Department of Mechanical Engineering - Annual Report 2016

Nielsen, Sten Tougaard; Carlberg, Lena Kristina; Thielsen, Anne-Marie Gøbel; Hansen, Hans Nørgaard; Lassen, Lisbeth; Hjartfeldt, Vivi Jessen

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Annual Report 2016

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DTU Mechanical Engineering had a remarkable 2016. Our colleagues applied for an impressive DKK 556 million for research projects, and secured more than DKK 93 million of externally funded project grants. Never before have our colleagues applied for so much project funding in one year. We all know that the competition for attracting research funding has increased over the last couple of years, so this excellent result gives me real confidence in the future.

Our research activities have resulted in 35 completed PhD projects and the start of 28 new PhD projects a year. Research at the department has resulted in an impressive 256 Web of Science journal publications and more than 200 contributions to international conferences. This level of activity is also a new record for the department, and we may expect the large number of publications to also increase the number of citations over the years.

Our BSc programmes in ‘Mechanical Engineering’ and ‘Design and Innovation’ have both experienced an increase in student enrolment in 2016. The admission requirements are high and the students admitted in these programmes have a high level of motivation and commitment. This challenges the programme, the courses, and the teachers, and we are only happy to meet these challenges. Our MSc programmes ‘Mechanical Engineering’ and ‘Materials and Manufacturing Engineering’ have also experienced an increase in student enrolment in 2016. In fact, the number has doubled since 2013 and is currently exceeding 160 students. We also increased our teaching activities during summer by offering summer courses in various fields in August.

In 2017, the department will focus on making even better applications to external funding bodies. In particular, we will relate to large societal challenges like sustainable energy and digitization. We will explore new opportunities in the fields of life science and bioengineering, utilizing the new bioengineering facilities internally at DTU. In the field of education, the department will work systematically on an e-learning initiative across the department.

2016 also saw a change in the department management. On 1 May, I took over as head of department after Professor Henrik Carlsen. I would like to thank all colleagues and collaboration partners for their warm
welcome, and also Henrik Carlsen for handing over a Mechanical Engineering department in great shape. I am sure we are ready to face the future together.

Hans Nørgaard Hansen
Head of Department

Advisory board

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Copenhagen

Jens Roedsted
Director
Market & Innovation
Force Technology
Brondby

Helle Olund Villumsen
Director
COO, Valcon Design
Valcon A/S
Horsholm
Key figures

Staff

Percentage distribution of staff groups at Mechanical Engineering
Total number of staff in 2016: 319 FTE (Full Time Equivalent)

Revenue - Internal and external in DKK million

PhD Theses

Publications
1. Christian Niordson appointed professor
On 1 April, Head of Section Christian Niordson was appointed professor at the Department of Mechanical Engineering. Christian Niordson graduated with an MSc from DTU in 1999, and earned a PhD three years later.

2. Hans Nørgaard Hansen new head of department
Hans Nørgaard Hansen, Professor and former head of the Section of Manufacturing Engineering, was appointed head of DTU Mechanical Engineering on 1 May.

3. Jesper H. Hattel new head of Section of Manufacturing Engineering
On 1 May, Professor Jesper H. Hattel took up his appointment as head of the Section of Manufacturing Engineering.

4. Mette Sanne Hansen new head of Maritime DTU
Senior Researcher Mette Sanne Hansen, who comes from DTU Management, took up her new position on 1 May.

5. Harry Bingham appointed professor
On 1 May, Harry Bingham was appointed professor at DTU Mechanical Engineering, where he has been an associate professor since 2005.

6. Metal expert Marcel A.J. Somers
Professor Marcel Somers has been made an ASM Fellow, an honour which has only been conferred once before on a scientist from Denmark.
7. **David Bue Pedersen wins Copenhagen Science Slam**
The 3D printing technology researcher won the competition for the best research communication at Denmark’s Political Festival on the island of Bornholm in June, among other things by talking about the manufacture of living organs.

8. **Two recipients of the H.C. Ørsted COFUND postdoc fellowships**
The recipients were Ali Davoudinejad from the Section of Manufacturing Engineering (for the project Micro 3D Additive Manufacturing and Integrated Process Chains (MICRO-AM)) and Emilio Martínez Pañeda from the Section of Solid Mechanics (for the project MICRO scale METAL plasticity: fundamentals and applications (MICROMETAL)).

9. **Student life and projects at Roskilde Festival**
Students from Design and Innovation and Mechanical Engineering made beer coolers, created loudspeakers from beer cans, carried out measurements of urine spray and much more at this summer’s biggest music festival.

10. **Successful student internships**
In October, 15 final-year high school students visited three of our study programmes: the BSc programmes Mechanical Engineering and Design and Innovation and the BEng programme Mechanical Engineering. Here, they had the opportunity to meet students and the head of studies, and to participate in the teaching.
11. Active involvement in symposium on product development
In early September, many delegates from the world of research and industry participated for four intensive days in the symposium, where they contributed their expert knowledge.

12. DTU hosts PRADS 2016
Ulrik Dam Nielsen and Jørgen Juncher Jensen headed the international symposium that discussed the design, construction, and operation of ships and offshore constructions.

13. 4M/IWMF2016 - combined conference and workshop
DTU Mechanical Engineering successfully held the 12th International Conference on Multi-Material Micro Manufacture and the 10th International Workshop on Microfactories as a combined event with many participants.

14. Students receive diplomas from Valcon Design
The 12 best students from Thomas Howard’s course ‘Robust design of products and mechanisms’ received the diplomas as an introduction certificate. Janus Juul Rasmussen, founder and CEO of Valcon Design, presented the diplomas.

15. DTU Innovator in Shell Eco-marathon
The prototype car DTU Innovator participated in the competition for the first time since 2006. The car finished ninth, and was entered in the competition as a proof of concept for petrol engines.
1. **PhD Thesis of the year**

Visweswara Chakravarthy Gudla received the prize for his PhD “Optically Designed Anodised Aluminium Surfaces: Microstructural and Electrochemical Aspects”. The PhD is part of the project ODAAS, Optically Designed Anodised Aluminium Surfaces.

2. **David Bue Pedersen receives Best Paper award**

At the newly established conference for 3D print, the 2nd International Conference on Progress in Additive Manufacturing, David Bue Pedersen received the award for his article ‘A Model of Parallel Kinematics for Machine Calibration’.

3. **SteamReg wins ELFORSK Prize**

The SteamReg project, a solution for energy recovery from drying air, was awarded the ELFORSK Prize 2016. The prize was presented by HRH Crown Prince Frederik at the Energy Summit of the Danish Energy Association on 9 June. From left: Thomas Rannow, CEO Cotes, Lars Ove Reinholdt, Head of Section at DTI, Ebbe Nørgaard, Director of Drying Mate, Rasmus Toftegaard, CTO Cotes and Postdoc Lorenzo Bellermo from DTU Mechanical Engineering.

4. **Art Stream wins Venture Cup**

The student start-up Art Stream from Thomas Howard’s ‘Innovation and Product Development’ course won in the ‘Mobile & Web, Active Stage’ category of the Venture Cup.

5. **Silver medal for instrument mechanic Frederik Bredal Merser**

The newly qualified instrument mechanic from the prototype workshop received the silver medal at Københavns Smedelaug for his apprenticeship test piece in 2015. The ceremony took place at Copenhagen City Hall in the presence of HM Queen Margrethe II.
6. Two Green Challenge winners
In the international competition for sustainable technology, two of the winners were from DTU Mechanical Engineering: A first prize for Claes Ronnenberg and Kirstine Maria Andersen for ‘Solar Bag’ in the Bachelor final project concept category (sponsor: HOFOR), and a third prize for Henrik Pieper for his ‘Prediction of Solar Heating Plant Performance’ in the Master thesis idea category.

7. Jan Høgsberg Lecturer of the Year
At DTU's Commemoration Day, Associate Professor Jan Becker Høgsberg was named Lecturer of the Year. Every year, the students at the University nominate different lecturers for the award, and this time as many as 62 names were submitted.

8. Jesper Graa Andreasen awarded EliteForsk travel grant
Together with two other PhD students from DTU, Jesper Graa Andreasen received the DKK 200,000 grant for research stays abroad. The travel grants were presented by HRH Crown Princess Mary and Esben Lunde Larsen, the Danish Minister for Higher Education and Science.

9. Relibond - Student start-up of the year
At DTU’s Commemoration Day 2016, the start-up Relibond received the Student start-up of the year prize. Relibond was established by Christian Michelsen and Martin Sander Nielsen from DTU Mechanical Engineering.
In deep water - project work for students

By Lisbeth Lassen

Already as first-year students on the courses offered by DTU Mechanical Engineering, students find themselves in deep water with project work and everything it involves in terms of interdisciplinarity, cooperation, and deadlines.

For engineers, it is absolutely crucial to have project work experience, and on many of the courses at DTU, they therefore learn about the CDIO principles: 'Conceive', 'Design', 'Implement', and 'Operate'. CDIO was originally developed at MIT, Massachusetts Institute of Technology, USA. On the BSc programmes Mechanical Engineering and Design and Innovation, and on the BEng programme Mechanical Engineering, even in their first year at DTU, students find themselves engaged in project work on one or more of the courses offered by DTU Mechanical Engineering.

“We throw the students in at the deep end in their first semester,” says Knud Erik Meyer, Head of Studies at Mechanical Engineering. “And they come up swimming beautifully.”

Build your own Stirling engine

“Using the heat from a tea-light, you must produce mechanical energy, and we will compete to see who comes up with the most efficient solution.” This was the instruction for an assignment which Associate Professor and Head of Studies Knud Erik Meyer and Associate Professor Anders Ivarsson asked their students on course 41000, Mechanical Engineering Practice, which is mandatory for first-year Mechanical Engineering students. Right at the beginning of the course, the students tried to build a Stirling engine out of a tin can and a balloon. In other words, they have already seen a solution that works. This type of engine was originally developed to replace the steam engine, but was superseded by the diesel engine. Today, it is used for special purposes, for example in submarines, because it is very quiet.

“The students find themselves in deep water, because really they ought to complete the courses on the programme first before launching themselves into engine design,” says Knud Erik Meyer. “However, we’re doing things the other way round: They’re thrown into it, and then they have to find out which disciplines they need, and then we give them simple tools during the process so they can find their feet.” Unlike many of the other subjects at DTU where the focus is on disciplines, the work on this course is project-oriented.
The students on the course are introduced to a wide spectrum of engineering skills. The report that the groups have to submit at the end teaches them how to write technical reports in the way that engineers like them. In addition, the groups learn about CAD drawing, 3D printing, technical measurements, and, not least, cooperating with the craftsmen in the workshop.

Professor Emeritus Henrik Carlsen, who gives presentations on the course as well as judging in the final competition, also mentions that a Stirling engine is a good starting point: “It involves basic disciplines and issues within solid and fluid mechanics, thermodynamics, materials and surface technology, tribology, design, and safety, and the Stirling engine therefore serves as an extremely good element in a course for mechanical engineers.”

What makes a good user experience, and how can we solve the problems that users experience?
On course 41010, User-oriented Design, the first-year Design and Innovation students are presented with a realistic issue that takes a specific problem for users as its starting point. Professor Per Boelskifte is head of studies at Design and Innovation, and teaches the new students on the course. This year, the task is called ‘Proposals for solutions which create a better user experience for citizens who are motorically challenged in Copenhagen’s urban space’.

On the course, the students learn basic techniques for identifying which problems users experience in various situations, and solutions then have to be prepared together with realistic users.
“The groups have to identify for themselves which problems users face when they use the city. This happens through ongoing dialogue with the users, and through fieldwork,” says Per Boelskifte about the project work. The solutions then have to be presented visually with posters, and with oral presentations.

In relation to analysing the problem and assessing the quality of the solution for users, the Design and Innovation students acquire special knowledge compared with other study programmes about using qualitative methods such as fieldwork, one-to-one interviews, and focus groups.
New race track - eco-car faces new challenges
In spring 2016, the DTU Roadrunners team had lots of participants, both third semester students and students who were further on in their studies. By autumn 2016, however, the DTU Roadrunners team had shrunk to a small, exclusive group with just six members, all students in their fifth semester who are now working to prepare the eco-car Dynamo 12.0 for the Shell Eco-marathon 2017.

“The eco-car assignment is not pre-defined. It is the students who together have to define the problem and the scope of the project - in other words develop ideas in the conceive phase.”

“As with a real CDIO project, we’re going the whole way with the team. The students have to be specialists within their own field - and generalists,” says laboratory engineer Claus Suldrup Nielsen, adding: “The eco-car assignment is not pre-defined. It is the students who together have to define the problem and the scope of the project - in other words develop ideas in the conceive phase.”

Every year, the students tackle new challenges, and this time round their biggest issue is probably the new race track in London, where the team had a really bad time of it at this year’s competition, which took place on 30 June – 3 July 2016. The track is also described as a ‘tricky track’, and not without reason, because the surface is very uneven. It proved too much for DTU Dynamo’s rear-wheel suspension, which broke under the strain, forcing the car out of the competition. However, when real-life circumstances cause a good and meticulously designed vehicle to drop out, it provides an obvious opportunity to tackle real engineering challenges.

So the new team is already busy trying to resolve the issues: “We want to redesign the rear-wheel suspension with springs that will better enable us to drive on the new race track,” says Claus Suldrup Nielsen. “Before London, we had competed in Rotterdam, where the track undulated slightly and was otherwise completely smooth asphalt. When we arrived in London, we discovered that plywood boards had been chosen for the parts of the track, and so there were some very distinctive shift from a flat surface one moment to a sloping surface the next, and this resulted in a lot of bumping for the car, which ended with the rear-wheel suspension disintegrating. The race track also posed problems for other cars, including Shell’s own entry, which was driven by Kimi Raikkonen.”

Facts about DTU Roadrunners
Results: DTU Innovator and DTU Dynamo results, see here: http://www.ecocar.mek.dtu.dk/english/achievements

The new DTU Roadrunner team is a small team of only six dedicated members facing the challenges of the London track in the summer 2017.
MICROMAN

By Lisbeth Lassen

Developing micro manufacturing competences for research and industry - a contribution to a stronger and more competitive manufacturing industry in Europe

The MICROMAN project - a training programme in micro manufacturing running from 1 October 2015 until 30 September 2019 - is coordinated by DTU Mechanical Engineering. The project includes research-based training for 13 early-stage researchers (ESR, the title early stage researcher is identical with the PhD study) in this specific field of manufacturing, and it is a collaboration between DTU and seven other European universities, IPU, and 13 European companies. Associate Professor Guido Tosello from DTU Mechanical Engineering is project coordinator.

Part of EU’s Horizon 2020 programme

MICROMAN is funded by the Horizon 2020 framework programme for research and innovation, making it part of a very extensive effort within the research and development area in the EU, with a total budget of EUR 74.8 billion in the period between 2014 and 2020, the largest total budget of its kind in European history. The overall target of EU’s Horizon 2020 is to create jobs and a sustainable economy in Europe. Funding MICROMAN is part of the strategy for supporting and developing the manufacturing industry.

Developing the manufacturing industry in Europe

The manufacturing industry has been an important source of export from Europe for many years, and also a source of many high-quality products. “But the amount of people employed in the manufacturing industry has been decreasing year after year,” says Project Coordinator Guido Tosello and continues: “And this is critical because if the work force within a specific field shrinks too much, companies cannot be among the best in developing new products. So the ambition is to change that trend.”

Guido Tosello says: “It’s not possible to obtain a better competitiveness in Europe through low wages or by simply lowering the price of products or elements. The only way for Europe is to compete by making products of a better quality and develop new products, manufactured with a decrease in material and energy consumption and this includes both business to consumer and business-to-business companies.”

“A large part of the European manufacturing industry is dedicated to building machines and tools. European machines and tools are sold in many countries in order to make products. There is a high
added value in machines, machine components, and tools,” the Project Leader relates. How to develop and engineer machine parts, tools and processes is one of the focus areas of MICROMAN, in close collaboration with European companies. This is also known as Public Private Participations (PPP), universities working with industries with the benefit of the companies delivering good business cases, and the universities delivering cutting-edge research results and access to specialized equipment.

“A strategic choice: developing the micro-manufacturing industry in Europe

The production of micro-components is an area of manufacturing engineering expertise where Europe currently has a leading role globally and can develop its competitiveness further. Micro components are often parts of larger and complex systems, and in order to access them it is necessary to take the bigger product apart, making reverse engineering very difficult, hence ensuring high barriers to entry for copycats and competitors. “Also, within MICROMAN we have access to the micro-manufacturing industry where the microproducts are applied,” Guido Tosello relates, “such as medical products, the tool industry, and the construction of machines - and basically anything between the final product and the machine. This is where the European manufacturing industry is very strong.” European machines are exported widely outside Europe, and are well known for high-quality standards. In the medical industry, products and devices are subject to strict legislations, and so it follows that the best solution is if the products are made in Europe for European as well as global costumers. Within the tool industry, it is necessary to have the design of the product in order to make a good tool. “So if you outsource the tool production, competitors may be able to understand how the main product is designed. For this reason, European companies must be able to manage the entire value chain, including design, tooling, and manufacturing, otherwise they may end up with the wrong outcome, that is, eventually losing highly valuable IP on their own product,” says Guido Tosello. So the MICROMAN project is strategically focused on the machine industry, the medical industry, and the tool industry.

“Also, within MICROMAN we have access to the micro-manufacturing industry where the microproducts are applied,”

Micro injection moulded medical component developed during the MICROMAN PhD Summer School organized by DTU Mechanical Engineering in June 2016.
By strengthening SME’s, new jobs are created

An important step in the set-up of the MICROMAN project was also finding companies active in these industries, and the chosen companies have mostly been SMEs - small and medium sized enterprises with up to 250 employees. “It’s not only about huge profits, it’s about innovation, growth, and creating new jobs,” the Project Coordinator states, “If an innovative company, particularly in the micro manufacturing sector, is doing well, they will hire more people, especially those people with this new knowledge from MICROMAN.”

After establishing the collaboration with the companies in the relevant industries, the next step was building the MICROMAN project around the ESR projects. Here, the first year of the project included hiring the 13 PhD students for MICROMAN. By September 2019, the 13 candidates will have a degree applicable within this area of the manufacturing industry, and all the companies taking part in MICROMAN can apply the new knowledge created in the project in their operations.

The MICROMAN project: An interdisciplinary training

The MICROMAN project is different from other research projects because the aim is not only about reaching a set of research objectives, but also about hiring new, young talents and put them through an interdisciplinary training programme while they are doing their research projects. During the project, all 13 PhD students will take part in eight workshops, each featuring a different topic within micro manufacturing, hosted by the universities in the MICROMAN consortium.

“All 13 MICROMAN ESRs will have the same qualifications by the end of the project, once they have completed the eight workshops. The PhD students also get a wide variety of skills across different technical disciplines, including soft skills such as scientific writing, project management, and effective communication.” Guido Tosello says. At the end of 2016, DTU Mechanical Engineering has organized a course in research project management for the PhD students, and so will the other partaking universities in MICROMAN at their institutions.

“So at the end of our project, our PhD students will have become highly-skilled researchers with project leadership skills - really ‘plug-and-play’, so when the companies in the European industry hire them, they get a person who is fully qualified and ready to make a significant difference in Research & Development, as well as in production,” Guido Tosello concludes.
FACTS about MICROMAN

The MICROMAN project began 1 October 2015

The project will finish 30 September 2019

The first ESR projects started 1 April and during spring 2016, the 13 PhD students or Early Stage Researchers, ESRs, were recruited.

The subjects of the ESRs projects are: Micro injection moulding, micro mechanical polishing, micro-electrical discharge machining, micro-electro-chemical machining, plasma-electrolytical polishing, micro grinding, micro forming, micro extrusion, integrated micro manufacturing metrology

Partners, see: http://www.microman.mek.dtu.dk/about-us/partners
World-class materials modelling: From atoms to structures

By Lisbeth Lassen

What properties do materials have, and how do they behave under different loads and circumstances? Provided that reliable models capable of predicting the above are available, it is also possible to produce materials with the required properties and dimensions.

DTU Mechanical Engineering has a strong tradition of professional collaboration enabling world-class research into materials modelling on every level - ranging from the atomic level to full-scale test beds. The collaboration offers multiple future opportunities, among other things by virtue of new research strategic collaborations on hard materials, where 3D modelling and 3D materials characterization are combined in connection with new facilities such as ESS, European Spallation Source, and MAX IV in Lund.

REWIND Center: Integrated materials modelling of wind turbine components

Three sections at the department - the Section of Manufacturing Engineering, the Section of Materials and Surface Engineering, and the Section of Solid Mechanics - already have a strong collaboration within materials modelling, among other things in connection with the REWIND Center, which was established in early 2011 and is funded by the former Danish Council for Strategic Research, currently Innovation Fund Denmark.

Research at REWIND has focused on identifying the link between the materials selection, process selection, and what happens to the metallic wind turbine components in the nacelle during the very heavy mechanical loads to which they are exposed when the wind turbine is in use. A wind turbine is exposed to loads imposed by wind and gravitation - and both in combination with the rotor’s revolutions and in interaction with the generator in the nacelle. Heavy loads can lead to early fracture of the individual components, or major breakdowns of the entire wind turbine.

The reason for the problems is often to be found in the way the components were originally designed and manufactured, as this significantly affects material behaviour during operation.

The reason for the problems is often to be found in the way the components were originally designed and manufactured, as this significantly affects material behaviour during operation. This could, for example, be the casting of the rotor hub and main shaft, and the forging of main bearings and gear parts. Casting and forging are processes which inherently cause unhomogeneous internal structures in the materials, and the resulting stress...
concentrations may impact components negatively during subsequent use. The research conducted at the centre is thus based on the entire chain - materials, processes, components, loads, and performance - to ensure the entire wind turbine’s increased long-term reliability and durability.

**Newly developed materials models provide insight into component performance and service life**

Since the REWIND Center was established in 2011, the different research projects have provided new insight into and better understanding of the interaction between materials, manufacturing processes, and subsequent loads. Specifically, this means, for example, that numerical models have been developed for simulation of the manufacturing processes as well as materials behaviour for the metal parts of the wind turbine’s hub and drivetrain which are subjected to heavy loads. Models have also been developed for the reliability and expected service life of the materials on the basis of mechanical tests and examinations of micro-mechanical defects. Finally, models have been developed to describe the relationship between different surface treatments and the microstructure of the material and their influence on the mechanical properties. Through numerical modelling and experimental observations, improved understanding has also been obtained of how a fatigue fracture occurs. This has been done by means of utilizing results from the models developed for the casting and forging processes, which have provided new input to the fatigue analysis thereby enabling more realistic prediction of the mechanical properties of the final components.
The many new models constitute tools which will help ensure a much better understanding of the performance and service life to be expected in relation to the various components of the wind turbine.

“The development of the models is based on a wish to describe the underlying multi-physical conditions, i.e. heat transfer and thermodynamical, solid, fluid, and material-mechanical issues, and this requires strong collaboration between the different sections here at the department,” says Jesper Hattel, Professor, leader of the REWiND centre and Head of Section of Manufacturing Engineering.

Modelling and new test facilities

To ensure that models for material behaviour are as accurate as possible under different conditions and loads, it is essential that they are adjusted according to the information gathered from experiments and test set-ups. DTU has established a unique facility for this purpose, i.e. the CASMaT, Villum Center for Advanced Structural and Material Testing, at DTU, where materials and components can be studied - ranging from full-scale level tests on, for example, wind turbine blades, to tests at micro-scale and nano-scale level in connection with electron microscopy.

“Here we can carry out full-scale tests of the components and subject them to heavy loads to get insight into fracture mechanisms and mechanical properties.”

“The Villum Center is an important element in the overall picture,” says Christian Niordson, Professor and Head of Section of Solid Mechanics. “Here we can carry out full-scale tests of the components and subject them to heavy loads to get insight into fracture mechanisms and mechanical properties.”

The researchers will also have access to the new facilities in Lund, ESS, and MAX IV, which will increase the possibilities of adapting the materials models developed at DTU based on validation of all scales from atomic to micro-level.

“The large international wave within materials research is integrated computational materials engineering, which means that you increase the use of materials modelling for designing materials from atomic level to macro-scale level to reduce the use of the trial and error methods, which was previously the standard procedure for development of new materials and processing into new products,” says Marcel Somers, Professor and Head of Section for Materials and Surface Engineering.
“This requires that we have reliable materials models, which is why they are in focus; experimental test facilities such as CASMaT, ESS, and MAX IV are indispensable for the validation and optimization of the numerical models.”

**Digitalization and modelling**

Once the materials models have been developed, they can be used to predict how a material will behave under certain manufacturing conditions, and later how the manufactured component behaves under different loads when it has been taken into use. This chain constitutes a key part of what is known as the component’s digital twin.

“The three sections MPP, MTU, and FAM look at the physical product and the digital representation of it using the numerical models,” says Jesper Hattel. “The manufacturing at system level with the description of product flow and the associated planning, on the other hand, is handled by P&K as well as DTU Management Engineering. We look at the production chain, i.e. from manufacturing where design, materials, and production methods are chosen, to the actual manufacturing and use of the product or the component.”

When talking about the digital twin, it is not only in relation to the component or product itself, but the entire context of which it forms part. Therefore, there is wide scope for materials modelling in connection with digitalization of the manufacturing industry. An overview of the manufacturing process in real time can be provided by incorporating new designs on a regular basis and testing designs and components virtually before they are manufactured and put into service, and the manufacturing itself can be adjusted as faults are detected.

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**Integrated Modelling of Materials, Manufacturing and In-Service Loads**

![Diagram of integrated modelling process](image)

The physical and digital twin part. Illustrated by Professor Jesper Hattel.

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**Facts about CASMaT**

CASMaT, Villum Center for Advanced Structural and Material Testing, is a partnership between DTU Mechanical Engineering, DTU Wind Energy, and DTU Civil Engineering. The establishment of the test centre was funded by a DKK 76 million donation from VILLUM FONDEN. The centre equipment partly consists of equipment donated by VILLUM FONDEN and partly of existing DTU equipment. DTU and the Danish Building and Property Agency provide funding for the two new buildings constructed at Lyngby and Rissø campuses.

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**Facts about REWIND**

The centre was founded in 2011 with a total budget of DKK 50 million and a DKK 30 million grant from the Danish Council for Strategic Research (now Innovation Fund Denmark) and will terminate in 2017. The centre has employed nine PhDs and eight postdocs. The 9 partners comprise five university units: DTU Mechanical Engineering, DTU Wind Energy, Aalborg University, Helmholtz-Zentrum für Materialien und Energie GmbH, and Michigan State University. Industrial partners: Dong Energy Power, Vattenfall Research & Development, VESTAS Wind Systems, Global Castings, MAGMA GmbH.
At the end of 2016, the Danish MADE initiative was expanded to include the MADE Digital collaboration, on which DTU Mechanical Engineering will have a large impact in connection with the digitalization of Danish manufacturing, which plays a key role in the Danish version of Industry 4.0.

In December 2016, DTU Mechanical Engineering received a DKK 14 million grant from Innovation Fund Denmark for the project ‘MADE Digital, driving growth and productivity in manufacturing by digitalization’. Among other things, the grant will finance three PhD positions, three postdoc positions, and one industrial PhD position. DTU Mechanical Engineering is already a project partner in the SPIR project MADE.

MADE and MADE Digital are initiatives that aim to maintain manufacturing companies and innovation competences in Denmark. The collaboration partners focus on ways of ensuring efficient manufacturing under Danish conditions such as high quality requirements, rapid product development and production, and proximity to the customer. As members of MADE, companies can participate in, for example, seminars and workshops. MADE Digital will ensure that in future, Danish companies have access to important knowledge on digitalization of manufacturing.

Digital quality assurance of manufacturing
Professor Jesper Hattel heads work package 4, Digital Manufacturing Processes, where researchers will be engaged in three important areas related to digitalization: integrated modelling of materials and processes, zero-defect manufacturing, and 3D printing. The researchers will also be involved in work package 3, Sensor Technologies and Manufacturing Data, together with DTU Compute. The objective is to study how data input from sensors can be used to digitize the physical production, thereby achieving higher quality.

“The idea is to make cross-disciplinary use of the registered data, so that it's possible to manage the processes proactively and adjust the ongoing manufacturing process.”

Together with DTU Compute, DTU Mechanical Engineering is involved in the work with sensor technologies, which focuses on quality assurance of the processes we are studying,” says Hans Nørgaard Hansen. “The idea is to make cross-disciplinary use of the registered data, so that it’s possible to manage the processes proactively and adjust the ongoing manufacturing process.” This will improve the quality of the products and significantly reduce the level of wasted time and resources.
The digital twin of manufacturing
Materials, process and design modelling means modelling across the entire value chain. Modelling will therefore ultimately be possible in relation to the most significant physical aspects of the product and production conditions. In connection with the ongoing digitalization of the production it is common to refer to this as the digital twin.

“The picture we want to draw is that of the entire production chain - from the product design, through the manufacturing processes to the manufacturing system, as well as the general factory layout and the entire basis of use of the product - we intend to make a digital representation of everything,” says Jesper Hattel.

“When we are able to do that, we will also be able to use the digital twin to control, predict, and optimize the properties and performance of the physical part. It will be particularly interesting to look at each element in the digital part and each element in the value chain, but it will also be exciting to see how things interact. The link between the digital and the physical world will largely be based on sensor technology.”

A problem: Many different designs and high quality requirements
Many companies are currently working with very comprehensive and complex designs (and product architectures) developed from scratch for specific solutions, where the individual parts of the products often cannot be interconnected. This means unnecessarily long time-to-market - from when the company concludes an agreement with a customer on solving a problem, until the customer actually receives a new design solution. Design is exactly what Head of Section and Professor Niels Henrik Mortensen from Engineering Design and Product Development at DTU Mechanical Engineering has been working with in connection with MADE. In MADE Digital, he heads work package 9, Digital Design, and is also involved in work package 3, Sensor Technologies and Manufacturing data.

“A major problem for manufacturing companies is that they often have a lot of design variations, and all products are subject to high quality requirements,” says Niels Henrik Mortensen. “Of course, it’s not possible to relax the quality requirements, but the combination of the many design variations and the large number of tests and certifications, which are a result of the huge amount of different...
designs, means that it’s becoming increasingly more difficult to react in due time in relation to the market and customer needs.”

An example of major design complexity could be the hydraulic cylinders used in offshore cranes or wind turbines, where they turn the wind turbine blades inwards or outwards to make best use of the wind. “If a company designs a new cylinder from scratch every time a new project is launched, it suddenly ends up with a large amount of very different types of design with different dimensions, material types, and ultimately new test set-ups and documentation,” says Niels Henrik Mortensen.

“The conclusion is that it becomes more and more time-consuming to develop new products; it becomes costly and complicated, and nothing can be reused.” Many companies will therefore spend a lot of time designing a new solution for the customer, and when the solution is finally ready for use, it will be expensive, and the customer and the market will probably have developed new needs. Consequently, the first part of MADE focuses on design simplification.

Modularization arranges the many designs

The large number of specially developed designs can be simplified using modularization, so that different sub-elements can be combined to form new solutions. Modularization is also a design structure that is suitable for digitalization due to the uniformity.

“Our contribution from K&P to MADE was modularization, which is also known as modular architecture,” explains Niels Henrik Mortensen. “It means that instead of establishing new design principles every time, we make certain decisions regarding interfaces, and we decide that from now on, some of the key interfaces will be in a certain way. This provides scope for consolidating things in new ways in the production without having to redesign the individual components. Modularization basically means that we get rid of dependencies - now we’re able to change the properties of the final product without changing all the components.”

“The interesting thing is what happens in the production, when the components become very similar, the first part of the production can be automated.”

Modularization means far less components within a product range. “The interesting thing is what happens in the production,” says Niels Henrik Mortensen. “When the components become very similar, the first part of the production can be automated. We get fewer test set-ups and fewer documentation requirements, the company is able to respond more rapidly towards the customer and the market, and maintenance and repair become much easier, and thereby also cheaper, throughout the product life cycle. We don’t have to reinvent the wheel every time.”

Ready for manufacturing automation: Digitalization of simplified designs

MADE Digital builds on these simplified designs and is to propose specific solutions to implementing them in the IT systems to enable automation of part of the manufacturing. The solutions will include, for example, developing new systems for configuration systems, better libraries for organization of CAD drawings, and PLM systems (product lifecycle management systems).

“A configuration system is a type of expert system that gives us a quick overview of which components can be combined with each other, and which cannot be combined with each other,” explains Niels Henrik Mortensen. “This allows the company in the tendering phase to swiftly design a specific solution and provide an estimate of the costs. New requirements regarding changes can also be handled quickly merely by creating a new configuration.” Overall, it means that the company can develop the solutions in close dialogue with the customer.

The new component designs must also be available to allow the company to find the right designs immediately, and therefore it is furthermore important to develop good libraries for the CAD drawings. This provides the possibility of making a quick search...
and retrieving design solutions, and for efficiently adjusting and changing designs.

PLM-systems are systems capable of creating complete documentation in connection with a product, ranging from drawings and calculations to simulations. "It's simply a tool for handling engineering issues across the fields of mechanics, electronics, and software. This way, the company becomes far better at handling changes due to the system's intelligence. It 'knows' that when a change is made in one place, control and software must be updated somewhere else, for example. Today, we have stand-alone systems for mechanics, software, and electronics - and it's expensive," concludes Niels Henrik Mortensen.

During the first six months of 2017, DTU Mechanical Engineering intends to recruit and employ new researchers.
Research within the K&P section aims at improving efficiency and quality of the way product development work is carried out within an industrial context. The main results are theory contribution and methods supporting synthesis activities within engineering design. Our research is focused on four areas: Conceptualization, Product/Service-Systems, robust design, and modular product architecture development.

New tendencies at the section

Our research is increasingly complimenting its qualitative approach with quantitative modelling. In the area of robust design metrics for the calculation of robustness have been developed and within product/service-systems (PSS), life cycle costing models have been developed. A project on digital definition of modular product line architectures is being carried out. The purpose is to apply configuration system for explicit definition of modular architectures, i.e. interfaces, rules, scalability principles and key dimensions. Within PSS, the methodology has been developed from a PSS design to a PSS procurement perspective, including the viewpoint of and co-creation roles of the PSS customer, particularly in a business-to-business setting. The Section’s research on life cycle-oriented design and product development has been in focus, where we have been invited into a number of project collaborations and research applications regarding readiness for circular economy transitions within industry. The Section sees great potential to provide research support in the areas of Resource Efficiency & Circular Economy - two highly prioritised research and development topics in both the European Commission and industrial companies operating in the EU. At a high level, the goal of Circular Economy is to create a new industrial economy that promotes greater resource productivity, aiming to reduce waste and avoid pollution by design, whilst Resource Efficiency contributes to Circular Economy by focusing on using limited resources in a sustainable manner to minimize cost and environmental impacts. The Section’s research on sustainable design and product/service-systems fits directly into the agenda of both Resource Efficiency & Circular Economy, by providing methodology,
DfX tools and quantitative case examples. For this reason, the Section is increasing the number of empirical cases in the areas of Resource Efficiency & Circular Economy and is furthermore focusing its research funding strategy in this direction.

**Expectations for the year ahead**

The section expects to start a number of Industrial PhDs and Industrial Postdocs with in our four core research areas. Furthermore, an internationally leading associate professor within the area of robust design and product service system is expected to be employed. In 2016, the Section hosted an international symposium on product development with 260 delegates. The event has positioned K&P at the heart of progress in the area of product development research and methodology and is to be run as an annual event, scheduled next for 7-10 November 2017. The section will have work package leadership in the project MADE Digital (Manufacturing Academy of DEnmark) within the area of digital design. The main focus will be on PLM (Product Life Cycle Management), i.e. digital definition of product assortments and product lines.

**Process architecture for correction protection of an offshore oil rig.**

**Modelling modular process architectures**

Modular process architectures have proven to be important means for reducing cost and preparing product lines for launching new product variants. In this research area a similar approach are being applied for processes. The thinking pattern is that, if a process can be decomposed into well-defined modules, it is possible to allocate properties such as cost, lead time, and other performance parameters. These process modules can then be configured to fit an actual task. This could for example be corrosion protection of off-shore installations. When modules are well defined, it is possible to systematically improve and innovate the process. Initial studies in construction industry and industrial manufacturing show that there is often a factor 2 difference in efficiency between the best and worst cases. This clearly indicates improvement possibilities. It is the goal to identify modularization principles for processes, i.e. how can interfaces be explicitly defined and processes thereby decoupled. Decoupling processes will normally reduce risk and increase the likelihood that processes can be carried in parallel. Another aspect is dependencies between the processes and the physical products. The example below explains elements of corrosion protection architecture. Process modules are establishing working light, setting up a scaffold, preparing welding, removing isolation, and ultimately the actual painting process. Contact: Professor Niels Henrik Mortensen

**Product Development Symposium (PDS)**

PDS focuses on the dissemination of leading research and best-practice approaches to industry. The symposium comprises four separate days based around the core research themes at K&P, namely: Conceptualization, Product Architectures, Robust Design, and Sustainable Product/Service-Systems, where expert delegates can get into in-depth with their topic area. PDS16 attracted 260 delegates over the four days, 65 per cent coming from industry, and the event was video achieved on the website: http://pd-symposium.org/. Delegates attended to share knowledge about product development, to see the world-leading speakers presenting at the event, and to learn about the new methods, tools, and research results from DTU. The event positions K&P at the heart of progress in the area of product development research and methodology and is to be run as an annual event, scheduled next for 7-10 November 2017. Contact: Associate Professor Thomas J. Howard, Professor Tim McAloone and Professor Niels Henrik Mortensen

The case for the final day’s work with robust design was Vavuud’s wind meter. Vavuud is a start up from DTU Mechanical Engineering.
Medical needles made from polymer

Every year, more than 16 billion steel medical needles are used for injecting or drawing liquids within medical treatment. Because of the risk of infections, all these needles must be treated like hazardous waste which must be disposed of in separate containers. Needles made from polymer are easier to inactivate and it becomes possible to dispose them as ordinary waste. Polymer needles also have a number of other advantages compared to metal needles: They are transparent, flexible, can be used within a magnetic scanner, and it is possible to make multi-channel needles enabling the simultaneous injection of liquids which first should be mixed when inside the body. DTU Mechanical Engineering has, in collaboration with DTU Fotonik, developed polymer needles. As a first application, the DTU spinout PolymerNeedle will produce polymer needles which can be used for diagnosis during cancer surgery. The polymer needles are used to inject a special contrast liquid directly into lymph nodes that have been surgically removed. The needle makes it possible to inject the contrast liquid while the lymph node is placed in a magnetic resonance (MR) scanner. Thanks to the contrast liquid, the physicians can identify the cancer cells within the lymph node and then decide on the extent of the operation. The method is faster and more precise than the techniques used today during the operation and will reduce hospitals costs and improve treatment.

Contact: Associate Professor Torben Anker Lenau

Product robustness - a manufacturing strategy

Given the ever-increasing quality requirements to increasingly complex products, systematic Robust Design efforts are vital for the success of development and production activities. The objective is high and consistent product performance in spite of the numerous variation sources in manufacturing, assembly, and application environment.

In order to enable future efficient realization of robust products, the DTU Robust Design Group follows a comprehensive approach. In close collaboration with industry partners, available Robust Design approaches are complemented with a strong focus on the potential of design-driven variation mitigation strategies in manufacturing and assembly processes. Based on an integrated consideration of assembly features from a design and manufacturing perspective, the research aims at a systematic absorption of individual part variation in intelligent assembly lines which are aligned with measurement plans and in-line adjustments in manufacturing processes.

The overall objective is to establish Robust Design not only as a key strategy in design, but also for production engineers, and thus to pave the way for a successful consideration of product and process robustness across the whole value chain.

Contact: Associate Professor Thomas J. Howard

Internet of trash bins

According to the Danish Environmental Protection Agency, it costs 2 euro to pick up a bottle from the ground. The cost for picking up a piece of gum is so high (1.5 euro) that some municipalities have stopped cleaning them off the streets. Beyond the economic challenges, inadequate waste management also represent a vast annoyance to the citizens - for example, one third of complaints submitted to the new Copenhagen app are about overfilled trash bins. This project explores the potential of an Internet-of-Things (IoT)-based solution to improve waste monitoring and collection. In collaboration with IBM, we developed an ultra-low power wireless sensor node that periodically transmits the amount of empty space in the bins to the cloud where we process the data and analyse the trends. We provide analytics to the managers to help to understand seasonal and intermittent use patterns and optimize the placement of the bins, and a mobile dashboard to the waste collectors in the field, so that they can respond to unexpected cases and optimize their routes. The system has been fully implemented and installed at outdoor trash bins around DTU; and evaluated in collaboration with Campus Service and DTU Smart Campus initiative - with very positive feedback. This project also provides the first public installment and evaluation of the Long Range Wide Area Network (LoRaWAN) technology in Denmark, which is one of the most anticipated wireless technologies that will boost the Internet-of-Things applications. All hardware and software will be released as open source in January 2017, at the International Conference on System Sciences.

Contact: Assistant Professor Ali Gürcan Özkil
The main research areas of the section are fluid mechanics, hydrodynamics, and the interaction with structures and sea beds. The methods applied include theoretical, numerical, and experimental modelling, and these methods are used for determining the behaviour of flows, including their impact on surrounding structures. Examples of technical applications include the scavenging process in two-stroke diesel engines, estimation of sediment transport, coastal morphology, and determination of wave loads on ships and offshore structures.

New tendencies at the section
The section directs its research towards three main industries. Fluid mechanics aims the research and study programmes towards the basis for development of new products and consulting of central areas of benefit for Danish society. In the coming years, coastal and offshore engineering will focus on the development of new utilities, including offshore wind farms and aquaculture that often are installed in nearshore regions/coastal areas. The maritime industry is changing its focus towards a supporting industry with a large focus on optimization of, for instance, sailing routes and marine operations. We have seen an enhanced cooperation on student projects with key external partners and institutes.

Expectations for the year ahead
After a high number of new PhD students in 2015, 2016 focused on the implementation of the projects. We expect the enhanced cooperation with external partners to continue, also within research. This could intensify the cooperation on research projects on a national and internationally scale, addressing both fundamental issues as well as grand challenges in society. Therefore, the section will pursue cooperation on larger scale projects - with both internal and external partners.
Flow in systems for catalytic cleaning of engine exhaust gases

In the near future, large marine engines will have to satisfy new requirements to limit pollutants in exhaust gases. A part of the solution is to use Selective Catalytic Reduction (SCR) of nitrogen oxides. Each marine engine is designed to a specific ship and the exhaust gas treatment is also specially designed, often with strong spatial restrictions. The flow distribution and mixing of a gaseous reductant in the catalytic chamber must be uniform. The system must therefore be designed using Computational Fluid Dynamics (CFD). Standard simulations have turned out to be unreliable, and the project will therefore conduct experiments in generic-scale models to produce data that can establish trust in CFD for design of future systems. The project uses laser-based measurements such as Particle Image Velocimetry (PIV). The project will also investigate different ideas for inserts that can promote uniform flow conditions. Hercules 2, 2015 - 2018, funded by EU. Mechanical Engineering participants: FVM: PhD student: Erik Gotfredsen, Associate Professor Knud Erik Meyer FAM: Postdoc Konstantinos Poulious, PhD Hannibal Toksvær Overgaard, Docent Peder Klit

Validation and commercialization of a seakeeping and added resistance tool for the Danish maritime industry

As a consequence of the recent global economic crisis, together with long-term pressures to reduce fossil fuel use, ships are generally sailing slower. Increasingly strict regulations for limiting greenhouse gases and other emissions by ships suggest that this trend will continue and require new ships to be designed and optimised for lower speeds. Reducing the installed engine power is, however, problematic, since it increases the risk of the ship becoming under-powered in heavy weather and hence unable to escape a lee shore under extreme conditions. In order to ensure adequate safety, designers and regulators need to be equipped to accurately assess the necessary reserve power required by the ship. The most uncertain effect in this assessment is the extra power required to maintain speed and course in large waves compared to that required in calm waters: the wave-added resistance. The goal of this project is to produce an open-source software tool which improves the state of the art for estimating this additional power requirement. This tool will be released to the public by the end of November, 2016. A two-year project funded by the Danish Maritime Fund 2014 - 2016 Mechanical Engineering participants: Professor Harry Bingham and Postdoc Mostafa Amini Afshar.

Force coefficients for fish cage structures

Aquaculture plays a significant role in the supplement of world food production, and has seen rapid growth in recent years. However, the rapid growth faces some limitations on the availability of suitable sites and the ecological carrying capacity of the existing sites. Offshore aquaculture is increasingly being promoted as necessary to overcome such limitations and meet global future seafood demand. However, the fish farms in offshore sites will be subject to more energetic waves and stronger currents, which requires a better understanding of hydrodynamic interaction with fish cages. Therefore, a key issue is to study the interaction of, for instance, flexible fish cages with waves and current; even under severe weather conditions. Porous media models have often been used in connection with typical coastal structures, such as porous breakwaters. Recently, this type of model was employed to simulate flow through and around fish cage structures, where the unknown porous resistance coefficients were adjusted by fitting the available experimental data. In this study, we proposed a new approach to calculate the porous resistance coefficients based on the transformation of the Morison type load model. The transformation follows the principle that the total forces acting on a net panel from the Morison type load model should be equal to the forces obtained from the porous media model. The model was implemented in a computational fluid dynamics model based on the open source CFD software OpenFOAM. Good agreement was achieved between the modelled results and the experimental data. Mechanical Engineering participants: PhD Student Hao Chen, Professor Erik Damgaard Christensen
Stability of large scale bedforms in the sea

In areas of the sea with sandy beds, there is an ongoing interaction between the sea bed and the motion of the sea water due to currents and waves. In deeper offshore locations, bedforms of very large scales can be observed, with lengths ranging from hundreds of metres to several kilometres. The ongoing dynamic behaviour of these large-scale bedforms makes their monitoring extremely important for offshore activities, as construction of offshore windfarms, pipelines, and vessel navigation are commonplace in such areas.

Providing a deeper understanding of the complicated interaction of such large-scale bed forms with complex (tide and wave) flow conditions typical of sea environments, including effects of offshore structures, is the motivation of the present project. Specifically, the project looks into three aspects: 1) What causes large-scale bedforms to emerge in the first place? 2) What processes are important for maintaining a fully developed ‘stable’ bedform? and 3) How will the introduction of structures - such as wind farms - affect the long-term dynamics and stability of existing bedforms?

As a demonstration, the figure illustrates a computed large-scale bed form (2) several kilometres in length, which has developed starting from a plane bed perturbed only with tiny random perturbations (1). Results demonstrate that the developed model is able to predict the evolution of essentially stable bedforms, similar in scale to those found in the field.

This project is financially supported by Energinet.dk, ForskEL project: Management of seabed and wind farm interaction, 2013-2017.

Mechanical Engineering participants: PhD Student Jonatan Margalit, Associate Professor David R. Fuhrman.

PRADS’2016

For the first time, PRADS was held in Denmark. PRADS - The International Symposium on PRActical Design of Ships and Other Floating Structures - brings together naval architects, engineers, educators, and industry leaders. PRADS is organized as a triennial symposium shifting between different parts of the world with Korea as host in 2013 and Japan as the next host in 2019. PRADS’2016 was chaired by Associate Professor Ulrik Dam Nielsen (DTU Mechanical Engineering/FVM) and it was the thirteenth version of PRADS since its kick-off in 1970. The venue of PRADS’2016 was Hotel Crowne Plaza in Ørestaden and the symposium was held from 4 to 8 September.

As with previous PRADS symposia, the broad aim was the interchange of ideas and discussions between naval architects and engineers from around the world to contribute to improvements in the design of ships and offshore structures in terms of safety, functionality, environment, and economy. PRADS 2016 was attended by about 250 persons who could follow 125 technical presentations running in 4 parallel tracks over four days. In addition, a number of high-profile keynotes were delivered, and PRADS’2016 was opened by Hans Nørgaard Hansen, Head of Department, DTU Mechanical Engineering. As a novelty, the proceedings of PRADS’2016 were given to participants on a tablet instead of 2 x 3 kg(!) printed books as had been the tradition with previous PRADS. The delegates seemed to be most happy with the novelty, and the tablets were used very actively to browse papers of corresponding presentations that were attended.

Contact: Associate Professor Ulrik Dam Nielsen.
The Section for Manufacturing Engineering performs theoretical, numerical, and experimental research in the field of manufacturing engineering. It covers a wide range of manufacturing processes and modelling approaches, metrology at all scales, micro/nano manufacturing, and additive manufacturing. The research is based on a multidisciplinary use of process technology, materials science, solid and fluid mechanics as well as thermodynamics and heat transfer in the analysis, modelling, and development of manufacturing processes.

The research objective is to promote ‘Precision Manufacturing’ to meet performance, durability, reliability, size, and cost requirements of modern products. Precision manufacturing is characterized by parts with tight tolerances and specific functional properties, often made in advanced materials with specific properties.

**New tendencies**

Focus is on integrated computational modelling of the interplay between geometrical design, materials selection, manufacturing processes, and subsequent mechanical properties of produced parts. This is addressed in a cross-departmental initiative between the sections MPP, MTU, and FAM.

**Expectations for the year ahead**

The section will further strengthen its activities within digitalization of manufacturing processes. This involves increased activities in additive manufacturing (a new European Training Network within precision 3D metal printing has recently been initialized) as well as integrated modelling of advanced manufacturing process chains in several new projects in e.g., composites manufacturing. The activities will be further strengthened by the initialization of the newly granted MADE-DIGITAL, which is a continuation of the MADE initiative with focus on digitalization of the production.
International Conference on Micro Manufacturing organized by the Section of Manufacturing Engineering at DTU Mechanical Engineering

13-15 September 2016, 100 experts in the field of micro manufacturing from Europe, America, and Asia gathered at the Technical University of Denmark to attend the 11th Multi-Material Micro Manufacturing (4M) International Conference.

The local host and organizer was the Section of Manufacturing Engineering at the Department of Mechanical Engineering.

This year’s joint 4M conference provided a global forum where the latest research on the processes, equipment, and systems for fabricating miniature parts with micro-nano-scale features were presented.

Researchers from more than 20 countries worldwide presented their research progress beyond state-of-the-art in the field of micro manufacturing: 65 oral presentations were given in 18 sessions held during the three days of the conference.

The industrial relevance of the conference was demonstrated by the support of seven corporate sponsors from Switzerland, Denmark, the UK, Japan, and the Netherlands. Among the sponsors were three world-leading Danish companies in the fields of micro acoustics and hearing aid technology: Oticon, Widex, and Ortofon.

The Conference Chairs were Dr. Guido Tosello and Prof. Hans Nørgaard Hansen from DTU Mechanical Engineering, Prof. Komel Ehmann from Northwestern University (USA), and Prof. Stefan Dimov from Birmingham University (UK).

The Organization Committee at the Technical University of Denmark, Department of Mechanical Engineering, was headed by Mrs. Pia Holst Nielsen, Secretary at the Section of Manufacturing Engineering, and Dr. Yang Zhang, Senior Researcher at the Section of Manufacturing Engineering.

Accurate Manufacture is an ambitious project in the field of advanced manufacture led by Professors Leonardo De Chiffre, Jesper Henri Hattel, and Hans Nørgaard Hansen. The research team is completed with René Sobiecki, Daniel Gonzalez Madruga, Mads Rostgaard Sonne, Giuseppe Dalla Costa, and Ali Mohammadi. Metrologic ApS and Lego Group are partners in the project as a metrology solutions provider and a final user, respectively.

The project concerns the development of an innovative type of measuring method conceived at DTU Mechanical Engineering and embodied in a new kind of measuring unit as an instrument to achieve high-accuracy, traceable, dimensional measurements in a production environment at manufacturing companies such as, LEGO, Novo Nordisk, Danfoss, Grundfos, etc.

The new method consists in simultaneously measuring all quantities affecting dimensions of a part over time (dynamically), using a series of sensors and references, and applying analytical or numerical modelling of the effects related to temperature and moisture to concurrently predict material properties and part dimensions at any point, time, and temperature.

Advanced thermo-hygrosopic-mechanical models hence play a decisive role in the calculation of the deformation of the part under production conditions to ensure accurate prediction of the part dimensions. The combination of precision sensors, data fusion from different kinds of sensors, and advanced modelling gives a new tool that can enhance production technologies and spread high precision measurement to several kinds of end user companies.
Example of the QR code produced by injection moulding developed in the QR Prod project.

The figure shows a surface with optical quality obtained by diamond machining on a material suitable for additive manufacturing.

**QR coding in high-speed production of plastic products and medical tablets (QRprod)**

The high speed of production yields high-efficiency and uniform products. However, it also leads to individual products being indistinguishable, which brings difficulties in complex assembly lines, in error detection, and consequently increases waste. Traceability at unit-level solves these issues and is a major advantage for manufacturers, distributors, and end-users, who can now verify, e.g., whether a product has been produced correctly. Traceability at unit-level brings the possibility to interact with a digital representation of the product - providing links to history, manuals, registration of ownership, recycling info, manufacturing process conditions, etc.

The QRprod project will create unit-level traceability by moulding unique QR codes in every piece being manufactured. A new encoding unit with special optical surface structures will be developed, able to create QR codes in plastic that smartphones can easily scan. The project will investigate the link between the moulding tool manufacture and the readability of the code. A prototype software for robust recognition will be developed as well. This knowledge will also be deployed for medicine tablets manufacturing with QR codes, to counteract piracy and in support of patient compliance in medical treatment. Advantages of counterfeit prevention and traceability are outsized.

The QRprod project is funded by Innovation Fund Denmark and runs from 01 March 2016 for 41 months. Innovation Fund Denmark has invested DKK 12.1 million out of a total budget of DKK 18.9 million. Five partners from academia and industry in Denmark participate (Inmold A/S, DTU Mechanical Engineering, LEGO System A/S, Gerresheimer A/S, Natoli Engineering Scandinavia ApS). DTU Mechanical Engineering participates in all the major work packages for tool manufacturing, surface characterization, and moulding processes. Contact: Guido Tosello and Yang Zhang

**Process chains for advanced tooling based on additive manufacturing**

Use of metal additive manufacturing in mould making opens the way to a new way of thinking the production process, exploiting design freedom and new material combinations. Current metal additive manufacturing process limitations do not allow generation of ultra-fine surfaces. Automated manufacturing of free form optical surfaces is indeed an open challenge. Currently available processes chains involve a heavy contribution of skilled manual labor and lack in repeatability and reproducibility. The project is carried out as part of the national initiative MADE (Manufacturing Academy of Denmark) and aims at integrating the potential of metal additive manufacturing in the mould production. The focus of the project is the development of alternative process chains enabling the robust and repeatable realization of optical surfaces on AM moulds. Thus, new printable materials and combinations of different AM techniques are used together with advanced machining processes, such as diamond machining, for production of ultra-low roughness surfaces. Electroforming and high-speed milling are also exploited in alternative process chains to reach the goal of producing mirror surfaces on AM moulds. Through comprehensive experimental work and testing the process chains are studied and validated. Modelling of surface generation process in ball end milling is also introduced in order to predict the performance of finishing operations. The project is carried out by PhD student Francesco G. Blondani under the supervision of Associate Professor Giuliano Bissacco and Professor Hans N. Hansen.
International benchmark test of cold forging lubricants

Severe cold forging operations of steel and aluminium alloys such as backward can extrusion requires very efficient lubrication to avoid pickup and cold welding of workpiece material to the punch during the forming operation. Conventional lubrication consists of a conversion layer of zinc phosphate lubricated with sodium soap, which is chemically bonded to the surface. Increased focus on environmental aspects, however, forces the cold forging industry to find new lubrication systems, which are generally less efficient. Testing of these in production causes expensive production stops, wherefore off-line test methods are sought to test the lubricant properties. Several such tests have been developed, and The International Cold Forging Group (ICFG) has initiated a benchmark study, where six different lubricant tests are applied by research groups in Germany, France, Denmark, Japan, and China. The same workpiece material, tool material, tool coating, and alternative lubricant films are evaluated for a direct comparison between the various tests.

At DTU Mechanics, we contribute with a custom-built tribology test on backward can extrusion of a rotating cylindrical billet with a conical punch ensuring very severe tribological conditions. In a previous industrial project for Raufoss in Norway, this test proved suitable to distinguish between good and bad lubricants for cold forging of aluminium parts.

Participants from DTU Mechanical Engineering: Peter Christiansen, Mohd Hafis Sulaiman, Esmeray Üstünyagiz, and Niels Bay

4D X-ray analysis combined with microstructural modelling: The key to high-performance ductile cast iron

Ductile cast iron is a natural composite material consisting of a steel matrix with graphite particles and carbides embedded in it. Today, it is widely used in key industrial sectors like off-shore, transport, and energy production, accounting for as much as 25 per cent of the total global casting production.

It is well known that the mechanical properties are controlled to a large extent by the size, morphology, and distribution of the graphitic phase. However, a comprehensive quantitative understanding of the process parameters controlling the formation of the graphite particles as well as their interaction with the surrounding matrix has not been fully achieved yet.

As this lack of knowledge is an obstacle to the manufacture of components with optimal in-service performance, new experimental and theoretical investigations are currently being carried out by the Process Modeling Group and Foundry Technology Group in collaboration with the University of Manchester (UK) and DTU Wind Energy. So far, the use of 4D (3D + time) X-ray analysis has enabled in-situ imaging of nucleation and growth of the graphite particles during solidification. Furthermore, the formation of local residual stresses associated with the thermal expansion mismatch between the graphite and the steel matrix has been documented and explained theoretically for the first time. These results constitute a key step towards establishing a quantitative link between process conditions, microstructure, and final properties of ductile cast iron.
The Section for Materials and Surface Engineering (MSE) performs research in the field of materials science and engineering involving theoretical, experimental, and numerical approaches. The research themes pursued in the section can be broadly described as:

- Materials design and surface engineering
- Microstructure evolution and phase transformations
- Materials performance and degradation

The research is multi-disciplinary and involves aspects of physics, mechanics, chemistry, and manufacturing technology.

New tendencies at the section
The establishment of the new large-scale facilities for materials characterization MAX IV and ESS in Lund (Sweden) provides a unique future potential for multi-scale materials characterization, ranging from atomic to macro-scale. The section has played a pivotal role in the formulation of a research environment for hard materials, where multi-scale materials characterization and multi-scale materials modelling are combined to establish a beacon. It is anticipated that this beacon is established in 2017.

Expectations for the year ahead
The section has submitted ambitious grants for new research initiatives and looks forward to starting research projects with (inter)national collaborators from academia and industry. Multi-scale materials modelling and integrated computational materials engineering (ICME) will be a focal point in relation to the abovementioned establishment of a beacon environment. A first step will be intensifying collaboration between complementary expertise in materials modelling already present in the department.
High-heat flux materials for future fusion reactors

Producing energy by fusion of hydrogen atoms - the same process as in the sun - requires extremely high temperatures. Reactor walls facing the hot, magnetically confined plasma have to withstand high particle and high heat fluxes. The most promising candidate for this environment is pure tungsten which is quite brittle, but becomes ductile after plastic deformation. At the operation temperatures in a fusion reactor, the microstructure becomes unstable leading to deterioration of the mechanical properties. Before applying tungsten in plasma-facing components of a fusion reactor, long-term annealing has been investigated for differently rolled tungsten plates within EUROfusion together with the Institute of Plasma Physics of the Chinese Academy of Science. A concise description of the kinetics has been achieved by models of recovery and recrystallization, allowing extrapolation to lower temperatures. Tungsten rolled to large reductions deteriorates too fast, but for moderately rolled tungsten, half-recrystallization is not expected before a million years at 800°C and for 1075°C only after more than two years, sufficient for use in future fusion reactors if the temperatures in the critical parts are limited accordingly. Angel Alfonso Lopez, who has worked on the topic within the Sino-Danish Center of Education and Research, in April 2016 received a double PhD degree from DTU and the University of the Chinese Academy of Science.

Surface-hardened titanium - the optimal material against corrosion and wear

In the project Metal Release from Implants (METIMP) funded by Danish Council for Independent Research | Technology and Production Sciences, surface hardening of implant materials was investigated and a new method for gaseous surface treatment of titanium was developed, resulting in very high hardness and extreme wear resistance. Titanium alloys are commonly used as implant materials due to a unique combination of lightweight, high tensile strength, excellent corrosion resistance, and biocompatibility. However, titanium suffers from poor wear resistance and a hardness below 500 HV. A surface layer with a hardness of up to 3000 HV and a depth of several hundreds of microns can be obtained by forming a so-called mixed interstitial solid solution/compound layer. The hard layer is obtained by gaseous surface treatment and is a result of incorporation of small carbon and oxygen atoms into the surface. The nature of the process and the high hardness of the supporting diffusion zone mean there is no risk of layer spallation during wear.

Wear improvement of titanium is not only relevant for implants, but also for many applications in automotive, aerospace, military and industrial processes. The technology can also be highly relevant in combination with new manufacturing technologies such as 3D metal printing, where titanium is one of the materials of choice.

Material models for metal forming

Ultimately, the behaviour of a metal during an industrial forming operation, e.g. stamping of a car door, depends on the properties of the individual grains and their interaction with each other. In a project funded by the Danish Council for Independent Research | Technology and Production Sciences, elastic and plastic interactions between neighbouring grains have been studied by means of synchrotron X-rays with the aim of formulating new material models for simulation of metal forming.

For an austenitic stainless steel, the elastic interaction between annealing twins which share a common elastically stiff direction was analysed. In spite of the common elastic directionality, the grain-averaged stress across the twin boundary exhibits the same scatter as conventional grain boundaries. Elastic grain interactions are therefore found to be complex and must involve the entire set of neighbouring grains.

While the grain-averaged orientation changes of individual grains induced by plasticity depend on the all neighbouring grains, the orientation changes near the grain boundaries are qualitatively well-predicted by a crystal plasticity model taking only pairwise grain interactions into account. The modelling results demonstrate that localized shear at the grain boundaries is an important mechanism of plastic grain interaction.

The project is a collaboration between DTU Mechanical Engineering (Grethe Winther, Nicolai Ytterdal Juul, and Mikkel Ravn Boye Jensen) and DTU Physics.
The high content of alkali and chlorine in biomass causes extensive corrosion of superheaters in biomass firing power plants.

**Surface modification of soft materials**

Research in the surface modification of soft materials has focused on the development of a new approach to functionalize silicone rubbers. Because of its distinct surface hydrophobicity, the applications of silicone rubbers in aqueous environments are often hindered or avoided. For this reason, hydrophilization of silicone rubber has been pursued in various ways to date. A new approach developed by Troels Røn and Seunghwan Lee - together with a team at DTU Chemical Engineering - is to disperse amphiphilic diblock copolymers within silicone rubber matrix. Upon interfacing with water, only hydrophilic blocks are segregated via the affinity with water (hydrophilicity), whereas the hydrophobic blocks remain immobilized on the surface for the reluctance to expose to water (hydrophobicity). This approach is particularly effective in maintaining the hydrophilic polymer layers in harsh environments because new layers of hydrophilic polymer films can be formed from internal source of materials.

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**High-temperature corrosion under conditions of biomass firing**

In recent years, the Danish government has increased the share of biomass, e.g. straw and waste wood, in heat production to replace fossil fuels such as coal. Although being available as a worthwhile CO2-neutral energy source, the high content of alkali and chlorine in biomass causes extensive corrosion of superheaters in biomass firing power plants. Increasing the lifetime of superheater tubes and reducing unwanted shutdowns of the plants due to corrosion induced failure require thorough understanding of the material’s performance at temperatures above 540°C in aggressive chemical environments, including, for example, HCl, SO2, O2, H2O.

As part of the strategic research centre GREEN and in collaboration with the Department of Chemical Engineering at DTU, superheater materials are investigated after both systematic laboratory-scale exposure to mimic conditions in biomass firing power plants and long-term field exposure in Danish plants co-firing biomass. Complementary advanced materials characterization methods involving microscopy, diffraction analysis, and spectroscopy are applied to study phase transformations and the evolution of the corrosion scale morphology. The novel application of depth-resolved energy-dispersive synchrotron diffraction in transmission geometry (carried out at the synchrotron facility BESSY II) has proved to be an efficient and reliable characterization tool, in particular for the very complex nature of full-scale plant exposed samples with rather thick and heterogeneous corrosion products.

Based on thorough materials characterization, which contributed to the understanding of the corrosion mechanism under biomass firing, various surface modifications of commercial superheater materials are applied and tested as potential future technologies to protect the superheaters and increase the service life of biomass firing power plants.

Contact: Associate Professor Karen Pantelon

Contact: Postdoc Troels Røn and Associate Professor Seunghwan Lee

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Present electrical contacts systems are based on heavy use of costly gold. The layers are typically made of a substrate with a layer of nickel followed by a layer of gold with thickness depending on the application and exposure conditions. The main issues with the electrical contacts are corrosion and wear, which limit the freedom to reduce the gold thickness. The goal of the HIPEC project is to develop electrical contact systems without the use of gold, while providing good corrosion and tribological performance.

The project focuses on understanding the corrosion reliability issues of the presently used gold-based contacts in detail, including the failure mechanisms. Furthermore, focus will be on understanding the problems with materials combinations including substrate material and coating as well as the electrical contact loss due to fretting corrosion. A special focus will be on the contacts used for hearing aid applications.

Furthermore, the HIPEC project will focus on developing new contact systems without the use of Au, while using an underlayer of easily passivating materials followed by a hard layer of conducting coating synthesized by PVD-based processes. The aim of the new contact material combination will be to provide greater freedom for substrate choice, while also building high-performance contacts with necessary electrical properties without the use of gold.

The HIPEC consortium project is funded by Innovation Fund Denmark and the partners are the research group CELCORR from DTU Mechanical Engineering, DTI, Widex A/S, and Elplatek A/S. The CELCORR group (www.celcorr.com) at DTU Mechanical Engineering focuses on various aspects of climatic reliability of electronics, including electrical contacts.

Contact: Professor Rajan Ambat
Research within Solid Mechanics is highly interdisciplinary, revolving around mechanics of materials, structural mechanics, machine elements, vibrations, and optimal design. International collaboration, both academic and industrial, is central to many of the scientific activities, and the goal is to deliver research that leads to new technologies and new insight at the frontier of our broad research field.

**New tendencies at the section**

Improved utilization of materials for large-scale structures and micron-scale components is currently facilitated by major leaps in new modelling capabilities. These include both theoretical advancements and new numerical methods, often exploiting recent high-performance computing capabilities. Unprecedented modelling detail provides a basis for understanding the interaction of many different physics, even for realistic 3D-problems. Experimental validation of the advanced models will be of ever-increasing importance.

**Expectations for the year ahead**

Newly developed high-fidelity modelling tools for materials and structures will lead to increased collaboration with industry, and the improved model detail will be integral to the development of better products. Within dynamics, new methods for damping vibrations that may be detrimental in structures and machine elements are developed based on active and finely tuned electromechanical actuators. Vibrations may also serve favourably as a source of information about structural integrity - a field receiving renewed attention.
Towards identification of rotordynamic properties for seals in multiphase flow using active magnetic bearings - design and commissioning of a novel test facility

The energy sector’s recent drive towards subsea oil and gas production brings about a requirement to locate process equipment in deep-water installations for which performing liquid and gas separation on the well stream is limited. Consequently, the subsea installed pumps and compressors are now required to handle multiphase fluids. Turbomachinery seals are pivotal for the performance of pumps and compressors for which reason the ability to predict the complex interaction between fluid dynamics and rotordynamics within these seals is a key aspect in the design of rotating equipment.

The research on multiphase seal rotordynamics is presently only in its infancy. In particular, the experimental validation of existing mathematical models is lacking, which is the focus of the ongoing research collaboration between Section for Solid Mechanics at DTU Mechanical Engineering and Lloyd’s Register Consulting. In this project framework a large effort is directed towards establishing facilities to experimentally acquire the needed benchmarking data.

The test facility currently being commissioned at DTU consists of four modules of which an industrial-scale rotordynamic test bench consisting of two radial active magnetic bearings with an embedded Hall sensor system, a rigid rotor, and a drive unit acts as the hub. In addition, the test facility includes a module facilitating calibration of the state of the art system of Hall sensors which provides important contact free force measurement capabilities. The third module houses the smooth annular test seals, and the fourth module adds a single-phase air flow supply to the test facility infrastructure.

The test facility enables DTU Mechanical Engineering to conduct experimental research ventures within seal the fields of seal rotordynamics and active magnetic suspension technology.
Piezoelectric vibration damping of structures

Many slender structures across various engineering disciplines are sensible with respect to external dynamic loading. Typical examples are vibrations in either wings due to aerodynamic interaction or in jet engine turbofans because of high-speed rotations. The amplitudes may become extraordinarily large at resonance, which occurs when the harmonic content of the external load coincides with one of the natural frequencies of the vibrating structure. An effective remedy against large resonant vibrations is the introduction of damping by for example smart devices that can be attached to the structure. Piezoelectric transducers are electromechanical devices that convert mechanical into electrical energy, and vice versa. These small size devices are therefore attached to the structure, dissipating vibrational energy in a supplemental electrical shunt, containing a resistor (R) and an inductor (L). The frequency of this RL shunt is then adjusted to optimally interact with the resonance of the structure and thereby effectively mitigate vibrations. However, for piezoelectric shunt damping to be effective the electrical components must be calibrated very accurately. The Danish Council for Independent Research has therefore financed the project ‘Resonant Piezoelectric Shunt Damping of Structures’ to formulate calibration procedures that explicitly take into account the substantial changes in the resonant vibration form of structure, due to the presence of the piezoelectric transducer. The initial outcome of the project will be more effective shunt damping, while in a longer perspective it may help increase the life time of structures exposed to dynamic loading. The research project is conducted at DTU Mechanical Engineering, in collaboration with Supméca in Paris and the Danish-based company Noliac A/S.

Predictive modelling of environmentally assisted cracking: A micromechanics conquest

The use of high-performance materials in energy infrastructure is firmly challenged by the detrimental effect of hydrogen; the ductility and toughness of structural steels is dramatically reduced when exposed to corrosive environments. With current approaches being mainly empirical and highly conservative, there is a strong need to understand the mechanisms of hydrogen-induced degradation and to develop a new generation of models able to reproduce the microstructure-dependent mechanical response at scales relevant to engineering practice.

A novel modelling framework has been proposed in the context of the H.C. Ørsted postdoc programme (DTU - EU: FP7 and H2020) and the HOTsolid project (DFF). The ground-breaking model developed has proven to reliably predict crack initiation and subsequent growth as a function of the environmental conditions, material properties and external loads. Calibration-free predictions have been made possible - for the first time - by enriching continuum schemes with relevant microstructural features through rigorous mathematical models. These scientific achievements can be integrated in a mechanism-based fitness-for-service methodology that will directly impact the fuel efficiency of next-generation automobiles, the development of new hydrogen transport systems, and the service lifetime of offshore structures and pipelines.

The research is mainly being undertaken by Emilio Martínez-Pañeda and Christian F. Niordson, and is part of a large collaborative effort with the University of Virginia, the University of Oviedo, and the University of Cambridge.
Vibrations for Estimating Bolted Joint Integrity

Many engineering structures are held together by arrays of closely mounted bolts. For the safety of, e.g., wind turbine towers, it is essential that all bolts are properly tightened. Currently, many resources are spent at mandatory regular checks of bolt tightness. For the inspectors, the work can take a long time, be monotonous, physically demanding, and risky, e.g. with heavy hydraulic tools at elevated height.

Funded by a grant from The Danish Council for Independent Research, this 3-year research project aims at exploring new ways for testing critical bolt connections in engineering structures. In a collaboration with Karlsruhe Institute of Technology and the company Brüel & Kjær Sound & Vibration, Associate Professor Jon Juel Thomsen from DTU Mechanical Engineering - along with a postdoc and a PhD student will explore why a well-tightened bolt sounds differently from a more loose bolt when struck by a hammer [listen to audio clip], and how this can be used for checking critical bolted joints faster, cheaper, more accurately, and with less physical effort than using conventional tools.

We aim at quantifying the difference in sound/vibration, so as to estimate bolt tension from measured vibrations, by using advanced mathematic modelling and analysis, and suitable measurement equipment and signal processing. Our pilot studies indicate a strong correlation between various features of vibrations and bolt tension, but also reveal difficult obstacles which will be addressed in the project.
Research in thermal energy is focused on optimization of thermal systems as units for power production, refrigeration, heat pumps, internal combustion engines, fuel cells, and biomass utilization. We apply numerical modelling of systems and components and develop simulation tools for these. This involves numerous engineering disciplines and methods. Experimental research includes facilities for performance and emission tests for internal combustion engines, and research on heat transfer in refrigeration, heat pump systems, and power cycles.

New tendencies at the section
In the coming year, we expect further developments in several experimental research fields, including facilities for hydrogen compression and for studies of heat transfer in combustion. Some research projects have recently led to innovations with potential for commercial exploitation. Further, the group is involved in several programmes under the International Energy Agency which will increase the international collaboration.

Expectations for the year ahead
We expect to obtain new results from the operation of power cycles onboard ships for waste heat recovery, and in the field of liquefied natural gas (LNG) production units. Novel solutions for fueling hydrogen as a vehicle fuel will be presented. In the field of heat pumps, new results regarding heat transfer and system configurations are expected. The DTU Roadrunners will participate in Shell Eco-Marathon with increased ambitions for the performance in several categories.
Design and optimization of flexible multi-generation systems

Flexible multi-generation systems (FMGs) are integrated facilities that convert one or several energy resources or services into multiple energy services and other valuable products, e.g. electricity, heating, cooling, bio-fuels, and bio-chemicals. FMGs are dynamic facilities that may adjust operation in response to changes in demands and market prices of resources and products. When properly designed, FMGs may therefore act as efficient energy system valves that integrate the various layers of the energy system (electricity, gas, fuels, heating, cooling) by allowing overproduction in one layer (e.g. electricity) to flow into another layer with sufficient storage capacity (e.g. gas), and vice versa.

This project focuses on the development of a holistic and generic methodology for optimizing the design of FMGs. The final methodology is based on consideration of the following points: Selection and dimensioning of energy conversion processes; systematic heat and mass integration; flexible operation optimization with respect to both short-term market fluctuations and long-term energy system development; global sensitivity and uncertainty analysis; biomass supply chains; variable part-load performance; and multi-objective optimization considering economic and environmental performance.

Tested in several case studies, the developed design methodology is found to be efficient in screening for promising FMG designs. In addition, the case study results emphasize the importance of considering flexible operation, systematic process integration, and systematic assessment of uncertainties in the design optimization. It is recommended that future research focuses on assessing the energy system balancing potential of optimized FMG concepts.

Contact: Associate Professor Fredrik Haglind.

Industrial processes often consume large quantities of heat, while dissipating similar quantities of waste heat to the ambient. As fossil fuels are the main energy carriers for industrial processes, this entails large emissions of CO2 and other pollutants. Heat pumps (HPs) can upgrade low-temperature waste heat to a high-temperature heat supply using only a fraction of primary energy, which may improve the energy efficiency and thus reduce emissions of industrial processes.

The constraints of commercial components currently limit the heat supply temperature to a maximum of 90 °C. However, a significant heat demand exists in excess of this limit, which implies a demand for cost-efficient high-temperature HPs. The ammonia-water hybrid absorption-compression heat pump (HACHP) is of specific interest for the development of high-temperature HPs due to two properties inherent to the zeotropic working fluid mixture: Increased efficiency due to the reduction of thermal irreversibilities and reduction of vapour pressure compared to that of pure ammonia. The HACHP can thus deliver higher temperatures at higher efficiencies than conventional HPs.

The feasibility of developing high-temperature HACHP has been investigated through the use of numerical models including details on cycle and component design as well as investment and running costs. These models were applied to investigate both the maximum possible heat supply temperature and economically viable operating conditions for heat pump implementations. This showed that with the commercial components available today, the HACHP can supply temperatures up to 150 °C with temperature lifts up to 60 K. Further, it was found that under most operating conditions the HACHP provides a better return on the investment than conventional heat pumps.

Contact: Postdoc Jonas Kjær Jensen.
RADIAD - Radiation modelling and verification in marine diesel engines

The purpose of the RADIAD project is to gain a better understanding of the influence of radiation on heat transfer inside a large two-stroke diesel engine. The goal is to obtain a better estimate of local temperatures during combustion by improving the description of radiation phenomena. This will add to a better estimate of essential engine parameters like particulate and NOx emissions and fuel consumption.

Heat transfer inside the cylinder of a combustion engine takes place via two main mechanisms: convection and radiation. Convection is quite well described and is usually the most important mechanism for heat transport. Radiation is not studied to the same extent - probably because convection is the dominant heat transport mechanism. However, more focus is now on larger engines for marine purposes, since these engines are undergoing dramatic changes due to upcoming and more stringent regulations with respect to emissions and fuel consumption.

The RADIAD project is supported financially by The Innovation Fund Denmark. The project is furthermore supported by the participating partners: MAN Diesel & Turbo A/S, Technical University of Denmark - DTU, Combustion Research Facility at Sandia National Laboratories, USA, University of Nottingham, UK, Malaysia Campus, and Lund University, Sweden.

Participants: from DTU Mechanical Engineering: Jesper Schramm, Anders Ivarsson, Kar Mun Pang, Sajjad Haider, Fredrik Westlye, Mads C. Jørgensen

System integration of bioenergy and agriculture

Increasing awareness of climate change, fossil fuel depletion, and energy security has lead to a global push towards changes in demand for alternative energy sources. Increased biomass utilization together with wind for energy generation are viewed as obvious options in addressing these issues. There are residual biomass resources in abundance in Denmark as a result of agricultural activity. However, despite increased demand, it is getting more common to leave cereal straw on the agricultural field instead of harvesting them for energy generation. The reason is that when removing straw from the agricultural system, essential elements like nutrients and carbon are removed as well, which can have a negative environmental and economic impact.

This study investigates the possibility of an integrated bioenergy and agricultural system where residual resources are used between the two systems to mutual benefit. By allowing, e.g., straw, to be utilized in the bioenergy system - with the condition that nutrients and carbon are recycled to prevent soil depletion - it is possible to ensure effective resource utilization. However, for that to be possible the bioenergy system would need to compromise with lower energy efficiency. To analyse the prospect of such a system, a modelling and evaluation framework was developed for assessments based on multiple criteria. It was found that such an integrated system might fully mitigate its climate change impact by increased biochar production resulting in approximately a 2.7 percent decrease in electrical efficiency while still being economically feasible.

Participants: DTU Mechanical Engineering: Hafthor Jøgur Sigurjónsson Brian Elmegaard Lasse Rangaard Clausen DTU Chemical Engineering Bregentved DONG Energy

Full project name: Integrated systems for bioenergy and agriculture in a future without fossil resources (BIOCULTURE)