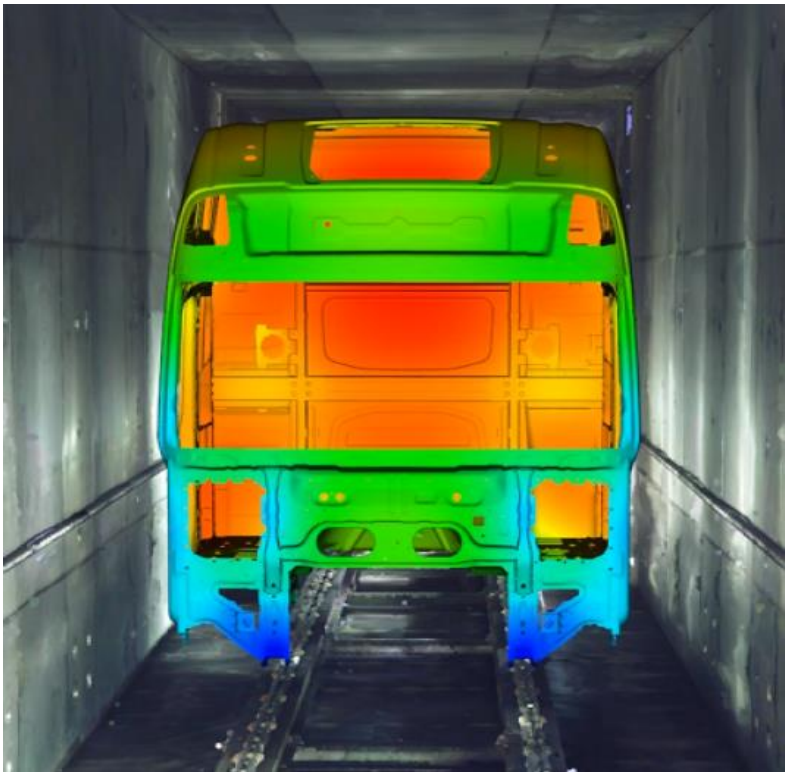
Virtual PaintShop – Simulation of Oven Curing

Public report



Project within FFI-Sustainable Production Technology

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FFI Fordonsstrategisk Forskning och Innovation

Content

1. Summary

The surface treatment is the process in an automotive factory that consumes most energy, water and chemicals, and produces most waste and pollution. Roughly 40% of the energy in major OEM operations is used in the paint shop with an average consumption of 700-900 kWh per car body. The paint shop is also a bottleneck in production with its length of two to three kilometres and processes that today are fine-tuned based on individual experience and testing on numerous prototypes. To meet the future demands on fast adaption and tailored solutions for new material combinations and products there is a great need to improve the product preparation process. Volvo Cars has for example the vision to reduce the lead time for new models by 50% between 2012 and 2020. Simulation is seen as one of the major enablers to reach this vision.

The main goal of the project as defined in the project proposal was to develop methods, techniques and software, and supporting measurement methodology, for simulation of curing in paint ovens. This is very challenging for several reasons. It is a multi-scale application ranging from the sub-millimeter thickness of the paint layers to the size of the ovens. The turbulent air flow in the oven, the thin turbulent boundary layers, the large temperature gradients on the surface of the object, the evaporation and transport of water and solvent, and the long curing times up to 30 minutes are other major challenges. The project was based on earlier successful work on the Virtual Paint shop (Dnr 2009-00278 and Dnr 2012-02148) that resulted in the only dedicated software tool on the market, which is used in production by the Swedish and international automotive industry, to predict the paint film thickness, and also the laydown of sealing material. The same platform was used in this project with the aim that all key processes in an automotive paint shop can be simulated in the same simulation environment - “The Virtual Paint Shop”.

Already at the kick-off it was decided to focus on convective ovens in the project, which are the ones mainly used in automotive industry, and for such ovens a software capable of fast and accurate simulation is the main outcome of the project. To include also IR ovens

is actually only a small extension that will be performed after the project. The software has been successfully verified on four different industrial case studies, and a multi-objective framework for placing of automotive parts on a skid has been developed. Comparison with available commercial tools for oven simulation indicates that the developed software tool is state-of-the-art when it comes to computational performance, input requirements and user-friendliness. For the AB Volvo case the mean relative difference between the measurements and the simulation, at a number of probes, is less than 2.5%, which is within the standard deviation of the measurements. For the Volvo Cars case the mean relative difference between measurements and simulations, is roughly 5%, which corresponds to an average temperature difference at the probes of around 10 degrees. This can be compared with the 5.4 ºC difference between the left- and right-hand exterior sides, which are expected to be heated equally. The latter difference can be viewed as an approximation of the variation in the measurements. This means that simulation results are also for this case almost within the measurement uncertainty. The conclusion from the case studies is therefore that the simulations can be used to predict the outcome of the process, optimize process parameters and detect areas with insufficient curing.

The main discrepancy from the goals defined in the project proposal is that the models for evaporation of water and solvent in the paint layer turned out to be a bigger challenge than expected. Measurements on different paint types were performed at RISE IVF, but they could not provide accurate enough input to a mathematical model. Here, more effort is clearly needed. However, it is important to stress that the temperatures on the object's surface give enough information if the paint layer will be sufficiently cured. The lack of the detailed paint curing models is therefore not considered to be a big limitation at the moment. It was also intended to include simulation of the thermal deformation and stresses in the software tool. Here, an intermediate step was taken to develop an export functionality, such that those analyses can be done in other tools based on input from IPS Oven Simulation. The longer term goal is to include these analyses on the IPS platform as well. Guidelines and methodology for oven curing of lightweight and multi-materials have been proposed. They constitute valuable input for future research and development projects.

The project contributed to the FFI HP objectives in several ways. The commissioning time and environmental impact of the oven curing processes of new car or truck models can be reduced since significantly less prototypes need to be physically tested. The accurate simulation can be used to realize a more uniform curing that in turn improves product quality, and reduce thermal deformation and stresses. Methodology to study the effects of oven curing on multi-material concepts, which is a key to future lightweight design, was investigated and generated valuable input for future projects, e.g. targeting adhesive joining.

Overall this was a very challenging project with the high ambition to develop the leading software tool on the market for oven simulation. Several different modelling approaches were proposed, implemented and evaluated. The chosen approach provides a perfect compromise between simulation accuracy, powerful computational performance, and user-friendliness. The project results are ready for industrial implementation and have been commercialized as a new module in the software IPS Virtual Paint.

2. Sammanfattning på svenska

Ytbehandlingen är den process i en fordonsfabrik som förbrukar mest energi, vatten och kemikalier samt producerar mest avfall och utsläpp. Måleriet är också en flaskhals i produktion där processerna idag finjusteras genom testning på ett stort antal prototyper. För att kunna möta framtidens behov av snabb omställning, allt kortare ledtider och nya materialkombinationer så behöver produktionsberedningen kraftigt förbättras. Det huvudsakliga målet med projektet var att utveckla metoder, tekniker, mätmetodologi och mjukvara, för simulering av ugnar i målerifabrik. Detta är mycket utmanande på grund av turbulenta luftflöden i ugnarna, tunna gränsskikt och stora temperaturgradienter, och dessutom stora skalvariationer från dom tunna färgskikten till storleken på ugnarna. Projektet baserades på tidigare arbete i Vinnovaprojekt som har resulterat i den enda mjukvaran på marknaden, som används i produktion av svensk och internationell fordonsindustri, för prediktering av färgtjocklek, och applicering av tätningsmaterial. Samma plattform användes i detta projekt och ambitionen är att alla processerna i målerifabriken ska kunna simuleras i samma ramverk – “Den virtuella målerifabriken”.

2.1 Syfte

Projektets syfte var att utveckla validerade simuleringsmetoder och mjukvara för ugnshärdning för att

- reducera behovet av tidiga prototyper vilket har stor påverkan på ledtider i produktutvecklingen genom att hela testserier kan plockas bort,
- öka flexibiliteten att möta utmaningarna i måleriet som skapas av ett ökat antal produkter och materialkombinationer,
- förbättra produktkvaliteten genom en mer uniform temperatur på objektet under ugnsprocessen, vilket ger bättre härdning och ytfinish av färgskikt, tätningsmassa och andra material.
- minska miljöpåverkan genom att signifikant mindre fysikalisk testing blir nödvändig.

2.2 Forskningsfrågor

- Vad är en lämplig simuleringsmetod för konvektionsugnar?
- Hur ska simuleringsmetoden implementeras för att säkerhetsställa att beräkningsprestanda och noggrannhet möter industrins krav?

- Hur ska en användarvänlig ugnssimuleringsmjukvara designas?
- Vad är en lämplig mätmetodologi för att skapa indata till simuleringarna och för att verifiera simuleringarnas noggrannhet?
- Hur ska riktlinjer för ugnshärdning av lättvikts och multi-material formuleras?

2.3 Projektresultat

Redan på projektets första möte så beslutades att fokusera på konvektionsugnar, vilka är vanligast inom fordonsindustrin, och en mjukvara för snabb och noggrann simulering av dessa är projektets huvudresultat. Att inkludera även IR ugnar är en mindre utvidgning som kommer att göras efter projektet. Mjukvaran har framgångsrikt verifierats i fyra industriella fallstudier. Ett ramverk för multikriterieoptimering av placering av detaljer på en ställning har också utvecklats. En jämförelse med tillgängliga kommersiella verktyg visar att mjukvaran som utvecklats inom projektet är ledande avseende prestanda, krav på indata och användarvänlighet. Även noggrannheten är mycket bra och för AB Volvos testfall i sektion 6.2.3 så är medelskillnaden mellan mätningar och simulering endast ca 2 ºC, vilket är inom standardavvikelsen för mätningarna och motsvarar ett relativt fel på mindre än 2.5%. För Volvo Cars testfall i sektion 6.2.4 så är medelskillnaden mellan mätningar och simuleringar 10.8 ºC. Denna ugn är varmare och det motsvarar en relativ skillnad på ca 5%. Detta ska jämföras med skillnaden i uppmätt temperatur på 5.4 ºC mellan vänster och höger sida av bilen, som förväntas värmas upp på samma sätt. Den senare skillnaden är därför ett mått på variationen i mätningarna. Detta betyder att simuleringarna i princip ligger inom mätosäkerheten även för detta fall. Slutsatsen från de industriella fallstudierna är därför att det är möjligt att använda mjukvaran för att prediktera processen, optimera processparametrar, och detektera problemområden.

Målet att även utveckla modeller för avdunstning av vatten och lösningsmaterial i färgskikten visade sig dock vara en större utmaning än förväntat. Här krävs mer arbete efter projektet. Det ska tilläggas att temperaturerna på objektetsyta som är ett resultat av simuleringarna ger tillräcklig information om härdningen av färgen. Avsaknaden av härdningsmodeller för olika färgtyper ska därför inte ses som en stor begränsning. För att möjliggöra analys av termisk deformation och restspänningar så har en exportfunktionalitet implementerats inom projektet. I förlängningen är ambitionen att även dessa analyser kan utföras i samma verktyg. Riktlinjer för ugnshärdning av lättvikt och multimaterial har också tagits fram. Dessa ger värdefull information till framtid forsknings- och utvecklingsprojekt.

Sammanfattningsvis var detta ett utmanande projekt med den högt ställda ambitionen att utveckla den ledande mjukvaran för ugnssimulering. Det krävdes ett flertal olika modelleringsansatser för att komma till en ansats som utgör en perfekt kompromiss av simuleringsnoggrannhet, beräkningsprestanda och lättanvändlighet. Projektresultaten är redo för industriell implementering genom en ny modul i mjukvaran IPS Virtual Paint.

2.4 Bidrag till FFIs mål

Projektet har bidragit till FFIs övergripande mål på ett flertal sätt såsom:

- Ytterligare stärkt Sveriges kompetens som avancerad användare och utvecklare av digitala verktyg i gränslandet av produkt och produktion.
- Ytterligare stärkt den världsledande forskargrupperingen inom ytbehandlingsprocesser som bidrar till att Svensk fordonsindustri fortsätter att vara konkurrenskraftig.
- Ökat produktportföljen hos uppstartsföretagen Industrial Path Solutions Sweden AB och IPS IBOFlow AB som fokuserar på kommersiell produktutveckling, support och marknadsföring av IPS mjukvaran. IPS används idag av ett hundratal företag i världen.
- Ett ökat samarbete mellan industri och institut.
- Bidragit till fortsatt utveckling av Paint Centre på RISE IVF som gör det möjligt för industrin att utveckla sina ytbehandlingsprocesser utan att förlora tillgänglighet i egen produktion.
- Stötta fordonsföretag, deras underleverantörer, och andra tillverkande företag med lättanvända verktyg för att prediktera och optimera sina ugnsprocesser.
- Göra instituten till attraktiva partners i internationella och EU projekt.
- Bidra till andra projekt på FCC som kräver simulering av luftflöden och värmeledning med förbättrade metoder, algoritmer och mjukvara till nytta för tex svensk pappers, kartong och elektronikindustri.

Dessutom har projektet bidragit till underprogrammet Hållbar Produktions mål:

- Simuleringsmjukvaran minskar behovet av tidiga prototyper vilket har stor påverkan på ledtiden i utvecklingen av nya modeller, och bidrar till att hela testserier kan plockas bort.
- Miljöpåverkan kan minskas eftersom betydligt mindre fysikalisk provning behövs för att finjustera ugnsprocesserna.
- Simuleringsmjukvaran kan användas för att förbättra produktkvaliteten genom att en mer homogen temperaturfördelning kan uppnås på ytan under processen, vilket i sin tur leder till bättre härdning och ytfinish av färgskikt, tätningsmassa och andra material. En bättre kontroll på uppvärmning och avkylningszoner minskar också termiska deformationer och spänningar.
- Den matematik-baserade simuleringsansatsen är en nyckel till att öka flexibiliteten som krävs för att kunna hantera utmaningarna som skapas av ett ökat antal produkter och materialkombinationer. Simuleringarna kan också bidra till att det blir enklare att flytta produktionen av en viss modell till en annan fabrik genom att härdningsvillkor kan verifieras på förhand.
- Projektet har också bidragit till målet om livscykeleffektivitet genom att utreda riktilinjer för hur nya lättvikt och multimaterial påverkas av ugnarna, tex avseende termisk deformation och restspänningar. Projektresultaten

kommer att ge värdefull input till det nyligen startade FFI projektet VIVFAP (Virtuell Verifiering av Falsningsprocessen, Dnr 2019-05848).

3. Background

Today, the margins of automotive manufacturers are moderate and competition is fierce. The industry furthermore faces shifts of paradigms regarding propulsion as well as styling, with environmental requirements ever-present. Effective product realization response is thus important. The rapid increase in computational power has made virtual tools an integrated part of the development of products and processes. Virtual prototyping stimulates industrial innovation and simulations offer an alternative to measurements, when these are too expensive or even impossible to perform. Furthermore, the risk for unforeseen costs and quality problems is reduced through the possibility to perform analyses and optimization in the early stages of product development. Today, although most development is done virtually, design decisions are still based on experience rather than mathematical analysis.

The surface treatment is the process in an automotive factory that consumes most energy, water and chemicals, and produces most waste and pollution. Roughly 40% of the energy in major OEM operations is used in the paint shop with an average consumption of 700-900 kWh per car body. Within the paint shop the dominating energy cost is the ventilation and heating of the air in the booth (50%) followed by the ovens (25%). The manufacturing process in an automotive paint shop is a process chain consisting of several different coating processes, see Figure 1.

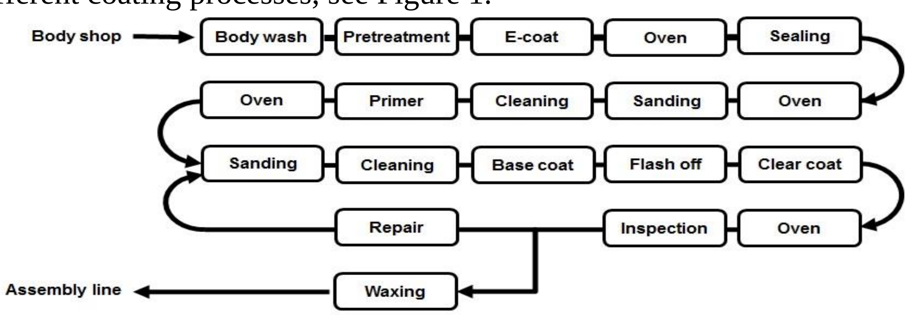


Figure 1. Process steps in a modern automotive paint shop.

The length of a coating line from the body-in-white shop to the final assembly is usually between two and three kilometers. Roughly 60 cars are coated per hour and the dwell time in the paint shop is about 8-11 hours. The CO2 emissions from a modern paint shop (BMW Shenyang) are around 140 kg/car, and considerably higher in older paint shops. The solvent based automotive paint is a major source of man-made volatile organic components (VOCs) and hazardous air pollutants including toluene, xylene, methyl ethyl ketone, and ethyl benzene, that may have long-term health effects and cause harm to the environment such as increasing the ozone concentration in the lower atmosphere. The water-borne paints still contain harmful chemicals and are more demanding to use. Also adhesives, sealants, noise damping materials, expanding foams etc. are cured in the paint ovens.

This means that the paint shop not only has a large environmental impact it is also a bottleneck in production. On the other hand, due to its great complexity the painting process offers many approaches to improve the use of energy, material and reduce emissions that in turn have direct impact on sustainable automotive production.

To meet the future demands on fast adaption and tailored solutions for new material combinations and products there is a great need to improve the product preparation process. Volvo Cars 2020-20 vision for example aims to have a lead time of only 20 months for a new car model in 2020. This can be compared to 36 months for the new XC90 model from project start until the first car was produced. Simulation is seen as one of the major enablers to reach this vision.

FCC has, partly within two successful research projects (Dnr 2009-00278 and Dnr 2012-02148), developed the only dedicated software tool on the market that can be used to predict the film thickness in industrial paint applications, and also the laydown of sealing material. The software tool is today used in production by Volvo Cars, AB Volvo, Scania, CEVT, Eisenmann, and GM, and several other companies are currently evaluating the software.

The painted layers are cured in ovens, where the heat transfer typically is through convection or infrared (IR) light. The ovens are often divided in several zones with an IR part first followed by several convective zones. The curing process is very energy intensive and in the convective oven fans direct a hot air flow on the body such that its surface reaches a temperature of around 190 °C in the E-coat cure oven, 165 °C in the filler/sealant oven, 150° C in the clear coat oven, and 75° C in the base coat oven.

For the IR ovens this includes to predict how the heat builds up and spreads on the target due to the IR lamp sources. The thermal properties of the respective parts are taken into account as well as the substrate thickness and evaporation of water and solvent from the paint layer during the process. In the convective ovens also the turbulent air flow created by the fan sources surrounding the object must be calculated. This is very challenging for several reasons. It is a multi-scale application ranging from the sub-millimeter thickness of the paint layers to the size of the ovens. The turbulent air flow in the oven, the thin turbulent boundary layers, the large temperature gradients on the surface of the object, the different thermal properties of the materials, the different substrate thicknesses, the evaporation and transport of water and solvent, and the long curing times up to 30 minutes are other major challenges for modeling and simulation.

4. Purpose, research questions and method

4.1 The project purpose

This project's purpose was to develop validated simulation methods and software tools for oven curing processes in order to

- reduce the need for early prototypes which has a large impact on the overall **lead time** for new models since entire test series can be removed,
- increase the **flexibility** to meet the challenge of increased complexity in the paint shops due to an increased number of product and material variants,
- improve the product **quality** by a more uniform temperature distribution on the object during the process, which gives a better curing and finish of paint, sealant and other materials,
- reduce the **environmental impact** since significantly less physical testing is needed.

4.2 Research questions

- What is a suitable simulation method for convective paint ovens?
- How should the simulation method be implemented to ensure a computational performance and accuracy that meet the industrial demands?
- How should a user-friendly oven simulation software be designed?
- What is a suitable measurement methodology to supply simulation input and to verify the accuracy of the simulations?
- How should suitable guidelines and methodology for oven curing of lightweight and multi-materials be formulated?

4.3 Method

To meet the present and future demands of the Swedish automotive industry Vinnova has funded several projects on the Virtual Paint Shop (Dnr 2007-02439, Dnr 2009-00278 and Dnr 2012-02148), where the aim has been to develop a novel framework for simulation of spray painting and surface treatment processes. The framework is based on unique algorithms for coupled simulations of air flow, electromagnetic fields and charged paint droplets. Particularly important for the computational efficiency is the Navier-Stokes solver, IBOFlow. Unique immersed boundary methods are used to model the presence of objects in the fluid and they are combined with a dynamic Cartesian octree grid. This enables modeling of moving objects at virtually no additional computational cost, and greatly simplifies preprocessing by avoiding the cumbersome generation of a body conforming mesh. A conjugated heat transfer solver including convection, conduction and radiation, has been recently developed, and required turbulence models, wall functions and thermal boundary layer models are also available (Svelander et al. 2016).

The earlier work consituted an excellent platform to start from in this project and the general approach has been to develop and implement models in a general form and continuously compare simulations to experiments, initially on test cases for simple geometries in a lab oven at RISE IVF, and later on full scale case studies at the OEMs. When the full model compares well to experiments model simplifications and simulation speed-up have been introduced in a controlled way.

5. Objective

The main objective of the project was to develop methods, techniques and software, and supporting measurement methodology, for simulation of paint curing in IR and convective ovens. The project results should support companies to develop and optimize their surface treatment

- to be more energy efficient,
- to be more cost efficient,
- to have a shorter lead time in product development,
- to give a higher product quality,
- to be able to predict and evaluate and thus enable future multi-material concepts.

More specifically the main goals were

- models, methods and algorithms for simulation of convective and IR ovens,
- model for the evaporation of water and solvent in the paint layer,
- models, methods and algorithms for simulation of thermal deformation and stresses,
- simulation software for fast and accurate simulation of oven curing,
- further development of Paint Center, a unique facility where the industry can evaluate their surface treatment processes off-line,
- verification on at least two industrial test cases,
- develop a multi-objective optimization methodology for oven curing and perform an investigation of optimal placement of plastic parts on a skid,
- develop guidelines and methodology for oven curing of lightweight and multi-materials.

Compared to the initial objectives it was early in the project decided by the steering group to put the focus on convective ovens, since none of the partners utilized IR ovens. However, IR ovens are easier to model than convective ovens, and the developed software will after the project be extended to handled also IR. Mainly what is currently missing is an IR lamp library, but radiation e.g. can already be handled. Furthermore, as mentioned in the next chapter, the detailed measurements of the curing of the paint material itself proved to be very challenging and could not provide the required model input for the evaporation of water and solvent. Therefore, the main emphasis in the project was put on a fast and accurate simulation of the conjugated heat transfer in the ovens, which is anyhow most important.

6. Results and deliverables

6.1 Models, methods, algorithms and software for oven simulation

6.1.1 Physical Model

The air inside the oven is an incompressible fluid, modeled by the incompressible Reynolds' averaged Navier-Stokes equation, together with the heat equation and the Menter SST turbulence model. Inside the solids heat transfer is modeled by thermal conduction. The coupling of solid heat transfer and fluid heat transfer in a system is known as conjugated heat transfer. The conjugated heat transfer coupling is responsible for the modeling of the transfer of heat between air and the solid objects. The properties of the conjugation are determined in the viscous layer of the fluid and requires the boundary layers at the fluid-solid interface to be resolved in order to achieve accurate results. A challenge here is the long physical time for the oven, and the separation of scales between the oven, the car body, and the boundary layer. Our innovative approach to resolve this issue and design an efficient method is described in the next section.

Within the current project our focus has been on developing the general heat transfer model inside ovens, the efficient method to implement this model, and presenting this in an easy to use software for the industrial partners. Therefore, the focus has been on the modeling of the heating of dry objects. The measurements carried out at the industrial partners are, but for exceptional cases, done on untreated objects. For the validation campaign it was thus natural to ignore paint curing models. As mentioned in the previous section and in more detail in the measurement methodology section below the curing measurements also turned out to be very challenging, which further complicated the development of a curing model. In the current heat transfer model, the coupling is isolated and could easily be extended to include a curing model, once such a model has been developed and validated within the framework.

The ovens are geometrically modeled using their length, cross section geometry, and nozzle locations. For each nozzle, the volume flow rate is set and for each section of an oven the temperature is set, which is then assigned to the nozzles in that section. An object is transported through the oven by setting a velocity of the conveyor through the oven. For stationary ovens, a transient temperature profile for the nozzles may be set.

6.1.2 Method

A direct brute force simulation of an industrial oven resolving all time and length scales would be enormously time and resource consuming. It is therefore clear that numerical modeling must be performed, including separation of scales, and a simplification of the heat transfer coupling. This turned out to be the most challenging part of the project.

Initially, attempts to fully resolve the lab scale oven were done using several different approaches for the coupling and the solid heat transfer. The original idea was to solve the solid heat transfer within the framework of a structural mechanics solver to allow for fully integrated curing and thermo-mechanical simulations. It turned out that the necessary ranges of scales both in length and time were too large for this to be a feasible approach. Even switching to solving conjugated heat transfer within the RANS solver did not sufficiently decrease the complexity. This meant that it was not possible to use fully resolved simulations in the lab scale oven, to model it, and then use this model in the industrial scale ovens, which could be one or even two orders of magnitude larger than the lab scale oven. Instead, an approach was chosen, where the individual nozzles in an oven are simulated to estimate the local nozzle Nusselt number. The Nusselt number is a dimensionless number describing the strength of heat transfer. For a full oven, the Nusselt numbers of each nozzle are combined to model the effect of the fluid on the solid, and thereby model the heating. To extend the method to include the curing process of paint, only the nozzle Nusselt number model needs to be extended.

Using the resolved local simulations to model the fluid-solid heat transfer coupling resolved one scale separation issue. The other scale separation issue is the size of the cab or car body itself. A tetrahedral or hexahedral volume mesh usable in a structural mechanics simulation would often have tens of millions of elements and be very computational resource intensive to solve. In our approach we utilize the novel geometric routines in IPS IBOFlow that efficiently and robustly compute the intersection between a triangular volume mesh and a hexahedral Cartesian mesh. This allows us to accurately describe the solid geometry on a coarse background grid and enables the efficient solution of the heating of objects inside the oven.

The temperatures in a curing oven can exceed 200 C, which is sufficiently high for the objects to deform. To be able to simulate the deformation is especially important at material interfaces, which are common when light-weight materials are included in a design. They feature e.g. interfaces between steel and aluminum. The possibility to analyze these deformations is also an important enabler for hemming and adhesive simulations. For the thermo-mechanical simulations, an interface has been written, where the necessary information is exported into a format useable within an external structural mechanics solver. IPS Oven Simulation reads scalar and volume meshes and interpolates the solution temperature to the necessary positions. This allows the thermo-mechanical simulations to be run as a post-processing step. It is our intention and intermediate term goal to extend IPS Oven Simulation with the capability to perform the thermo-mechanical simulations. This will enable us to perform the curing and deformation simulations in an integrated application.

6.1.3 Software

The model and method described above has been implemented in IPS Oven Simulation and provided to the participating industrial partners. The test cases for each participating company has been set up and run in the software. This allows for an easy to use integrated solution where paint, sealing, adhesive, and curing simulations are possible on the same platform. To set up an oven the user defines the nozzles, which could be both circular and rectangular, their mass flow and locations. To simplify the setup of a group of periodically repeating nozzles, which is often the case, the user only needs to define the first nozzle in a repeating pattern. The temperature can be set separately for each section of the oven.

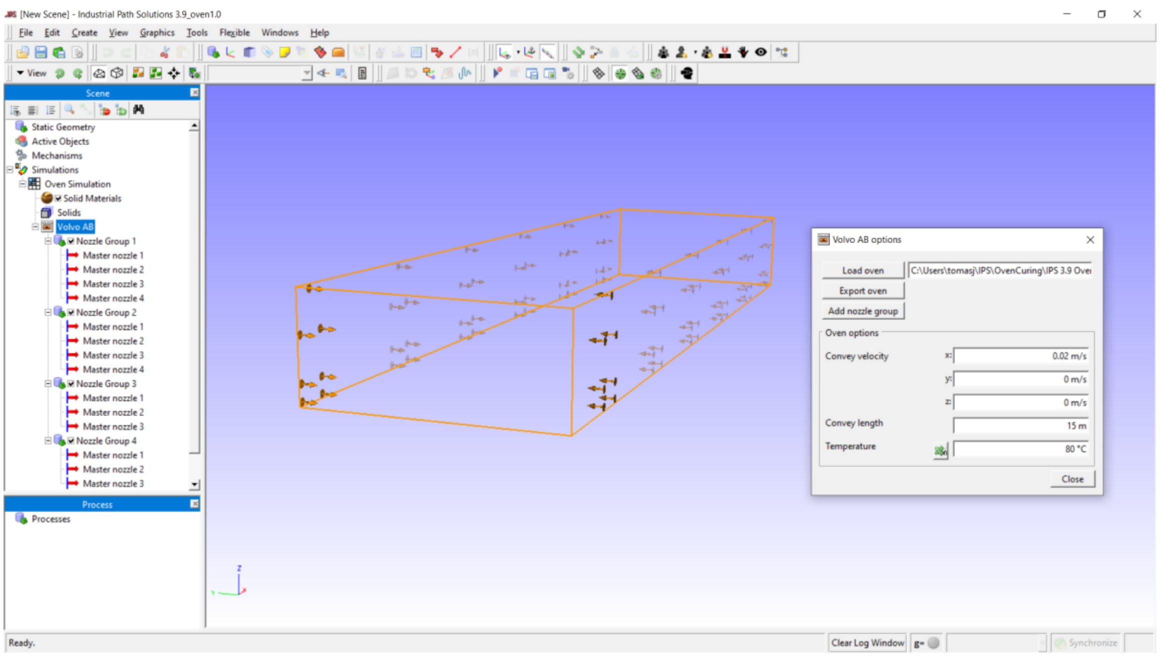


Figure 2 - Oven Setup with nozzles and properties

The next step is to add objects and set material properties for each object. Several objects can be added separately. The solution can be tracked on each individual object using probes and measures that record the transient heating of the objects.

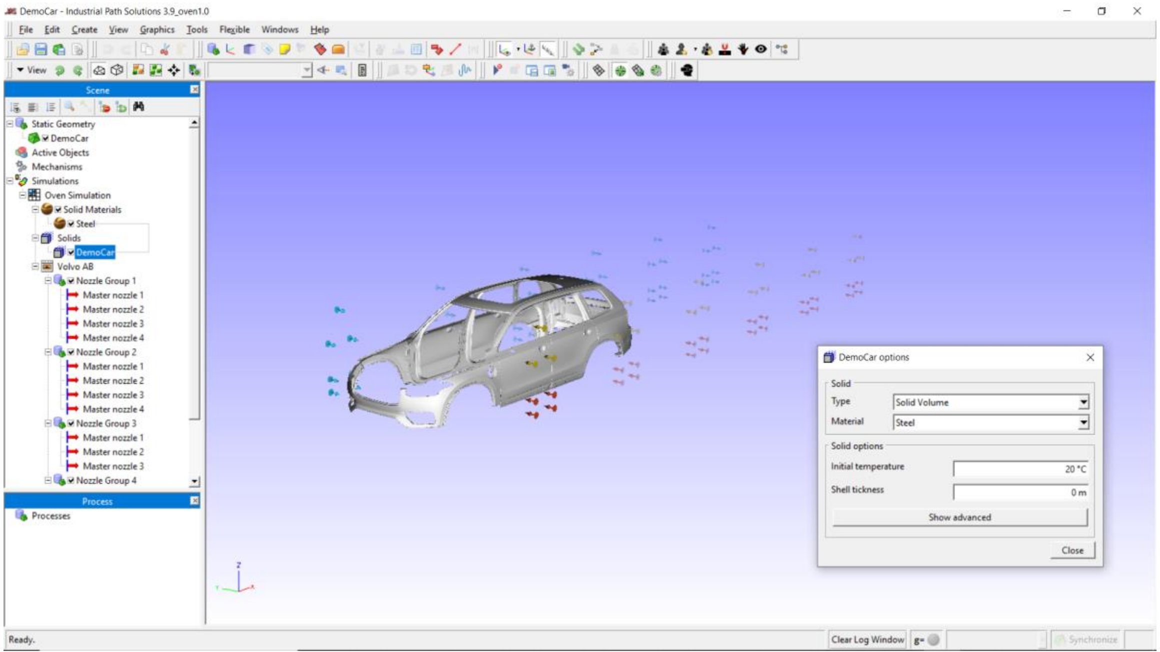


Figure 3 - Setup of object and material

Stationary and moving objects are set up in the same interface. For an oven with stationary objects the temperature can be given transiently instead of being defined by the oven sections. This enables IPS Oven Simulation to be used for the common use case that stationary objects are put in a cold oven which is heated to the desired temperature in the given time.

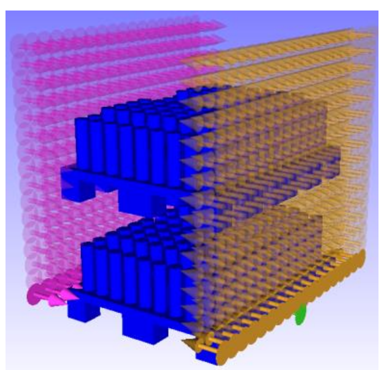


Figure 4 - Stationary objects inside a small oven with many nozzles

The simulation and the results can be followed in the software, and the recorded temperatures can be viewed inside the software or exported for further analysis, including external thermo-mechanical simulations.

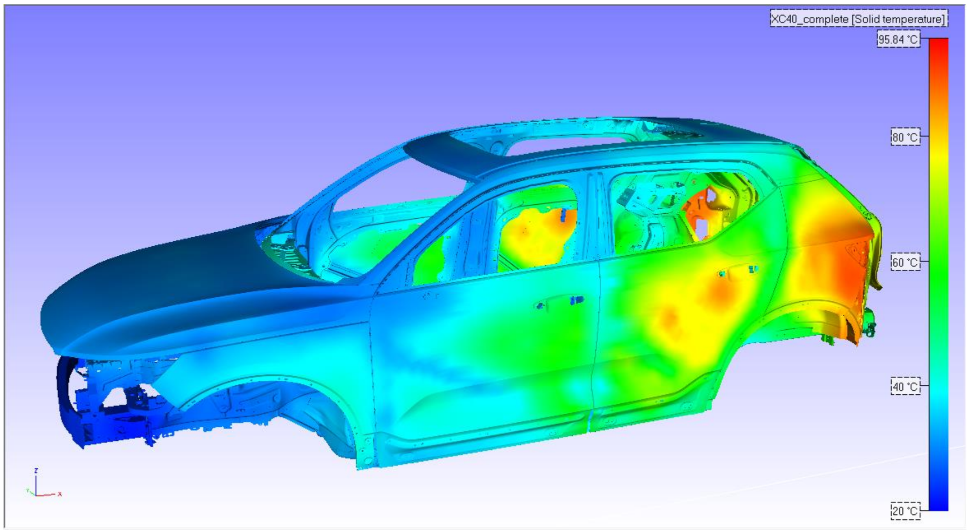


Figure 5 - Simulation result inside IPS Oven Simulation¨

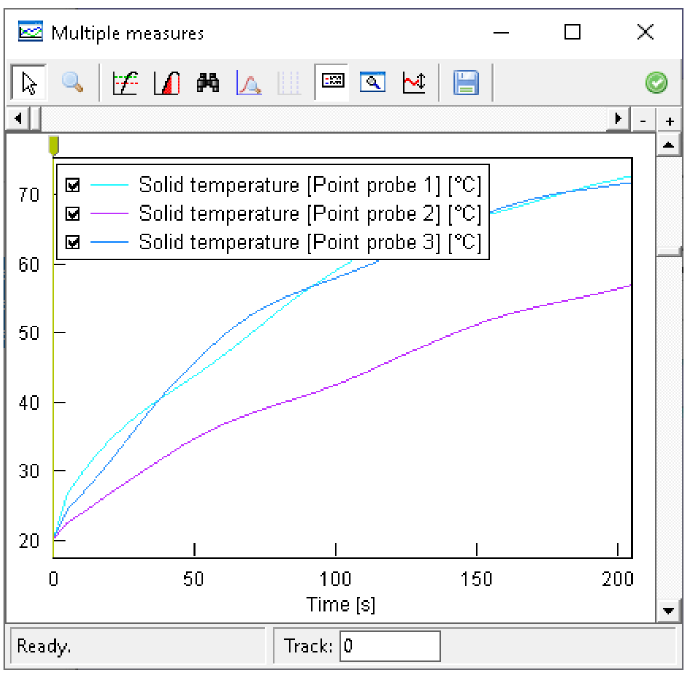


Figure 6 - Temperature curves for measurement probes

The run time of a simulation depends on several factors: the size of the oven, whether the objects are stationary or moving inside the oven, and the resolution of the objects that are cured. Comparing the run time with real time for the case studies in the project: for stationary objects, the simulation could be up to 50 times fast than real time, whereas for a moving object it is 2-10 times longer than real time, depending on the resolution.

6.2 Case studies

6.2.1 RISE IVF / Scania

The first case study in the project was performed in the lab scale oven at RISE IVF, where several measurements were performed early in the project to support the model development and validation. Three different objects from Scania were measured. The components were chosen so that they would highlight the differences in curing properties due to material differences. One steel and two thermoplastic objects were measured. To validate the solver implementation the computational results for the steel object were cross validated with an independently implemented FEM approach.

Figure 7 - Scania parts used for validation. The bottom part is steel, the other two pc/pet.

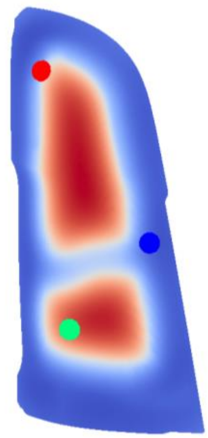


Figure 8 - Probe positions for measurements, numbered 1,2, and 3 from the top and down.

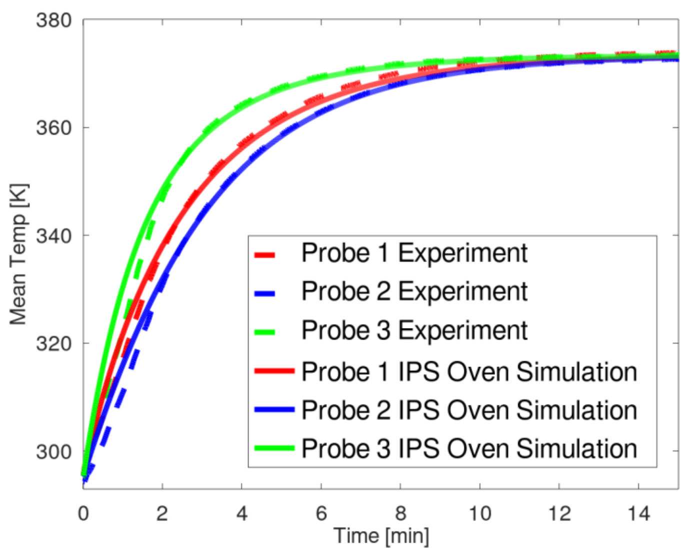


Figure 9 - Validation of the Scania steel object

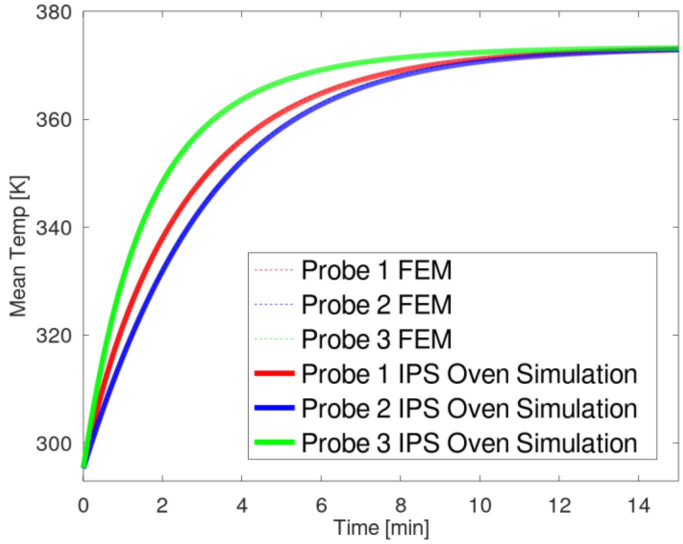


Figure 10 - Simulation method cross validation

The experimental results for the Scania objects are averages of two sets of measurements. The steel object was measured at the three probe locations illustrated in Figure 8 and validated in Figures 9 and 10. For the two thermoplastic objects there were only small gradients within the objects and therefore only averages are shown for the validation in Figures 11 and 12.

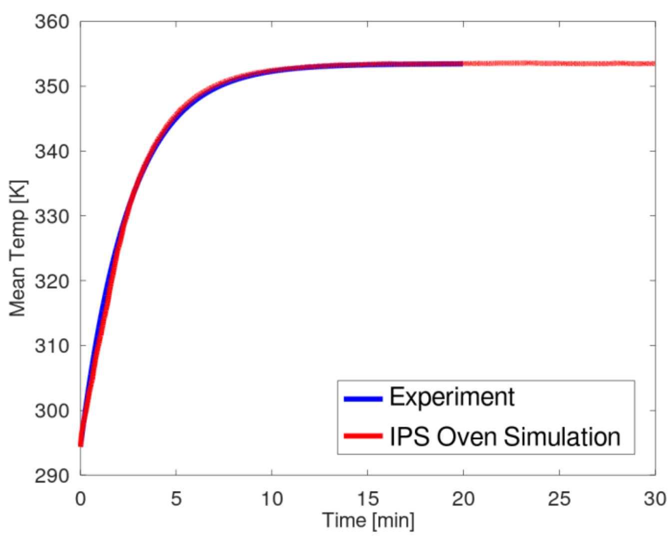


Figure 11 – Validation of the smaller thermoplastic object

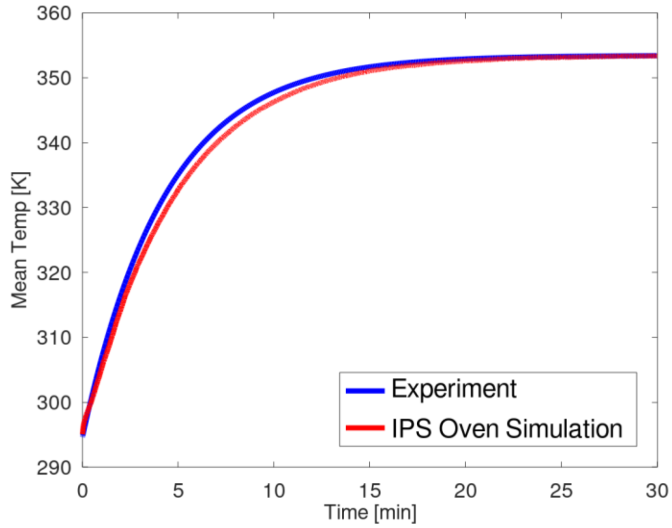


Figure 12 - Validation of the larger thermoplastic object

As seen in the figures above the transient heating of the test objects is captured very well with the developed model and implemented method. In addition, it is sufficiently accurate quantitatively to enable qualitative analysis of the different heating at different locations. For the steel object the separation between the three probes is clearly seen in the simulations and correspond well to the differences seen in the measurements.

6.2.2 ElectroHeat AB

ElectroHeat AB designs and manufactures industrial ovens. As a case study in the project one of their ovens was used together with stacks of zinc pucks placed on pallets inside it. The oven is shown in Figure 13, and a snapshot from IPS Oven Simulation with the pallets and pucks is shown in Figure 14. The oven was heated to almost 500 ºC in 5 h and then held at that temperature for another 15 h. The simulation time was 30 minutes, i.e. 40 times faster than real time. Inside the oven there was four pallets with stacks of zinc pucks on them. The temperature was measured on the zinc pucks at 10 locations: the corners and the middle on both levels. For the comparison, the outer and inner temperatures were averaged since they are very similar. In the results these are denoted minimum and maximum. All results for the simulation and the measurements refer to zinc temperatures. The pallets are included in the simulation, where the material thermal properties have been set to generic wood. A comparison between the experiments and the simulations is shown in Figure 15.

Figure 13 - ElectroHeat oven with zinc pucks used for validation

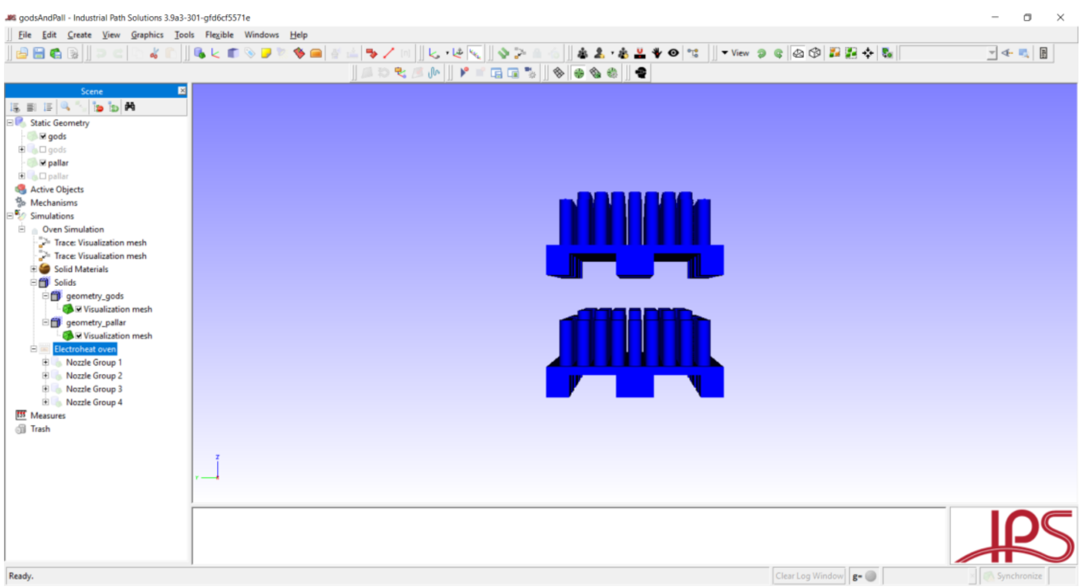


Figure 14 - Setup of the oven inside IPS Oven Simulation

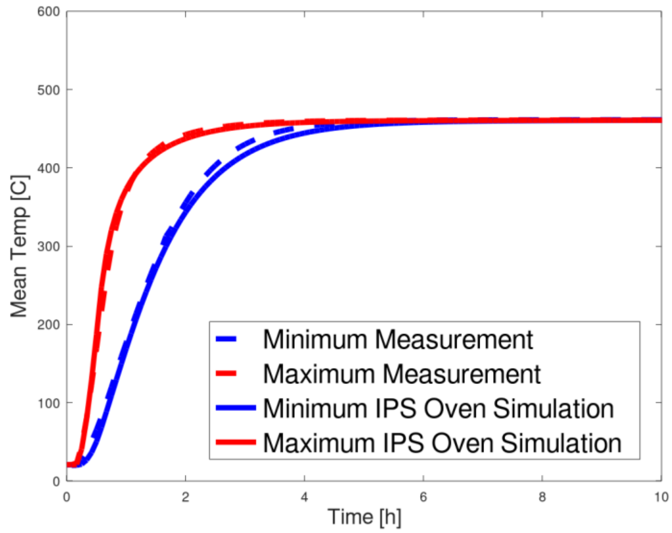


Figure 15 - Validation of the ElectroHeat oven

As is seen in Figure 15, there is a strong correspondence between the measured and the simulated temperatures. This shows that the models and methods developed within the project not only applies to sheet metal objects common in the automotive industry but also to other solids which allows for curing applications in many other industrial sectors. It should be stressed here that the results are based on physical modelling and not an extensive parameter fitting or optimization procedure. After completing resolved nozzle simulations and setting the nozzles inside the oven to their correct physical properties, only one free parameter remains, the background heat transfer coefficient. This strongly indicates that the method, model, and implementation is physically sound and easy to use without large amounts of fine-tuning. This enables an oven designer to add simulations to his workflow without extensive knowledge of the method, and without using exorbitant time for calibration.

6.2.3 AB Volvo

At the Umeå paint shop AB Volvo are running monthly measurements of a dry test cab, based on the FH24 model. Five months of measurements were provided in the project together with the geometry and the location of the probes. The measurements show some variation; the maximum transient standard deviation is 2 ºC. The oven itself was scanned and the scan was used for the setup of the simulation.

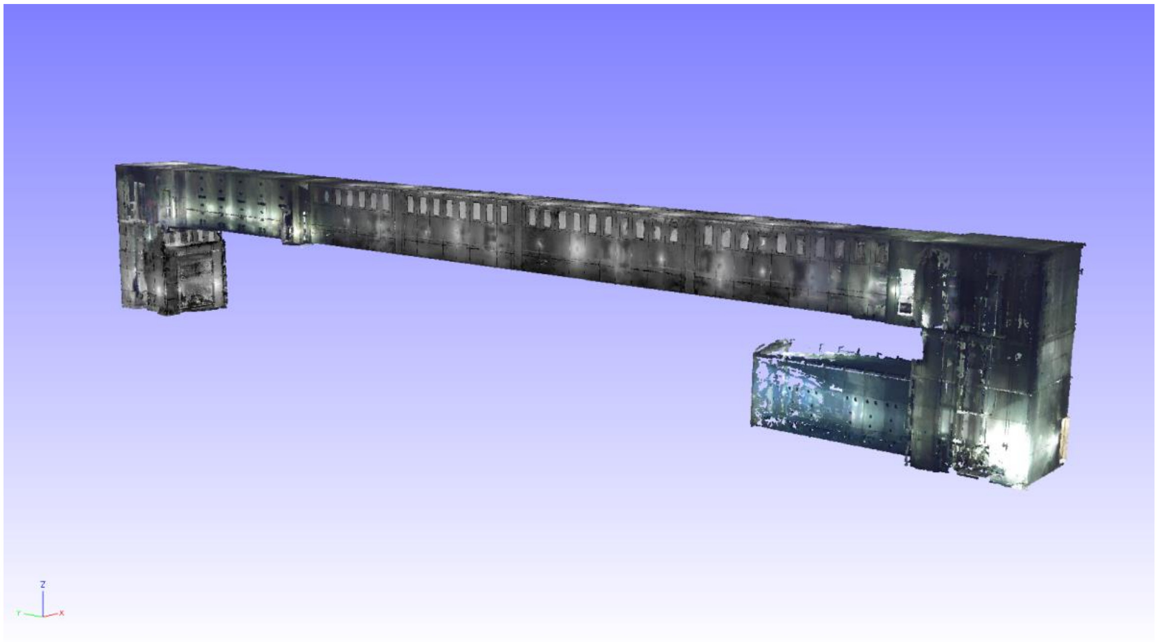


Figure 16 - Overview of the AB Volvo Umeå top coat oven, from 3D scan.

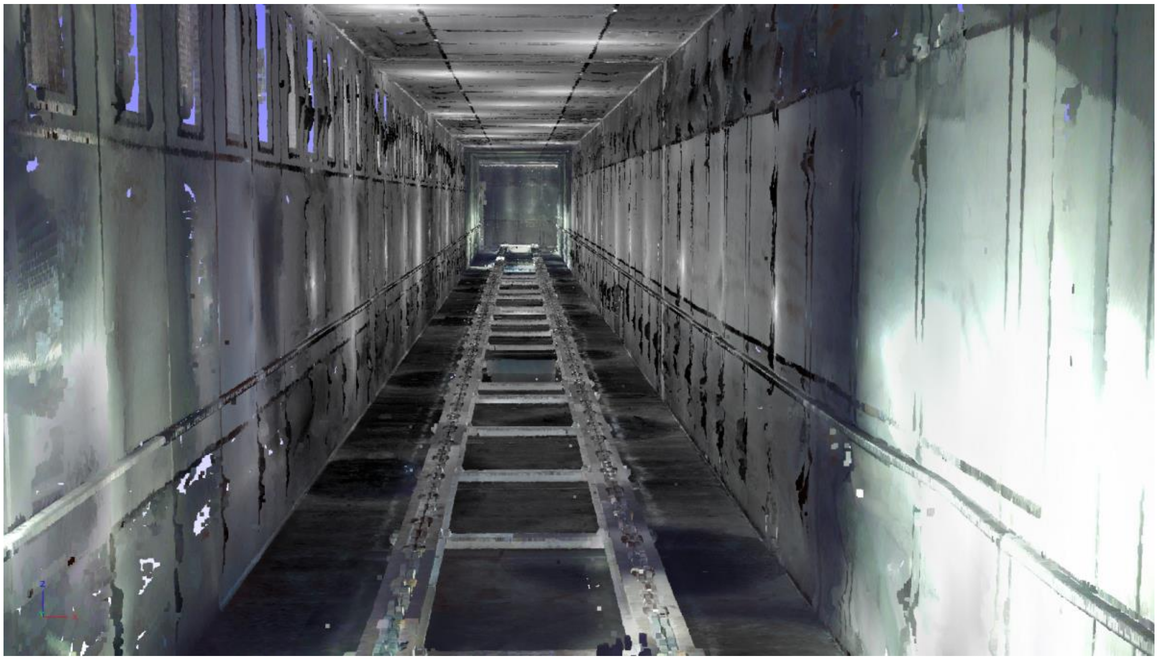


Figure 17 - Inside of the AB Volvo Umeå top coat oven, from 3D scan.

For the comparison between simulation and experiments the average values are used. For four positions on each side of the cab there are symmetric measurements on the left- and right-hand sides, and, additionally, there are three centre probes located at the front, roof, and back of the cab. The comparison is performed in the heat up and holding zones of the oven. It takes around 45 minutes for the cab to go through; the simulation took around 100 minutes, i.e. about twice real time.

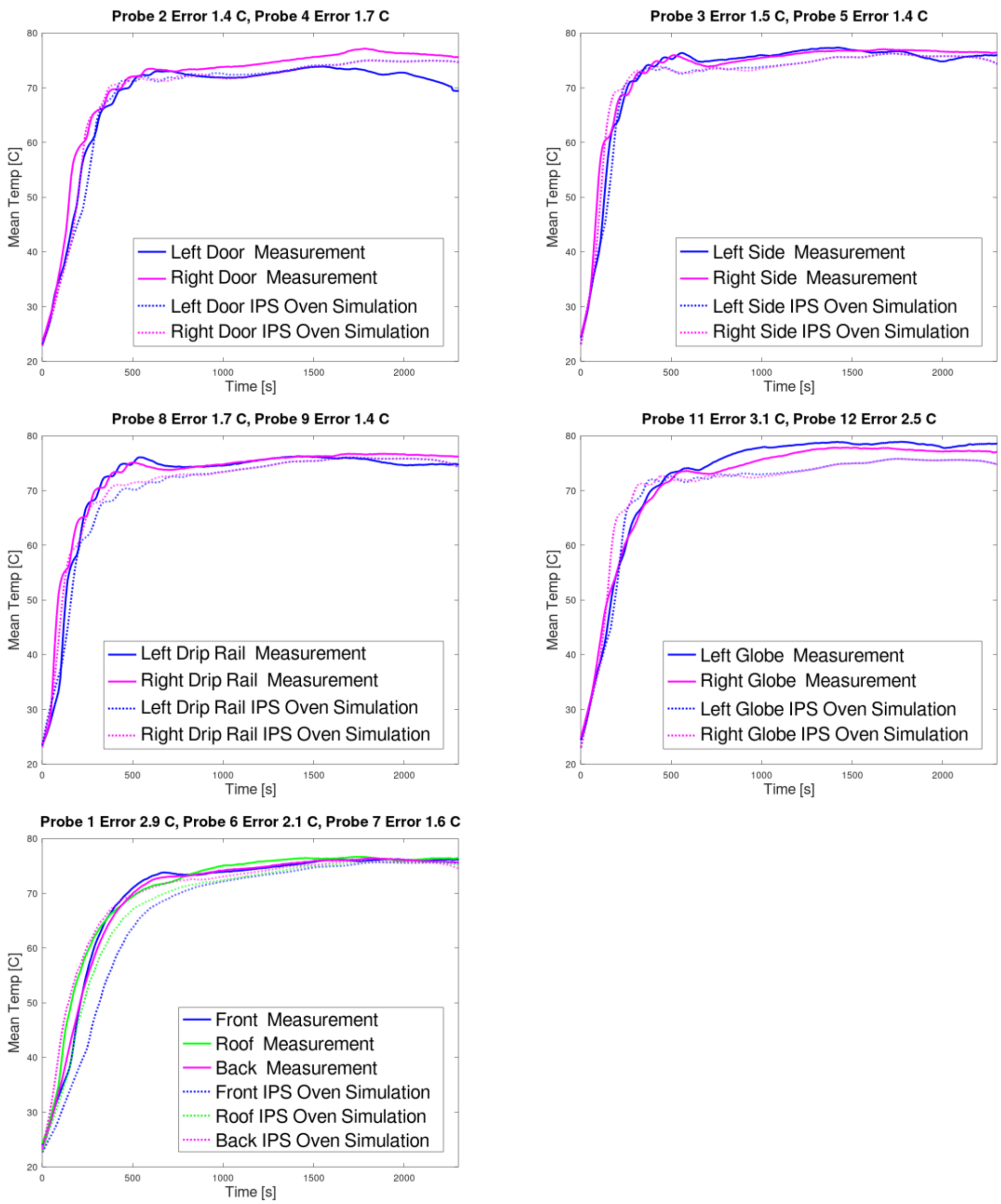


Figure 18 – Comparison of simulation results and measurements on the AB Volvo truck cab

As seen in the Figure the overall qualitative and quantitative behaviour is correct; the mean error is below 2 ºC. The alternation between the left- and right-hand sides of the cab is also predicted. This is due to the periodic structure of the oven, where nozzles are only present on one side at the time.

6.2.4 Volvo Car Corporation

The case study for Volvo Car Corporation is a curing oven for electro coating at the factory in Gent. These ovens are among the highest temperature ovens in an automotive factory. In the current case the highest temperatures are around 200 C. This makes it challenging to cure all parts of a car properly. The heat up time for thicker parts, such as beams is significantly longer than for thinner parts. For the case study a XC40 is used. The body is primarily made from steel, but the hood is aluminum, and several smaller parts are made from bitumen, polyamide, and polypropylene. The oven is 150 m long and consists of several sections: heating zones, hold zones, and finally a cooling zone. In each section shown in Figure 19 below the temperature is set to a given value. A close up of one section of the heating zone is shown in Figure 20. The goal with the curing is to reach a certain target temperature for a minimum time.

Figure 19 – Electrocoat oven at the Volvo Car Corporation Gent factory. Each section of the car is marked with a different color.

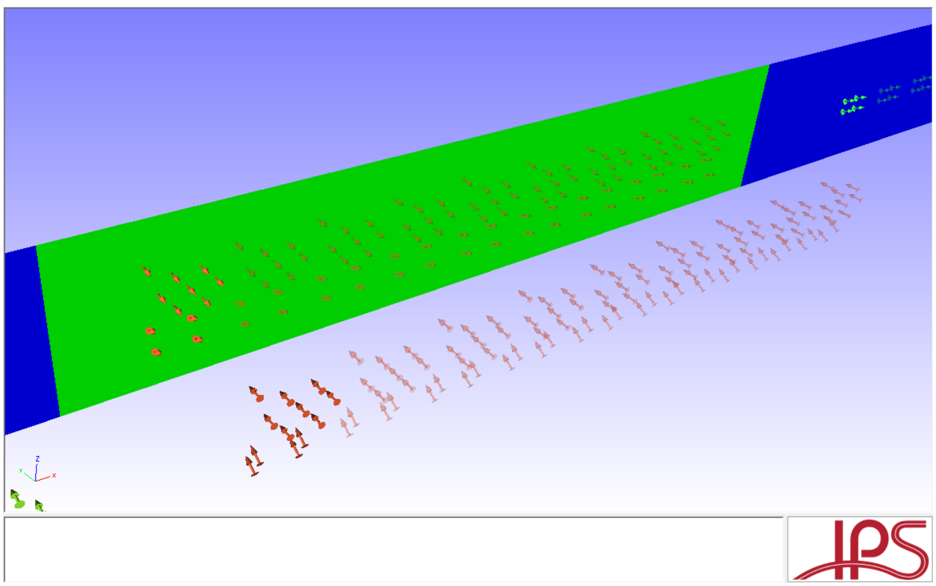


Figure 20 - One heating zone in the oven with the nozzles displayed.

Before the simulation starts several probes are set to the car body, corresponding to the measurement probe locations. The simulation took around 20h for 1h of physical time. A snapshot from inside the oven during simulation is shown in Figure 21. The simulation results are exported and compared with the measurements. They are showed for probes with different locations in Figure 22.

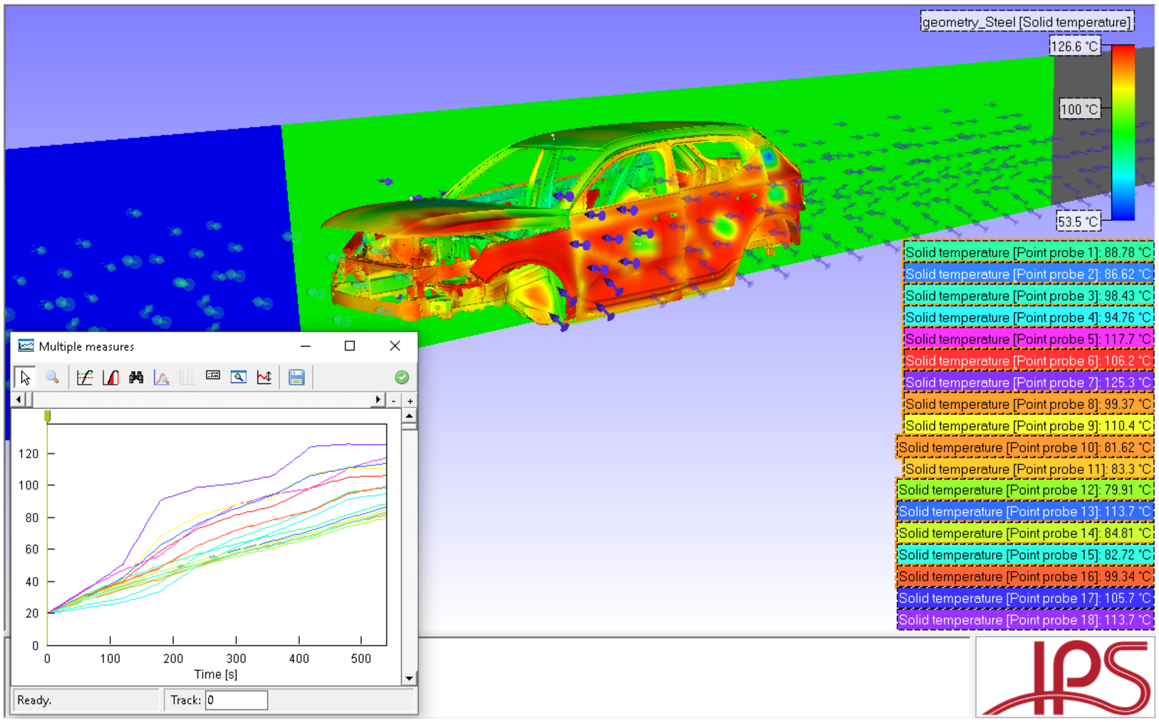
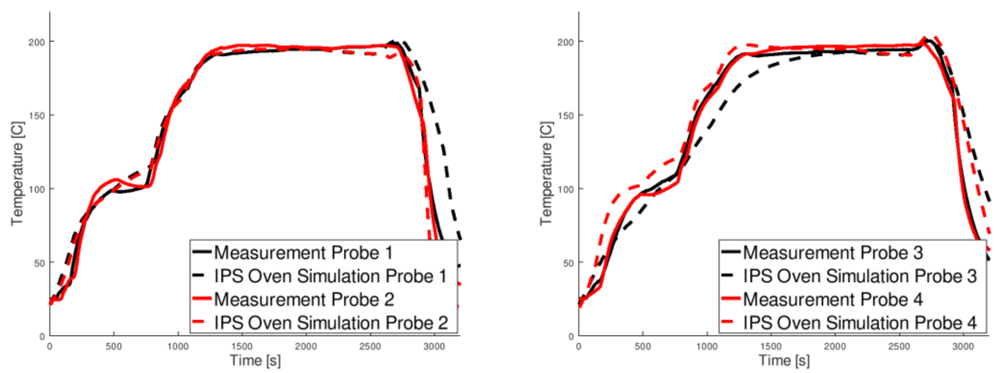


Figure 21 - Simulating an XC40 inside the Gent oven, with nozzles and probes.



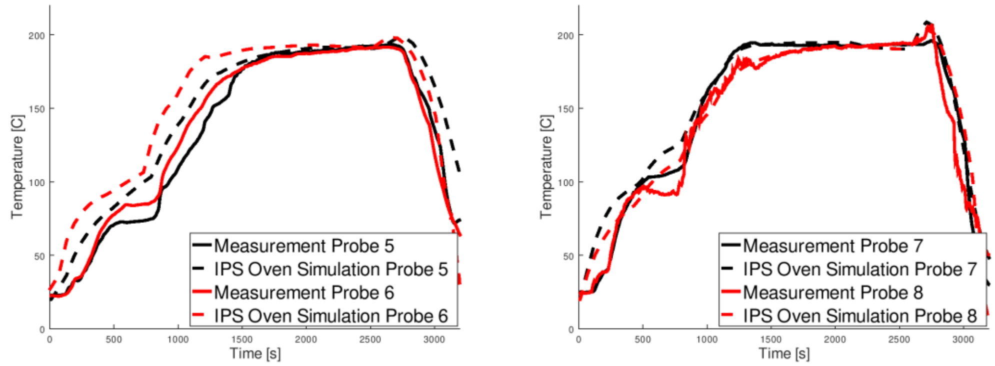


Figure 22 – Results for the heating of the XC40, clockwise from top left: exterior side, exterior above, exterior below, and interior measurement.

As seen in the results in Figure 22 above, the results have reasonable accuracy for all four types of positions: exterior side, exterior above, exterior below, and interior. The mean difference between the measurements and the simulations is 10.8 ºC. This can be compared with the 5.4 ºC difference between the left- and right-hand exterior sides, which are expected to be heated equally. The latter difference can be viewed as an approximation to the variation in the measurements. The highest accuracy is achieved for the exterior side and above parts, where the nozzles hit directly, and the interior parts where the nozzles do not hit at all. For the parts on the underside of the car the accuracy is lower but still acceptable. The lower accuracy is probably due to the under resolved airflow under the car body.

6.3 Measurement methodology and guidelines for lightweight materials

In the report ”Measurement methods – WP3 Simulation of oven curing”, measurement methods and instruments identified within the project are summarized for mapping different stages of the painting and drying processes within the automotive industry in particular, but also for paint and drying processes in general. The methods presented essentially represents the methods used in this specific project in lab- and pilot scale with purpose to supply the project with input data for the simulation. The methods are categorized as lab, pilot- or production scale measurements indicating where each method being most feasible. The instruments and methods have been tested in lab and pilot scale at RISE (former Swerea) IVF's facilities. The report includes cost estimations of the methods described and if specialist knowledge is needed to use the equipment or to evaluate the measurements.

Oven curing of complex parts consisting of different materials is also challenging due to the different thermal properties, especially the coefficient of thermal expansion (CTE). When two or more materials are joined, the difference in thermal expansion between the materials and changing temperatures can cause additional loads in the joints and also deformation of the product. In addition to the difference in CTE of the materials, the size of these additional loads and deformations depends on both the global geometry of the adhesive joint and the product. Oven curing of paint is performed at up to 180 – 200 °C for the electrocoated paint layer. This is also the temperature range where structural adhesives cure. The adhesive is thus cured at a deformed geometry and when cooling down to room or usage temperature, stresses will develop in the product. Multimaterial products must be designed to accommodate these stresses, without weakened joints and/or deformed geometry.

Oven curing of future lightweight materials was investigated and summarized in a Guideline (“Guidelines - Oven curing of lightweight multimaterials”, Project report 26162, RISE IVF, 2020). The work on a methodology to evaluate the effects of oven curing on geometry, tolerances and quality on assembled or multi-materials products of different shape and size has been started and the initial results are summarized in a report (“Temperature and Geometry Measurements”, O.Albinsson, , L-O. Ingemarsson, J. Skogsmo, F. Wandebäck, RISE IVF, June 2020). The methodology will be used to investigate guidelines of suitable temperatures and process times for future lightweight multi-material combinations. This is a very large and complex area and much more work will be needed in future activities to take control over thermal behaviour of light weight multimaterial constructions.

6.4 Multi-objective optimization of oven curing

In many curing applications there is a freedom to choose the position of the object inside the oven. This is especially true for truck cabs where there typically are many small parts that are painted and cured separately before final assembly. It is important to position the objects so that all objects get properly and evenly cured. This can be stated as an optimization problem. As an example, from the Scania factory in Meppel the following skid with several parts with different materials is painted and cured.

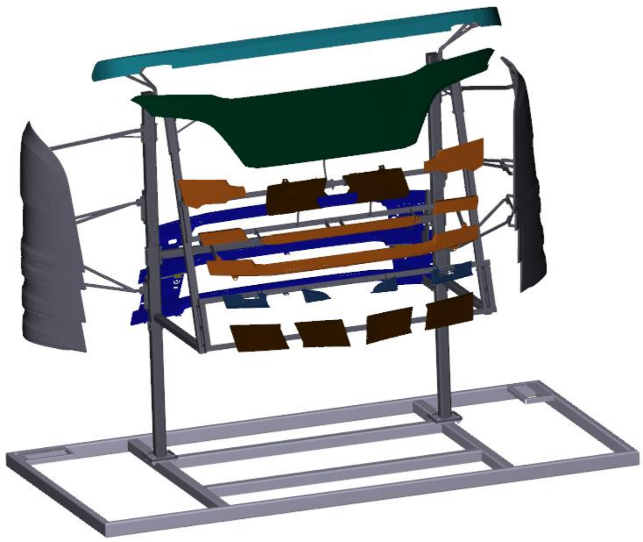


Figure 23 - Scania skid with objects

This skid includes the three objects studied in the lab oven at RISE IVF within the project. The general problem is to position all objects on the skid to optimize the curing properties. Towards this goal we have studied the optimal position of three objects inside an oven. To make the problem even more interesting we have formulated it as a multicriteria optimization problem, where we maximize the curing properties of the objects while simultaneously minimize the energy consumption in the oven. The multicriteria optimization problem was solved using the sandwiching method. Before tackling the optimal positioning of automotive parts, a simpler problem was studied; in order to develop and evaluate the simulation-optimization framework, the optimization strategy, and the properties of the coupled algorithms. To this end we chose to study geometric optimization of heat sink fins.

6.4.1 Optimization of heat sink design

A heat sink, heated from below, inside a square channel was studied. The number, the height, and the thickness of the fins was allowed to vary. The two competing objectives was to minimize the temperature on the heat sink and minimize the pressure drop in the channel. The latter condition, which corresponds to the energy used by a fan blowing on the heat sink, was used to represent the cost of the design. Varying the number of fins makes this a mixed integer problem, and the multicriteria problem was solved separately for each n. As a first step to limit the number of n studied the height and width was fixed and only the number of fins was altered.

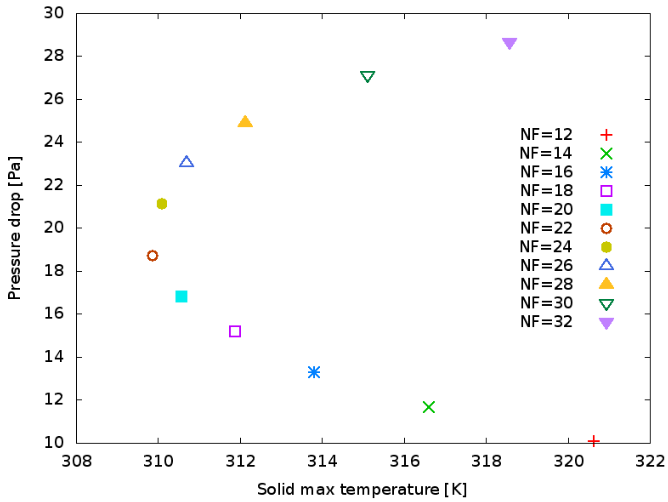


Figure 24 - Heat Sink Fin number optimization

Following this study, the number of fins was restricted to vary between 18 and 24. The resulting multicriteria problems were solved. The results for 18, 20, 22, and 24 fins are shown in the Figure below, where the approximation to the Pareto front is shown. As seen in the Figure, most of the pareto optimal designs for this setup have 18 fins.

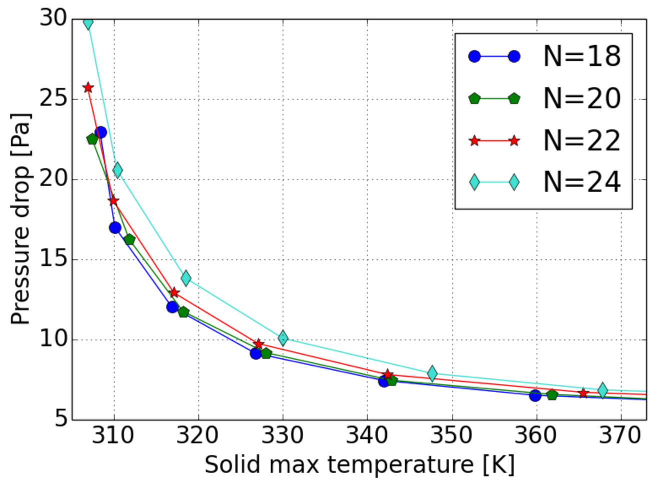


Figure 25 - Pareto front approximation for the heat sink design problem

In conclusion, in this initial study a framework for automatic simulation-based geometry optimization has been proposed. It combines a conjugate heat transfer solver, a CAD engine and an adapted Sandwiching algorithm. The coupled framework is automatic in the sense that geometry generation, simulation set-up, volume meshing, execution of simulation, and post-processing are performed without user intervention. The design optimization of the geometry of a plate fin heat-sink has successfully been performed and demonstrates how the framework can be applied.

6.4.2 Optimal positioning of automotive parts inside a convective oven

To illustrate how the developed methodology and algorithm can be used for oven curing applications a case with three objects inside a stationary convective oven has been studied. For this case, the two objective functions were: to maximize the curing time for each object and to minimize the inlet temperature. The oven has been constructed to mimic the design of a section of a real oven. The oven and the temperature distribution for one example is shown below.

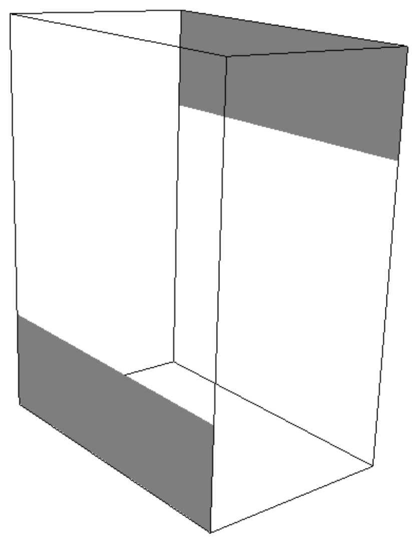


Figure 26 - Setup of the oven with inlet on top and outlet at the bottom

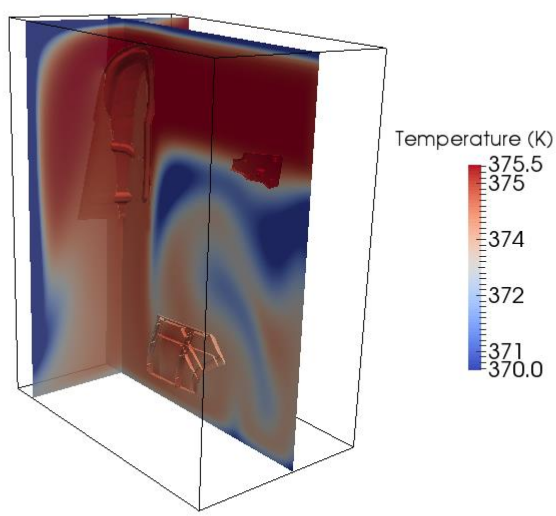


Figure 27 - Temperature inside the oven for one Pareto point together with the objects

To solve for the optimal positioning of parts inside the oven the optimization procedure had to be adapted, and a new ε-constraint version was developed and implemented. The optimization method is illustrated in the following Figure.

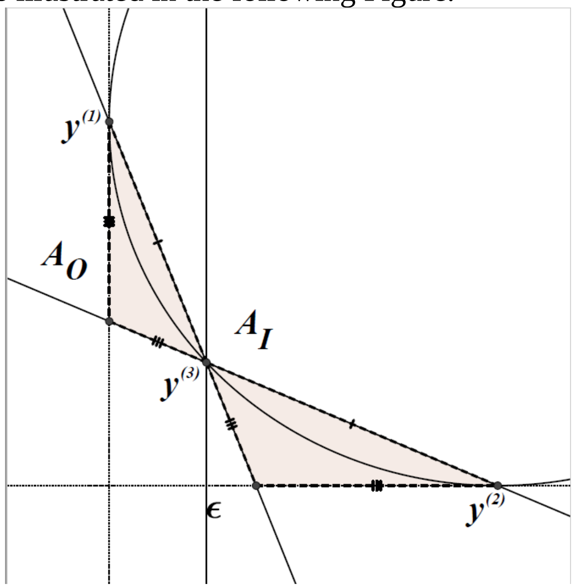


Figure 28 - Illustration of the epsilon-constraint sandwiching method. The previous sandwich is bisected, and the next point is found on the vertical line at epsilon.

For the optimization one part at the time was entered into the oven, first the cab corner, then the small thermoplastic part and finally the larger thermoplastic part. Each time a new object is added to the oven the domain is first searched for feasible positions with a pre-processing step, and then the actual optimization algorithm is run. Note that when a new object is added to the oven all objects currently inside may move. The resulting positions of the objects in a centre plane in the oven is shown for five Pareto point below. The actual Pareto front is shown in the second Figure below.

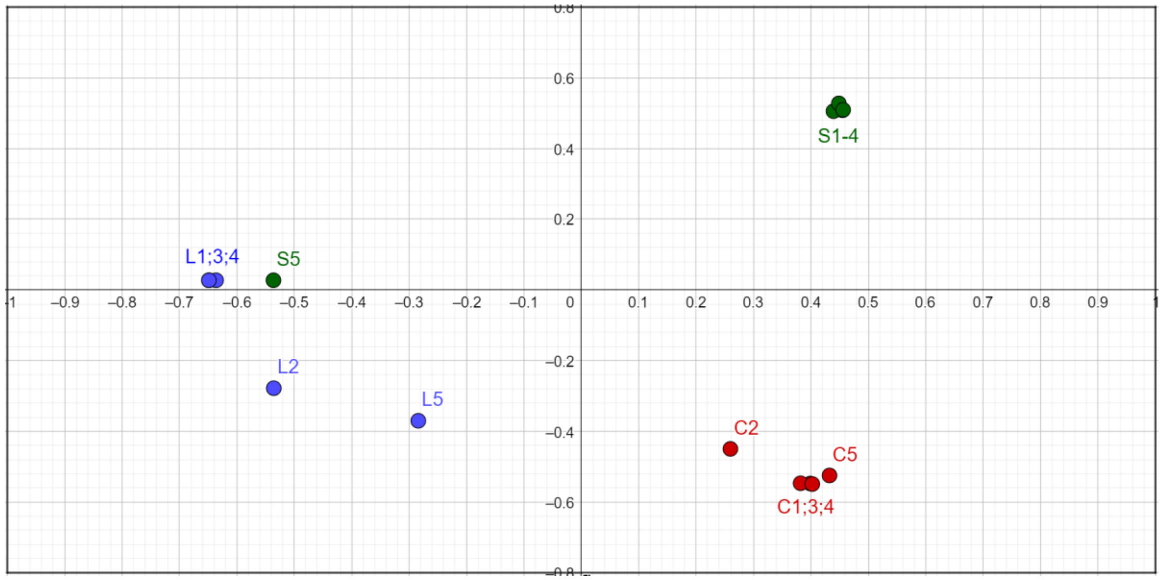


Figure 29 - Pareto optimal positions for the three Scania objects. Label C for cab corner, S for small thermoplastic part, and L for large thermoplastic part.

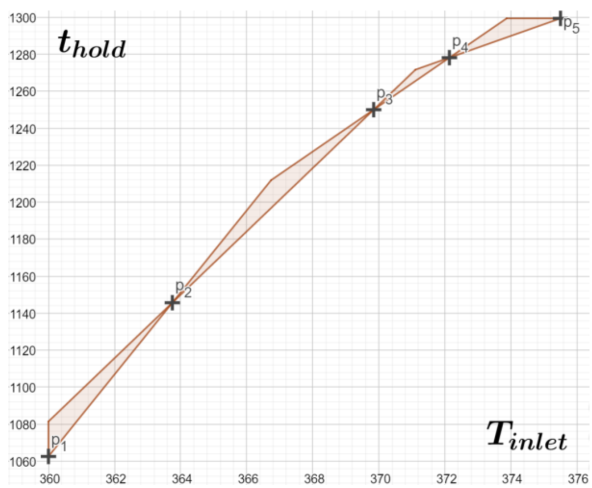


Figure 30 - The Pareto front for the optimal positioning of Scania objects

In this study we have successfully developed a simulation-optimization framework for optimal positioning of objects inside a convective oven. Its efficiency and applicability for curing applications within the automotive industry is shown in the results above.

6.5 Delivery to FFI goals

The project has contributed to FFI's overall objectives in several ways including:

- Further strengthened Sweden's competitiveness as advanced user and developer of digital tools in the border line of product and production.

- Further strengthened the world-leading research team in simulation of paint and surface treatment processes that contributes to a vehicle industry in Sweden that continues to be globally competitive.
- Increased the product portfolio of the start-up companies Industrial Path Solutions Sweden AB and IPS IBOFlow AB that focus on commercial product development, support, marketing and sales of the IPS software. IPS is today used by more than 100 automotive companies world-wide.
- Increased the collaboration between industry and research institutes.
- Contributed to further development of the Paint Centre at RISE IVF. The centre makes it possible for the industry, to evaluate the painting and curing processes without losing availability in their own production line.
- Supporting automotive supplier companies, and other manufacturing companies, with easy-to-use software for optimizing their oven curing processes.
- Making the institutes attractive partners in international and EU projects.
- Promoting other projects at FCC that require simulation of air flows and heat transfer with improved methods, algorithms and software to the benefit of e.g. the Swedish paper and packaging, and electronics industries.

Furthermore, the project contributed to various aspects of the sub-program Sustainable Production's objectives:

- The simulation software reduces the need for early prototypes which has a large impact on the overall **lead time** for new models since ultimately entire test series can be removed.
- The **environmental impact** can be reduced since significantly less physical testing is needed to tune the oven curing processes.
- The simulation software can be used to improve the product **quality** by a more uniform temperature distribution on the object during the process, which gives a better curing and finish of paint, sealant and other materials. A better control of heating and cooling zones also reduces thermal deformation and stresses. Performing simulations early in the design phase before any prototypes are available makes it possible to introduce design changes and unforeseen costs later in the product life-cycle can be avoided.
- The math-based simulation approach is a key to increase the **flexibility** to meet the challenge of increased complexity in the paint shops due to an increased number of product and material variants. Furthermore, the simulations also facilitate a shift of production of a certain model to a different plant, and to optimize the line speed, since the curing conditions can be verified in advance.
- The project has contributed to the target on **life cycle efficiency** by investigating guide lines for how the new lightweight and multi-material combinations are affected by the ovens e.g. regarding thermal stresses and deformation. The project results will be used in the recently started FFI project VIVFAP (Virtual Verification of Hemming Processes, Dnr 2019-05848).

The main goal of the project was to develop methods, techniques and software, and supporting measurement methodology, for simulation of paint curing in IR and convective ovens. Already at the kick-off it was decided to focus on convective ovens, which are the ones mainly used in automotive industry, and for such ovens a software capable of fast and accurate simulation is the main outcome of the project. To include also IR ovens is actually only a small extension that will be performed after the project. The software has been successfully verified on four different industrial case studies, and a multi-objective framework for placing of automotive parts on a skid has been developed. Comparison with available commercial tools for oven simulation indicates that the developed software tool is state-of-the-art when it comes to computational performance, input requirements and user-friendliness.

The main discrepancy from the goals defined in the project proposal is that the models for evaporation of water and solvent in the paint layer turned out to be a bigger challenge than expected. Measurements on different paint types were performed at RISE IVF, but they could not provide accurate enough input to a mathematical model. Here, more effort is clearly needed. However, it is important to stress that the temperatures on the object's surface give enough information if the paint layer will be sufficiently cured. The lack of the detailed paint curing models is therefore not considered to be a big limitation at the moment. It was also intended to include simulation of the thermal deformation and stresses in the software tool. Here, an intermediate step was taken to develop an export functionality, such that those analyses can be done in other tools based on input from IPS Oven Simulation. The longer term goal is to include these analyses on the IPS platform as well. Guidelines and methodology for oven curing of lightweight and multi-materials have been proposed. They constitute valuable input for future research and development projects.

7. Dissemination and publications

7.1 Dissemination

This project has resulted in an increased interest to simulate surface treatment processes to be able to reduce the time required for introduction of new products, reduce the cycle-time, reduce the environmental impact and increase quality. Several training sessions were arranged during the project and in total around 15 engineers have already been educated in the oven simulation tool. All three OEMs are already using other IPS Virtual Paint modules and bilateral activities are currently ongoing with them to deploy also the oven simulation tool. The results have also attracted considerable international interest and an agreement is in place with the German company fleXstructures GmbH and GLB in China to become resellers of the future commercial software version.

The project results and demonstrator have continuously been disseminated during company visits, seminars and educations, including e.g.:

- Project presentation, Trade magazine Ytforum, 2017
- Project presentation at DigiDemoDay at RISE IVF, March 2018
- Project presentation SPF workshop for coating industry, March 2018
- Project presentation at company visits at Airbus, BMW and Audi, 2018
- Project presentation at The Swedish Manufacturing R&D Clusters, Katrineholm May 2018
- Company visit at AB Volvo, Umeå, January 2019
- Booth and presentation at the Scandinavian coating fair, March 2019
- Software education for project partners, March 2019
- Project presentation at The Swedish Manufacturing R&D Clusters, Katrineholm May 2019
- Project presentation for IKEA, October 2019
- Project presentation at SPF Annual meeting, November 2019
- Short project presentation for German Ambassador visiting FCC, December 2019
- Software demonstration for CEVT, December 2019
- Software education for project partners, December 2019
- Software demonstration for GLB China, April 2020

The developed models, methods and algorithms are not only useful for oven simulation but the project results have already contributed to other conjugated heat transfer applications at FCC including electronics cooling and heating of food. In addition, the project results will be an important enabler in other R&D projects. In the recently started VIVFAP project (Dnr 2019-05848), the oven simulations will e.g. be utilized to predict the effect that the curing has on adhesives used for hemming.

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Modeling and simulation is a key technology to increase the understanding and improve the oven curing processes
Be passed on to other advanced technological development projects	X	The project generates key input to the recently started VIVFAP (Virtual verification of the hemming process) project (Dnr 2019-05848) since the oven curing has a significant impact on adhesive joining
Be passed on to product development projects	X	Most likely in the future since valuable input for investigation of lightweight materials and adhesive joining processes has been provided
Introduced on the market	X	The company IPS AB that focus on marketing, sales and support of the math-based software developed by FCC will launch the oven simulation software on the market during 2020
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

- D. Nowak, T. Johnson, A. Mark, L. Erhardsson, D. Ståhlberg, C. Ireholm, F. Pezzotti, F. Edelvik, K.-H. Küfer, “Multiobjective Optimization of an Oven with a Novel ε-constraint Based Sandwiching Method”, submitted to ASME Journal of Heat Transfer, June 2020.
- M. Vasudevan, “Numerical modelling of paint curing in convective ovens”, Master thesis, Chalmers University of Technology, June 2018, supervisors: Andreas Mark, Tomas Johnson and Tommy Andersson.
- T. Andersson, D. Nowak, T. Johnson, A. Mark, F. Edelvik, K.-H. Küfer, “Multiobjective Optimization of a Heat-Sink Design Using the Sandwiching Algorithm and an Immersed Boundary Conjugate Heat Transfer Solver”, ASME Journal of Heat Transfer, 140(10), 102002, May, 2018.
- F. Svelander, G. Kettil, T. Johnson, A. Mark, A. Logg, F. Edelvik, “Robust intersection of structured hexahedral meshes and degenerate triangle meshes with volume fraction applications”, Numerical Algorithms, 77(4):1029–1068, April 2018.
- F. Edelvik, A. Mark, N. Karlsson, T. Johnson, J. S. Carlson, “Math-Based Algorithms and Software for Virtual Product Realization Implemented in Automotive Paint Shops”, In “Math for the Digital Factory”, L. Ghezzi, D. Hömberg, Ch. Landry (eds.), Springer Verlag, Berlin, pp. 231-251, July 2017.
- J. Skogsmo, F. Wandebäck, O. Albinsson, F. Pezzotti, C. Ireholm, “Guidelines - Oven curing of lightweight multimaterials”, Project report 26162, RISE IVF, 2020.
- C. Ireholm, J.Skogsmo, ”Measurement methods – WP3 Simulation of oven curing”, Project report 26162, RISE IVF, 2018.
- O.Albinsson, , L-O. Ingemarsson, J. Skogsmo, F. Wandebäck, “Temperature and Geometry Measurements”, RISE IVF, June 2020.

8. Conclusions and future research

Overall this was a very challenging project with the ambitious goal to develop the leading software tool on the market for oven simulation. Several different modelling approaches were proposed, implemented and evaluated. The chosen approach provides a perfect compromise between simulation accuracy, powerful computational performance, and user-friendliness. The project results are ready for industrial implementation and have been commercialized as a new module in the software IPS Virtual Paint, which is used by Volvo Cars, AB Volvo, Scania, CEVT, Plastic Omnium, Hyundai and Chang‘an among others. The spin-off company IPS IBOFlow AB will handle the marketing, sales and support, and utilize its global network of resellers.

In the surface treatment cluster an application for simulation of the electrocoating process is under preparation, and planned for submission during 2020. This extension of the IPS

Virtual Paint software completes the aim that all key processes in an automotive paint shop can be simulated in the same environment - “The Virtual Paint Factory”.

However, more research is still needed. The longer term vision with the research on the virtual paint shop is to radically rationalize the surface treatment in Swedish industry by developing simulation tools that make it possible to completely automate the product preparation process in the paint factory. With a geometry description and available brushes as input, optimal robot paths and process conditions that guarantee a certain coverage and visual results such as gloss and color match, should be automatically calculated. This is obviously an extremely complex problem but the research group has a unique platform to take on this challenge. If successful it would dramatically improve the productivity and reduce the environmental impact during product preparation as well as in production. In the Fraunhofer SelfPaint project that ended during 2019 important steps were taken, but further VINNOVA projects will be needed to realize the vision.

9. Participating parties and contact persons

This has been a collaboration project with the industrial partners Scania CV, AB Volvo, Volvo Car Corporation, ElectroHeat AB and Industrial Path Solutions Sweden AB, and the research partners Fraunhofer-Chalmers Research Center (FCC) and RISE IVF. The project leader was Fredrik Edelvik, Fraunhofer-Chalmers Centre.

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