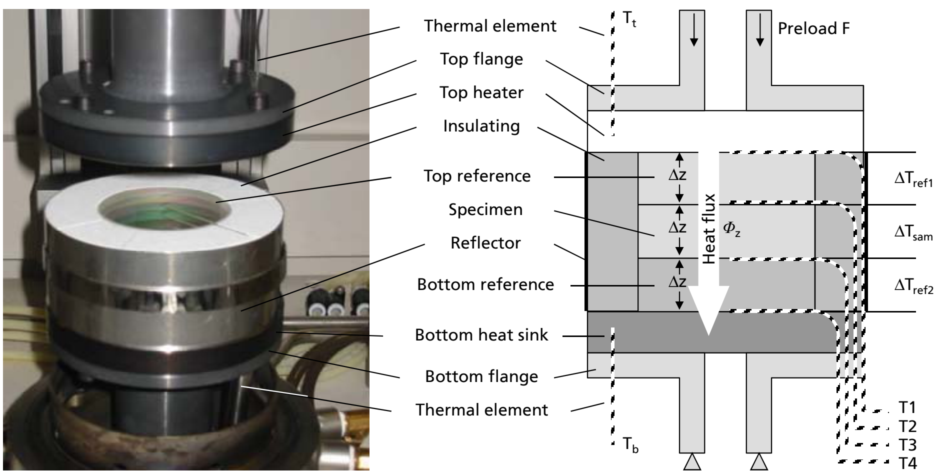
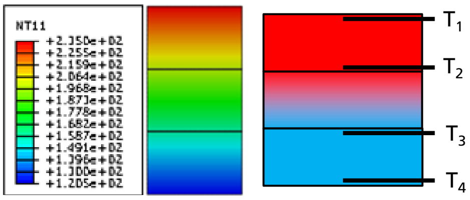


Figure 3-16: Experimental setup of sandwich heat transfer test

During the test, a temperature difference was generated between upper and lower mould, until the temperature distribution reached static state. Four thermal elements were located in the 1 mm depth channels on the upper and lower surface of Pyrex ® 7740 reference glasses. The thermal conductivities of reference glass materials are listed in the right side of Figure 3-17, which are offered by material suppliers. A FEM simulation of sandwich heat transfer test was carried out with the real moulding environment as boundary conditions. The comparison results shows a good match between FEM simulation and experiment (Figure 3-17), when the value of contact heat conductance is 250 W /(m°C).

	Position (mm)	Temp Exp (°C)	Temp Sim (°C)
T1	1	232.7	232.7
T2	14	199.4	199.4
T3	31	155.7	156.0
T4	44	122.8	122.8



	Mean Temp (°C)	Mean k (W/(m°C))
Pyrex7740	216.05	1.3443
B270	175.50	1.1685
Pyrex7740	139.25	1.2565

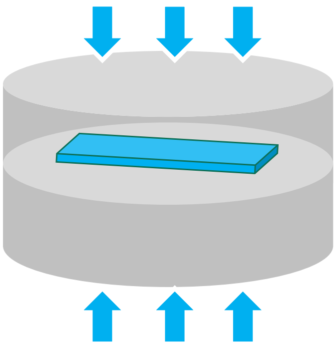
Figure 3-17: Comparison between simulation and experiment of sandwich heat transfer test

Cooling test

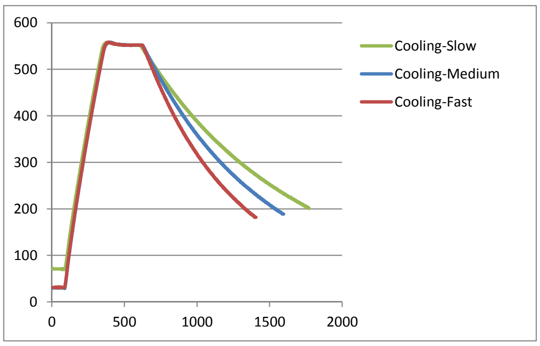
The cooling test was carried out to verify the integration of convection coefficient. The schema of experiment set up is shown in

Figure 3-18(a). This experiment was carried out on the Toshiba moulding machine, and the mould temperature was measured with a sample frequency of 1 Hz on the thermal coupling elements, to test the machine thermal dynamics as well as to obtain the FEM simulation required boundary conditions. Furthermore, several cooling experiments with different flow rates of the nitrogen gas used in the real moulding processes were carried out, as shown in

Figure 3-18(b), to gather the mould temperature curves under different cooling rates.



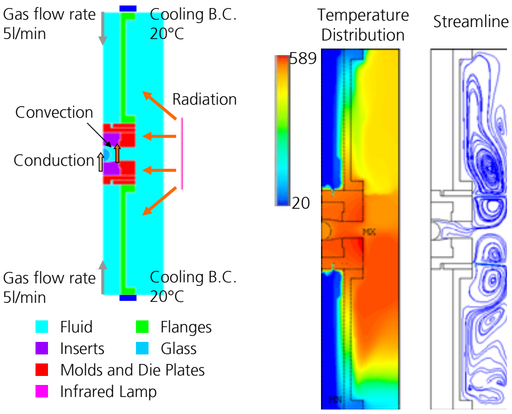
(a)

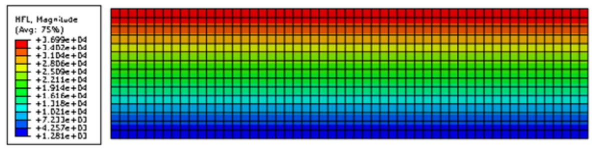


(b)

Figure 3-18: Experimental setup of cooling test: (a) schematic of test arrangement; (b) experiment results with different cooling rates

A corresponding CFD simulation model (Figure 3-19) was established based on these mould temperature curves to calculate the heat convection coefficients on the mould surfaces, which was then applied as the boundary conditions in the FEM model. As for validation of the CFD simulation results, the in CFD calculated convection coefficients were implemented in the FEM model, which then calculated the cooling rate of glass disc and compared with the real experiment results, as shown in Figure 3-19. The comparison shows that the convection coefficients generated from CFD simulation are reliable and can be applied in the FEM simulation.





FLOW RATE (L/min)	h (W/m2C)	Cooling Rate Exp (°C/s)	Cooling Rate Sim (°C/s)
15	55	0.46	0.46
25	70	0.58	0.59
40	90	0.74	0.75

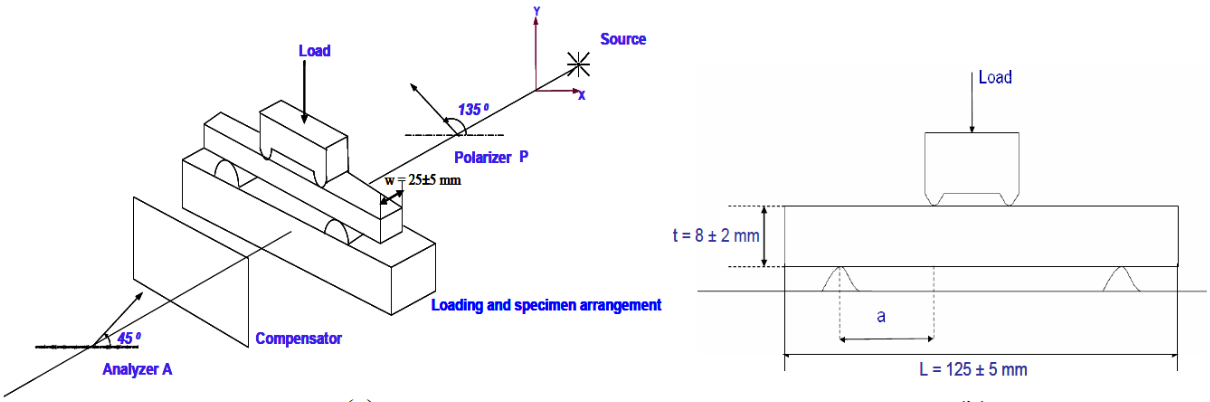
Figure 3-19: FEM simulation results (right) of cooling rate based on the calculated heat convection coefficient by CFD simulation (left)

Residual stress measurement

Photo-elastic constant of glass, also known as the stress optical coefficient, has been measured as per the ASTM Standards "C770-77". The experimental arrangement is depicted schematically in Figure 3-20a. The glass specimen, which is weakly bi-refringent is loaded with a suitable loading arrangement and kept in a transmission polar-scope. A support span of 115 mm and a moment arm, a, of 45 mm are recommended by ASTM with a tolerance of ±5%. The test specimen is a glass beam of rectangular cross section along with the loading arrangement is shown in Figure 3-20b. The specimen needs to be annealed carefully so that it is free of residual stresses.

Two different digital photo-elastic methods have been developed to determine the photo-elastic constant 'C' using a beam made of the glass material subjected to four point bending:

- Carrier Fringe Method (CFM)
- Phase Shifting Technique (PST)



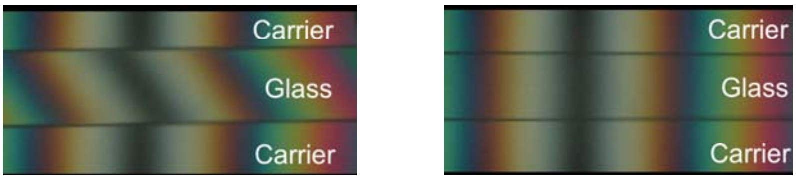
(a) (b)

Figure 3-20: Experimental setup for determination of stress optical coefficient: (a) schematic of test arrangement; (b) loading mechanism for flat glass plates

In order to measure the retardation accurately, one of the methods employed is to introduce carrier fringes to amplify the retardation in the glass plate. The carrier fringes are introduced by a stress frozen specimen of the beam under four point bending. The carrier beam should be aligned in such a way that the stresses vary linearly in the horizontal direction whereas it remains constant along the vertical. The glass plate should be so aligned that the stresses remains constant along the horizontal and varies linearly along the vertical direction. As the glass sample is loaded, the composite fringes rotate and this rotation could be used to determine the retardation in the glass plate. Figure 3-21a shows the experimental set-up for the calibration of glass by CFM. A detailed method of calculating the photo-elastic constant ‘C’ for measuring the deviation has been developed at IIT Madras. The calibration using carrier fringe method has an advantage that only a single image of the loaded specimen is required for the determination of the photo-elastic constant. At no-load conditions, the composite fringes would be vertical as in the carrier (Figure 3-31a). As the glass beam is loaded, the composite fringes rotate (Figure 3-31b) and the angular deviation is proportional to the applied stress.

(a) (b)

Figure 3-21: Two experimental set up for the calibration of glass: (a) CFM; (b) PST



(a) (b)

Figure 3-22: Dark iso-chromatics in a glass beam under the influence of carrier fringes when it is (a) no load; (b) subjected to a load of 47 N

Since glass beam is subjected to pure bending, the stresses vary linearly and hence, the fringe order varies linearly with height. This is shown in the experimentally determined plot of fringe order versus distance from the neutral axis of the beam.

Apart from the flat glass specimens, residual birefringence and circumferential stresses were measured for the moulded lens. For achieving these objectives, a specially designed experimental facility based on automatic transmission polar-scope AP-07 has been built as shown in Figure 3-23.

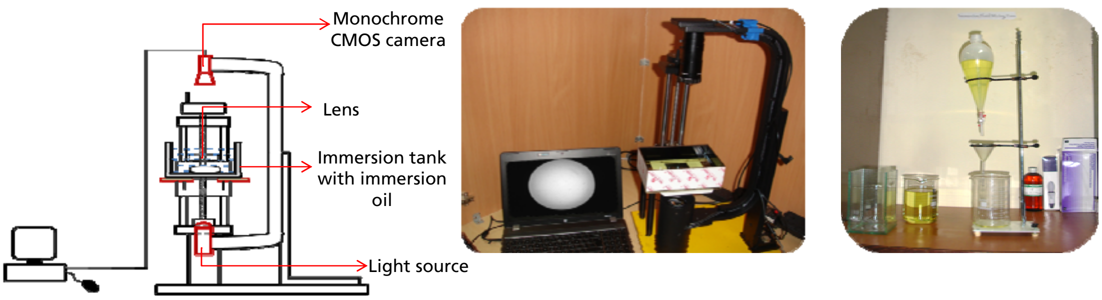
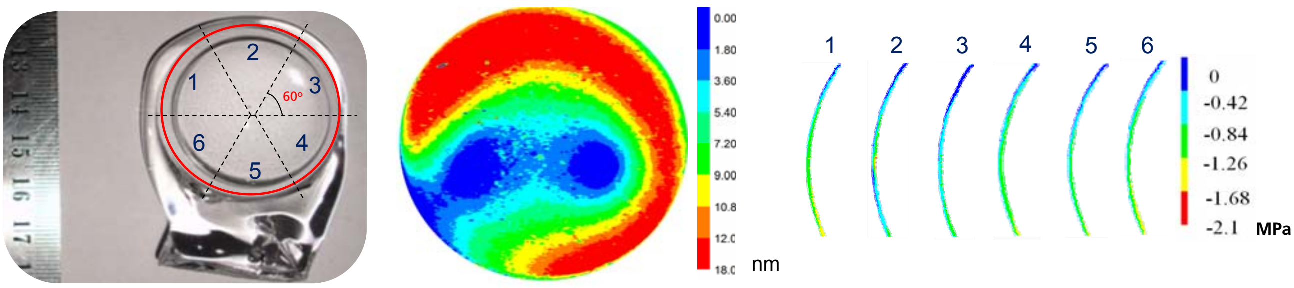


Figure 3-23: Schematic arrangement of the experimental setup for residual stress analysis in lens

This equipment essentially uses six-step Phase Shifting Technique (PST) in photo-elastic analysis to determine the fractional retardations/fringe order. Since Glass is weakly bi-refringent, the retardations are very low. Hence the techniques of phase unwrapping is not necessary. After the specimen is immersed, polarized light is passed through the lens specimen and six phase stepped images are grabbed and processed to determine integrated residual retardations. Figure 3-24 show the region of lens analysed and the residual integrated retardation distribution for EcoGlass Demo lens along the radial and circumferential directions, respectively.



(a) (b) (c)

Figure 3-24: Residual stress measurement in EcoGlass Demo lens: (a) Lens specimen with a dark circle marked to indicate the field of view; (b) Birefringence field of the lens along the radial direction; (c) Circumferential stress distribution close to the free surface of the lens

Achieved Deliverables and Milestones

Deliverable No.	Deliverable Description
D6	Simplified test models
D7	Most suitable integration methods of developed material model and properties into commercial FEM software

Milestone No.	Milestone Description
M4	Specification of the proper FEM software for subsequent research tasks

WP5: OPTIMIZATION IF TEST MODELS
Leader: IITD
Participants: IPT, KAL, ECOG, IITD, IITM, CGCRI

The objective of WP5 is to optimize test models in the selected FEM based on error analysis between simulation and experimental results. The main achievements of this work package are:

Error analysis and improvement on test models

Based on the study carried out in WP4, the simulation error was found and analysed in the test model "cylinder compression test" and "thermal expansion test". Relevant improvement methods were given:

Cylinder compression test

Cylinder compression test, which was close to the moulding process, was carried out to verify the integration of viscoelasticity material property. Figure 3-25 shows the schematic of the machine setup of relaxation experiments. Compression furnace was heated up by infrared heating elements to the desired temperature. The temperature was kept constant during the experiment by a proportional-integral-derivative (PID) controller utilizing two k-type thermocouples. A servomotor drives an actuator which uses a ball screw for high accuracy position control. Position feedback was accomplished through an encoder which can resolve 1 μm displacements. Position feedback control enabled a constant applied strain on the glass sample during the relaxation stage (by holding the mould position constant). The compressing moulds were made of high temperature steel. The contact surfaces were coated with a layer of graphite lubricant to reduce the friction between mould and glass cylinder. Additional thermal couples were integrated in the compressing moulds via two through holes (one each in the upper and lower moulds), which allowed the direct temperature measurement of glass cylinders within measurement accuracy of ±1 °C.

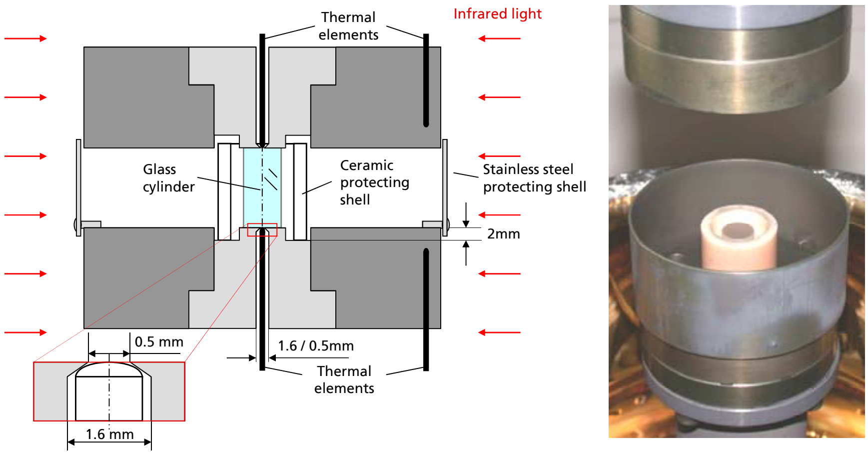


Figure 3-25: Experimental set up of cylinder compression test

After the glass and the mould both reached the specified testing temperature, the temperature was held for 2000 to 3000 seconds to achieve a good homogenous temperature in the glass specimen, and then the glass was compressed for maximum 2 seconds to generate the initial stress and strain. The overall strain of the glass was less than 10%, so that its cylindrical form could be maintained. During the relaxation phase the position of the mould was kept constant and the temperature was kept at the testing temperature, while the force was reduced as a result of the relaxation behaviour. After a time range of 1000 seconds to 2000 seconds the stress was relaxed to almost zero. Then the cooling stage began until the room temperature reached. The whole process was controlled by NC program, which were custom written for this experiment and loaded onto the control unit of the testing machine.

A numerical model was built for cylinder compression test under the same condition. Where the glass is modelled by viscoelastic material with the property measured from 4-point bending test. A mismatch between experiment and simulation results for cylinder compression test was observed (solid lines in Figure 3-36a). The reason was considered as that measurement result of cylinder compression test is not the real response of glass material, but the response of the whole system, including the non-ignorable machine elasticity. The schema of the machine-glass system and the transformation function of the system are given in Figure 3-36b. Applying this transformation on the experiment curve, the red solid line was shifted to the red dash line in Figure 3-36a, which matched the simulation result (blue solid line) very well, while the slight difference could be explained by the geometrical nonlinearity of the cylinder compression test. Two important conclusions were obtained from this test model:

- The Prony Series acquired from 4-point-bending test can be integrated into the moulding simulation;
- Machine elasticity has to be included into the numerical modelling.

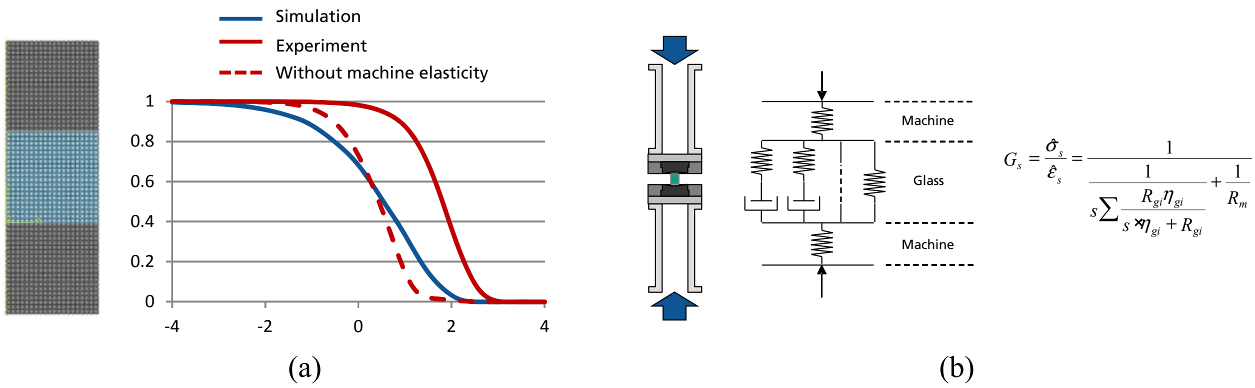


Figure 3-26: Analysis of cylinder compression test

Thermal expansion test

Thermal expansion test was a numerical test method to verify the integration of the measured material property as the input (in this case the thermal expansion coefficient) for the FEM simulation. Figure 3-27a shows the schematic of the test method. Since the measured material properties, such as the temperature dependent thermal expansion coefficients are consisted of a large amount of dataset, and there is a standard pattern of the material property input format in the FEM simulation software such as Abaqus (see Figure 3-28b), the question stands then how much data should be considered as sufficiently to be integrated into FEM simulation model.

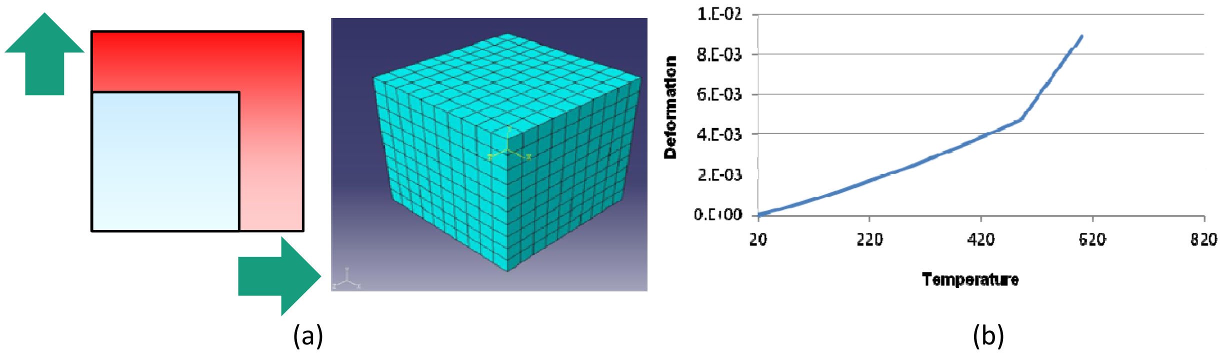
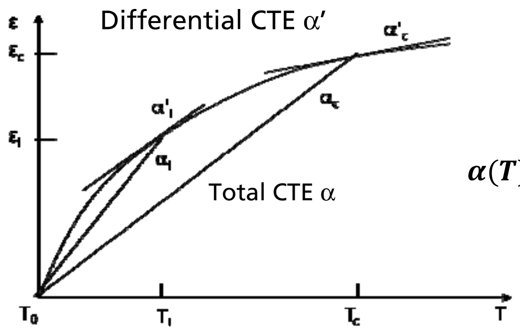


Figure 3-27: Numerical test method for the integration of measured thermal expansion coefficient into FEM simulation model: (a) schematic of the test method; (b) CTE value measured from dilatometer

In the measurement of thermal expansion coefficient performed in WP2, the coefficient of thermal expansion (CTE) was obtained from the dilatometer test in differential form, and then transferred to total form as input for the FEM simulation, as shown in Figure 3-28a.

To verify the influence of input temperature interval on the simulation accuracy, different temperature intervals (ΔT) from 10°C to 100°C were selected out and their simulation accuracy were compared, as shown in Figure 3-29a and Figure 3-29b.

As a conclusion, a ΔT of maximal 10°C as the temperature interval for CTE input into FEM simulation is recommended, since only his simulation accuracy is below 1 µm, which is allowed as the affordable simulation error.



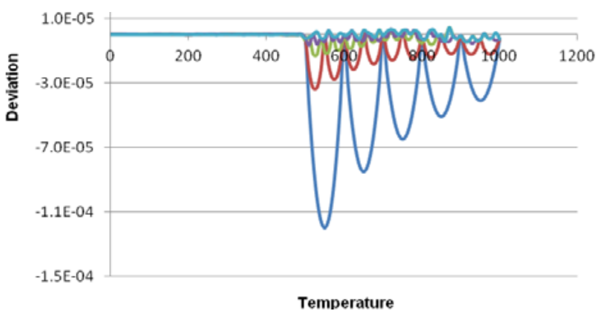
$$\alpha(T) = \frac{1}{T - T_0}\int_{T_0}^{T} \alpha' \, dT$$

Temp	CTE
T_0	α_0
$T_0+\Delta T$	α_1
$T_0+2*\Delta T$	α_2
…	…
$T_0+n*\Delta T$	α_n

(a) (b)

Figure 3-28: Input of measured CTE value into FEM simulation model: (a) Differential- vs. Total CTE value; (b) standard input format of temperature dependent CTE values in Abaqus

ΔT	Accuracy (µm)
100	120
50	33.6
30	29.5
20	16.0
10	0.58



(a) (b)

Figure 3-29: Comparison of simulation accuracy by different input temperature intervals: (a) table of comparison; (b) diagram of comparison

Achieved Deliverables and Milestones

Deliverable No.	Deliverable Description
D8	Clear identification of the source of error and improvement suggestion for the test Models
D9	Improved test models for each influence factor

Milestone No.	Milestone Description
M5	Preparation of the improved test models

WP6: DEVELOPMENT OF SIMULATION TOOL FOR GLASS MOULDING

Leader: IPT

Participants: IPT, KAL, ECOG, IITD, CGCRI

The objective of WP6 is to develop a software tool for the simulation of the moulding process including its shrinkage characteristics in the tolerance related to form accuracy. The main achievements of this work package are:

Development of FEM simulation software tool

A simulation software tool was developed with a friendly graphical user interface (GUI), which allows the user, who has no simulation background knowledge, to perform the simulation of glass moulding process. Simulation tasks could be defined by the operation on the GUI. Beneath the graphical user interface, numerical models were generated based on the user definition and implemented on the commercial FE-platform ABAQUS. This simulation software tool brings the theoretical model to the application level (Figure 3-30).

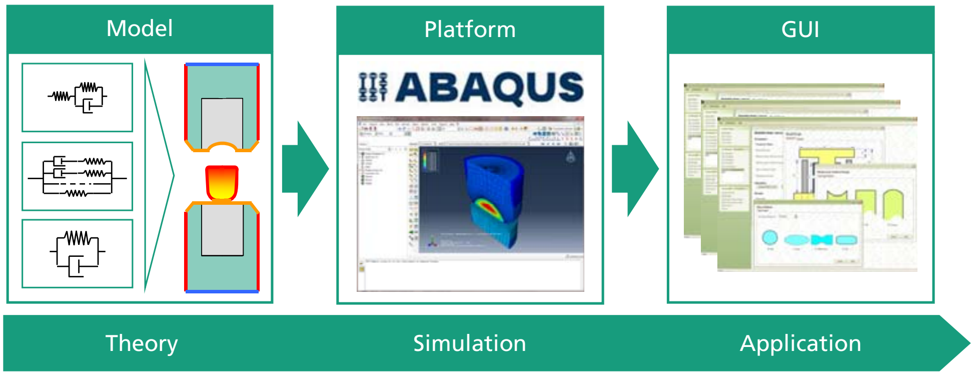


Figure 3-30: Realization approach of the development of simulation software tool

Furthermore, the FEM simulation software tool was constructed based on client-server concept, which realizes the integration of computational resources and the reduction of costs for the user (Figure 3-31).

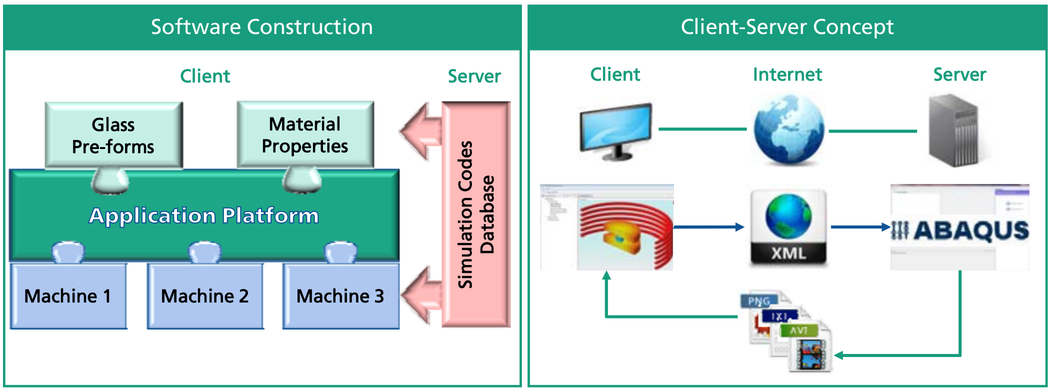


Figure 3-31: Software construction based on client-server concept

FE-Client

The FE-Client was development on Java-Eclipse based on RCP and Plug-in technology. Firstly, an "application platform" was built, which supported display windows and data operation. Then glass pre-forms and material properties were "inserted" into this "application platform" as "public plug-in", which were shared by all users. The user specific moulding machine was created as "private plug-in", which was private for each user. Simulation tasks were generated by FE-Client according to user input, and sent to the FE-Server through network. Because no Simulation is run on the FE-Client, there is no hardware requirement for the computer, where FE-Client is installed.

FE-Server

For each "plug-in" at client side, relevant Simulation code was developed and saved as a "simulation codes database" on the server side. According to the simulation task sent from server, simulation codes were generated and merged as one "input file", which could be submitted to ABAQUS to start the simulation. When the simulation was finished, simulation results were automatically processed into picture, data and video formats according to user specification, and sent back to the client. In order to carry out simulation activities, a powerful work station is required to run the FE-Server.

In SimuGlass project, specific FE-Clients were installed at the end user Kaleido and EcoGlass respectively, while the FE-Server was installed at the RTD performer. The most important advantages of this development are:

- Concentrated computational resource at RTD performer side;
- Easy in-house debugging and maintains for RTD performer;
- No hardware and software investment for the user;
- Free maintains for the end user;
- Reduced costs for the end user.

Transfer numerical models into simulation program

Numerical models were transferred into simulation program in form of Python codes. Those Python codes were modularized match along with the plugins on the FE-Client into isolated files and stored in an extendable database on the FE-Server. According to the user definition, corresponding python files were selected and merged into one input file, which could be submitted to ABAQUS o start the simulation (Figure 3-32).

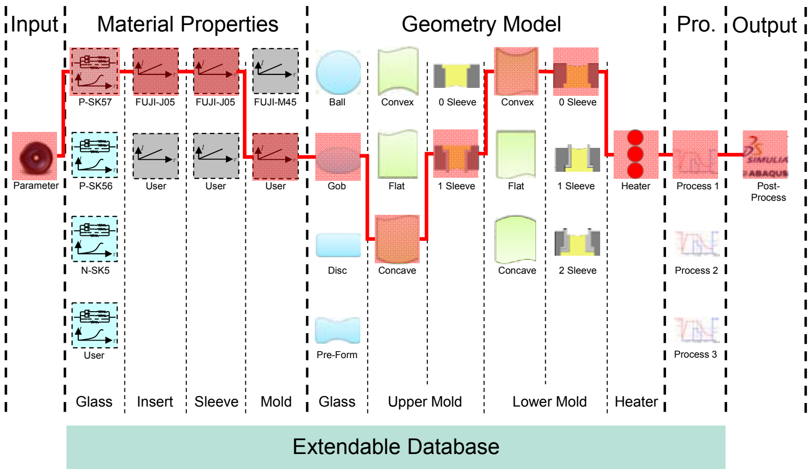


Figure 3-32: Simulation program Modularized

Achieved Deliverables and Milestones

Deliverable No.	Deliverable Description
D10	Complete simulation program for the precision moulding process
D11	Integration of improved test models into simulation program

Milestone No.	Milestone Description
M6	Development of a general simulation program for precision glass moulding process

WP7: DEMONSTRATION OF THE GENERAL SIMULATION TOOL

Leader: KAL

Participants: IPT, KAL, ECOG, IITD, IITM, CGCRI

The objective of WP7 is to test the general simulation tool by means of real application and to compare simulation results with the measurement of moulded lenses after real moulding process. The comparison provides reference for the software improvements in WP8. The main achievements of this work package are:

Moulding demonstration

For the validation of the developed simulation software with respect to the precision moulding process at Kaleido, a meniscus lens in the centre with four bi-convex reference lenses near the wafer fringe was moulded from a plane glass wafer. The manufactured mould inserts and moulded glass wafer are illustrated in Figure 3-33:

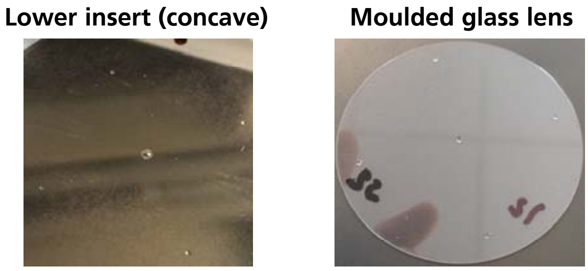


Figure 3-33: Kaleido demo lens and mould insert

For the verification of the simulation software in relation to the EcoGlass moulding process, two concave-plane lenses were moulded (Figure 3-34):

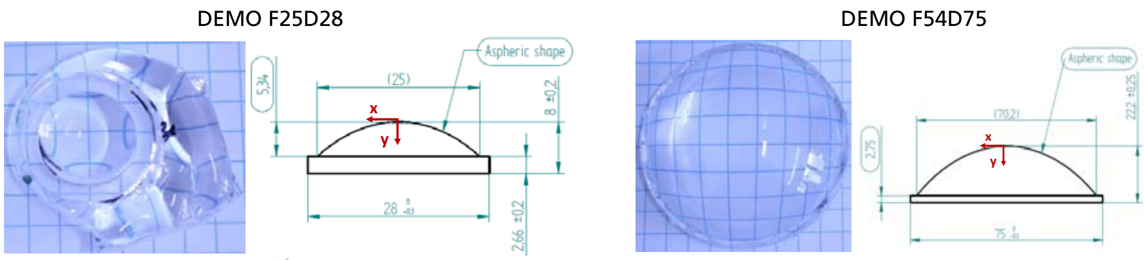


Figure 3-34: EcoGlass demo lenses

Simulation demonstration

Based on the moulding concepts of Kaleido and EcoGlass, the physical modelling was carried out (Figure 3-35). In the next stage, the complete simulation will be carried out, and compared with demo lenses, in order to compensate aspheric surface on mould.

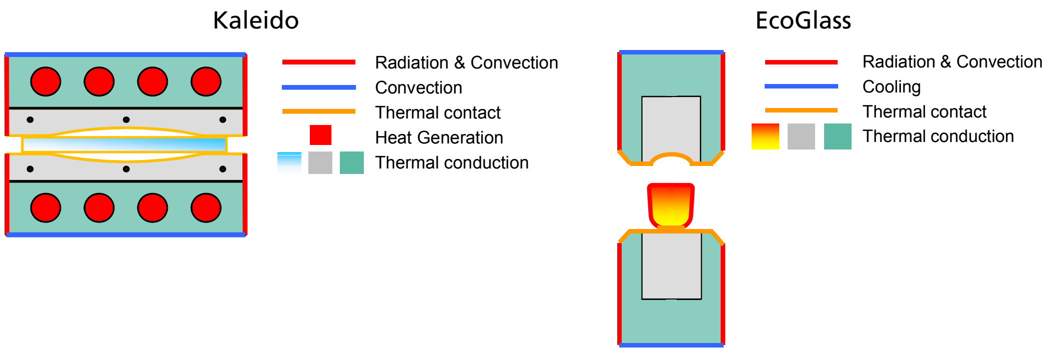


Figure 3-35: Simulation modelling of Kaleido and EcoGlass mould-insert concept

For the modelling of Kaleido moulding process, the heat generation was modelled by the body heat flux from heating pipe, and controlled by a PID controller, which was realized by ABAQUS user subroutine. The heat transfer inside moulds and glass were modelled by conduction, while the heat transfer in between was modelled by contact heat conduction. At the outer surface of mould, radiation and convection model were used to describe the heat loss of the system, and forced convection heat transfer was considered on the top of mould in order to simulate the cooling effect by cooling gas.

For the modelling of EcoGlass moulding process, the heat transfer from hot glass to cold moulds was considered. The temperature distribution of the moulding system was measured by FLIR thermo-camera at the beginning moulding cycle start and used as the initial temperature in the simulation model. The heat transfer inside moulds and glass were modelled by conduction, while the heat transfer in between was modelled by contact heat conduction. At the outer surface of mould, radiation and convection model were used to describe the heat loss of the system to the ambient.

With the boundary conditions from real moulding conditions, above mentioned simulation models were implemented on the simulation platform ABAQUS. The comparison between simulation and moulding experiment could be found in WP8.

Achieved Deliverables and Milestones

Deliverable No.	Deliverable Description
D12	Complete simulation program for the precision moulding process
D13	Manufacture of according mould sets
D14	Moulding of a real application
D15	Simulation of defined mould process

Milestone No.	Milestone Description
M7	Simulation of a real glass moulding application

WP8: VALIDATION OF THE GENERAL SIMULATION TOOL

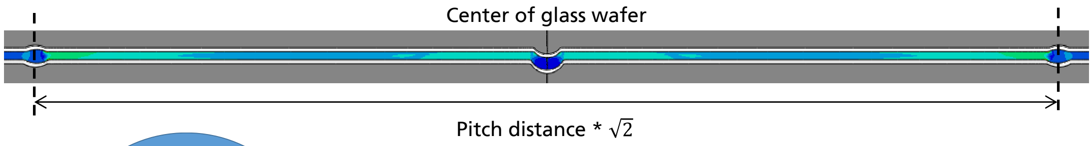
Leader: IPT

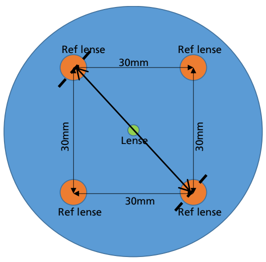
Participants: IPT, CRIBC, KAL, ECOG, IITD, IITM, CGCRI, BELMC

The objective of WP8 is to validate and improve the general simulation tool based on the comparison result from WP7. The main achievements of this work package are:

First simulation compared with experiment

The simulation result of Kaleido demonstrator was firstly compared with the experiment results as shown in Figure 3-36. The comparison focus was the shrinkage of pitch distance between 2 reference lenses on the glass wafer (the difference between mould pitch distance and glass wafer pitch distance) after moulding. The simulation (92.5 µm) showed good match with the measurement results (100.34 µm), where approximately 7.8% simulation error was found.





	Pitch mould (mm)	Pitch wafer (mm)	Shrinkage (µm)	Deviation (µm)	Percentage
Experiment	30.0003	29.8999	100.34	-	-
Simulation (Upper)	30.0000	29.9079	92.10	8.24	8.2%
Simulation (Lower)	30.0000	29.9072	92.80	7.54	7.5%
Simulation (Mean)	30.0000	29.9075	92.50	7.84	7.8%

Figure 3-36: Comparison of form deviation between simulation and experiment for Kaleido Demo

The simulation result of EcoGlass demonstrators were compared with the experiment results as shown in Figure 3-37. The comparison focus was the form deviation (difference between moulded surface and designed surface) on the curvature side of both pressed lenses. The simulation showed good match with the measurement results (measurement carried out by Talysurf Profiler), where approximately 10 µm simulation error on form deviation was found.

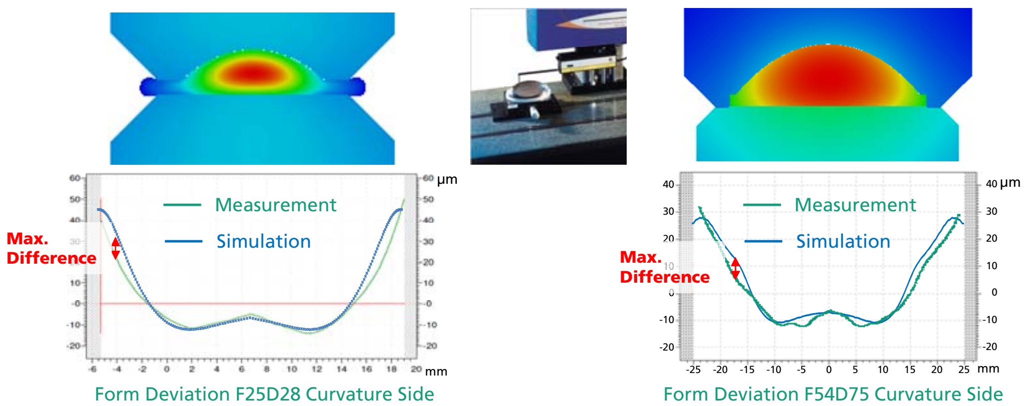


Figure 3-37: Comparison of form deviation between simulation and experiment for EcoGlass Demos

Second simulation for compensation

The pitch error on the pressed wafer (Kaleido) and the form deviation on the optical surface of pressed lenses (EcoGlass) were compensated on the mould inserts, so that the shape and structure of pressed lens could shrink to the desired value.

For Kaleido Demo, iterations of the pitch error compensation on moulds were carried out with the help of simulation. As shown in Figure 3-38, the pitch error was successfully reduced from more than 90 µm down to below 2 µm (within tolerance) after 2 compensation iterations. Recommended pitch values between two reference lenses were also determined for mould re-machining, where 30.0135 mm was for upper surface and 30.0139 mm was for lower surface.

		Upper surface (mm)	Lower surface (mm)
Initial design	Pitch on mould	30.0000	30.0000
1st moulding	Pitch on wafer	29.9079 (Δ=92.1µm)	29.9072 (Δ=72.0µm)
1st compensation	Pitch on mould	30.0921	30.0928
2nd moulding	Pitch on wafer	30.0135 (Δ=13.5µm)	30.0139 (Δ=13.9µm)
2nd Compensation	Pitch on mould	30.0786	30.0789
3rd moulding ✓	Pitch on wafer	30.0016 (Δ=1.6µm)	29.9997 (Δ=0.3µm)

Figure 3-38: Pitch error compensation iterations on moulds with the help of FE simulation (Kaleido)

The shrinkage compensation for EcoGlass Demos was carried out on modifying the shape of moulds, based on the results of first simulation. With compensated moulds' form, second simulation was carried out for both EcoGlass Demos under the same boundary conditions as the first simulation. The form deviations of EcoGlass Demos after second simulation were shown in Figure 3-39. The maximum form deviation of F25D28 was 1.5 µm, while that of F54D75 was 8 µm. The compensation results fulfilled the requirement of EcoGlass.

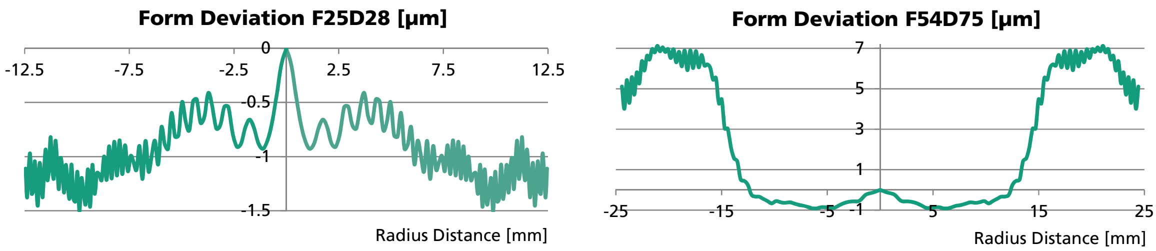


Figure 3-39: Form deviation of EcoGlass Demos after compensation

Achieved Deliverables and Milestones

Deliverable No.	Deliverable Description
D16	Modification and compensation of mould
D17	Improved simulation of defined mould Process with modified mould

Milestone No.	Milestone Description
M7	Simulation of a real glass moulding application

WP9: PROJECT MANAGEMENT

Leader: IPT

Participants: IPT, CRIBC, KAL, ECOG, IITD, IITM, CGCRI, BELMC

The objective of WP9 is to control the realization of the defined objectives according to the conditions of time, budget, control, effectiveness and quality of output. The main achievements of this work package are:

Communication with European Commission

As the coordinator at European side, Fraunhofer IPT took the response of the communication between EC and project partners as well as between EU and Indian consortia during the project duration period.

Co-ordination

At the kick-off meeting, a co-ordination strategy was defined to manage the interactions between single work packages. The information exchange inside the consortium was free for partners. The information exchange across European consortium and Indian consortium was through coordinators.

Data transfer and reporting

The inter-media of data transfer were email, ftp and Lotus Quickr system. Email was used to transfer information and small data. Huge data was transferred through ftp-server. The technical documents such as internal reports and deliverables were uploaded on Lotus Quickr system and shared with all project partners.

Organization of project meetings

A plan of all project meetings for the whole project period was made at the kick-off meeting based on the agreement of all partners. The meeting host took care of the organization, while EU and Indian coordinators offered necessary supporting to the partners from each consortium. Besides project meetings, telephone conferences were also well organized due to the needs of project.

Achieved Deliverables and Milestones

Deliverable No.	Deliverable Description
D18	Internal status report (12 months)
D19	Project review with EU project officer with overall status report
D22	Status report (36 months)
D24	Final report

Milestone No.	Milestone Description
M9	Project administration and communication implemented

WP10: TRAINING

Leader: CGCRI

Participants: IPT, CRIBC, KAL, ECOG, IITD, IITM, CGCRI, BELMC

The objective of WP10 is to develop necessary common knowledge basement for every participants in the consortium groups to cooperate smoothly with each other during the project execution and dissemination of certain research results and the final software tool to outside target groups to extend potential market. The main achievements of this work package are:

Software training for end users

Due to previous defined training plan, a training of developed simulation software tool was given by RTD performer Fraunhofer IPT to the industrial end users Kaleido and EcoGlass on 27th January 2014. The training program included:

- Introduction of software conception;
- Introduction of graphical user interface and basic software operation;
- Case study workshop;
- Results extraction from simulation output file.

Training of Indian students and co-experiment

From 2nd to 6th December 2013, two Indian students from IIT Madras visited Fraunhofer IPT for the co-experiment on the topic of residual stress measurement. At the beginning of the visit, a training of the operation of Toshiba moulding machine was given by Fraunhofer IPT. Based on that, a series of cooling cycle tests and moulding tests were carried out, in order to get glass specimens with different residual stresses due to different cooling rates.

Achieved Deliverables and Milestones

Deliverable No.	Deliverable Description
D26	General training work plan
D27	General training program

Milestone No.	Milestone Description
M10	Agreement on training work plan and matrix of planned training programs

4. Potential impact

Potential impact

On the one hand, SimuGlass strongly strengthens the research competitiveness of the involved European research activities. On the other hand, based on a better understanding and modelling of optical glass material properties, processing and performance, the competitiveness of the European glass industry is increased, in particular in relation to the east Asian and American competitors. Starting on a view on the market analysis, in the following the involved research activities and the SME contribution towards the expected impacts from SimuGlass is presented.

With respect to potential target markets for the developed simulation tool in SimuGlass, in general all branches can be involved in which glass forming process with high accuracy requirement are implemented. Emphasized are those branches where ambitious moulded optical glass components are required. Parts of the potential fields of business are the following emerging markets (Figure 4-1):

Medical Technology
Examples: high-sensitive optical systems for gentle X-ray medical equipment (Mammogram), endoscope-optics, …

Communication Technology
Examples: optical switches and arrays for fibre connections

Laser Technology
Examples: optics for beam shaping for material machining systems, medical and display technology

Automotive Industry
Examples: optical sensors, Head-Up-Displays, IR night vision systems

Lightning
Examples: LED

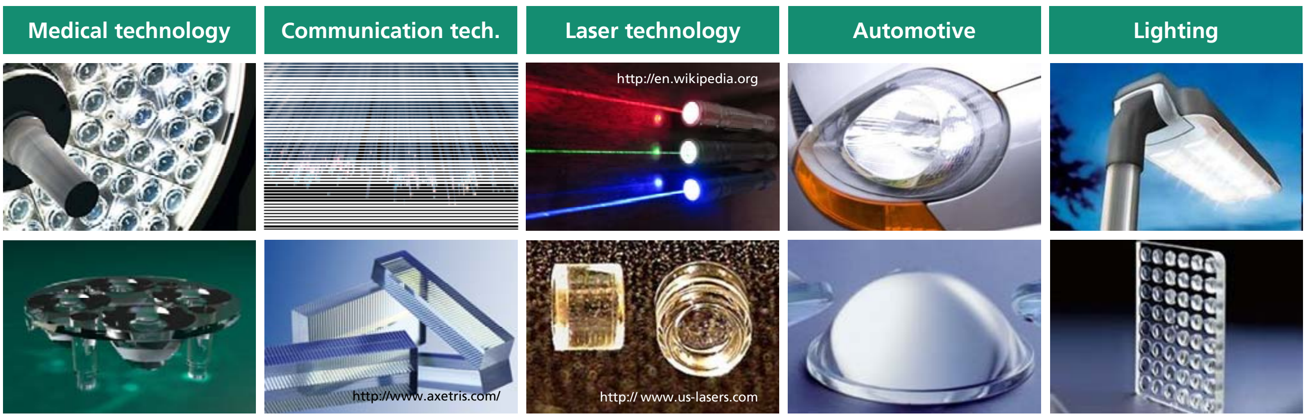
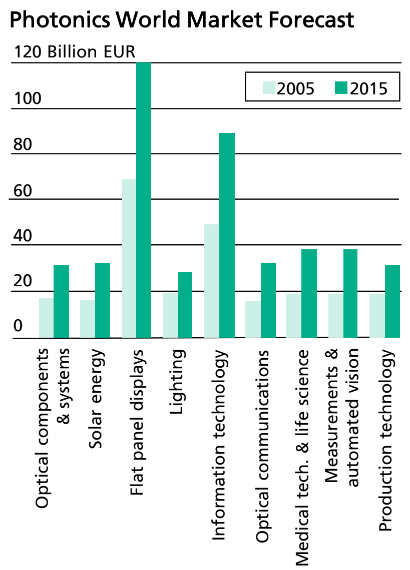


Figure 4-1: Fields of application for glass optics

Market research shows that there is a quick increasing of requirement for glass optical components in above market branches (Figure 4-2). SimuGlass project targets 50% of European photonics market, which means 22 billion Euro in the near future. The rapidly increased optical market challenges the

R&D department of optical companies, who has to release new products in shorter time and lower cost. The general simulation software tool developed in SimuGlass project can be implemented into the mould compensation and moulding process development, to provide an optimized mould design and process design, thus an optimized production of optical components. The involved partners can participate directly in this rapidly developing technology. In particular, aspherical lens with high numerical aperture (EcoGlass) or micro-lens-arrays (Kaleido) can be manufactured much more efficient. All those parts are used in sectors of strategic importance in Europe, such as laser technology, optical telecommunications, sensor technology, medical applications and consumer optics. It is obvious that an increase in part quality and variability will be associated with a decrease in production development cost.



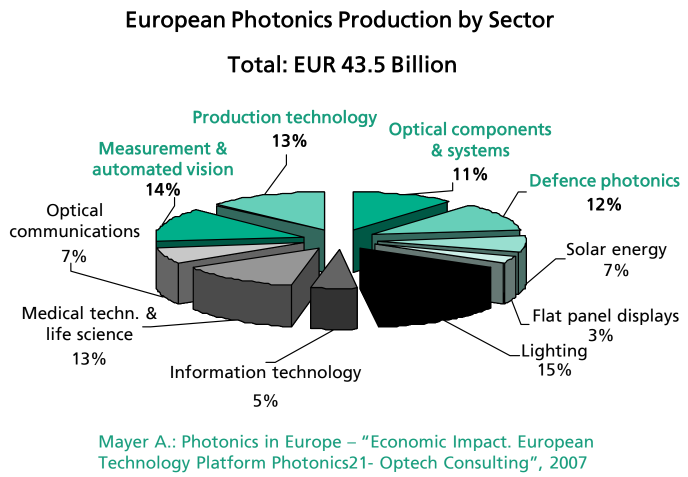


Figure 4-2: Photonics world market development (left) and European photonics production divided by sector the targeted sectors of SimuGlass

Furthermore, the developed simulation software has the potential to be transferred to other glass forming applications such like bottle manufacturing or windscreen bending in the automobile industry. The development in simulation of glass material properties will help them to achieve a better understanding of their process and thus to an optimization of the production line, which lead to higher production quality, lower rejection rates in combination with lower environmental impact.

During the implementation of the research work of SimuGlass, the complex behaviour of optical glass material was understood especially for the precision glass moulding process. The following statement gives the estimation about the expected individual scientific profit for the involved partners.

Fraunhofer-Institute for Production Technology IPT (IPT)

Few years ago, Fraunhofer IPT has introduced precision glass moulding technology into Europe. Since then, Fraunhofer IPT is keeping on investigation for both basic knowledge and implementation method for the precision glass moulding technology. As an institute for manufacturing technology, it has gathered a mass of experience in this area. And with the result of the SimuGlass project, Fraunhofer IPT has achieved a further scientific understanding and modelling of the optical glass material properties during the forming process, and a software tool which can reduce significantly the effort of mould design and process establishment. It is proved that for the process development for each new optic design, about 5,000 to 10,000 Euro can be saved by a successful prediction of the shrinkage error of the simulation tool. Furthermore, the simulation models and the corresponding FEM simulation models developed for the glass forming process can also be applied to the research work for other glass production process, such as bottle manufacturing or windscreen bending. Therefore, an even wider research application is expectable.

Centre de Recherches de l'Industrie Belge de la Céramique (CRIBC)
CRIBC is currently specialising in inorganic materials, soils and the environment. SimuGlass has enhanced the research activities in the following two ways:

- The results of the requirement analysis conducted at the beginning of this project helped CRIBC to understand the present technology, and became involved in this area. Also, the technical information on precision glass moulding enhanced the potential and ability of CRIBC to proceed with the development of new materials for the glass industry.
- Communications from this research group, and the results of SimuGlass provides CRIBC with theoretical models to describe the complex behaviour of optical glass during the forming process, which can be expanded on. Furthermore, it provides a computational modelling procedure to represent complex behaviour of new materials.

Kaleido Technology ApS (KAL)
The impact of the SimuGlass project is for Kaleido split in three areas: network, technical knowledge, and business advantages. The SimuGlass project has allowed Kaleido to extend its technical network with some of the leading companies and institutes in Europe, a network that will be of great value in the future. The benefit of the network is mainly of a technical nature, where we will discuss concrete problems with the former partners in order to draw on their experience and knowledge within the respective area of expertise.

Regarding knowledge gained from the project, which will have impact in the future for Kaleido. This is especially focused on the interplay between physical experiments, testing and simulations. The work in the project has shown us the importance of supplying accurate input to the models in order to be able to trust the results of the models. It is clear that access to accurate models in the future will enable Kaleido to develop faster and avoid obvious pitfalls in the moulding process.

The direct business impact for Kaleido will be significant – Since the establishment of the SimuGlass project Kaleido has become part of a major Chinese company, manufacturing components for cell phones. Kaleido's role is now mainly in the R&D, product design and development phase. The cell phone industry is characterized by extremely short time to market constraints – a tool as the one developed in the SimuGlass project will be essential in ensuring success in this very competitive field.

EcoGlass, a.s. (ECOG)
Results of SimuGlass Project can help EcoGlass with production of better lenses. In these days, several tooling need to be manufactured to reach a correct lens shape due to unpredictable shrinkage. Software enabling shrinkage prediction will lower the number of tries, which will lead to faster and cheaper production. This is one of the ways how to compete with the low-cost countries – by higher level of the know-how and process knowledge. Biggest advantage of the software is, that it was designed based on results obtained in EcoGlass manufacturing process and glass properties in the material database were determined for glass used by the company, therefore results predicted by the software are expected to be in a very good agreement with reality. The output of the SimuGlass project gave a feedback to the technologists and R&D which helps to understand the moulding process. This would not be possible by the currently used trial – error method.

Indian side (RTD and SME partners)
Indian market for optical products including opthalmic and other components is estimated conservatively at more than US$ 1.3 billion, due to the "The optical industry in India - Market Research" published in 2008 by Italian Trade Commission. According to a five year old estimate, the prescription eyewear market in India is worth Rupees 23 billion. India is predominantly a glass lens market (87% of total market) with sales of approximately 115 million pieces per year. However, production is mainly taken care of by the unorganized sector in an old fashioned manner of manual craftsmanship with minimum machinery. With the exponential growth in the income of urban middle class population in India (According to a McKinsey study, more than 130 million upper middle class consumers are expected by 2025) and with increasing life expectancy due to better healthcare for citizens, the opthalmic eyecare industry is poised for rapid growth where quality of product will be as important as the cost. Apart from opthalmic sector, the precision optical components required for consumer electronics sectors are dependent of imports. However, Indian strategic sector produces precision optical components by traditional multi-step abrasive machining route.

The SimuGlass project has established a demonstration unit for precision forming of glass lens at CSIR-CGCRI. The Indian partner BEL, Machilipatnam will evaluate the efficacy of the precision forming of glass lens and feasibility of integrating the technique in their process chain. CSIR-CGCRI is also envisaging dissemination workshops for the precision forming process among relevant Indian industries. With dissemination, the process is expected to find increasing application and integration in the Indian industry sector and bring down the cost of mass produced opthalmic and optical lenses while enhancing the product quality. The only critical issue which may affect the precision forming process is the fabrication of the moulds for which ultra-precision multi-axes CNC grinding machines are needed which are extremely costly and are available in a few places for strategic use.

SimuGlass project is a successful attempt in the direction with the help of an integrated approach of putting together the multifaceted domain knowledge and skill sets of various collaborative institutes and experts in Europe and India in the form of focused and well-coordinated work packages. The project has create a knowledge base and a viable technology base for precision forming of optical glass components in India and Europe that can put both of them at par with some of the Asian leaders in the field, such as, Japan, Korea and Taiwan. This technological knowhow can be further transferred to both European and Indian industries on case to case basis.

Main dissemination activities

Conference
$10^{th}/11^{th}/12^{th}$ Euspen: The European Society for Precision Engineering & Nanotechnology (Euspen) conference aims to advance the arts, sciences and technology of precision engineering, micro engineering and nanotechnology; to promote its dissemination through education and training, and to promote its use by science and industry. The $10^{th}/11^{th}/12^{th}$ Euspen (Delft 2010, Como 2011, Stockholm 2012) can be considered as one of the major events, for more than 500 audiences attended each meeting and the number of countries to which the conference was addressed (Europe, USA and Asia). There are conference papers, posters and oral presentations delivered in each above mentioned Euspen conference which demonstrates and disseminates the SimuGlass related project results.

$6^{th}/7^{th}$ Optics Colloquium: The International Colloquium on Optics (Aachen 2011, Aachen 2013) offers an international forum of information about current perspectives, technological innovations and new applications from industry and research. The 6^{th} and 7^{th} Optics Colloquium, which takes place every two years in Aachen, focused on the three topics – »Strategy and Markets«, »Technology and Production« and »Products and Innovation«. Around 150 audiences participated in both colloquiums. Many high-level contributors promise a presentation of current developments and trends. The participation of a number of top-class speakers gave application-oriented presentations outlining the latest developments and trends. In addition to this, the panel discussion moderated by the well-known television journalist Nina Ruge and the guided tour of the facilities of the Fraunhofer ILT and IPT were provide plenty of opportunities for interacting and networking with other experts. Part of the SimuGlass project results were presented with poster form in both colloquiums.

6th AOMATT 2012: The Advanced Optical Manufacturing and Testing Technology (AOMATT) (Xiamen 2012) is a well-established international symposium on the design, manufacturing, and testing of optical components and systems. It features high quality plenary presentations by well-known experts, parallel oral sessions, poster sessions, banquet, and tours to local attractions. All accepted papers were published in SPIE (The International Society for Optics and Photonics) Proceedings and SPIE Digital Library. SPIE Proceeding papers are indexed by major scientific and engineering databases. An oral presentation together with a conference paper was held in this conference, which well presents the SimuGlass project results.

ICGF 2011: The International Conference on Specialty Glass & Optical Fiber (ICGF) (Kolkatta 2011) is well known in India. A paper and a presentation with respect of SimuGlass project results were given in this conference.

INCAM 2013: Indian Conference on Applied Mechanics (INCAM) (Chennai 2013) is the culmination of efforts made by Applied Mechanics departments in India, to provide a technical platform for discussion among researchers in the field. This conference is probably the first conference of its kind in India. A paper and a presentation with respect of SimuGlass project results were given in this conference.

ISEM-ACEM-SEM-7th ISEM 2013: The Joint International Conference of the 2nd International Symposium on Experimental Mechanics, the 11th Asian Conference on Experimental Mechanics, 2012 Society for Experimental Mechanics Fall Conference and 7th International Symposium on Advanced Science and Technology in Experimental Mechanics (Taipei 2013) is an international conference held in Asia with well-known dissemination effects. A paper and a presentation with respect of SimuGlass project results were given in this conference.

ICEM 2013 – ACEM12: The International Conference on Experimental Mechanics 2013 (ICEM 2013) and the 12th Asian Conference on Experimental Mechanics (ACEM12) was held in Bangkok, Thailand, during November 25-27, 2013. This conference was organized by National Metal and Materials Technology Center (MTEC) and aimed at attracting prominent researchers, engineers and scientists to present their important findings and discuss on new developments in the board areas of the Experimental Mechanics. These cover all aspects of Optical Methods and Techniques, Nano and Micro Testing, Hybrid Concept and Methods, Biomaterials and Bioengineering, Functional Materials, Smart Materials and Structures, Residual Stresses, NDT/NDE and etc. A paper and presentation with respect of SimuGlass project results were given in this conference.

CAE 2013: The international conference on computer aided engineering 2013 was organized by the Department of Mechanical Engineering, IIT Madras. A wide range of topics in Computer Aided Engineering are covered. A paper and presentation with respect of SimuGlass project results were given in this conference.

Workshop

$3^{rd}/4^{th}$ Glass Forming Simulation: The 3^{rd} and 4^{th} Glass Forming Simulation Workshop were held in 2011 and 2013 in Velké Karlovice by GLASS SERVICE INC. (Vsetín, CZ), a member of Czech Glass Society. These seminars and workshops target the field of advanced technologies for the glass industry such as mathematical simulation of furnaces and advanced control using models, and provide an excellent opportunity to present and learn about the newest developments in these areas. It is well-known in Czech Republic and around 150 audiences attended both workshops. Presentations which contain SimuGlass project results were given in both workshops.

Exhibition

$10^{th}/11^{th}$ Optatec: Optatec: The international trade fair for optical technologies, components and systems (Optatec), provides the optical industry with the world's most important information, communication and business platform in Frankfurt Exhibition Centre. On a two-year cycle, Optatec focuses the innovation potential of the industry in a way that no other event achieves. In co-operation with conceptual sponsors as well as technology and institutional partners SPECTARIS (the German Industry Association for Photonics and Precision Engineering) and the Fraunhofer Institute for Applied Optics and Precision Engineering (IOF), Optatec is presented as an international, high-tech shop window. Around 500 exhibitors and a total of 5000 audiences from Europe and all over the world attended both exhibitions and displayed the future technologies of industrial optics. SimuGlass project results as the form of video media and information sheet were shown and spreaded on both exhibitions.

Lens Expo 2012: Organized by OPTRONICS Magazine in Japan, the Lens Expo is launched as an annual trade show covering the wide range of lens design and manufacturing technologies. As the only exhibition in Japan dedicated specifically to lens design and manufacturing, The Lens Expo 2012 was the best opportunity to find the most interested and motivated buyers and decision makers, who are eager to see the very latest products, technologies and services of lenses and lens design or manufacturing. As a further enticement to both exhibitors and attendees, the Exhibition coincides with a comprehensive technical program of seminars, and is co-located with "LASER EXPO", "Positioning Expo", "IR+UV EXPO", "Medical & Imaging EXPO". A poster with respect of SimuGlass project results was presented on this exhibition.

Exploitation of results

The results of the project lead to a direct benefit for the partner institutes and companies and are utilized as competition advantages. After the conclusion of the project all partners intend to continue their work in this field and go further on with the research. The international scientific network between EU and India built up through this project will also keep on close contact to contribute to the interactive development of the further research as well as a broader research communication. They will co-operate and publish further research results together.

The in project developed simulation tool will be spread among not only industrial partners within the project, but will be made available for wider uptake from potential users from the market. A post-project co-operational structure will also be established to support further development of the project results in order to upgrade the robust and usable functions of the simulation tool. Furthermore, this newly developed simulation tool together with the in SimuGlass project generated knowledge will be commercially exploited by all project partners in Europe and India and eventually worldwide.

5. Project public website and contact information

Project website

www.simuglass.com

Contact information

Beneficiary name	Short Name	Contact Person	Country	Logo
Fraunhofer Gesellschaft zur Förderung der allgemeinen Forschung e.V.	IPT	Dr.-Ing. Olaf Dambon	Germany	
Centre de Recherches de l'Industrie Belge de la Céramique	CRIBC	Jean-Pierre Erauw, ir	Belgium	
Kaleido Technology ApS	KAL	Dr. Jesper Falden Offersgaard	Denmark	
EcoGlass, a.s.	ECOG	Dr. Helena Krutská	Czech Republic	
Indian Institute of Technology Delhi	IITD	Prof. Dr. Puneet Mahajan	India	
Indian Institute of Technology Madras	IITM	Prof. Dr. K. Ramesh	India	
Central Glass and Ceramic Research Institute	CGCRI	Dr. Dipayan Sanyal	India	
Bharat Electronics Limited, Machillipatnam	BEL MC	V.K.V. Gupta	India	

6. Use and dissemination of foreground

Section A (public)

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
1	*A simple approach to photoelastic calibration of glass using digital photoelasticity*	*K. Ramesh*	*Journal of Non-Crystalline Solids*	*378, June 2013*	*Elsevier*	*Luxembourg*	*2013*	*pp. 7 - 14*	*http://www.sciencedirect.com/science/article/pii/S0022309313003414*	*no*
2	*Case Study Applications in Numerical Simulation for Precision Glass Molding Process*	*G. Liu*	*Proceedings of EUSPEN Annual Meeting 2010*	*Vol.2, May 2010*	*EUSPEN*	*Netherlands*	*2010*	*pp. 148-151*		*no*
3	*Systematic Influence Investigation of Key Parameters for Precision Glass Molding Process Based on Self developed Simulation Tool – SimPGM*	*G. Liu*	*Proceedings of EUSPEN Annual Meeting 2011*	*Vol.2, May 2011*	*EUSPEN*	*Italy*	*2011*	*pp. 256-259*		*no*
4	*SimPGM - Commercial Simulation Tool for Precision Glass Molding Industry*	*F. Wang*	*Proceedings of EUSPEN Annual Meeting 2011*	*Vol.2, May 2011*	*EUSPEN*	*Italy*	*2011*	*pp. 252-255*		*no*
5	*Using Abaqus to Simulate the Precision Glass Molding Process for Freeform and Wafer Optics*	*Y. Wang*	*Proceedings of SIMULIA Customer Conference*	*May 2011*	*SIMULIA*	*Spain*	*2011*	*pp. 842-853*		*no*

[2] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).
[3] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

6	*3D Process Simulation for Precision Glass Molding of Freeform and Wafer Optics*	*Y. Wang*	*Proceedings of EUSPEN Annual Meeting 2011*	*Vol.2, May 2011*	*EUSPEN*	*Italy*	*2011*	*pp 132-135*		*no*
7	*Development of a Flexible and Reliable Numerical Simulation for Precision Glass Molding of Complex Glass Optics*	*F. Wang*	*Proceedings of SPIE*	*Vol.8416, October 2012*	*SPIE*	*China*	*2012*		*http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1379959*	*no*
8	*Intelligent Process-Design-Software-Tool for Precision Glass Moulding*	*G. Liu*	*Proceedings of EUSPEN Annual Meeting 2012*	*Vol.2, June 2012*	*EUSPEN*	*Sweden*	*2012*	*pp 246-249*		*no*
9	*Precision Glass Molding of Wafer Lens Optics*	*Y. Wang*	*Proceedings of EUSPEN Annual Meeting 2012*	*Vol.2, June 2012*	*EUSPEN*	*Sweden*	*2012*	*pp 181-184*		*no*
10	*An Integrated Solution for Compensation of Refractive Index Drop and Curve Change in High Precision Glass Molding*	*F. Wang*	*Proceedings of EUSPEN Annual Meeting 2012*	*Vol.2, June 2012*	*EUSPEN*	*Sweden*	*2012*	*pp 42-45*		*no*
11	*Mould Shape Optimization of the Precision Glass Moulding Process*	*P. Mahajan*	*Proceedings of 3rd Glass Forming Simulation Workshop*	*June 2011*	*Glass Service Ltd.*	*Czech Republic*	*2011*	*pp194-203*		*No*
12	*Process Modeling of Precision Glass Molding for Freeform Optics*	*Y. Wang*	*Proceedings of 4th Glass Forming Simulation Workshop*	*June 2013*	*Glass Service Ltd.*	*Czech Republic*	*2013*	*pp 13-42*		

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
1	*Posters*	*IPT*	*Case Study Applications in Numerical Simulation for Precision Glass Molding Process*	*1-3 Jun. 2010*	*10th EUSPEN, Delft, Netherlands*	*Scientific Community*		*International*
2	*Exhibitions*	*IPT*	*n. a.*	*15-18 Jun. 2010*	*10th OPTATEC, Frankfurt, Germany*	*Industry*	*5000*	*International*
3	*Organisation of Conference*	*IPT*	*6th Optics Colloquium*	*23-24 Nov. 2010*	*Aachen, Germany*	*Industry*	*150*	*International*
4	*Oral presentation to a scientific event*	*IPT*	*Using Abaqus to Simulate the Precision Glass Molding Process for Freeform and Wafer Optics*	*17-19 May. 2011*	*SIMULIA Customer Conference 2011, Barcelona, Spain*	*Industry*		*International*
5	*Posters*	*IPT*	*Systematic Influence Investigation of Key Parameters for Precision Glass Molding Process Based on Self developed Simulation Tool – SimPGM*	*23-26 May 2011*	*11th EUSPEN, Como, Italy*	*Scientific Community*		*International*
6	*Posters*	*IPT*	*SimPGM - Commercial Simulation Tool for Precision Glass Molding Industry*	*23-26 May 2011*	*11th EUSPEN, Como, Italy*	*Scientific Community*		*International*
7	*Oral presentation to a scientific event*	*IPT*	*3D Process Simulation for Precision Glass Molding of Freeform and Wafer Optics*	*23-26 May 2011*	*11th EUSPEN, Como, Italy*	*Scientific Community*		*International*
8	*Oral presentation to a scientific event*	*CGCRI*	*Simulation driven manufacturing of precision*	*4-6 Aug. 2011*	*ICGF 2011, Kolkatta, India*	*Scientific Community*		*International*

[4] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[5] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

			optical elements from Low Tg glass – an India EU collaborative venture					
9	*Oral presentation to a scientific event*	*EcoGlass*	*SimuGlass – Development of a Synergistic Computational Tool for Material Modeling, Process Simulation and Optimization of Optical Glass Moulding*	*20-21 Jun. 2011*	*3rd Glass Forming Simulation Workshop, Velké Karlovice, Czech Republic*	*Industry*	*150*	*International*
10	*Exhibitions*	*IPT*	*n. a.*	*25-27 Apr. 2012*	*Lens EXPO 2012, Yokohama, Japan*	*Industry*	*12000*	*International*
11	*Oral presentation to a scientific event*	*IPT*	*6th AOMATT*	*26-29 Apr. 2012*	*6th Int. Symposium on Advanced Optical Manufacturing and Testing Technologies, Xiamen, China*	*Scientific Community*		*International*
12	*Exhibitions*	*IPT*	*n. a.*	*22-25 May 2012*	*11th OPTATEC , Frankfurt, Germany*	*Industry*	*5000*	*International*
13	*Posters*		*Intelligent Process-Design-Software-Tool for Precision Glass Moulding*		*12th EUSPEN , Stockholm, Sweden*	*Scientific Community*		*International*
14	*Posters*	*IPT*	*Precision Glass Molding of Wafer Lens Optics*		*12th EUSPEN , Stockholm, Sweden*	*Scientific Community*		*International*
15	*Oral presentation to a scientific event*	*IPT*	*An Integrated Solution for Compensation of Refractive Index Drop and Curve Change in High Precision Glass Molding*	*4-7 Jun. 2012*	*12th EUSPEN , Stockholm, Sweden*	*Scientific Community*		*International*
16	*Organisation of Conference*	*IPT*	*7th Optics Colloquium*	*27-28 Nov. 2012*	*Aachen, Germany*	*Industry*	*150*	*International*
17	*Oral presentation to a scientific event*	*IITM*	*Design of an apparatus for residual stress analysis in lenses*	*4-6 Jul. 2013*	*Indian Conference on Applied Mechanics, Chennai, India*	*Scientific Community*		*India*
18	*Oral presentation to a scientific event*	*IPT*	*Process Modeling of Precision Glass Molding for Freeform Optics*	*25-27 Jun. 2013*	*4th Glass Forming Simulation, Velké Karlovice, Czech Republic*	*Industry*	*150*	*International*
19	*Oral presentation to a scientific event*	*IITM*	*Use of carrier fringes in the evaluation of edge residual*	*8-11 Nov.2013*	*ISEM-ACEM-SEM-7th ISEM, Taipei,*	*Scientific Community*		*International*

			Stresses in a glass plate by photoelasticity		*Taiwan*			
20	*Oral presentation to a scientific event*	*IITM*	*Measurement of residual birefringence in thin glass plates using digital photoelasticity*	*25-27 Nov. 2013*	*ICEM 2013 – ACEM12, Bangkok, Thailand*	*Scientific Community*		*International*
21	*Oral presentation to a scientific event*	*IITD*	*Numerical simulation of thermal cycling of glass plates*	*19-21 Dec. 2013*	*International conference on computer aided engineering, Chennai, India*	*Scientific Community*		*International*

Section B (Confidential[6] or public: confidential information to be marked clearly)
Part B1

TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.					
Type of IP Rights[7]:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)

[6] Note to be confused with the "EU CONFIDENTIAL" classification for some security research projects.

[7] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

Part B2

Type of Exploitable Foreground[8]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[9]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
Commercial exploitation of R&D results	*SimPGM Software*	*Yes*		*Simulation software tool for glass moulding process*	*C.26.70 Manufacture of optical instruments and photographic equipment*	*2014*	*Proprietary Licence*	*Fraunhofer IPT*
Commercial exploitation of R&D results	*Glass material property database*	*Yes*		*Glass material properties measured in SimuGlass project*	*M.72.19 - Other research and experimental development on natural sciences and engineering*	*2014*	*Proprietary Licence*	*CRIBC, Fraunhofer IPT*

In addition to the table, please provide a text to explain the exploitable foreground, in particular:

- Its purpose
- How the foreground might be exploited, when and by whom
- IPR exploitable measures taken or intended
- Further research necessary, if any
- Potential/expected impact (quantify where possible)

[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[9] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

4.1 Report on societal implications

Replies to the following questions will assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information *(completed automatically when **Grant Agreement number** is entered.*	
Grant Agreement Number:	N°NMP3-SL-2009-233524
Title of Project:	DEVELOPMENT OF A SYNERGISTIC COMPUTATIONAL TOOL FOR MATERIAL MODELING, PROCESS SIMULATION AND OPTIMIZATION OF OPTICAL GLASS MOLDING
Name and Title of Coordinator:	Dr. Olaf Dambon

B Ethics	
1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***No***
2. Please indicate whether your project involved any of the following issues (tick box) :	***No***
RESEARCH ON HUMANS	
• Did the project involve children?	No
• Did the project involve patients?	No
• Did the project involve persons not able to give consent?	No
• Did the project involve adult healthy volunteers?	No
• Did the project involve Human genetic material?	No
• Did the project involve Human biological samples?	No
• Did the project involve Human data collection?	No
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	No
• Did the project involve Human Foetal Tissue / Cells?	No
• Did the project involve Human Embryonic Stem Cells (hESCs)?	No
• Did the project on human Embryonic Stem Cells involve cells in culture?	No
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	No
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	No
• Did the project involve tracking the location or observation of people?	No
RESEARCH ON ANIMALS	

• Did the project involve research on animals?	No
• Were those animals transgenic small laboratory animals?	No
• Were those animals transgenic farm animals?	No
• Were those animals cloned farm animals?	No
• Were those animals non-human primates?	No
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	No
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	No
DUAL USE	
• Research having direct military use	No
• Research having the potential for terrorist abuse	No

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	0	2
Work package leaders	0	6
Experienced researchers (i.e. PhD holders)	7	12
PhD Students	1	5
Other	2	13

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	**0**
Of which, indicate the number of men:	0

D Gender Aspects

5.	**Did you carry out specific Gender Equality Actions under the project?**	X O	Yes No

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective				Very effective
❑	Design and implement an equal opportunity policy	O	O	O	O	X
❑	Set targets to achieve a gender balance in the workforce	O	X	O	O	O
❑	Organise conferences and workshops on gender	X	O	O	O	O
❑	Actions to improve work-life balance	O	X	O	O	O
O	Other:					

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

O Yes- please specify

X No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

O Yes- please specify

X No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

O Yes- please specify

X No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

O Main discipline[10]: 2.3

O Associated discipline[10]: 1.1 | O Associated discipline[10]: 1.2

G Engaging with Civil society and policy makers

11a	**Did your project engage with societal actors beyond the research community?** *(if 'No', go to Question 14)*	O X	Yes No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

X No

O Yes- in determining what research should be performed

O Yes - in implementing the research

O Yes, in communicating /disseminating / using the results of the project

[10] Insert number from list below (Frascati Manual).

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

- ○ No
- ○ Yes- in framing the research agenda
- ○ Yes - in implementing the research agenda
- ○ Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

- ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- ○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
- ○ No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid		Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport	

13c If Yes, at which level?

- ○ Local / regional levels
- ○ National level
- ○ European level
- ○ International level

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**12**
To how many of these is open access[11] provided?	
How many of these are published in open access journals?	**0**
How many of these are published in open repositories?	**0**
To how many of these is open access not provided?	**12**
Please check all applicable reasons for not providing open access:	
❑ publisher's licensing agreement would not permit publishing in a repository X no suitable repository available X no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other[12]: ……………	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	**0**

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	**0**
	Registered design	**0**
	Other	**0**

17. How many spin-off companies were created / are planned as a direct result of the project?	**0**
Indicate the approximate number of additional jobs in these companies:	

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

X Increase in employment, or	❑ In small & medium-sized enterprises
❑ Safeguard employment, or	❑ In large companies
❑ Decrease in employment,	❑ None of the above / not relevant to the project
❑ Difficult to estimate / not possible to quantify	

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*

[11] Open Access is defined as free of charge access for anyone via Internet.
[12] For instance: classification for security project.

Difficult to estimate / not possible to quantify	X

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

○ Yes X No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes X No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

X	Press Release	X	Coverage in specialist press
X	Media briefing	X	Coverage in general (non-specialist) press
❑	TV coverage / report	X	Coverage in national press
❑	Radio coverage / report	X	Coverage in international press
X	Brochures /posters / flyers	X	Website for the general public / internet
❑	DVD /Film /Multimedia	❑	Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

X	Language of the coordinator	X	English
X	Other language(s)		

Question F-10: Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]

2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. SOCIAL SCIENCES

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]