Final report

1. Project details

Project title	Easy Energy Efficiency made Industry Available via Thermal Topology Optimisation
File no.	64020-1026
Name of the funding scheme	Indkaldelse af ansøgninger om støtte fra det Energiteknologiske Udviklings- og Demonstrationsprogram – EUDP 2020-I
Project managing company / institution	Teknologisk Institut
CVR number (central business register)	DK 5697 6116
Project partners	DTU Mechanical Engineering Danfoss A/S Per Aarsleff A/S OQTON Denmark ApS Asetek Danmark A/S GRAM Equipment A/S Haas-Meincke A/S
Submission date	22 March 2024

2. Summary

Project summary:

The purpose of the project

The project tackled energy inefficiency in product design for companies. It developed and demonstrated thermal topology optimization (TTO), maximizing performance in industrial settings. The innovation lay in integrating TTO for energy efficiency in real industrial settings, bridging academia and practical implementation for sustainable advancements.

Results, conclusions and perspective

The project yielded significant outcomes both within research and for the individual case-partners. Among these can be mentioned:

- Improved energy exploitations in various industrial applications.

- Development and implementation of thermal topology optimizations.
- Commercialization of TTO in software for engineers worldwide.
- Collaboration with industrial partners for case optimization.

Future utilization on TTO involves the continued development of the methods and preferable further integration into commercial software. For each of the case partners the coming years will include work on implementing the developed design into their products and products owned by their customers.

The expected effects include increased energy efficiency of the demonstrator cases and thereby reduced environmental impact, leading to enhanced product performance and cost savings for either the case companies or their customers. The potential widespread adoption of energy-optimized designs is anticipated to result in pushing the industry towards making energy efficiency a governing factor as production price is today.

Projektresumé:

Formålet med projektet

Projektet omhandlede energieffektivitet i produktudvikling. Det udviklede og demonstrerede termisk topologioptimering (TTO), der maksimerede ydeevnen af reelle industricases. Innovationen lå i at integrere TTO til energieffektivitet i virkelige industrielle miljøer, og på den måde bringe viden fra akademia i spil til praktisk implementering.

Resultater, konklusioner og perspektiv

Projektet resulterede i betydelige resultater både ved at drive forskningen i TTO fremad og for de enkelte case-partnere. Blandt disse kan nævnes:

- Forbedret energiudnyttelse i de forskellige industrielle cases.
- Udvikling og implementering af termiske topologioptimeringer.
- Kommercialisering af TTO i software til ingeniører globalt.
- Samarbejde med industripartnere om case-optimering.

Fremtiden for TTO indebærer fortsat udvikling af metoderne og forhåbentligt yderligere integration i kommerciel software. I de kommende år vil hver case-partner arbejde på at implementere de udviklede design i deres egne produkter og i produkter ejet af deres kunder.

De forventede effekter inkluderer øget energieffektivitet i demonstrator-cases og dermed reduceret miljøpåvirkning, hvilket fører til forbedret produktpræstation og reduktion af omkostninger for enten case-virksomhederne eller deres kunder. Den potentielle bredere udbredelse af energioptimerede design forventes at påvirke industrien til at gøre energieffektivitet til en styrende faktor, som produktionsprisen er i dag.

3. Project objectives

The overall objectives of the project were in the application described as:

"*The EASY-E's purpose is to enable EASY, Efficient, Effective and Environmentally friendly Energy optimisation for Danish and international companies. All too many products continue to be designed and manufactured for the lowest price but in a less than an optimal way concerning energy (use, absorption, reuse, and cooling). The project brings the two aspects in perspective by introducing a fast-thermal optimization development and considering the manufacturing restriction, these enable quick business implementation and fast environmental benefits. EASY-E aims at unlocking the industrial potential of thermal topology optimisation (TTO) – computer-generated designs optimised to maximise the given set of features according to given constraints – based on existing and new industrial products that can be improved to the benefit of environment and business.*

Ultimately, EASY-E targets an integrated commercial AI service (FactoryOS) accessible to all via cloud computing, and with both programming and computing power to help companies improve their products for more efficient and better performance and reduced environmental footprint. This is what we call "Easy Energy Efficiency made Industry Available via Thermal Topology Optimisation". These services will be sustainable at the end of the project and will be added to other services from one partner through their FactoryOS solutions".

Which can be summarised as an overall objective of bringing the research at universities within thermal topology optimisation into play in real industrial settings.

Thermal topology optimisation is a field still at a relatively low TRL at universities and the groups at DTU are world leading experts within this. The goal of EASY-E was to explore to which degree this technology is ready for a broader implementation and to ensure that Danish industry players would be in the forefront when it came to harvesting the benefits of this implementation.

The developed energy technologies were along two parallel tracks. Firstly, DTU and OQTON worked on maturing TTO for commercialisation and on implementing this commercialisation in OQTONs software. Secondly throughout the entire project period the five industrial case partners (Asetek, Danfoss, Aarsleff, Gram, and Bühler) provided cases that while functioning as test cases for development with TTO was treated and optimised by DTU, OQTON and DTI.

4. Project implementation

The project period has been influenced by unforeseen problems originating from the turbulence in the surrounding society in the beginning of the project, which delayed the acceleration in the casework, however all care partners caught up to this and on average more than two cases have been solved for all case partners.

The main technical risk associated with conducting the project was the maturity of the TTO technology and whether this was ready for commercialisation and throughout the project several limitations relating to this was found and overcome. Early on it was realised that TTO is not ready for commercialization when dealing with too high flow rates, and the selected cases had to be adjusted to accommodate this.

Approximately halfway through the project the software supplier OQTON was bought by the American company 3DSystem. This changed the situation for implementing the developed solutions into a commercially available software. 3DSystem markets their own software for component design and component optimisations (3DXpert) and the prospect of implementing project results in this would significantly increase the potential number of users reached. It was agreed with 3DSystems that OQTON would be allowed to incorporate project results in the form of a "guided user experience" making it easier for non-experts in TTO to benefit from the project learnings when designing their components in 3DXpert.

5. Project results

As explained above the project objectives was slightly adjusted with the transfer to a new software for implementing the projects results into. Considering that adjustment the project results meets the objectives in terms on working on software development. The target group of the 3DXpert software is engineers worldwide working with CAD, implicit modelling, and optimising part design for additive manufacturing.

Project results in relation to case development are summarised in Table 1 below. Overall, this can be summarised as that throughout the project 14 industry cases have been treated to obtain energy optimisation through thermal topology optimisations and subsequent design changes which is close to an average of three per case partner.

Furthermore, As the software focus was moved from the original scope of FactoryOS to 3DXpert OQTOn brought two cases into the project. Descriptions of these and results from these can be found in table 2.

Table 1: Summary of project results for industrial case partners.

Case owner	Case name	Case summary	Environmental impact
Asetek	CPU/GPU cold plate	CPUs and GPUs are getting more and more advanced for each new generation, which results in a much more complex heat map, and thus there is a need to factor-in and handle steep local power gradients in terms of cooling. The cold plate was redesigned by thermal topology optimisation at DTU during several iterations. The case resulted in simulation time on the LUMI supercomputer in Finland and 4 scientific publications (one already published and three in preparation). The case has furthermore been used to push the boundaries of TTO within: - Performance compared to CFD models. - Mesh density. - Producibility filters. Scientifically this case is, from DTU knowledge, the largest topology optimization model for conjugate heat transfer, up to date. It was found that only the optimized design using the fine mesh is able to outperform the reference design. This highlights the need of very fine details when optimizing compact geometries such as CPU heatsinks.	Comparison with baseline design: Maximum CPU temperature 2,5% higher and pressure drop 60% lower in optimized design Topology optimized coldplates can deliver a higher thermal performance, which means: - Less pumping power is required to deliver the same performance - Can work with higher liquid temperatures, meaning that energy re-use is higher (better quality) - Less or no need for air-condition/heat pump to lower the ambient temperature - Higher power density and thus less equipment for the same computational capability - Faster calculation per CPU/GPU = higher "calculation density" per node - Lower fan rpm = lower power consumption + lower noise - Lower chip temp. = lower internal resistance equalling lower power consumption - Less mass flow required for cooling = lower power consumption

Danfoss	Danfoss Case 1: Liquid Cooling Evaporator (Chiller) for Secondary Loop Battery Thermal Management System of Electrical Cars	The product application is thermal management of electric vehicles batteries using a secondary loop. So, the evaporating refrigerant will not be in direct contact with the battery pack, but it will cool down a brine flow by means of an evaporator. It was attempted to make a flow distribution manifold in the HEX inlet. Manifolds have been optimized for single-phase flow, but the distribution is primarily a two-phase flow issue causing issues for the model.	
Danfoss	Suction Gas-to-Liquid Heat Exchanger	The recent EU regulations are pushing hard toward the adoption of low carbon footprint solutions and high efficiency. This is especially true for building heating, where the focus is now on solutions working with natural refrigerants (low global warming potential and 0 ozone depletion potential). Together with component improvement initiatives, the industry is looking into system level improvement to reduce energy consumption. In this context the Suction-Gas-to-Liquid Heat Exchanger are gaining increasing interest in Propane Heat Pumps. The new case for the simulation was defined in terms of operating conditions, geometrical boundaries, and manufacturing limitations so as to make it representative of current industrial trend for this kind of devices. The partial simulation results provided by DYU have also been discussed to make sure the assumptions made are consistent and leading to a feasible commercial solution. A novel calculation procedure has been developed to enable a topology optimized geometry that could be manufactured by means of sheet metal forming. The concept of "Topografy" Optimization has been implemented in the commercial software “Comsol Multiphysics” by means of an ad-hoc developed set of equations and it is showing promising results in this preliminary stage of exploration. In the first iteration plates can freely deform normal to original plate and constraints on pressure drop is implemented. Later iteration included several different manufacturing constraints: - Forming angle constraints - Improved contact area density - Including area nearby the distribution ports and excluding lateral area for optimal brazing	Danfoss finds the optimizer working principle and the work done so far by the team at DTU to have high potential, and the software development, deserves further investigation. This will be done through further investments after the project closure.

		- Reduction of small gaps to prevent false brazing and/or copper clogging First productions tests have been made and the collaboration with the simulation team at DTU will be continued after the project end. The application to EU projects will enable further development of the concept	
Aarsleff	Gyroids structures in light trains	The Aarsleff parts within EASY-E relates to LED hardening of glue for pipe renovations. The high-power LEDs require cooling within a limited space to survive. In this first attempt at optimising the cooling power of the light trains the existing light train geometry was utilised and the internal cooling geometry was replaced with a gyroid structure with increased surface area. It was unfortunately found that the increase in pressure drop trough the light train was too substantial to continue this route.	
Aarsleff	More aerodynamic design of light trains	As the previous case showed that the pressure drop through the light train was the main factor influencing the performance of the light train. A combination of TTO and CFD was utilised to design a more aerodynamic design allowing for a lower pressure drop through the structure.	The optimised inner structure resulted in 20% flow increase using the same pumping power. This could either be used for increased cooling or be converted to keeping the same flow with a lower pumping power and thereby decreasing the electricity consumption.
Aarsleff	Thin walls	By implementing the learnings from the case above and new possibilities within thin-walled print Aarsleff hope to be able to bring an entire new even smaller light train to market	
Aarsleff	Ejector	To be able to further utilise the learning from the other Aarsleff case throughout the project, it was decided to add a fourth case to the project from Aarsleff. This fourth case relates to upscaling the developed light train to much higher ratios. To be able to effectively cool a larger structure a significantly increased airflow is needed. To avoid having to equally increase the pumping power (end thereby electricity consumption) a new approach is needed. The fourth case from Aarsleff investigate increasing the airflow employing an optimised ejector. A first iteration of this was designed and tested at Aarsleff facilities, based on this experience a second iteration was designed. Aarsleff will invest further into this development after the project closure.	No final results yet, but a substantial potential for expanding the deployment of Aarsleff technology for repairing instead of constructing new pipes.
Gram	Ice cream mould cup	Mould cups are used for casting ice creams in production. This case investigates the opportunities of improving heat	

		transfer of the mould cups to reduce overall energy consumption of ice cream production. New structures were designed, based on thermal topology optimisation at DTU, and produced at DTI. Improvement in cooling were observed, however the increased production price challenge the business case.	
Gram	Moulding Cup brine flow	The mould cups are during production inserted in brine for freezing the ice cream. The model simulates the process inside the brine system, to improve for energy efficiency. Simulations indicate potential for energy savings, which will be further explored outside the EASY project.	The potential of the brine flow has been found to be substantial enough that Gram is continuing the development outside of EASY-E.
Gram	Freezing tunnel	Reducing the energy consumption of a freezer tunnel for ice production. Full simulation model of the GRAM freezing tunnel has been developed, and simplification has enabled simulations to be carried out at reasonable timeframes. The model enables simulation tests of various design solutions to improve the flow within the tunnel and reduce the freezing time of ice. Significant energy improvements have been verified experimentally and the solutions are implemented in production.	Significant energy savings potentials are verified experimentally. They can be implemented on new tunnels and offered as a retrofittable option for Grams costumers.
Gram	Freezer	The case relates to a freezing process for ice cream at Gram. The system is very complex with 3 phases at microscopic level and was only added to the EASY-E project later in the process as it is at the limit of what the simulation software can handle. The model simulates the process inside the freezer, as a function of the mechanical design of the rotating mechanical system. Simulations shows potential energy savings, which will be further explored outside the EASY project.	The case was found to have substantial potential for energy saving, however, as it was added late in the project, it did not reach its full potential during the project and work are continued through investments from Gram.
Bühler	Jet optimisation	Today, the main heat transfer to baking e.g. cookies is by convective heat transfer using an array of circular jets. Investigating whether more optimal heat transfer (and consequently lower energy consumption) could be obtained was chosen as the first case from Bühler to be treated. It was found that the ratio between jet height and jet diameter was not optimal. This shows that there is a potential of increasing the convective heat transfer coefficient by changing the jet geometry. However, the uniformity of the heat flux shall still ensure an evenly distributed baking profile of all products in the oven.	Improvement of heat transfer by 6.7%

		It was shown that the heat flux distribution can be optimised however TO framework is not suitable for turbulent jets.	
Bühler	Heat exchanger in recovery unit	The Bühler baking lines has a high percentage of waste heat in the baking process itself. To minimise the environmental impact of this they are operated with heat recovery units. This case investigates optimising the effect of these units. Improvements was investigated for the heat transfer inside the tubes of an air-to-air heat exchanger through two different approaches, either by placing inserts or by changing the shape of the tube itself. Inserts generate swirl motions, allowing a better mixing and therefore a better overall heat transfer from the hot side to the cold side.	Results for the shape optimised pipe: Up to 109% heat transfer increase, however this was at the expense of a substantial increased pressure drop. The best solution has a simulated 28% increased heat transfer and even a 9% lower pressure drop.
Bühler	Distance between nozzles and baking plate	Industrial tunnel ovens for baking of e.g. biscuits are traditionally powered by natural gas and may consume in the order of 1 MW for 6-8000 hours pr year. The Bühler ovens transfer heat by blowing hot air through a distributed circular nozzle array onto the products, also known as jet impingement heat transfer. The relationship between the nozzle diameter and height is investigated in relation to baking performance.	Results show a significant increase in heat transfer from today's design. This opens a potential for substantial energy savings by lowering baking temperatures. The potential was validated by experiments and simulations. Furthermore, the findings of the project unlock new technologies to be applied to baking ovens, which in turn could result in energy savings beyond what was realized in this project, a possible revolution the baking industry.

Table 2: Overview of cases brought into the project by OQTON

Case owner	Case title	Summery
OQTON	Wafer table	Halfway through the project it was decided that the project would either go with pan A for software development or plan B. Plan A was described as the full solution where simulation based TTO was implemented into the available commercial software, whereas plan B was implementing a user-guided solutions based on the learnings from the EASY-E project. To evaluate which of these solutions was the most suitable the current state of TTO was benchmarked against other calculation methods based on a known case. This case was selected to be a wafer table for handling critical semiconductor equipment. The table should be sufficient cooled while also keeping the temperature deviations across the table below 0.12 K. The treatment of the case resulted in good results, though not fully meeting targets.
OQTON	Thin walls in 3DXpert	Thermal applications like heat sinks and heat exchangers are dependent on fine structures in the printing process. The 3DXpert software contains dedicated scan strategies for optimising this kind of structures which were among other things relevant for the Aarsleff cases.

		The project investigated different scan strategies for obtaining thinner walls in the printing process and found that one of the investigated strategies allowed for thinner walls and thereby holds a potential for further energy optimizations in thermal applications going forward. Based on the thin wall tests, an exemplary heat exchanger was designed in 3DXpert. The entire design chain, including parametric modelling, implicit (gyroid) generation, build preparation and support generation, as well as slicing and toolpath generation was carried out in 3DXpert. By allowing for thinner, reproducible walls in the gyroid section of the heat exchanger, this design can perform at higher efficiency compared to conventionally designed and sliced heat exchangers.

On the commercial side the integrated software solution is already being sold worldwide as an add-on module for the 3DXpert suite. All partners except one expect further investments in the developed solutions after project closure. This is expected to sum up to more than 7 mill Dkkr with in the five years after project closure. Simultaneously with this all partners are expecting a ramp up in revenue based on the results from EASY-E. After 5 years the combined consortium expects more than 200 mill Dkkr in revenue from the thermal solutions developed in EASY-E, and more than 40 new full-time employees created. Of the 200 mill Dkkr more than 130 mill Dkkr is expected to export out of Denmark, however, this number is more difficult to quantify as several partners have revenue streams based in non-Danish parts of the organisations.

The project results have been broadly disseminated to both a technical audience and a non-technical audience. For a full overview of dissemination activities see annex 1 (dissemination report).

6. Utilisation of project results

The main technical results relate to the developments in codes for TTO and the implementation of TTO inspired workflows into a commercial software. DTU has throughout the project pushed the boundaries of TTO in research settings and has among other things gained access to a super cluster computer, published the to date largest topology optimization model for conjugate heat transfer, and developed new codes for thermal "Topografy" Optimization This work will continue at DTU both by DTU alone and in a follow up project being sat up between DTU and EASY-E participants from Danfoss. Several research groups worldwide are working on TTO, however as DTU was among the universities establishing this method and is still world leaders in it they are assessed to have a good competitive position. OQTON has implemented the “user guides experience” into the 3DXpert software and this will going forward be a part of the software package that 3DSystems will market as one of their selling points. Resent years have seen several new softwares for parts optimisation entering the market. This is e.g. nTopology whose software was also utilised in EASY-E. nTopology is assessed to be a few years ahead of 3DXpert when it comes to finite modelling, however, as 3DXpert are offering a more full package integrating workflows of both CAD, finite modelling and slicing, it is assessed to have a good competitive position. Making integrating energy optimisations into component design easily accessible for engineers in their daily work.

Throughout the project DTI has seen very fast growth in interest in thermal solutions from outside the EASY-E consortium. The knowledge built through the project is consequently already being implemented in commercial activities at DTI where Danish companies get access to previously unseen solutions. As this is done on commercial terms most of the work is confidential, however, an example of what is done can be found here: https://www.teknologisk.dk/ydelser/3d-print-giver-bedre-udnyttelse-af-fjernvarme-i-heatflow-og-8217-s-fordamper/45463.

DTI has furthermore during the project period initiated an international project on advanced cooling for data centres (https://www.m-era.net/materipedia/2022/am2pc) and have recently applied for funding for advanced cooling for power electronic modules. The latter builds strongly on the learnings from EASY-E and spans the entire value chain from developing the optimised cooling structures to implementing it in an end-user product.

The results of all the casework will be utilised by the individual case owners as described in Table 1. Fourteen very different cases give fourteen very different sets of challenges to be overcome before commercialisation is reached, but to summarise a few repeated challenges can be mentioned.

Fine structures. Several of the cases depends on very fine structures to obtain their full potential. Aarsleff has already during the project period together with DTI demonstrated thinner structures then previously applied, and will going forward implement this in their cooling solutions. Asetek has moved significantly forward towards reaching a new cooling solutions based on a finer structure TTO solution and have initiated commercial collaborations to bring the solution the final way to the market.

Big constructions requiring retrofitting. Two case partners are working with very big industrial facilities and one of the main considerations required to bring the solutions to market for these structures, will be the prospects of retrofitting the solutions at already established facilities not owned by the case partner but by their costumers. The case partners will themselves continue this work after the project closure.

7. Project conclusion and perspective

The EASY-E project has over the last three and a half year helped bringing TTO forward for the benefit of both the research community and also the case partners who while functioning as test cases for this development has obtained results on own components. Two of the case partners are expected higher impact of the conducted development then when the entered the project, while four of the project partners expect the environmental impact of the project to continue or increase after project closure.

TTO is still a field experiencing several progresses, and among these DTU has concluded that resolution and computational power, multiphysical models and models for complex physics, and manufacturability is among the ones that should be solved before a final commercial breakthrough can be expected. In the meantime, the user guided experience of the EASY-E project aids in bringing new ways of thinking about design for energy and not just for price to market. The EASY-E project has thereby ensured EASY, efficient, effective, and environmentally friendly energy optimisation for Danish and international companies.

8. Appendices

- Annex 1. D3_9: Final report on dissemination.