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Department of Civil Engineering
Annual Report 2010
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Review of 2010
It is with great pleasure and pride that I present this review of the activities at the Department of Civil Engineering at the Technical University of Denmark – DTU Byg. Thoughts on the challenges we face in future are given elsewhere in this magazine by our new Head of Department, Michael Havbro Faber. I will concentrate on reviewing last year’s activities, and at the same time give some idea of the Department’s potential to meet these future challenges.

Last year, I emphasized the huge responsibility that rests on present and future generations of engineers to provide the scientific and technological basis to meet the challenges related to global resource depletion, sustainable global development, the climate change challenge and the threat from global pollution – to mention just a few. In particular, I emphasized that civil engineers will play a central role in developing our society in a more sustainable direction in future, for example by ensuring that energy consumption in buildings is reduced from the current excessive levels, that new infrastructure is sustainable with minimized energy and material consumption, and that the huge investments made in new infrastructure are long-lasting.

Even though the civil engineering profession is a lifelong education, the essential and extremely important years spent at university engaged in studies at Bachelor, Master’s or PhD level are not to be underestimated. It is here that students acquire basic knowledge, but it is also where personalities are molded and, in many cases, lifelong personal missions take shape through interacting with researchers, professionals and other students. Therefore it is a very important – and big – step to start a new study programme, and the mission, profile and added value should be carefully evaluated. Last year, the Department undertook the task of developing a new study programme – Bachelor of Science in Architectural Engineering. This programme will provide candidates with a strong, scientific background in sustainable building design. The studies will provide the best possible background for our existing Master of Science in Architectural Engineering, and I am sure that candidates from these study programmes will play a very important role in building and rebuilding habitats for our society in the future – in Denmark and worldwide. With the new Bachelor in Architectural Engineering, the set of study programmes rooted at the Department is now complete with two main directions – Building Design and Building Technology, with both offering a Bachelor of Engineering and a Bachelor/Master's track plus the rapidly growing study programme in Arctic Technology. Clearly a very attractive set of programmes, which in 2010 attracted more than 750 applicants. All study programmes are research-based, and a strong research environment is vital, not only for the educational activities but also for the innovation and public sector consultancy which are all-important elements of the Department’s activities. I am happy to report that the research environment in 2010 proved as strong and productive as ever, not only by numeric indicators – such as the number of ISI publications and the number of citations – but also by relevance and added value to society. You will quickly realize this when browsing though the exciting articles in this magazine, all dealing with current and central issues in the building sector and society as a whole and ranging from advances in building materials, structural testing and analysis, the energy infrastructure, resources and waste management to the indoor climate, construction processes, and safety issues. For the researcher or highly qualified professional, doing a PhD constitutes a very important stepping stone. The Department is taking a very active role in the offensive national strategy to significantly increase the number of PhD students in the technical scientific area in the 2007-2012 period. The number of PhD students at the Department has now reached 67. All candidates follow a very demanding programme, including a research project, professional education and training in the dissemination of scientific knowledge. For most candidates this is also associated with a challenging personal development – which can often be quite stressful. In the magazine, you can read about the ‘intervision project’, which is designed to help students manage the challenges of PhD life at the Department. Finally, I would also like to draw your attention to the article on the ‘PhD of the Year 2010’ at DTU Civil Engineering, which demonstrates the very high quality and relevance of the PhD projects carried out at the Department. The project applies the full range of scientific tools from experimental to advanced numerical modeling work in an area of high relevance, resulting not only in scientific publications, but also patenting. I hope you enjoy reading the magazine.

Deputy Head of Department
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Challenges ahead

After three very eventful months full of new impressions as Head of Department, not only have I gained a good insight into the many different activities, competencies and resources at DTU Civil Engineering, I also have a clear sense of the tremendous development potential which the department holds. DTU Civil Engineering possesses a wealth of values, traditions and human resources, and we must use them as a platform in the coming years as we gear up for the challenges ahead. But what sort of challenges are we facing? They are many, and they are not to be taken lightly. Civil engineers play a key role in society. On the one hand, homes, buildings and infrastructure are the foundations for the functions and processes that lead to economic growth and thereby welfare, health and quality of life for individual citizens. On the other hand, from a global point of view, these very same activities are some of the biggest consumers of energy and materials. This is the complex field in which DTU Civil Engineering operates.

Never before has the building and construction sector had to shoulder such responsibilities and tasks. We must ensure that built-up areas are developed and maintained in step with the demand for buildings and infrastructure – and we must devise sustainable and optimal solutions while taking account of quality of life, security, the environment and the economy. The recent earthquakes in Japan and their knock-on effects highlight the importance of high engineering standards. Civil engineers are responsible for the safety and reliability of buildings and infrastructure, both in daily use and in extraordinary situations. Also, our built-up surroundings must be robust and up to date; in other words, they must be capable of withstanding and being adapted to climate change as well as the varying needs, functionalities and the considerable uncertainties associated with it.

Assuming responsibility for all this demands far more than experience and traditions – it takes a strong sense of relevance combined with basic knowledge, innovation and visions. DTU Civil Engineering possesses these components – but to develop them further we need to take a critical view of where we are starting out from. During the past eight to ten weeks, we have therefore launched and implemented a number of situational analyses of the department which, at different organizational levels, map the roles we regard as being essential, as well as our strengths and weaknesses, both in relation to the academic areas we represent, our research facilities, the way in which we are organized and, in particular, the way in which we go about our work – and also how we define our working culture. The situational analysis is the starting point for establishing visions and goals for the department as well as identifying the strategy and the means for ensuring that we do not just aim for the goals, but that we are also able to adjust our course along the way in line with changing opportunities and conditions.

In my view, one of the department’s most important tasks is to help industry and society find new approaches to sustainable building and future-proof solutions in connection with major infrastructural and renewable energy projects. And we must be pioneers in this role. It is crucial that we set ourselves ambitious goals, and establish an inspiring framework for our work that will help us to find innovative solutions and open up as yet unseen opportunities. We obviously also have to further improve existing concepts and methods – but we must seek new boundaries to a much greater extent. We can only do this if we strive to achieve goals that do not appear possible with existing technology – that is our challenge.
Organisation

Head of Department:
Michael Havbro Faber (1/1 2011)
Deputy Head of Department
Professor Henrik Stang

Advisory Board:
Professor (adj) Louis Becker, Architect MAA, AIA, RIBA, Design Director, Partner, Henning Larsen Architects A/S
Director Niels Ole Karstoft, ALECTIA A/S
Division Director Niels Kjeldgaard, MT Højgaard A/S
Head of Division Marie Voldby, Danish Enterprise and Construction Authority

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Building Design
Professor Kristian Hertz
Building Physics and Services
Professor Carsten Rode
Construction Materials
Professor Ole Mejhede Jensen
Geotechnics
Associate Professor Ole Hededal
Indoor Environment
Professor Bjarne Olesen
Structural Engineering
Professor Jeppe Jönsson
Administration and IT
Søren Burcharth
Laboratories and Workshops
Jørgen Bjrnbak Hansen

Centres:
ARTEK, Arctic Technology Centre
Professor Arne Villumsen.
ICIEE, Centre for Indoor Environment and Energy
Professor Bjarne W. Olesen.

Study Programmes:
Civil Engineering (MSc)
Associate Professor Staffan Svensson
Building Technology (BSc)
Professor Per Goltermann
Architectural Engineering (MSc)
Associate Professor Jan Karlshøj
Architectural Engineering (BSc)
Associate Professor Toke Rammer Nielsen
Architectural Engineering (BEng)
Associate Professor Lotte Bjørregaard
Building Engineering (BEng)
Associate Professor Anette Krogsgaard
Arctic Technology (BEng)
Associate Professor Hans Peter Christensen

HC: Head of Centre
PM: Project Manager
EM: Education Manager
*: Project/Education Participant
Concrete is the world’s most important construction material. In Denmark, 10 million tons are produced annually. Conventional concrete requires vibration to overcome its yield stress and become compacted. Vibration is noisy, labour intensive, and can introduce inhomogeneities in the concrete.

To overcome the need for vibration, Self-Compacting Concrete (SCC) was introduced in Japan in the 1980s when new types of admixtures became available. SCC is a tailored concrete with special, engineered properties in its fresh state. SCC flows into the formwork and around reinforcement by its own weight. This dramatically improves both productivity and the working environment during construction, and potentially improves the homogeneity and quality of the concrete. Moreover, SCC allows greater architectural freedom in structural design. The main challenges and opportunities in using SCC lie in its robustness and the compatibility of constituent materials, the modelling of flow and virtual mix design, and last but not least, its sustainability.

A major obstacle to using SCC more extensively is the lack of understanding of the form-filling process. Possible heterogeneities induced during the casting of the SCC may lead to variations in local properties and hence to a potential decrease of the load carrying capacity and durability at the structural level. Heterogeneities in SCC are primarily caused by the static and dynamic segregation of coarse aggregates. Thus, to predict castings with SCC, a necessity is numerical model(s) capable of simulating flow patterns at the structural scale, and at the same time the impact on the flow of the varying volume fraction of aggregates and other phenomena at the scale of aggregates.

Efficient modelling framework
Combining the competencies of the multidisciplinary project group at the Technical University of Denmark, DTU, an efficient modelling framework was established. The framework is capable of simulating macroscopic phenomena at particle level simultaneously, since one influences the other. At the structural scale, a finite volume-based single-flow model with a proper particle tracking technique can be used. A micro-mechanical fully coupled model for the flow of particulate suspensions based on the Lattice Boltzmann Method provides the link between local flow patterns and arrangement of phases with effective properties on the macro-scale. This leads to the development of a robust and efficient solver for fluid-particle dynamics for materials with similar densities (results in high accelerations).

Members of the group
The project “Prediction of flow-induced inhomogeneities in self compacting concrete” runs from November 2008 to October 2012 and employs both Jon Spangenberg, PhD student at the Mechanical Engineering Department, and Jan Skocek, Post Doc at the Civil Engineering Department. The project group consists of researchers from the Department of Civil Engineering at DTU (Henrik Stang, Jan Skocek and Mette Geiker), the Department of Mechanical Engineering at DTU (Jesper Hattel, Jon Spangenberg and Jesper Thorborg), and the Department of Chemical and Biochemical Engineering at DTU (Peter Szabo) together with a group of associated partners from the industry and the international research institute LCPC (IFSSTAR since 1 January 2011), France (Nicolas Roussel). The project is funded by the Danish Research Council.

The first two years of the project were spent establishing the modelling framework. Over the next two years, the framework will be further developed and documented based on experimental and in-situ observations. In addition, the applicability of the modelling framework for process optimisation will be demonstrated.
Monopile foundations for offshore wind turbines

Centrifuge modelling is used by the geotechnical group at DTU Civil Engineering to investigate the response from monopiles. The observations are being used to develop design tools for offshore wind turbine foundations.

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Energy from offshore wind turbines
More and more energy is being generated by offshore wind turbines, and new wind farms are being sited in deeper and deeper waters. The sea offers the opportunity of installing large wind farms, but the installation and running costs of these wind turbines are huge. If energy from offshore wind turbines is to compete with energy from coal, it is important to cut the total cost of offshore wind turbines. The monopile foundations concept is today the most widely used concept for supporting offshore wind turbines. Monopiles are single, large diameter tubular steel piles. If this foundations concept can be successfully used in deeper waters, the price of the foundations can be minimised and thereby also the total cost of the wind turbine. Today this is not possible with the available design tools.

Research in the geotechnical group
The response from monopile foundations for offshore wind turbines is one of the main research objectives of the geotechnical group at DTU Civil Engineering. Centrifuge and numerical modelling is being used to develop engineering tools for monopile foundations in the future. The work is being carried out in collaboration with other universities and the industry to ensure the good and practical use of research findings.

Centrifuge modelling
Compared to fullscale testing centrifuge modelling is a low-cost tool for investigating soil-structure interaction. By applying artificial gravity on a soil sample, a scaled model of a foundation can be investigated. Due to the artificial gravity, the soil sample will have soil stresses identical to the prototype conditions. Soil is non-linear in its behaviour, and to ensure the same behaviour in the model and the prototype, the stresses have to be equal. As long as the soil behaves as a continuum, the length of the models is scaled linearly with the increase in gravity. This means that a model pile with a diameter of 0.04 m to which an increase in gravity of 100 is applied behaves like a prototype pile with a diameter of 4 m.
The centrifuge at the Technical University of Denmark is a beam centrifuge and is capable of providing an increase in gravity of approximately 85. A grant from the COWI Foundation facilitated the development of a new load system for testing monopiles for wind turbines. Following this upgrade, the geotechnical centrifuge is today the only geotechnical centrifuge in the world dedicated to conducting research into monopile foundations for wind turbines. Scale effects in centrifuge modelling can occur if shear bonds occur. When developing tools for foundations 85 times bigger than the model, it is extremely important that small scale effects are also recognised. At the moment, the research is focused on these scale effects. This part of the research is being carried out in cooperation with Professor Sarah Springman, leader of the geotechnical group at the Swiss Federal Institute of Technology Zurich, ETH Zurich.

Outlook
The preliminary findings from the scale effects investigation is that the installation process is a key modelling parameter. An installation process corresponding to prototype behaviour is important. Proper installation of the model monopile will not only minimise scale effects but also simulate prototype behaviour of monopiles. With this clarification of scale effects, further centrifuge research on monopiles can continue with the possibility of scaling up to prototype conditions. The centrifuge modelling, together with the numerical modelling, creates a strong toolset in the further development of the monopile foundations concept for offshore wind turbines.
Upgrading waste to secondary resources

Many types of ashes are unusable in the construction material industry because they are polluted. A research area at DTU Civil Engineering aims at using more particulate waste material such as ashes in the construction industry by cleaning the ash during electrochemical extraction.

In Denmark, fly ash from coal combustion is the only ash type used in concrete. There are, however, many other ash types which have not found such use, and today these are regarded as waste (often hazardous waste) and consequently landfilled. This untenable situation calls for a more sustainable solution, which is the focus of a research area at DTU Civil Engineering. The construction material industry in general uses large volumes of particulate raw materials and is a potential user of the various ashes.

Direct use not possible

In recent years, an increasing number of international scientific papers have been published on the addition of different ashes to cement, concrete and ceramics. Often the ashes can be used if their material strength is the only consideration, but usually the chemical composition of the ash fails, for example if the ash has a high heavy metal content which hinders environmentally sound use, or if the ash contains unwanted salts.

The research area at DTU Civil Engineering is looking at using more particulate waste materials such as ash in the construction industry, but rather than producing the waste and waiting for a possible use to emerge, the waste is being upgraded to meet the requirements of users and what is required in terms of sustainable management.

Contact was made to different producers of construction materials to outline the characteristics (chemical as well as physical) of the raw materials used, and which raw materials might potentially be substituted with an upgraded secondary raw material.

Upgrading by means of electrochemical extraction

At DTU Civil Engineering, a special method for upgrading ashes is under development – electrochemical extraction. The method stems from the earlier development of an electrodialytic method for removing heavy metals from soil. The major new step is that the method now embraces an overall separation method rather than solely a method for heavy metal removal. The focus is now on the characteristics of the treated matrix to optimise possibilities for use, as well as on recovering the removed resources (e.g. P, K and heavy metals).

The upgrading is based on separation in an applied electric DC field, which causes ions in the material to move according to their charge. This separation [5], but phosphorus is not available directly from the ash. In the ash is necessary. Electrochemical extraction is a possibility for this separation [2], [3]. Treated ash was tested as a partial substitute for cement in Portland cement mortar [4], and the study showed potential for this use. The SSA contains a high concentration of phosphorus, an essential element which will become scarce in primary resources within the next century or so. The SSA may be a secondary resource of phosphorus, but separation from cadmium in the ash is necessary. Electrochemical extraction is a possibility for this separation [5], but phosphorus is not available directly from the ash. The phosphorus must be separated from the particulate ash, and possible uses of the remaining ash in mortar need to be tested.

Ongoing research and some results

Process conditions for electrochemical extraction must be optimised for each ash type, but the method can be used for ashes in general. Major focus is presently on upgrading air pollution control residues from municipal solid waste incineration (MSW APC) and sewage sludge combustion ashes (SSA) to secondary resources (the Danish EPA recently financed two projects). MSWA APC is produced in large amounts and constitutes a huge problem when landfilled as it is chemically unstable. The mobile fraction of heavy metals and the easily soluble salts are removed during electrochemical extraction, which solves the leaching problem. A pilot plant was constructed for the electrochemical extraction [2], [3]. Treated ash was tested as a partial substitute for cement in Portland cement mortar [4], and the study showed potential for this use. The SSA contains a high concentration of phosphorus, an essential element which will become scarce in primary resources within the next century or so. The SSA may be a secondary resource of phosphorus, but separation from cadmium in the ash is necessary. Electrochemical extraction is a possibility for this separation [5], but phosphorus is not available directly from the ash. The phosphorus must be separated from the particulate ash, and possible uses of the remaining ash in mortar need to be tested.


Bridge dynamics

DTU Civil Engineering is internationally recognised for its research into Bridge Dynamics. The institute’s current research projects include the fatigue assessment of bridge cables, pedestrian-induced vibrations of footbridges, bridge icing, long-span bridge monitoring and the well-publicised understanding and control of bridge cable vibrations.

With international bridge stock numbers growing steadily, the understanding of their often complex dynamic behaviour is increasingly important. Cable-stayed bridges are a relatively new form of bridge introduced in the later half of the previous century and their cable fatigue resistance is not well understood.

Pedestrian-induced vibrations have gained prominence in recent years with the vibrations of several high-profile bridges. Unusual meteorological conditions have increased the risks of bridge icing, and bridge cable vibrations are becoming ever more difficult to control with the tendency for longer bridge spans.

CESDyn

With this in mind, a small research group was established to initiate research into bridge dynamics in early 2005. In 2007, the group expanded to examine the dynamic behaviour of other structures, and a year later the Civil Engineering Structural Dynamics Group (CESDyn) was born under the umbrella of the Section for Structural Engineering. The group now has nearly 15 members, made up of academics, PhD students and visiting professors and researchers, the majority of which focus their research on Bridge Dynamics.

Facilities and collaboration

In 2008, Femern A/S approved funding for a DTU Civil Engineering-led five-year collaborative research project on bridge cable vibrations. As part of this project, a new state-of-the-art climatic wind tunnel facility was built. The tunnel has been in operation for over a year now, and preliminary test results are proving exciting. Publications relating to these have already been prepared for several conferences in 2011.

Collaboration is strong with the Universities of Bristol, Stavanger and Reggio Calabria, whilst a new collaborative PhD project in fatigue risk assessment of bridge cables has been initiated with Stanford University. In 2010, DYWIDAG Systems International approached DTU Civil Engineering to propose joint research work into the assessment of bridge cable fatigue due to bending effects. The work has not only led to a novel preliminary bending fatigue spectrum for cables, but also to an Industrial PhD sponsored by ATKINS A/S. For this project, full-scale tests on bridge cable/anchorage assemblies have been proposed to be undertaken through a research agreement with the University of Texas, Austin.

2010 also saw the initiation of construction of a new 1.5m x 1.5m uni-axial shaking table facility for the dynamic testing of all types of structure. Tests in the areas of vibration control and pedestrian-induced footbridge vibrations are planned using the facility as early as mid-2011.

Results and future work

In contrast to most previous attempts by other prominent researchers in the field, DTU Civil Engineering’s recent work into the pedestrian-induced vibrations of footbridges has uncovered the dominant driving mechanism behind the Millennium Bridge vibrations of 2000 in the form of unsynchronised pedestrian-induced velocity-proportional forces. The large amplitude hanger vibrations on the Great Belt Bridge in 2001 have now largely been explained and mathematical models have been developed and experimentally verified to determine the likelihood of vibrations in future.

Tests are currently being undertaken to improve the aerodynamic performance of bridge cables through novel surface and shape modifications. Full-scale monitoring of both the Great Belt and Øresund Bridges has revealed interesting vibrations coupled with specific meteorological conditions. As part of this monitoring, new techniques are being developed to measure previously unquantifiable structural dynamic properties. Research continues on the fatigue assessment and icing of bridge cables.
The purpose of the Integration of sustainable construction processes project is to enhance the market and cooperation in the construction sector across the Øresund Region. The project is sponsored by the EU through the Interreg IV A Øresund programme, and the total budget for the project is EUR 1.7 million. The project started in September 2009 and will end in September 2012. There are many similarities between the Danish and Swedish construction sectors, with many players working on both sides of the Sound. Despite this, it is not possible for the sector to benefit from the Øresund Region as a single market. This is due to differences in traditions and structures and differences between the national codes of practice. There is a pressing need for a regional network, and for common “interpreters” of the national systems for stakeholders in the construction sector to work together and to be able to work across the Øresund Region.

Better quality
The project combines the need for more sustainable construction processes, high productivity, better quality and the adoption of ICT solutions in the Øresund Region. In particular, the use of virtual building models, often referred to as Building Information Modelling (BIM), which can be used to visualise the building as well as provide input for programs that can simulate a wide range of factors such as comfort, structural behaviour, energy consumption, life cycle assessment, scheduling and the costing of a facility. BIM can be regarded as a database for storing information from construction projects from cradle to cradle. DTU Civil Engineering is the leading player in the project, which is being carried out in collaboration with Lund University (LTH), Technical University of Denmark (DTU), Danish Building Research Institute (SBI) and Øresund Environment. The project is headed by Associate Professor Jan Karlshøj, who is also active in work packages regarding BIM guidelines and classification. Professor Svend Svendsen is leading the work package on verifying the national building code using BIM with the primary focus on energy-related issues. Søren Burcharth, Head of Administration at DTU Civil Engineering, is responsible for the overall economy of the project. Several employees at the department are involved in the project e.g. PhD student Lies Vanhoutteghem, Associate Professor Flemming Vestergaard, Research Assistant Helle Juul Bak and Professor Carsten Rode.

Economic benefits
DTU Civil Engineering exploits its experiences from participating in the national Digital Construction programme, training and testing in its BIM Laboratory, identifying the economic benefits of using BIM and from participating in international standardisation through ISO and buildingSMART in the work package regarding BIM guidelines and classification. DTU Civil Engineering is also looking into how buildings can be evaluated in terms of access for disabled people. Although both Denmark and Sweden are following the same basic energy requirements from the EU, implementation has been different in the two countries. DTU Civil Engineering is collaborating with Lund University on comparing the differences in the building code for new buildings and the retrofitting of buildings in Denmark and Sweden. The parties will identify how barriers can be removed for all work packages that prevent the Øresund Region from operating as an open market. The main goal of the project is to increase competitiveness in the region.

Website: www.baerebyg.org
Results from the software-based evaluation of a building formation model in relation to access for the disabled. Illustration: Salam Saghdosh Pey

The use of Building Information Modelling (BIM) is becoming more widespread and is increasingly being integrated with analytic software programs. Illustration: Salam Saghdosh Pey
Intervision for PhD students

The PhD School at DTU Civil Engineering organised intervention meetings for PhD students. These aimed at collectively tackling common challenges in PhD projects.

Isolation, excessive workload, poor work/life balance, lack of project planning and dissatisfaction with supervision: during a 2005 survey by DTU’s PhD Association, these five issues were identified as being the main hurdles to completing PhD projects. These challenges are faced by most PhD students, and generally they manage to tackle the challenges based on their own technical and/or personal skills, or with help from their supervisors, colleagues, friends or family.

Sometimes however, the solution to these challenges is not within easy reach, and PhD students may become stuck. Such a situation can easily give rise to frustration, hampering the PhD student professionally and personally.

In such instances, intervention with other PhD students may be the key. Intervention is a learning methodology in which professionals learn about professional issues from other professionals, by collective reflection on given problems. Intervention is being used in a wide range of professions, from financial managers and environmental workers to consultant engineers. In short, intervention is a methodical approach to tackling work-related problems with a small group of equals, the main objective being to improve the professional well-being of the people involved.

Pilot project

Given the potential benefits for our PhD students, the PhD School at DTU Civil Engineering initiated the pilot project “Intervision for PhD students” in the spring of 2010. With this pilot project, we wanted to evaluate the possible benefits of intervention for our PhD students and the PhD School. The project was coordinated by Associate Professor Hans Janssen, Deputy Manager of the PhD School, and facilitated by Mads Bendixen, work psychologist at Alectia and also a former PhD student at our department. Mads Bendixen had been working previously with intervention in Alectia, and his experience and expertise were greatly appreciated within this project.

Eighteen of our school’s PhD students participated, out of which three groups were formed. PhD students were gathered in groups, largely according to which stage the students had reached in their respective PhD projects. At each meeting, group members had the opportunity to raise an issue – for instance “improving my supervision meetings”. The correct understanding of the issue and possible ways of tackling it were first explored in a one-to-one interview. This was followed up by a discussion amongst the other group members. From talking to the interviewer to listening to the others and back provided the “focus person” with a deeper understanding of the challenge, and new inspiration to move forward. At each meeting, about three group members were able to raise an issue. In total, each group had four intervention meetings during 2010.

Permanent arrangement

At the end of the pilot project, the participating PhD students were asked for their opinions on “Intervision for PhD students” by means of a questionnaire. Almost everyone was satisfied with the pilot project and supported the continuation of the initiative. 80% of the students agreed that they had found “assistance in managing the challenges of PhD life”, which was the main aim of the intervention project. While not being a real objective, 40% of the students stated that the project had also helped in “improving the quality of my PhD-project”.

Given these very positive outcomes, the PhD School at DTU Civil Engineering is continuing “Supervision for PhD students”, now in a more permanent format.

A 2005 survey by DTU’s PhD Association identified the shown issues as the main hurdles for the completion of PhD projects.

The final evaluation of the ‘Intervision for PhD students’ indicated great satisfaction for most of the participating PhD students.

1: “Livet som ph.d.-studerende” (The PhD Association at DTU, February 2005)
Ventilation of spaces is essential for occupants’ health, comfort and performance. It is also a recognised method for decreasing the risk of airborne cross-infection. Present ventilation methods aim to dilute contaminated room air with large volumes of clean and conditioned outdoor air and thereby improve inhaled air quality (and to reduce the likelihood of inhaling pathogens). However, this strategy has several disadvantages: 1) it dilutes instead of removing the pollution at source; 2) supplying large volumes of clean air generates high velocity and increases the risk of draught discomfort; 3) conditioning and transporting large volumes of outdoor air for ventilating the entire room, including unoccupied areas, increases energy consumption; 4) initial and maintenance costs are high and more space is used inefficiently due to large air-handling units and duct systems; 5) ventilation rates/ventilation systems are designed based on occupants’ activities, reducing flexibility in terms of how the space is used (for example, in hospitals most rooms and corridors are not sufficiently well ventilated to be used in the event of a major influx of patients with communicable disease, such as during an influenza pandemic).

More efficient strategies for ventilation
A team of researchers and students at DTU Civil Engineering lead by Associate Professor Arsen Melikov has developed and studied advanced and more efficient strategies for ventilating office buildings, theatres, health care facilities and vehicle compartments. Unique experimental facilities, including breathing and coughing thermal manikins resembling occupants have been designed and used together with sophisticated measuring techniques.

Recently, a novel method for advanced ventilation in hospitals based on two important principles – source control and airflow control – was developed by the team. Two units, each consisting of a linear fan (with low energy consumption and low noise level), cleaning devices (HEPA/ULPA filters and UV light) and air distribution arrangements (slots and airflow guiding devices) are attached to the patient's bed (Fig. 1). Polluted room air is drawn in and cleaned in one of the units and then discharged horizontally to guide the polluted exhaled/coughed air (can be infected!) from the patient in the bed so it is extracted through the suction opening of the second unit before being mixed with the room air. The air is cleaned in the device and then is either discharged upwards to an exhaust duct as an air curtain between the patient and the person standing beside the bed (as shown in Fig. 1) or is discharged into the room (thus the device cleans the room air), or it is recirculated through the two units. The method allows for flexibility in bed layout and space use. The “plug and operate” principle can be applied, i.e. patients in beds with Hospital Bed Integrated Ventilation and Cleaning Units (HBIVCU), as they are called, can be moved from one room to another together with their personal ventilation. The devices can be portable and easily attached to the beds. The method can be applied in infectious wards as well as in rooms with patients with non-infectious diseases. The units and the ventilation principle are in process of being patented.

Efficient method
Physical measurements in a full-scale test chamber simulating a hospital room with two patients and a standing doctor simulated by breathing and coughing thermal manikins performed together with Computational Fluid Dynamics (CFD) simulations (Fig. 2) confirmed that the method is efficient at improving indoor air quality and reducing the risk of airborne cross-infection in hospitals, both for medical staff (and visitors) as well as patients. Moreover, implementing the method in practice may also lead to substantial energy savings. The research is in progress.
Controlling flow interaction to ensure more clean air for occupants at reduced supply flow rates

The 'PhD of the year at DTU Byg' for 2010 is proudly awarded to Zhecho Dimitrov Bolashikov for his thesis ‘Advanced Methods for Air Distribution in Occupied Spaces for Reduced Risk from Air-Borne Diseases and Improved Air Quality’.

The assessment committee praised the high scientific quality of the work, combining experimental tests and numerical simulations. Full-scale measurements and CFD simulations of air flow around and thermal comfort of building occupants mutually supported each other. The assessment committee moreover applauded the research production resulting from his thesis: four papers are submitted to international journals, three of which are currently published. One of the developed ventilation solutions is furthermore currently being patented.

Figure 1. Vector velocity plot based on PIV measurements showing the direction of the flow at the breathing zone as a result of the interaction between the free convection and the PV flow supplied from the front to the face of a seated breathing thermal manikin: a) without control and b) with control. The control makes it possible for the PV air to reach the mouth and nose of the manikin. The breathing thermal manikin has a realistic body shape and closely resembles a human being at a state of thermal comfort. RMP stands for Round Movable Panel and is a desk-mounted PV device.
A PhD project at DTU Civil Engineering aims to develop novel methods for improving the performance of Personalized Ventilation by controlling the airflow interaction close to the human body. The new air-distribution control methods result in improved energy efficiency, more clean air, and reduced risk of airborne cross-infections.

Today, existing ventilation techniques supply clean air some distance from the occupied zone: diffusers are placed on the ceiling, in the upper walls or close to the floor, ventilating parts of the room that are not occupied. By the time the air reaches the occupants it is already mixed with the rest of the room air providing mediocre air quality at best and resulting in numerous complaints including an increased prevalence of Sick Building Syndrome symptoms, such as headache, fatigue, lack of concentration etc. Personalised Ventilation (PV) is a new way of distributing air that supplies clean air from a diffuser close to the breathing zone of each individual. The benefits of PV are increased well-being, better performance compared to other ventilation techniques, protection from airborne contagious diseases and the possibility of individual control over the volume and direction of the clean air being supplied (frontally, slightly from above or below). The volume of clean air in the breathing zone depends on many factors such as supply flow rate, PV supply opening area, distance from face, flow interaction close to the face etc. It is important that the clean air supplied is able to penetrate the free convection surrounding the body (stemming from the temperature difference between the surrounding room air and surface body temperatures), so that the occupant can benefit from the clean air. In order to do so, a velocity in excess of 0.2 m/s is needed close to the face, otherwise the PV air will not reach the occupant’s breathing zone and will be deflected. Increasing the flow rate, i.e. increasing the velocity near the face, will result in more clean air being inhaled, but doing so is energy-inefficient and may also cause draught discomfort to the occupant. A way of achieving higher efficiency (more clean air, better protection from airborne diseases) but at reduced flow rates (energy-efficient method) is clearly needed.

**Improved strategies**

A PhD project with the objective of developing strategies for improving PV performance but at much lower air supply rates through controlling flow interaction close to the human body (face) was completed at DTU Civil Engineering. Computational Fluid Dynamics (CFD) simulations, Particle Image Velocimetry (PIV), breathing thermal manikins, tracer gas measurements etc. were used during the research (Fig. 1). Some of the strategies which have been developed are used for controlling the convection layer around the human body either by blocking it (a retractable board below the table pressing against the abdomen) or by exhausting it locally (PV incorporated into chair headrest with local suction above the shoulders) (Fig. 2). Other methods rely on controlling the PV flow itself: supplying the clean air very close to the body (mouth/nose) at significantly reduced volumes of clean air; at less than 0.4 L/s (headset microphone incorporated PV) (Fig. 2).

**Improved energy efficiency**

The control strategies studied are effective solutions for offices, cinemas, theatres, opera houses, public transport services etc. where occupant density is very high, as is the risk from airborne cross-infections. The benefits include improved energy efficiency through reduced supply flow rates, more clean air inhaled and increased contaminant (pathogen) removal effectiveness compared to conventional total volume ventilation systems used today or relative to situations where PV is used with no control (Fig. 3). The new strategies for controlling airflow interaction follow the future trends in ventilation and air handling: individually controlled environments at low energy cost with the flexibility and adaptability to satisfy the personal comfort needs of even the most demanding occupants.
Reinforced concrete is the most used structural material of all. Therefore, there is considerable economic interest in the safety and durability of concrete structures. Reinforced concrete cleverly exploits the individual strengths of the constituent materials, concrete and steel, to form economic structures, which explains their widespread use.

Cracks in reinforced concrete structures are, however, inevitable. They are the price of the fruitful interaction between concrete and steel. Thus, activating the steel reinforcement is normally associated with the formation of cracks in the concrete. Fortunately, cracking concrete does not have a directly negative impact on the load-carrying capacity of the structure. Nevertheless, cracks should be controlled and their influence on structural behaviour should be foreseeable. In order to achieve this, detailed modelling and simulation of the cracking processes during the service-life of the structure is necessary.

A better understanding of cracking processes will allow for more reliable modelling and simulation of the structural performance of a structure during its lifetime. Here, the overall goal is to provide simulation tools capable of handling any complex reinforced concrete structure, and to give a detailed forecast of the state of the structure at any time during its predicted lifetime.

The work is being conducted by a research group at the Section for Structural Engineering, which focuses on computational structural

Simulation of crack propagation in concrete structures

A better understanding of cracking processes in reinforced concrete structures leads to more reliable modelling and simulation of structural performance during the lifetime of the structures. The work is conducted by a research group within the Section for Structural Engineering.
Material and numerical models
Cracking in itself is a mechanically degrading process which may develop throughout the lifetime of the structure; and the state of a structure is a function of its history, since loads and material properties vary with time. In some cases, cracks are detrimental to protecting the steel against corrosion. Corrosion of the steel reinforcement may be very critical, since this will jeopardise structural integrity. The ability to predict the structural performance is essential to the design engineer, and the better the tools that are available for this, the more economic the design. Such tools comprise material models as well as numerical models.

Today there is a lack of well-documented material models for describing the properties of the crack surfaces and their interaction. The challenge here is, on the one hand, to predict the behaviour of the crack when it has experienced various degrees of opening, sliding and closing, and to embed this into a mathematical model. On the other hand, experimentally measuring the fundamental physical properties and their degradation is not a trivial task. Interesting results have been achieved in a testing machine with custom-made modifications to allow for bi-axial loading and control. Further, a mathematical model has been developed, which in a subtle manner captures the characteristic features of a crack, taking into account the degradation of the surface roughness and the dependency of the opening, sliding and closing history. With this model for the crack, it has been possible to convincingly mimic the test results.

Numerical simulation of fracture processes in concrete structures poses yet another challenge. The proper handling of crack formation and development is a topic which has recently resulted in two distinct contributions, one with an appealingly simple concept, and one that is much more complicated but more efficient. They serve different purposes. Where the complicated approach is suited for detailed analysis of a few cracks, the simpler approach lends itself to large-scale analysis with a multitude of cracks. Simulation tools for overall structural analysis must be very efficient to be of any interest in the everyday design process. Therefore, the effect of cracking on the structural performance of structural members has been integrated into ordinary beam elements for use in finite element programmes. These elements allow for the modelling of reinforced concrete structures, taking into account the effect of cracks on the stiffness of the structure. Furthermore, this tool permits a precise prediction of the cracking in terms of crack spacing and crack width.
Emergency evacuation of mixed populations

An INTERREG project led by DTU Civil Engineering has provided rare and valuable data and results concerning the evacuation dynamics of children. Special evacuation models are required for children in order to keep them safe in case of fire.

New data

In 2010, the EU granted DKK 10 million to an INTERREG project led by DTU Civil Engineering. The project KESØ (Competence Center for Evacuation Safety in the Øresund Region) is a cooperation with the Department of Fire Safety Engineering and Systems Safety at Lund University, investigating the evacuation of complex buildings for heterogeneous populations. As a part of the project, experiments with tunnel evacuations have been carried out and experiments on the evacuation of high-rise buildings are planned.

At the Technical University of Denmark (DTU), the focus is on describing heterogeneous populations. In order to map the movement parameters and evacuation characteristics of people with impairments as well as of children and young people, new data need to be collected and analysed.

Seven evacuation experiments with children and young people were carried out in autumn 2010, in collaboration with the fire authorities in the Municipality of Lyngby-Taarbæk. The experiments focused on the egress from primary and lower secondary schools of children and young people aged 6-15 years. The experiments were linked to full-scale fire drills carried out by the emergency services. By filming the course of action, data were collected on the flow of people in corridors and stairways as well as the pupils’ behaviour. Several models on evacuation are currently being validated using the data obtained.

Valuable results

Our research has provided rare and valuable data and results concerning the evacuation dynamics of children. So far, the findings show that existing evacuation theory and models cannot be directly transferred to children without further consideration. The evacuation velocity peaks at around the age of 10, where the children are keen to evacuate quickly and efficiently and have the physical and psychological ability to do so. Younger children move more slowly and with some hesitation, while older pupils seem to lack motivation to evacuate and are more sceptical about the situation. This was seen when observing movement through doors and down stairways, but also when observing the pupils’ initial response to the alarm.

More research is needed to develop models that describe the entire heterogeneous population and provide equal egress opportunities. As the KESØ project is a three-year project, the research continues with high expectations regarding the final outcome.

Background

Chapter 5 of the Danish building regulations demands safety for the occupants of a building in case of fire. Since Denmark introduced performance-based fire codes in 2004, it has become even more important to have a rational basis when designing buildings for evacuation. Nowadays, models are based on a normative and homogeneous description of people. In other words, heterogeneous groups, including people with disabilities, young people and children are poorly represented. At the same time, an increasing number of complex buildings, such as high-rise buildings and tunnels, are being built, buildings which are difficult to evacuate. New strategies are needed in order to keep people safe in these types of buildings.

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New BSc in Architectural Engineering

DTU Civil Engineering is launching a new BSc in Architectural Engineering, starting in autumn 2011

Architectural engineering is the discipline of applying engineering knowledge from the very early stages of building design. It requires multidisciplinary engineering skills, design skills and skills to work in an integrated way with other partners in the building design process, especially architects.

To achieve the goal of a sustainable future, buildings play a major role. Today, buildings account for 40% of total energy consumption in the EU, and a large amount of energy and other resources are also used during their construction. New buildings must be designed and existing buildings renovated with sustainability in mind from the very outset. Here, success requires that engineers influence and participate in the preliminary design stages by providing useful technical knowledge.

The goal of this BSc programme is to give engineers genuine design competencies, a good understanding of architecture and the latest research-based knowledge within the fields of building energy, building construction and sustainability assessment. The focus areas of the programme are design, energy, construction and sustainability. The goal is also to educate engineers who can initiate and drive the development of new, sustainable building materials, components and systems through a thorough understanding of the needs and technical possibilities.

Basic scientific courses

The BSc in Architectural Engineering is a three-year bachelor of science programme that gives direct access to the MSc in Architectural Engineering at DTU Civil Engineering. The study plan of the bachelor programme consists of mandatory and elective courses. The mandatory courses include basic scientific courses on mathematics, physics and chemistry and basic engineering courses on building energy, building construction and engineering design. Other mandatory elements are several project-based courses that include the final bachelor project. Elective courses constitute 25% of the study programme, and can be used by the students to define their own identity within the overall themes of the programme.

Interdisciplinary work

Engineering design is an important aspect of the study programme and is incorporated in the studies through theoretical courses on design and practical project experiences. During the studies, several design projects will require interdisciplinary work between the group of students on the programme, including cooperation with architectural students.

After completing the MSc programme, candidates will be able to work at all levels in the building industry, developing sustainable solutions from the individual materials, through building components and systems to the design of entire buildings. This could be in consulting companies, both traditional engineering consultants and architectural consultancy firms, or companies producing building materials and building components.

The new BSc in Architectural Engineering aim to educate engineers with genuine design competences, a good understanding of architecture and the newest research based knowledge in the fields of building energy, building constructions and sustainability assessment. Photo: Mikkel Strange
Greenlandic mining waste as a raw material in construction materials

A PhD Study at the Arctic Technology Centre is currently investigating whether waste from the Greenlandic mining industry can be utilised in construction materials such as concrete, bricks or insulation materials.
The mining of natural resources is expected to be one of the leading industries in Greenland in future. The Greenlandic government is working hard to ensure that the Greenlandic people and the environment are major considerations in this development. In the mining industry, waste products of crushed and chemically treated rocks, also known as mine tailings, often pose a serious environmental problem. Greenland has already experienced environmental problems relating to mine tailings, for example from the Black Angel Pb-Zn mine in north-west Greenland, where a decision to discharge the tailings into a nearby fjord proved disastrous for the local marine environment. High concentrations of heavy metals are still observed in the area today, even though the mine closed down in 1990. In today’s mining industry, mine tailings are usually stored at disposal facilities within the mining area and are continuously monitored with regard to their environmental impact. The storage and monitoring of the mine tailings are major concerns for the mining company. Currently, a lot of research projects worldwide are focusing on how to treat the mine tailings in order to neutralise their harmful effects.

Environmental and economical benefits
In this study we want to go a step further and investigate whether or not the waste can be reused for construction materials, for example as admixtures in concrete. Construction materials are usually expensive in Greenland because most are imported from other countries, especially from Denmark. Thus, introducing local materials, such as mine tailings, in construction materials could have both environmental and economic benefits for the Greenlandic community.

The overall aim of the PhD project is to characterise and test a wide range of resources, such as different types of waste products (mine tailings included as a resource of major importance) and natural resources, in order to determine their suitability for use in construction materials. The goal is to provide a manual that can be used to assess new resources. The manual should specify how to best characterise a new resource and determine what construction material (if any) could be produced from this resource.

Greenlandic mine tailings
Currently, only one mine is operating in Greenland: the Nalunaq Gold Mine in South Greenland, run by the British company Angel Mining plc. A cooperation has been established with the company, and in August 2010 PhD student Louise Belmonte visited the processing plant at Nalunaq. The visit provided an insight into the processing procedure, whereby the ore is crushed, chemically treated and gold is extracted. This procedure has a key bearing on the composition of the Nalunaq mine tailings. Although only one mine is in operation at the moment, several mining projects exist, and these are likely to develop into actual mines within the next couple of years. One such project is the Tanbreez Project in South Greenland, where a large deposit of rare earth elements is being investigated in preparation for mining. At present, small-scale extraction has begun and “pilot tailings” are being produced, which will also be available for this project. Furthermore, as it is considered highly important to be at the forefront in terms of sustainable solutions for mine tailings, Louise Belmonte and supervisors Professor Arne Villumsen, Associate Professor Lisbeth M. Ottenso, researcher Pernille E. Jensen and Post doc. Gunvor Kirkelund, all from DTU Civil Engineering, hope to extend the study basis by establishing contact with other mining companies working in Greenland in the coming year.
During the last four years, DTU Civil Engineering has been involved in a large study looking at the impact of the indoor environment on asthma and allergy among children. The study is being carried out in collaboration with Odense University Hospital, the Municipality of Odense, Aarhus University, Karlstad University and SP, the Technical Research Institute of Sweden. The project is providing substantial new information on current ventilation practices among Danish families.

Methods

The first phase of the study was a questionnaire survey involving 11,082 families with children aged 1-5 years on Funen. The questionnaire addressed the health of the child, characteristics of the dwelling, the keeping of pets, food habits and the habits of the occupants in relation to e.g. cooking, washing and cleaning. A subset of 500 children in Odense aged 3-5 years was selected for a more detailed investigation of the indoor environment in their dwellings. Each of the 500 dwellings was visited by two inspectors, who completed a checklist of building characteristics. As part of the inspection, CO₂ concentrations in the children’s bedrooms were continuously measured over an average of 2.5 days. The night-time ventilation rates in the rooms when the children were sleeping were then calculated.

Increased energy costs have resulted in buildings being better sealed and reduced ventilation rates in homes since the early 1970s. More recently, the increased focus on global climate change has lead to growing pressure to further reduce energy consumption in buildings. One way of doing so is to reduce heat loss from either natural or mechanical ventilation. However, low ventilation rates may result in increased concentrations of indoor-generated pollutants, which are associated with sick building syndrome symptoms and other comfort and health effects. Insufficient ventilation is suspected of being associated with the increase in allergic diseases among children. Moreover, low ventilation rates can be associated with increased indoor air humidity and thus a greater risk of dampness in dwellings, and of moulds and dust mite infestation.

So what are the ventilation rates in Danish homes? Surprisingly, we have very limited information about this. Two studies indicated that the outdoor ventilation rates in naturally ventilated dwellings were often lower than 0.5 air changes per hour, which has been the minimum required outdoor air change rate in the Danish building code for more than 20 years. These studies were done on a relatively small number of homes, built only in the mid-1980s.

Do our children have enough fresh air in their bedrooms?

The Indoor Environment group at DTU Civil Engineering measured the ventilation rate in the bedrooms of 500 children in Odense. One of the largest studies of its kind in the world reveals that the majority of Danish bedrooms are insufficiently well ventilated.
Results
The average air change rate in the 500 bedrooms was 0.62 air changes per hour. As Figure 1 illustrates, approximately 57% of all children slept at a lower ventilation rate than the minimum required ventilation rate of 0.5. The CO₂ concentration is a simple measure of how well an occupied room is ventilated. The indoor CO₂ concentration should not exceed 1000 ppm. Only 32% of bedrooms had an average CO₂ concentration below 1000 ppm during the measured nights. 23% of the rooms experienced at least a 20-minute period during the night when the CO₂ concentration was above 2000 ppm and 6% of the rooms experienced concentrations above 3000 ppm (see Figure 2).

Questionnaires distributed to the families, home inspections and interviews with the parents provided information about a broad range of residential characteristics and occupant behaviour. These data made it possible to construct a statistical model predicting the ventilation rate in a room. Some of the most important parameters influencing ventilation in homes were room volume (better ventilation in smaller rooms), the number of people sleeping in the bedroom (better ventilation with more people, see Figure 3), window and door-opening habits (better ventilation with more opening), sharing the bedroom with other family members (better ventilation in shared rooms), and year of construction of the dwelling (poorest ventilation in buildings from the early 1970s). The results further suggest that occupant behaviour influences ventilation rate to a much greater extent than parameters related to the building and its construction. While occupant behaviour was able to account for 30% in the variation of the measured ventilation rates, building-related parameters could only account for 9% in the variation, when such partial statistical models were built.

Discussion
The study shows that a large proportion of Danish children spend many hours every day in insufficiently ventilated rooms. The ventilation rate may be even lower when looking at the volume of air entering the measured room from outdoors, as opposed to the total ventilation rate including air entering the bedroom from neighbouring rooms. Other studies from around the world indicate that ventilation is a critical parameter in terms of the quality of the indoor environment and, in fact, the more fresh air the better – fewer indoor-generated pollutants and less moisture. Although saving energy is important, it should not compromise the health and well-being of our children and ourselves.
Low-temperature District Heating for Low-energy Buildings

DTU Civil Engineering is cooperating with Danish energy companies such as Danfoss, Logstor, COWI etc. as well as the Municipalities of Roskilde, Gladsax etc. to develop solutions with low-temperature district heating (LTDH) for low-energy buildings.

Fig. 1 Pilot LTDH project at Lærkehaven – Lystrup
Low-temperature DH for future energy supplies

As the world-leading district heating (DH) country, more than 60% of homes in Denmark are supplied with heat from district heating. The high market penetration and the high degree of consumer connection poses challenges for future DH industry development, especially when Denmark achieves 100% fossil fuel independence in 2050, with all buildings turned into low energy buildings.

In order to remain economically competitive and realise long-term sustainable development, the design and operation of DH systems needs to be re-examined. This is the main driver for bringing forward the next generation DH concept.

In 2005, Professor Svend Svendsen from DTU Civil Engineering initiated the low-temperature district heating concept and started conducting research into analysing heat loss from DH pipelines. In 2009, a DH group was formed at DTU Civil Engineering, which included one professor, one senior researcher and three PhD students, with LTDH as the focus area of their research. The next generation DH system is based on low network heat loss due to low network supply temperature and small pipe dimensions, and will be capable of widely exploiting renewable heat including waste heat from incineration and industrial processes, central solar heating plants and geothermal heat.

The essence of LTDH involves reducing the network supply/return temperature to 50/22 °C. Based on this concept, the network heat loss can be kept as low as 10-15% even when supplying heat to low energy buildings [1]. This concept has been implemented through an EUDP project carried out at Lærkehaven in Lystrup on Jutland to supply 40 low-energy houses (Fig. 1) [2]. Promising results have been achieved so far based on the field measurements.

Optimal DH system design

The new generation DH concept is stimulating both academic research and industrial product development. To provide an optimal solution for LTDH, it is necessary to implement various measures involving the DH network and the in-house substation to reduce pipeline heat losses, save on DH network installation and operational costs, and provide economical comfort and hygienic space heating and domestic hot water supply.

Distribution heat loss is one of the key factors affecting the operating economy of the DH supplier. To reduce heat loss, the branch pipe which connects the DH network to the house should be designed as small as possible with respect to capacity. For this purpose, a new Alu-flex twin pipe with an inner diameter of as little as 10 mm was developed and used for the Lystrup project (Fig. 2) [3]. Related research to investigate the temperature-dependent thermal conductivity of PUR insulation and different pipe design with a triple service pipe has been conducted [4].

The design of the DH distribution pipeline can adopt the same philosophy as that used in the design of branch piping. The maximum allowable network pressure drop should be exploited for each street in a DH network. Booster pumps can be applied to further reduce the pipeline size. To reduce the bypass flow rate in summer, the thermal bypass temperature at the critical user should be set lower than the current standard. The bypass water can be cooled off through additional heating load such as bathroom floor heating in the summer.

Two types of in-house substations have been applied in the LTDH concept including a DH storage tank and instantaneous heat exchanger (IHE). Due to the reduced operating temperature difference, a new type of heat exchanger with an enhanced heat transfer rate was developed (Fig. 3) [5]. The traditional domestic hot water storage tank was redesigned as a DH storage tank to avoid problems with legionella (Fig. 4) [5]. Due to the reduced network supply temperature and the elimination of water recirculation, the dynamic of the in-house substation becomes important and the related issues have been investigated [6].

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2010¹ : Calculated in FTE, full-time equivalent

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## Research

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<tr>
<td>Doctoral theses</td>
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</table>

## Finances

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td><strong>Revenues</strong></td>
<td></td>
<td></td>
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<tr>
<td>DTU-grant</td>
<td>73,944</td>
<td>70,340</td>
<td>66,718</td>
<td>59,827</td>
<td>56,656</td>
<td>53,184</td>
<td>52,523</td>
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<tr>
<td>External revenue</td>
<td>34,348</td>
<td>44,188</td>
<td>46,489</td>
<td>30,326</td>
<td>31,033</td>
<td>30,862</td>
<td>28,563</td>
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<tr>
<td><strong>Total</strong></td>
<td>108,292</td>
<td>114,528</td>
<td>113,207</td>
<td>90,153</td>
<td>87,689</td>
<td>84,046</td>
<td>81,094</td>
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<tr>
<td><strong>Expenditures</strong></td>
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<td>Wages</td>
<td>83,843</td>
<td>77,830</td>
<td>68,846</td>
<td>66,782</td>
<td>63,021</td>
<td>62,725</td>
<td>62,917</td>
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<tr>
<td>Other expenses</td>
<td>34,034</td>
<td>34,471</td>
<td>31,933</td>
<td>23,954</td>
<td>26,420</td>
<td>19,628</td>
<td>16,445</td>
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<tr>
<td><strong>Total</strong></td>
<td>117,877</td>
<td>112,301</td>
<td>100,779</td>
<td>90,736</td>
<td>89,441</td>
<td>82,353</td>
<td>79,362</td>
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<tr>
<td><strong>Result</strong></td>
<td>-9,585*</td>
<td>2,227</td>
<td>12,428</td>
<td>-583</td>
<td>-1,757</td>
<td>1,693</td>
<td>1,732</td>
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<td>Available amount</td>
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<tr>
<td>January 1</td>
<td>(11,281)</td>
<td>9,054</td>
<td>7,839</td>
<td>6,200</td>
<td>7,957</td>
<td>6,264</td>
<td>4,532</td>
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<tr>
<td>Carried forward</td>
<td>(1,696)</td>
<td>11,281</td>
<td>9,054</td>
<td>5,617</td>
<td>6,200</td>
<td>7,957</td>
<td>6,264</td>
</tr>
</tbody>
</table>

*Deficit caused by transition to a new income accounting principle.

STÅ²: 1 STÅ is one student annual work (1 STÅ=60 ects points)