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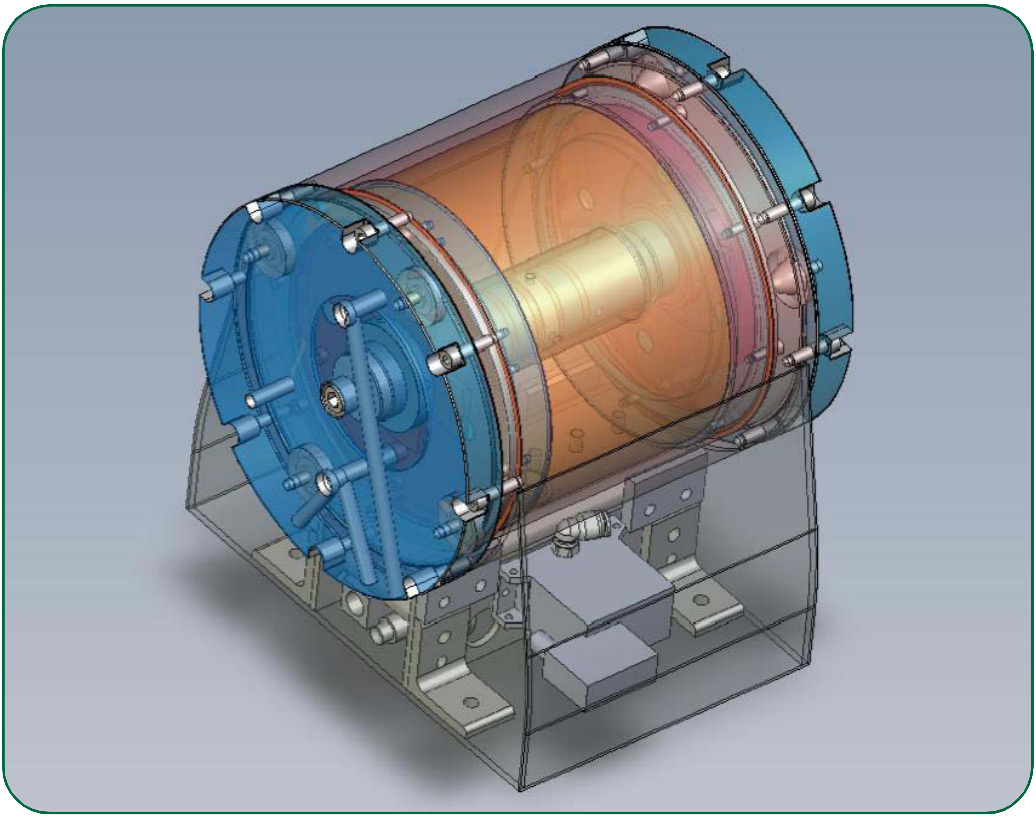

Olli Ventä (ed.)

Intelligent Products and Systems

Technology theme – Final report

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Keywords intelligent products and systems, functional inks, sensor systems, printing methods, printed codes, electronically readable indicators, printable conductive wiring, electric thin-film indicators, wireless sensors, distributed energy, smart energy storages, embedded structural intelligence

Abstract

"Intelligent Products and Systems" has been one of the four strategic technology theme programs of VTT Technical Research Centre of Finland during 2001–2006. This theme program consisted of three topic areas with their respective research projects. The topic area "Active and Communicative Package Systems" has significantly increased knowledge on designing functional inks and sensor systems combined with relevant printing methods, printed codes and printed electronically readable indicators. Also a series of projects focused on the development of printable conductive wiring and electric thin-film indicators. The projects could demonstrate a wireless humidity sensor and the fabrication and measurement of thin-films for room-temperature oxygen sensors. In the topic area "Distributed Energy", the basic idea of a distributed simulation environment has been presented and elaborated in a new context, in which building energy simulators and district heating network simulator are hydraulically and thermally linked from the power plant via the district heating network to the internal room conditions in buildings. In addition, new concepts were defined for the plug-and-play interconnection and management of distributed electric power systems. The topic area "Embedded Structural Intelligence" was aimed to produce know-how, verified technologies as well as integrated technological solutions for machines and vehicles industry products to improve their competitiveness. The activities have covered several aspects in facilitating intelligent and adaptive structural concepts: novel material technology, information technology solution in form of control systems as well as virtual design environments for intelligent products.

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Tiivistelmä

Älykkäät tuotteet ja järjestelmät on ollut yksi VTT:n neljästä nk. teknologiateemasta (tutkimusohjelmasta) vuosina 2001–2006. Teemaohjelma koostui kolmesta hankealueesta projekteineen. Hankealueen "Aktiiviset ja kommunikoivat pakkausjärjestelmät" projektien ansiosta tietämys funktionaalisista musteista tai indikaattoriväreistä, vastaavista antureista, tulostustekniikoista, koodeista ja sähköisesti luettavista indikaattoreista on kasvanut merkittävästi. Muutamissa projekteissa kehitettiin myös tulostustekniikalla tuotettavia johtimia ja ohutkalvoja. Hankealueen "Hajautettu energia" projekteissa kehitettiin alallaan ainutlaatuinen simulointiympäristö, jossa voidaan joustavasti yhdistää sekä talojen energianhallinnan simulointia että lämpöverkkojen ja lämpövoimalaitosten simulointeja. Toisissa projekteissa vastaavaa mallinnusta ja simulointia tehtiin sähköverkkojen osalta. Kehitettiin myös energiavarastoja. Kolmannessa hankealueessa "Sulautettu rakenneäly" kehitettiin monia funktionaalisten ja adaptiivisten materiaalien ratkaisuja kone- ja kuljetusvälineteollisuudelle. Projekteissa tutkittiin uusia materiaaleja, virtuaalitekniikoita ja aiheeseen liittyviä ohjausjärjestelmiä.

Preface

VTT Technical Research Centre of Finland has selected multi-year technology themes as one tool for the implementation of its strategy. The main goals of the internationally high-level theme programmes are technological breakthroughs and major economic and societal impacts. Networking both inside VTT and globally with the best partners is essential in order to achieve first-class results. Advanced technologies are translated into competitive products in partnership with companies. After careful preparations the theme projects were launched at the beginning of 2002.

The theme programmes started in 2002 were the following: 1) *Future Communication Technologies (2002–2006).* The Future Communication Technologies Theme is concerned with basic electronic technologies and advanced communication technologies. The key focus areas are RF modules, network interaction and mobility, service architectures, and intelligent environments. 2) *Clean World (2002–2006).* The aim of the Clean World Theme is to achieve a cleaner environment by utilising renewable natural resources more efficiently. The research Theme focuses on developing new technologies and applying new biotechnology, catalysis and energy technology in selected areas to create new product innovations. 3) *Intelligent Products and Systems (2002–2006).* The aim of the Intelligent Products and Systems Theme is to develop intelligent products and systems suitable for the society and business concepts of the future. 4) *Safety and Reliability (2002–2005).* The objective of the Safety and Reliability Theme is the appropriate and safe interaction of people and technology without unexpected faults or breakdowns during the life cycles of machines and equipment. The aim is to raise the productivity of production systems by improving their life-cycle reliability, to create world-class solutions for the life-cycle management of production systems, and to make use of these globally in competitive applications.

Years 2005–2006 have meant reforming both VTT itself and the contents and titles of the technology themes but the operational instrument has still been regarded valid and useful. The new theme programmes are the following: 5) *Service beyond (2005–).* Acceleration of service businesses by means of new technologies and concepts. 6) *Biorefinery (2006–).* Efficient use of industrial biotechnology. Efficient refining of biomass, particularly wood. New value-added products, process technology, bioenergy. 7) *Digital World (2006–).* Production, delivery and use of digital information in everyday life. 8) *Complex Systems Design (2006–).* Human-technology interaction, sensor networks and intelligent machines.

Embedding intelligence to products and systems has been an ongoing target and vision in science and engineering actually for decades. What is meant by intelligence in such a technical context may not be easy to answer. In the early days of computers, very often researchers, engineers, and even general public made parallels to human brains or intelligence. Later on the notion machine intelligence typically meant certain special kinds of information processing which became known as cybernetics, artificial intelligence, neural computing, or pattern recognition – all as opposed to more ordinary information and communication technology (ICT). Apart from ICT many other technologies are nowadays employed to engineer intelligent technical properties. Significant examples include at least the so-called intelligent or functional materials and the wide area of micro and other types of electronics.

Finnish r&d has been very active in studying so-to-say ICT enabled or electronics based intelligence. There have been several key projects, significant and extensive research or technology programmes promoting such type of intelligent products and systems. In 2001 VTT wanted another focus to intelligence that would pave the way for more competitive machine, energy, and consumer products and systems – by the aid of both ICT or electronics enabled intelligence and the emerging new materials science. The theme programme took shape accordingly, and the ensued projects showed how significant such a biasing course of strategy has been.

In the preparing phase in 2001 and for the first two years of theme programme implementation the theme was lead by Professor Matti Hakala. The overall programme contents and structure was created already during these years. After prof. Hakala's resignation from VTT in Autumn 2003, the theme programme has been managed by Dr. Olli Ventä. Active and Communicative Package Systems topic area was first managed by Professor Helene Juhola, and from Autumn 2003 on, Senior Research Scientist Eero Hurme. Distributed Energy topic area was at first lead by Dr. Ritva Hirvonen but, after hew resignation, in Spring 2003, by Dr. Raili Alanen. The largest topic area, Embedded Structural

Intelligence, has been lead throughout the entire program by Senior Research Scientist Ismo Vessonen.

The authors would like to thank everyone at VTT who have taken part in the implementation of the projects, as well as, all external but close partners, financiers, and supporters for excellent research and co-operation.

Espoo 30.11.2006

Authors

Contents

1. Introduction to Intelligent Products and Systems

Olli Ventä
Programme manager

1.1 Initial descriptions and definitions

Embedding intelligence to products and systems has been an ongoing target and vision in science and engineering – for decades. During the planning of the theme programme in 2001, by intelligence it was referred to products and systems that 1) continuously monitor their status and environment, 2) react and adapt to environmental and operational conditions, 3) maintain optimal performance in variable circumstances, also in exceptional cases, and 4) actively communicate with the user, environment or with other products and systems. The product or system concepts can include the product itself together with its performance, maintenance, recycling, and even financing.

As technology building-blocks that implement such intelligent features were foreseen functional, adaptive or active materials, sensor technology, MEMS (Micro Electro Mechanical Systems), signal analysis techniques, control theory, soft computing methods, ICT technology, RF communication, internet, virtual reality techniques, advanced structural mechanics, and dynamic simulation of multi-technology systems. The main purpose or application focus was to enhance the competitiveness of the so-called conventional but increasingly important industrial sectors – machines, devices, and vehicles, structures and buildings, process and energy industry, consumer products – by means of intelligent technologies.

After extensive analysis, internal brainstorming workshops, careful planning and evaluation activities during the year 2001, the theme programme adopted the following ***topics structure*** which was kept throughout the entire programme time:

1. **Active and Communicative Package Systems**
2. **Distributed Energy**
3. **Embedded Structural Intelligence**

The overall technology profile of the resulted theme program can be characterized as follows:

- Development, exercising, and application of intelligent or functional materials, for various applications
- Development and working on novel product, system, and mechatronic concepts
- Multi-technological modelling and simulation regarded as generic, key design tool for pilot and further applications
- Intelligent, computational or ICT enabled control – developed as far as needed
- Strong tendency to choose, actually or potentially, low-cost solutions of technologies
- Strong application orientation while maintaining generity, if possible.

VTT management designed certain principles or policies that would differentiate the theme program projects from the so-to-say average projects, as follows:

- High scientific and technological ambition level
- Maintaining or reaching for international level
- When successful, high impacts to industry and VTT
- Partnering with the best international R&D organizations, both as a means to reach the goals themselves or as a target position in the course of recognized advancement
- Benefit of implicit or discovered synergies, both inside multi-technological VTT and the partner network.

Furthermore, the proposed projects must be planned, evaluated, and followed-up according to the following:

- Goals, expectations
    - Compliance with the overall theme goals and VTT technology strategy?
    - Enough ambition?
    - Clear problem definitions and goal settings?
    - What kind of impacts will be provided by the results, what are the foreseen time-spans?
    - Are there generic benefits?
- Balanced risk and opportunity
    - Proper risk level vs. directly foreseen or evident results?
    - Evaluated risk vs. expected benefits?

- Long-range approach
    - Visible in project plan and implementation?
    - Comparisons to global R&D?
- Novelty in global scale
    - What is new?
    - How does the project compare with what is available in global R&D?
    - Are there related projects elsewhere? If yes, how does VTT differentiate?
- Substance spectrum, team composition
    - Enough multi-science and multi-technology?
    - Enough cooperation and partnering
    - Project teams should consist of 2 to 4 junior scientists and a couple of senior or mentoring scientists. Most of the team members should be able to spend continuously most of their time to the project.
- Project size
    - In the beginning 2 man-years minimum. Increase to 3 and 4 man-years in 2004 and 2005, respectively.
    - At the same time decrease the number of projects or obtain other funding sources, without significantly compromising with the goals.

During the theme lifespan, each topic area contained 2 to 6 projects. The preparing group was very well aware of the fact that there are many other kinds of intelligent techniques, methods, theories, features, systems, etc., practiced both at VTT and elsewhere. Several key projects, national and international programs, and other research activity forms were, or had been recently, ongoing and, therefore, the preparation group suggested somewhat other focusing directions. The selection of topics was thus a compromise of VTT's technology strategy, foreseen needs and opportunities, ongoing activities, existing expertise, and finally evaluation of competing proposals.

1.2 Topic areas

1.2.1 Active and Communicative Package Systems

<u>Motivation</u>: Packaging represents about 2% of the GNP in the developed countries. The volume of the packaging industry is about 345 mrd euros, about

which 1/3 in Europe. Packages will exist and their amount will increase also in the information societies. Digital commerce will increase the number of packages. The importance of packages as communicative media is increased. On the order of 50% of all packages are food packages.

Objectives:

1. Develop technologies and new solutions for marking, measuring, detection, tracking, tracing, information collection, storing and analysis, communication inside and outside of the logistics chain and management of the logistics chain.
2. The solutions are based on new or restrictedly used technologies like RFID, micro-radio technologies, biosensors, printable indicators, etc. Some of the technologies are existing whereas some have to be developed.
3. From the logistics point of view the most important is to apply IT, embedding instrumentation and software both in the product or package and in the logistics system.

Benefits: New functional characteristics can be created to the customer packages in order to create added value in the package itself (advertising, consumer information and education; edutainment, infotainment, etc.). Added value can be created also to the packed product (prohibition of the damages, freshness), or to bring in savings for the consumers (smaller waste, no overpacking), or to delivery (traceability, optimisation of the logistics chain).

1.2.2 Distributed Energy

Motivation: Liberalization of energy markets changes business environment. Globally growing energy demand and ageing power plants increase need for new investments. Moving from decentralized to distributed energy by renewables is a major trend. Cheap solutions for integration are needed. – By energy it is meant both electrical energy and thermal energy. Distributed electricity market is perhaps not a new idea. District heating is a common concept in Scandinavian urban areas, and the business and technology is very centralized. Achieving conditions of open thermal energy market is a huge technical and business-form challenge.

Target: Intelligent and cost-effective integration of distributed energy resources. Cost of integration must be reduced to 50% of the present costs.

Focus: Two-way communicating and controlling interface (plug-and-play operable 'fU or pT adapter') between grid and end-use. Intelligent control of production of grid and end-use. Energy storages, both electrical and thermal are a second focus.

1.2.3 Embedded Structural Intelligence

Motivation: Machine and vehicle industry is looking for new product concepts to maintain and gain competitive edge. The advances of information technology and modern materials technology are expected to bring great benefits. Embedded structural intelligence means including sensing, active reaction, decision making and communication capabilities into structures in order to achieve optimum performance, with minimized life cycle costs, in all operational conditions even in conditions unknown at the time of product design. The potential VTT's multidisciplinary know-how can be combined to find innovations and to promote the utilization of new technology in conventional machine industry products.

Target: Know-how to design and implement cost-effective embedded structural intelligence solutions to form a base for the design of innovative and competent product concepts for conventional machine industry.

Focus: Functional materials, cost-effective wireless measurement technique and adaptable control strategies for vibration, durability and shape control of machine structures.

Having defined these, the wide original scope was thus narrowed or biased to intelligence to be implemented preferably by intelligent or functional materials, electronics, modeling and simulation, and by systems science.

1.3 Topic maps

The selected topic areas represent fairly large research domains and, therefore, an effort was made to outline the intended or, according to literature, generally accepted topics decompositions or topic maps, to serve as program profiling tool. These topic maps, and the subsequent focuses selected from these maps also document the priorities seen at VTT, in 2001.

1.3.1 Active and Communicative Package Systems

Figure 1 decomposes further technology categories of the topic area. By active and communicative package systems it was meant technologies for measuring and monitoring the conditions in which the product itself is sealed, technologies for information exchange from and to a package, the respective logistics systems, and technologies for manufacturing the packages together with their intelligent features.

Monitoring consists of measurement or sensing itself, possibly of further signal processing (diagnostics), measurement readout and, depending on application, actions or controls onto package. Products are often packed either in vacuum or in a certain controlled atmosphere, such as nitrogen. To monitor the tightness or durability of the package is thus important which is usually realized by sensing the presence of oxygen inside the package. Similarly, moisture may be a desired or harmful condition, within a package. Certain goods must be kept within certain temperature limits throughout the logistics chain, whereas some goods are sensitive to mechanical shocks, vibration, pressure, etc. The freshness of many food products can be deduced by the appearance of certain gases.

Regarding information exchange the visual contents and appearance is the normal purpose. Product identification is an elementary feature for many advanced end-uses. Identification data is often encoded on the package and reading it out is often analogous to sensing physical conditions within the package. Visual read-out, of course, has been the predominant or only communication mode but along with increased functionalities of packages, increased automation in logistics, etc., electronic, laser or camera-based, magnetic, RF, etc., readout are becoming more common. In addition to product identification, packages are expected to give information of the manufacturing conditions, ingredients, risks to consumers, and many kinds of instructions. Authentication of the origin of raw materials, IPR, quality control in manufacturing and logistic chain is needed ever more.

To bridge the gap between package and logistic system, the logistic system is often equipped with interfacing or communicative instruments (sensors). To build intelligent or flexible package systems the many kinds of wireless or mobile communication technologies were regarded essential. Manufacturing packages themselves was excluded from the theme topic, whereas, producing the various elements of the intelligent features received a lot of emphasis in the ensuing projects.

Depending on the end-uses of packages, many kinds of other restrictions must be taken into account, eg., due to the fact that packages are used to seal food, medicine, or electrical components. Recycling is also a growing concern. Finally the cost of embedding intelligence to packages may become a serious obstacle on competitive markets.

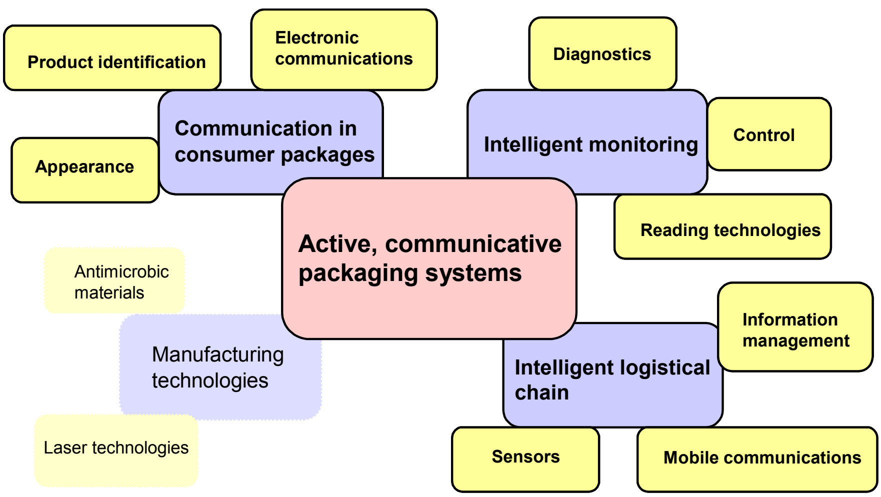


Figure 1. Active and communicative package systems and its major topics decompositions.

1.3.2 Distributed Energy

Intelligent techniques for distributed energy production and consumption is typically an issue of far-end of the energy delivery grid, close to private citizens to be equipped with better conditions to choose how to behave as a rational energy consumer or producer, or both. This is very contradictory to today's paradigms where energy is produced in big units or power plants and delivered in unidirectional manner to customers. Also and especially in Scandinavian countries, district heating is very common in urban areas, i.e., heat energy is distributed analogously to customers – in a very centralized way. But as often postulated, energy can be produced very locally, in small scale, and regarding both electricity and heat (and sometimes cool). A small producer-consumer entity (private home, farm, urban block, industrial campus, etc.) could then be full or partly self-sufficient regarding energy. Depending on conditions it may be connected to the energy grids in order to sell or buy energy, or remain autonomous and disconnected. Today technical or business infrastructures, even legislations, do not favor open, free, and small-scale energy market.

Figure 2 decomposes the topics or challenges relevant to be solved in such a distributed energy concept. The theme program focus is also shown in the figure. Energy production may be either centralized or large-scale, or distributed or small-scale. The are many kinds of energy sources or production technologies, some more appropriate to small-scale, other to large scale, and some technologies may be reasonable to both (just volumes differ). Energy must be distributed both within a small entity or via extensive energy grids. It is necessary to develop flexible and reliable interconnection technologies between local production-consumption entities and the wider grids. The respective technologies do exist for large-scale interconnection but it is far too expensive for small-scale nodes, and it is not in general meant to be flexibly or frequently switched on or off. Energy storages are also essential components in such concepts, and the technology does not exist today on a satisfactory level. Modeling and simulation is again a crucial methodology to study novel and non-existing energy production and consumption modes. New types of monitoring and controlling techniques are needed both on the grid realm and – especially – in the local node. Respectively, new device technologies need to be developed. Also the business structure is not there to enhance distributed energy. On such an abstract level the titles for all energy forms, preferably electricity and heat, are the same or analogous although going further in details they become very different. The distinction is naturally very obvious in the ensued projects.

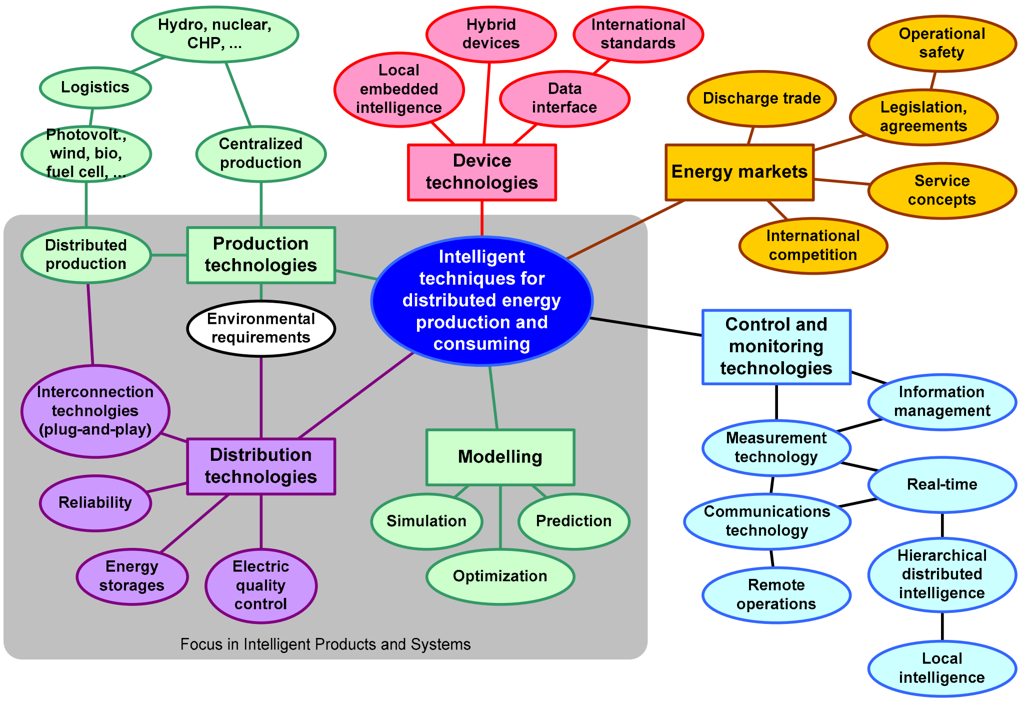


Figure 2. Distributed energy and its major topics decompositions.

1.3.3 Embedded Structural Intelligence

Mechanical engineering can be decomposed into relevant topics, from embedded intelligence point of view, as depicted in Figure 3. The first stage decomposition consists of sensing, actuation, communication, and decision-making reflecting the main functions of any intelligent system. The theme program was especially interested in functional material based sensing and actuation, and in advanced control of respective intelligent mechanical structures or systems. In mechanical engineering the most typical quantities measured are strain or force, various kinds of pressures, various position and kinematic variables, and condition monitoring related variables. Preferably the projects were looking for inexpensive sensors, and wireless depending on context. Recently, autonomy in energy has become a hot research topic in the field of sensor networks but, at least in 2001 this was not regarded as a primary goal.

Conventional actuators are often present in applications. Intelligent actuations often adds the necessary striking features, on top of or embedded in existing actuator structures, whereas in some applications the actuation may be, solely or to a significant extent, functional material based. By technology, functional or intelligent materials can be decomposed into magnetostrictive, piezoelectric, rheology based, the many kinds of polymers, elastomers, and shape-memory alloys. Composite materials are a very interesting domain. The supply energy to drive the intelligent structures exhibit often serious engineering problems; often annoyingly high voltages are needed. The topic was not especially addressed in the projects but there seems to be a clear need of advanced power electronics, etc.

Communication among various architectural parts is again a special topic in sensor network research but we did not put more emphasis on that, than practically needed. We wanted to keep the projects mechanical engineering oriented. Similarly, user interfaces were not in focus.

Control in general can be an intended property of a functional material structure, or it is based on electronic hardware and/or software embedded or connected to the application. Modeling and simulation is a very important approach taken in almost every project. Regarding the control methods themselves, both the so-called conventional control algorithms (PID, logic controls, etc.) and especially the many adaptive or learning control algorithms are necessary. Certain emphasis was also paid to the implementation hardware suitable for such machine automation applications.

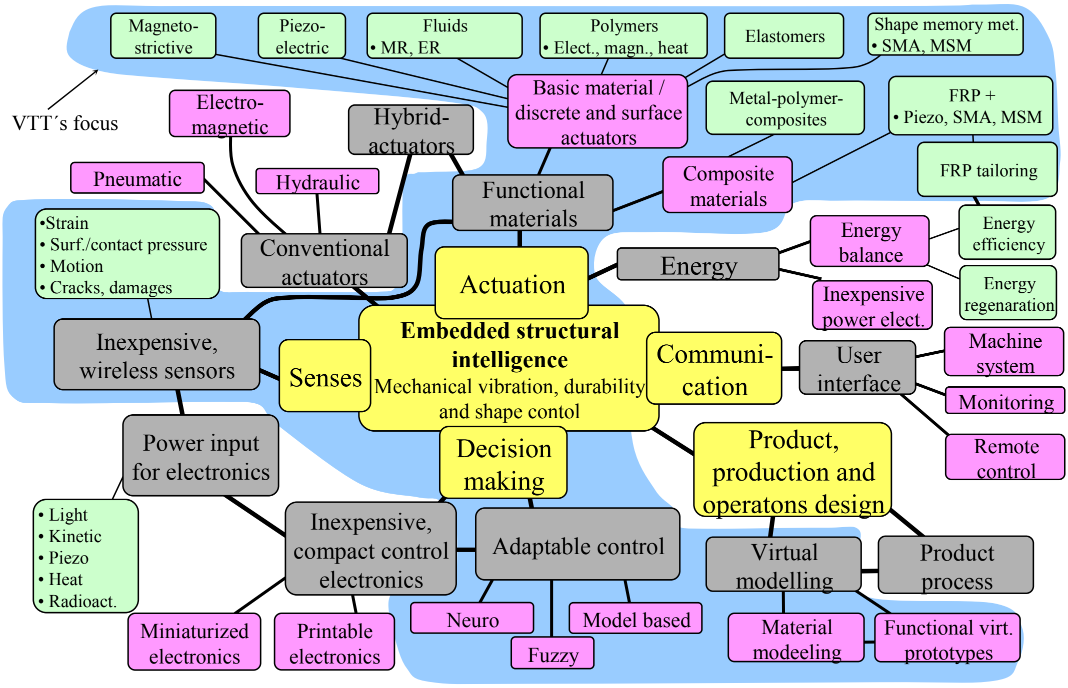


Figure 3. Embedded structural intelligence and its major topics decompositions.

1.4 Visions, goals and drivers

1.4.1 Active and Communicative Package Systems

Intelligent packaging devices embedded in or onto food packages by using, e.g., printing techniques, open up extensive possibilities to monitor product quality, to trace critical points, and to give information of the supply chain. The intended concept in this theme program is built upon an idea of chemical or other **indicators** embedded on packages. Perhaps the most well-known indicator to public is the pH indicator where certain material is applied to a sheet of paper, and the material changes colour when the ambient pH changes. The idea of changing colour in response to numerous other ambient conditions are extended here and exploited in package or product quality monitoring. Indicators can give information about the product directly, about the package and its headspace or about the storage conditions of the package. It would also be most interesting and advantageous if the indicator substance could be applied or attached to packaging substrate by using inkjet technology which is the cheapest, most flexible, and most common technology to any kind of packaging phase printing.

Certain information, such as ‘sell before’ or ‘expired’ dates or fabrication batch identifications, needs to be printed on packages and, from technology point of view the field dominated by inkjet printing. Compact inkjet printing devices are integrated into packaging lines in order to print small areas rapidly and on different substrates. Quality monitoring information enabled by visible or invisible indicators can be included in packaging data.

Many foods today are packed or sealed in a protective oxygen-free atmosphere. Accordingly, indicators sensitive to oxygen attached inside the package can be used to signal whether the package has been damaged or not (Figure 4). Various promising substances exhibiting colour change in redox-reactions and enzymatic systems have been demonstrated. The colour change reaction of the enzymatic indicator system has been studied using different types of enzymes in water-borne binder systems. Analogously, freshness indicators may show directly the microbiological quality of the product. The indication is based on a reaction between substances in the indicator and volatile substances from chemical, enzymatic and/or microbial spoilage reactions in the product. Other types of intelligent packaging systems are, e.g., time-temperature indicators and humidity indicators. The most important requirement for product quality indicators is the correlation of the sensor indication with the product quality. The colour change or other readout must be irreversible and easy to understand. Some product quality indicators are already commercially available, and it is foreseen that they are becoming more common particularly when they can be read at a distance. This will need electronically or magnetically readable indicator sensor elements. Visually readable indicators seem to be a necessary intermediate phase at the introduction of the concept.

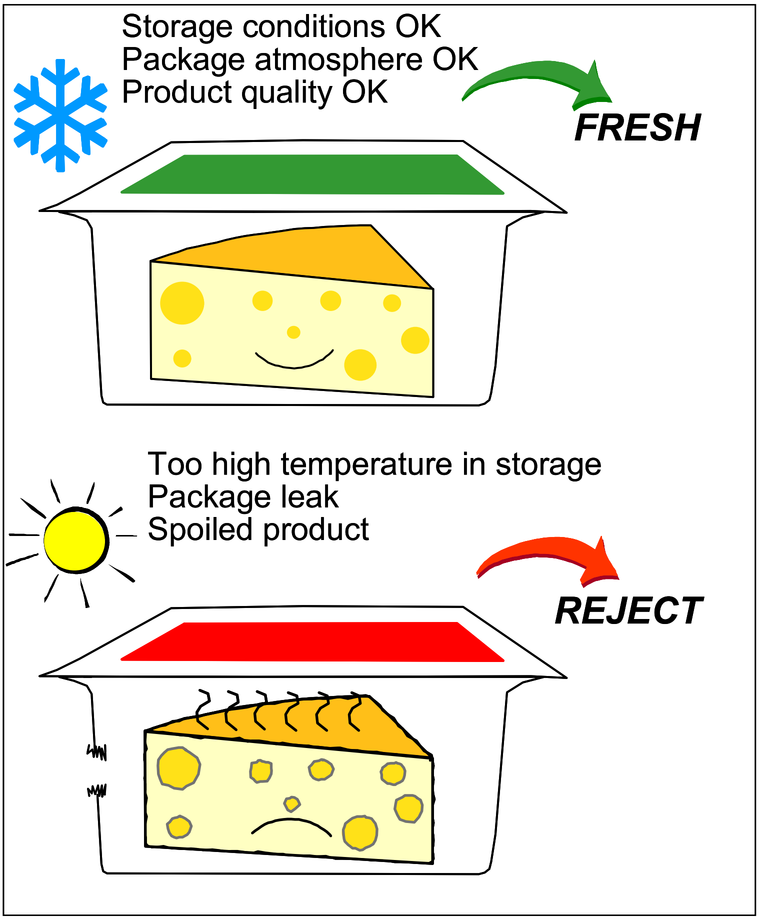


Figure 4. Principle of product quality indicator in a food package.

Two-dimensional **bar-codes** offer great benefits to package production and logistical chain. The codes may carry large amounts of information and this information is carried along with the package. Two-dimensional bar-codes can be easily read with a digital camera which is nowadays becoming a common feature in mobile phones. Anyone with a camera can read the information in the code at anytime during the logistical chain. The codes can also contain extra information that the consumer may access further with his camera phone. Only the compulsory information will be written in plain text, whereas, other information can be embedded in the code. Such bar-codes carrying the extra information need not much printing space. (Figure 5.)

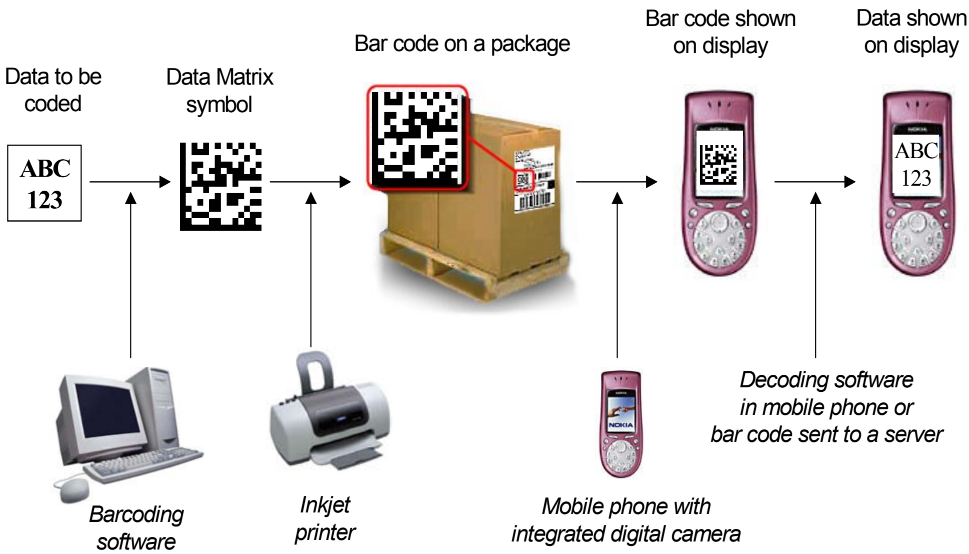


Figure 5. Envisioned embedded coding and detection of information on packages.

Thirdly, efficient and reliable supply chain is important to trade and industry. By instrumenting packages or other transported entities with indicator-based or any kind of intelligent devices, also capable of wireless communication may change the business models in logistics and trade significantly.

The main purpose or vision has been to **develop and integrate active, communicative packaging with an effective logistical system** for sensitive and demanding products. The developed system shall be based on wireless communication. Basics for projects (2002–) was to build a modular research environment for the development of intelligent packages and to develop ink-jet printable diagnostic inks (onto plastic materials) monitoring the quality of especially packed food. Research and experimental studies for coding and optical and electrical detection systems, with the purpose to outline the possibilities of logistical, as well as, anti-counterfeit systems based on printed indicators has been studies, too.

1.4.2 Distributed Energy

There have been many potential drivers for distributed energy generation (DG) development such as open electricity markets, environmental issues (green values), development of small power generation systems, cost of power and heat transmission and increased power quality and reliability demands of end-users. Properly applied distributed generation can have many benefits such as more reliable energy supply, better management of energy use and production, energy savings and increased use of renewable energy. DG can also give wider possibilities for end users to manage energy e.g. to sell the surplus energy that can be electricity, heating or cooling energy. On the other hand the increase of the distribution of energy production can include many risks and also the implementation level and time of DG can also vary in different countries.

The optimal implementation and use of DG systems and their integration to public energy distribution can be very challenging task and may require a lot of new products and systems. That means not only the need to develop energy production technologies but all kinds of products and systems, international and local guidelines, standards and process models for supporting the cost-effective and intelligent interconnection and management of local energy production, storage, use and trade. The two-way energy flow and energy production units in end-users facilities will give higher demands for the control and safety systems. The intelligence of the energy management will have an essential role for the optimal implementation and use of the distributed resources. (Figure 6.)

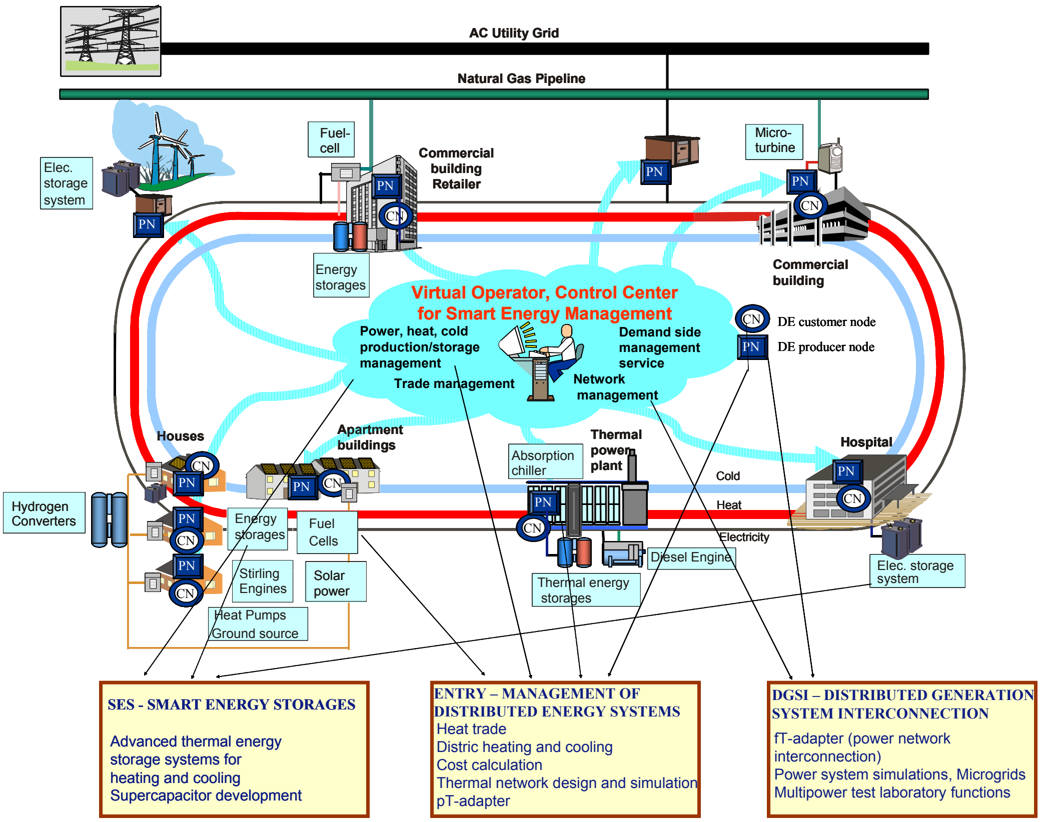


Figure 6. Postulated distributed energy system benefiting of local production and consuming capabilities.

1.4.3 Embedded Structural Intelligence

Finnish or European machine and vehicle industry are looking for new business and product concepts to maintain and gain competitive edge. From technological point of view, the huge steps taken forward especially in information technology and modern materials technology can give opportunities for innovations. With co-operative research VTT's multi-disciplinary know-how can be combined to catalyze the innovation process and to promote the utilization of new technology in the products of conventional machine industry.

At the same time the businesses are moving from product orientation to extended product or service orientation, i.e., appropriate performance, capability or reliable operation is sold and bought. Customers optimize the overall cost-effectiveness of an investment which brings under consideration the whole life-cycle, from product idea through design, manufacturing, after-sales, decommissioning and recycling. Data, information and knowledge, generated in products and processes are rapidly transferred to almost anyplace via information networks, and are fuel for the new service businesses. This new service oriented business model calls for innovative intelligent products which will also be in the future an important cornerstone of industry competitiveness. Integration of novel and conventional technology combined with innovation capabilities are becoming critical keys to success.

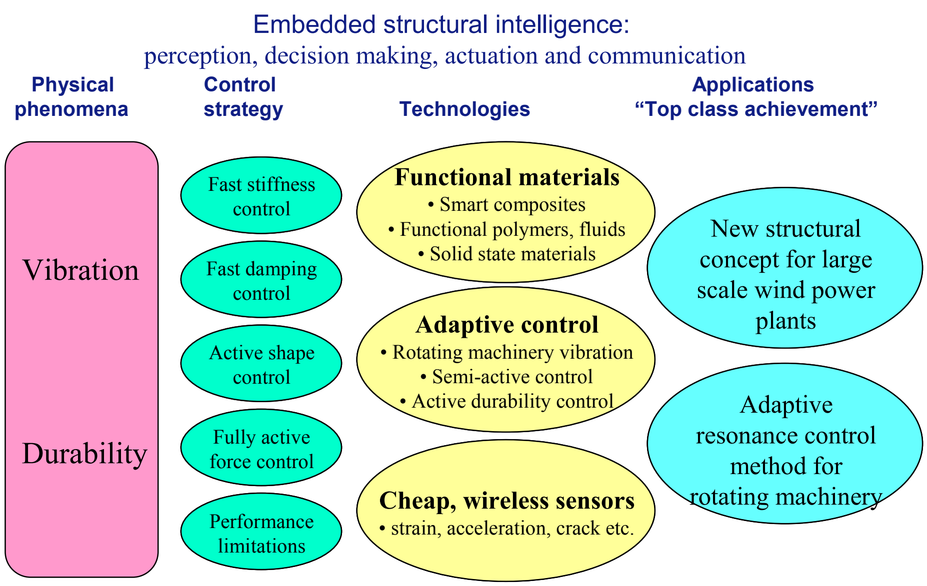


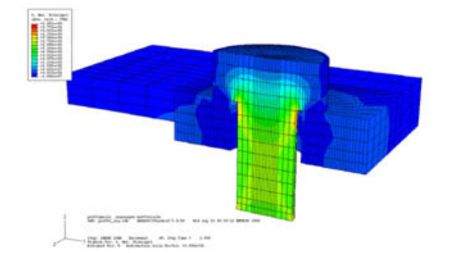
Figure 7. Building envisioned demonstrators benefiting of embedded structural intelligence.

Embedded structural intelligence means incorporating an appropriate set of sensing, active reaction, decision making, and communication capabilities into mechanical structures in order to achieve optimum performance in all operating conditions – even in conditions unknown at the time of product design. Minimization of life cycle costs is an important objective. The research topic

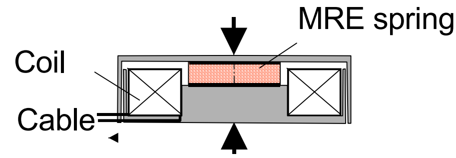
Embedded structural intelligence is about studying the implementation of product or component level intelligence. (Figure 7.)

Embedded intelligent technologies enable novel structural concepts intended to implement the required functionality and are a way to make the most of the properties and the information content of a structure or machine. One important feature is also the capability of the product to independently adapt its operation according to changing conditions. An intelligent product or structure shall be simple in design, well-performing, cost-effective, reliable, easy to use and environment-friendly. The aim is to save material and energy. The abilities to diagnose, make decisions, tune operation, fix and heal problems and damages i.e. to adapt are important. The overall usability is improved by the aid of communication ability. (Figure 8.)

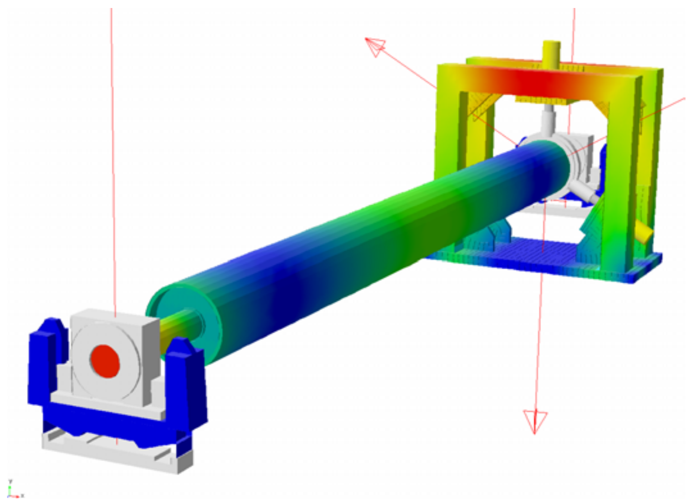
The speed of product development cycles is constantly increasing. Possibilities to conduct technology developments striving for innovations and technology leaps along with the actual product design are limited. The new technological ideas, concepts and solutions have to be ready-to-go and reliable in order to be accepted for commercial use.



a) An adaptive joint.



b) An adaptive damper.



c) An actively controlled rotator

Figure 8. Intelligent mechanical structures.

1.5 Technology roadmapping – the method

Strategic planning is an essential part of any technology or research programme. Based on the on the recommendations of the interim evaluation report, an effective roadmapping activity was started in Spring 2004. The following roadmapping scheme is adapted from numerous sources and adjusted to research management, especially. The method is based on theme leader's long-time experience on research strategy work, as a practical group leader and as a national technology programme leader.

In most descriptions or depictions there are four levels of roadmaps. Companies typically design *product level roadmaps* which indicate how their product or product family generations are expected to evolve over the coming years. Such plans will be based on a) how businesses or markets are foreseen or predicted to behave (*market level roadmaps*), and b) what the company reasonably expects to be capable of producing or developing (*technology level roadmaps*) either itself or within a partner network. The advancement or evolution of enabling technologies is a useful level of technology roadmaps for an applied research institute, such as VTT. Underneath, we may say that science makes progresses (*science level roadmap*) in its own manner. The roadmap levels are strongly interlinked, and in general, it is not possible or worthwhile to define them in isolation.

Furthermore, there are many disciplines or templates how to form a technology roadmap but certain common elements are always represented. In the beginning of the *time-dimension* is the technology, product, science or market *baseline* or *state-of-art*. It is then useful to consider a *short-term* future, usually 1–3 years ahead from the present. At the other end of the time-dimension are *visions* that are planned, predicted, or expected to reach, in long run, usually beyond five to ten years from now. In between it may be possible to distinguish *middle and long term* stages. Filling in items to a technology roadmap essentially means describing how things are expected to develop, with alternatives, from the state-of-art to visions. A *technology strategy* then means selecting or deriving actions that are necessary to implement at least part of the roadmap, from present to vision.

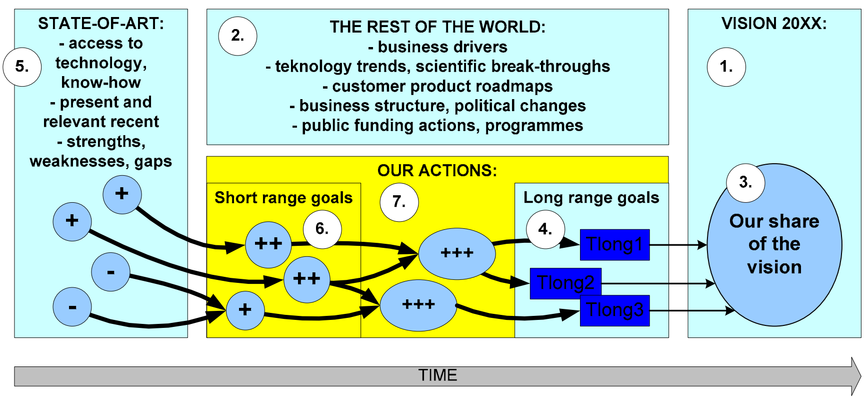


Figure 9. Simple roadmapping procedure to effectively bring together existing expertise, knowledge, visions, and opinions and to force teams to produce a technology strategy from the present to the envisioned future.

For many reasons, it is often difficult to develop useful technology roadmaps. The following structure and systematics has proven to be very effective, and it was used in steering the projects from 2004. The methodology consists of four elements: state-of-art, vision, the rest of the world, and our actions, i.e., the core roadmap or ensuing technology strategy. (See Figure 9.) If the topics are not too large, the roadmap can be produced in 1–3 intensive one-day workshops, provided that enough expertise of the organization is present, i.e., the knowledge, experience, and visions needed are available in the workshops. Before the workshops, it is useful to focus the discussions by the aid of topic maps or lists. We used the topic maps of the three topic areas, as described in Chapter 1.1.3.

The procedure *starts from Vision* (1) that describes the future world without technical, or any kind of problems. Vision must be written or is useful to write from applications or end-uses points-of-views, in an ideal way. There are perhaps systematic procedures to arrive in good visions but, in a research-oriented group, this is seldom a problem! Moreover, if visions are depicted in applications-oriented phrases or notation, it is easy to communicate about them with applications specialists.

The second step is to review the *rest of the world*, in regard to vision (2). What is happening there? What must be taken into account? In a research organization this section may be conveniently divided into what is known about relevant products development in key companies, what are other research institutes or universities doing, and what public funding research initiatives are ongoing or expected to open. The third step is to *review the vision* (3) by taking into account the findings, facts, or beliefs from step 2, and decide about narrowing what is our part of the vision that often in the beginning is extended to wider areas the organization or team can ever cover.

While visions are, on purpose, very idealistic or even unrealistic, the fourth step is meant to bring the visions on ground, i.e., to describe what technologies and other *enablers* are needed that make the vision (or our share of it) possible (4). Here the workshop must be as concrete as possible, use technical language, etc.

The decomposition or list of the enabling items also serves as an effective counterpart for comparing to what the organization has or has not, that is the *state-of-art* or technology baseline, with regard to vision (5). In workshop discussions, it is practical to make *access to technology* a synonym to state-of-art. Comparing the state-of-art with the list of long range goals gives the identification of respective and relative strengths, weaknesses, and gaps.

From state-of-art it is fairly easy to advance to *short range goals* (6), if the workshop defines them as goals that are directly achievable based on state-of-art. Often the team or organization already has ongoing projects or activities that list such shot term goals as results or deliverables of their research tasks. The last stage (7) is to design the roadmap steps between short and long term goals. It is perhaps difficult to give advice how to do it – but again an experienced and knowledgeable expert team probably finds ways to do it!

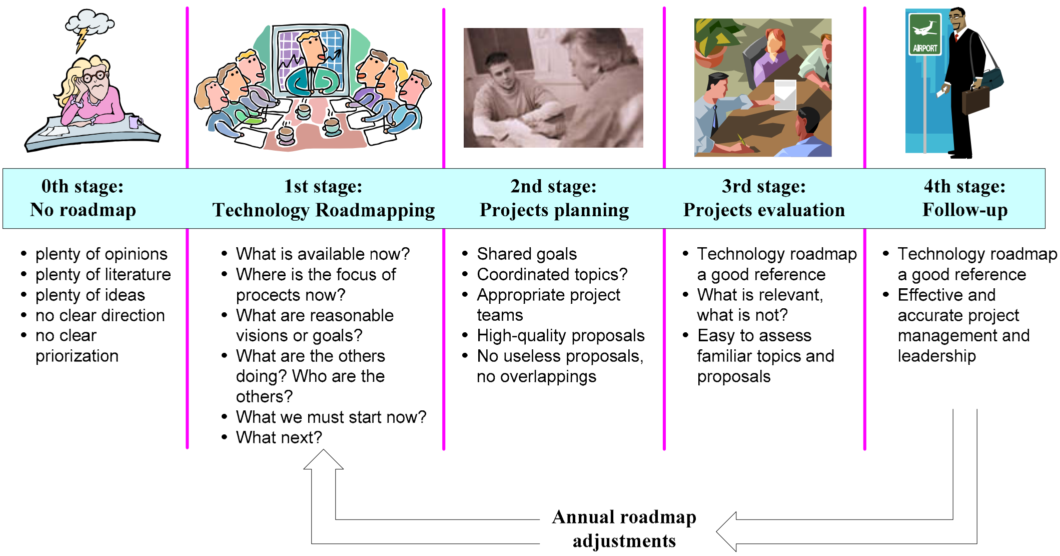


Figure 10. Shifting from undetermined stage to effective, strategy or technology roadmap enabled research management.

Such a topic specific technology roadmap becomes a very effective tool for managing a technology or research program. The benefits are depicted in Figure 10. A technology roadmapping workshop(s) usually creates an open, forward-leaning, motivated, and sharing attitude to projects planning. A successful roadmapping explicitly indicates the most important activities that must be taken next in order to reach the commonly agreed goals. The organization or project teams become capable of writing better proposals that are easier to coordinate and evaluate, and later on, when the selected projects are ongoing, it is easier to follow-up how the projects are other activities are advancing.

This roadmapping procedure has been adapted by the theme program leader based on numerous strategy making sessions at VTT, based on the author's experiences on business analysis and modeling techniques in software engineering, based on several books and short courses given by business consultants, and most recently based on extensive experiences on national level when acting as a programme leader of the Tekes technology program called Intelligent Automation Systems (2001–2004). This structuring and procedure seems to be one of the only ones that work in the practice. This has also been proven by several recent other technology roadmapping activities at VTT.

1.6 Roadmaps for 2005–2006 – and beyond – and the decided projects flows

In spring 2004, after the mid-term evaluation of all the four VTT technology theme programs, the above described roadmapping workshops were held among projects leaders and researchers of each topic area, Active and communicative packaging systems, Distributed energy (further divided into distributed electrical energy, distributed heat energy, and smart energy storages), and Embedded structural intelligence. As mentioned before, the topic maps of Chapter 1.3 and the visions of Chapter 1.4 served as excellent starting points. To various readiness these were crafted already in the preparation phase of the technology theme in 2001.

1.6.1 Active and Communicative Package Systems

The topic area group first envisioned the domain for year 2010: usage and needs of packaging is still increasing, package production is integrated to product fabrications, packages contain ever more information, packages will be active and communicative, packages provide product traceability and safety, packaging is high-quality and cost-efficient, package functionalities are compatible with the interfaces of logistics or other information systems, demanding customers are ready to expect accurate information, services, etc., and they are ready to pay for them, packages deliver experiences, trust, and ease of use, the logistics chain is transparent and integrated, business processes are changed, VMI (Vendor Managed Inventory) is commonplace. The team kept the original goal, defined already in 2001 during theme program planning.

The environmental values, product safety, packaging innovations, etc. seemed to be significant trends to follow, together with the gradually extending ICT to support the more networked, flexibility, and efficiency bound businesses.

Based on, e.g., the activities during the first two years of the theme program projects, the indicator concepts showed promising in the laboratory but also first commercial – yet technically simpler – R&D contracts were about to start.

Regarding actions for the rest of the theme program period and beyond, the chemistry and applicability of the indicator substances clearly needed further research. However, visual detection of indicator-enabled product or package quality was felt too narrow and, on the other hand technically fairly mature. The group concluded that in many logistical chains the consumer packages are kept inside so-called transport packages, meaning invisible to possible cameras or human operators, most of the time. Therefore, project planning for electronically readable indicators, possibly based on RFID, was started immediately. – The evolution of logistics infrastructure perhaps remained unclear. How would the giant food industry shape up, what are the value chains, what kind of information system will be used in logistics control, warehouses, grocery stores? Joint projects with the respective stakeholders would be more appropriate to obtain a better insight.

The roadmap of Active and communicative package systems is presented in Figure 11.

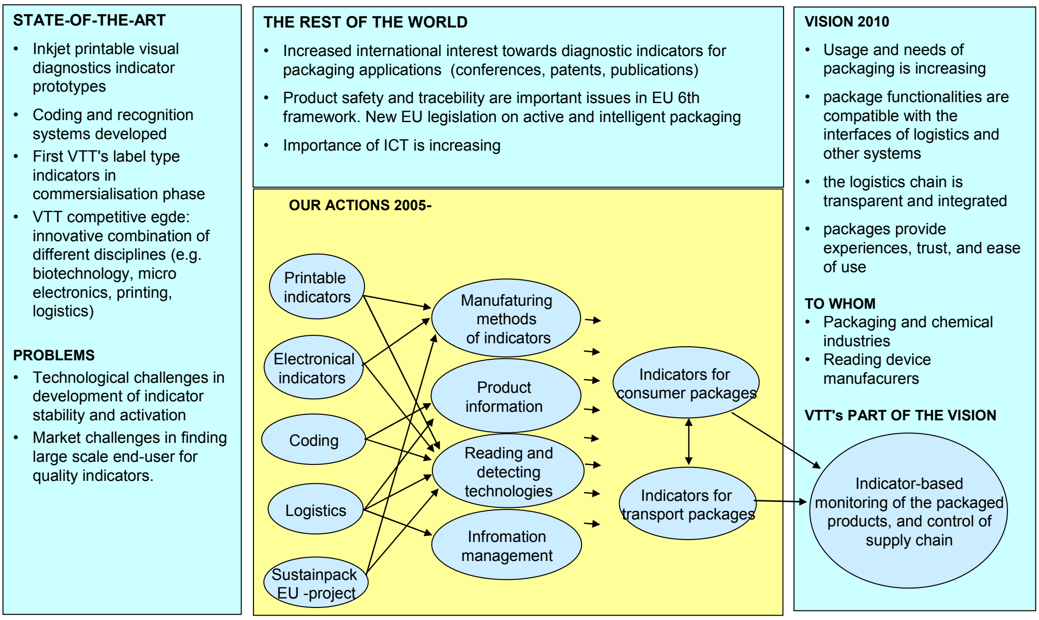


Figure 11. Technology roadmap of Active and communicative package systems, as analyzed in 2004.

Accordingly the decisions taken regarding the projects for 2005 and 2006 can be summarized as follows, and as also shown in the projects flow of Figure 12.

- The concept of indicator ink printed on packages and read optically together with 2D encoded information was left aside; ink development was continued.
- The electronic reading projects are started. Optical or camera based reading is essential for the end-user of the package but for the future functions in a logistics chain an electrical reading was foreseen necessary.
- Projects developing intelligent logistical chain were redirected other project instruments.
- EU project (SUSTAINPACK) started already based on success in earlier years of the theme programme.

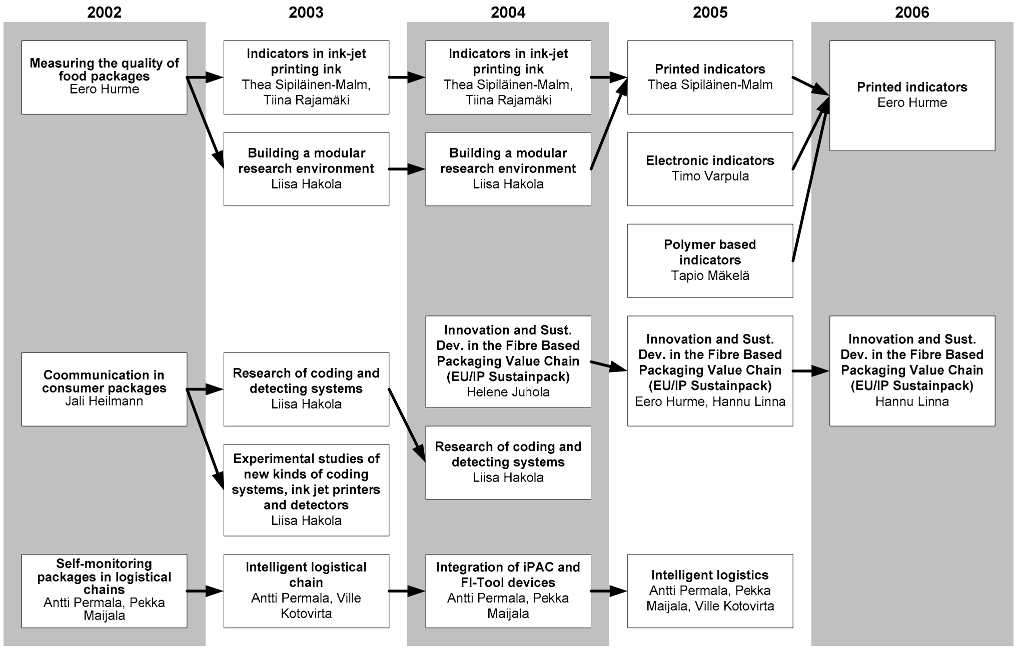


Figure 12. Actual projects flow of topic area Active and communicative package systems.

1.6.2 Distributed Energy

Today there are a lot of activities worldwide, which are some way related to DG issues. On the domestic level, there are, e.g., Tekes technology programs in the field of Building Services (CUBE 2002–2006) and distributed energy systems (DENSY 2003–2007) promoting the technology transfer from theory to the practice. VTT Processes started in 2002 the Distributed Energy research project within the Intelligent Products and Systems Theme. The Distributed Energy research project consists of three sub-projects for intelligent interconnection and management of distributed energy systems: "DGSI" (2002–2006, "FU-adapter" in 2002–2003) focusing on power systems, "ENTRY" (2002–2006), focusing mainly on thermal energy (heat/cold) systems in building and areal level (distributed simulation environment development) and "SES" (2005–2006) focusing on smart energy storages for the power and thermal energy management.

The framework of the project is defined and presented in the technology road map of distributed generation. The ultimate goal is a **Virtual Utility** which means intelligent technology and management of distributed energy (power, heat and cold) generation and use, i.e., a concept where a group of local small DG units operate virtually like one energy utility. The focus is the intelligent management of the energy production, network and use and intelligent cost-effective two-way interconnection of distributed energy production units. These mean also the need of many new design, modelling and simulation concepts.

1.6.2.1 DGSI – Distributed electric power system interconnection

The focus in first two years has been to create a two-way communicating and controlling interface 'fU-adapter' (plug-and-play) that is the core part of DGSI. fU-adapter project was mainly concentrating on the interconnection of fuel cells with DC and inverter connection, and wind power unit with AC or inverter connection.

In the beginning of 2004 the sub-project dedicated technology road maps were generated based on the earlier work and present idea. An expanded project DGSI was started with the focus on the intelligent control system concept of the "Virtual Utility". DGSI controls and connects the interconnected production to the customer preserving the distribution network stability and power quality both in the normal loading and fault conditions. New network solutions such as microgrids, adaptive intelligent protection and modern system control principles (forecasting, communication solutions, demand side management etc.) have been studied.

Later the microgrids concept was investigated more careful. By using that concept the original objective of the project – easy interconnection procedure – might be possible to realise in the longer run, because a microgrid acts as a single connection node for the supply network whatever internal structure it has. Concept was indented to be simulated and tested in the real testing environment MULTIPOWER which is the topics of one DENSY project. Due to the delay in that project we have to postpone these verifications.

The roadmap of Distributed electric power system interconnection is presented in Figure 13.

STATE-OF-ART
- energy markets, NordPool allow IPPs
- interface technology often based on inverters but no unified standards or compatibility principles
- Finland, Sweden, Norway advancing slowly, other Europe when subsidized (photovoltaic, wind)

Problems:
- connecting to grid expensive for small devices, diverse requirements
- traditional technology for distribution changes slowly
- small-scale production still coming, becomes a problem when volume exceeds 20%
- management of the entire distributed energy system

THE REST OF THE WORLD
- EU focus, research coordinated in ERA
- Tekes-DENSY technology program
- ICT as a key enabling technology
- DG spreading in many countries: subsidization, regulations, energy prices affect

OUR ACTIONS
- energy web, microgrid, micronode
- exploiting power electronics
- prediction methods for production and consumption
- EU cooperation

Technical challenges
- cost of power electronics

Solve other obstacles:
- create home market for small units, profitability, knowledge sharing
- focusing the subsidizations, etc.

WHAT: Virtual energy factory - a distributed production and consumption of electrical energy
- intelligent interconnection to grid
- modeling and simulation
- business

To whom:
- all stakeholders in energy sector, device manufacturers, energy producers (IPP), energy consumers, grid companies

How:
- readyness to design, modeli, and simulate
- understanding the system and business realms
- bottleneck technologies solved

VTT competitive edges:
- solving multitechnologycal challenges
- domestic and international networkin

Figure 13. Technology roadmap of Distributed electric power system interconnection (DGSI) in 2004.

1.6.2.2 ENTRY – Distributed thermal energy systems

Conventional combined heat and power generation (CHP) used in large power stations is a process where heat (generated as a by-product of electricity production) is captured and delivered by means of district heating network to heat buildings. In recent years smaller CHP prototypes have emerged (e.g. fuel cells, Stirling engines) and the concept of decentralisation of energy systems has become a subject of research. In this context, mini- or micro-CHP solutions scaled down for a single building come to the focus. The main objective of this project was to develop tools to enable a versatile analysis of the entire energy supply chain covering the source (remote or local), distribution system and utilization of heat in buildings.

Figure 14 shows how we saw in the year 2004 the drivers, trends and future development of distributed energy and how we planned to respond in research projects, also in the future. Currently, on the domestic level, there are separate confidential industrial assignments going on in this field. In addition, networking with private companies, and other research organisations is strengthening via technology programs funded by Tekes in the field of distributed energy systems (DENSY) and building services (CUBE) promoting the technology transfer from theory to the practice, see listing of the projects below. Integrated software prototype is being further developed within the frames of newly established SIMANTICS-project. Preparation for demonstration of fuel cell system is in the scope of the new large project SOFC-Power 2007–2011 that is in the final phase of preparation. This project has international collaboration connections (within present Framework Program FP6 and soon starting FP7 of European Commission) and will belong to new Tekes funded technology program on fuel cells.

International co-operation has been established and continued mainly within the frames of International Energy Agency, Implementation Agreements on:

- Energy Conservation in Buildings and Community Systems (ECBCS), Annex 42 and its planned follow-up, Annexes 37, 43 and 49
- District Heating and Cooling (DHC), Annex VII and VIII.

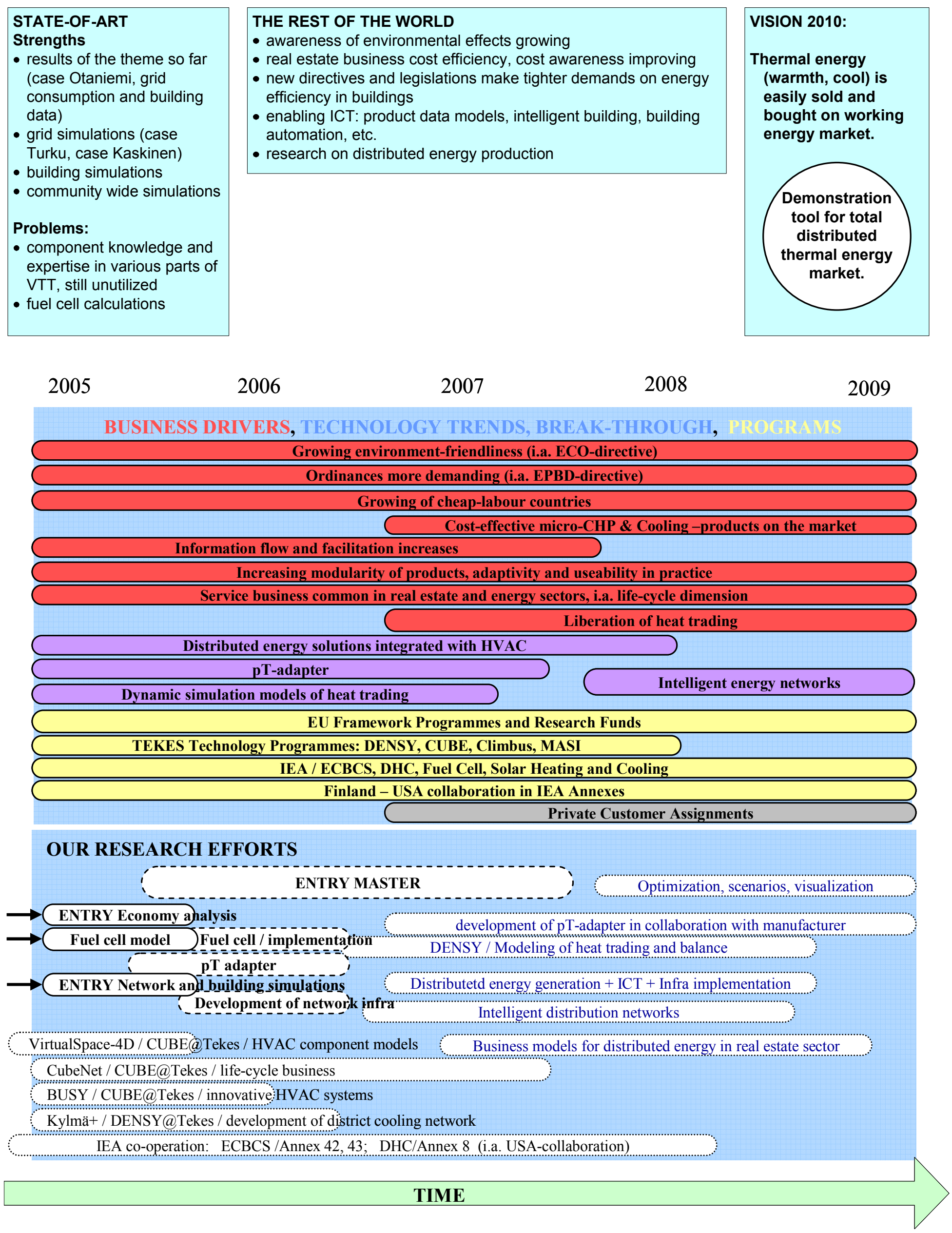


Figure 14. Technology roadmap of Distributed thermal energy systems (ENTRY) in 2004.

1.6.2.3 SES – Smart Energy Storages

Energy storages have been internationally seen as a key component for the further implementation of distributed energy (Figure 15). Most of the problems in power quality, distribution reliability and peak power management can be solved with energy storages. Energy storages give new possibilities for demand side management, and for customer level energy cost control.

Cost effective, smart energy storages give new potential for building energy management especially when they are used in combined heat and power (CHP) production systems such as fuel cells and micro turbines. Energy storages give possibilities to manage uncontrollable power production in renewable energy production systems such as photo voltage and wind power systems. Uninterruptible power delivery can be essential even in single family houses for example when they are used as a home office with computer systems or they has critical medical equipments that could be more common in near future. In spite of keen development of different kind of energy storages during latest ten years it is still a lack of smart, cost effective and efficient thermal and electrical storages.

The project activities were performed in the subprojects of DGSI (electric power network), ENTRY (thermal energy network) and SES (energy storages) Distributed power system interconnection (DGSI) research focused in first two years on a two-way communicating and controlling interface 'fU-adapter' (plug-and-play) that is the core part of DGSI. fU-adapter project was mainly concentrating on the interconnection of fuel cells with DC and inverter connection. An expanded project DGSI was started with the focus on the intelligent control system concept of the "Virtual Utility". DGSI controls and connects the interconnected production to the customer preserving the distribution network stability and power quality both in the normal loading and fault conditions. New network solutions such as microgrids, adaptive intelligent protection and modern system control principles (forecasting, communication solutions, demand side management etc.) were also studied.

Management of Distributed Energy Systems (ENTRY) was over its entire lifespan carried out in a number of sub-projects that can be grouped in three complimentary parts focusing on: background, collection of digital data and economy analysis, distributed co-generation technologies (micro-CHP, fuel cell), and coupling of building's internal and external networks in simulation (Figure 16).

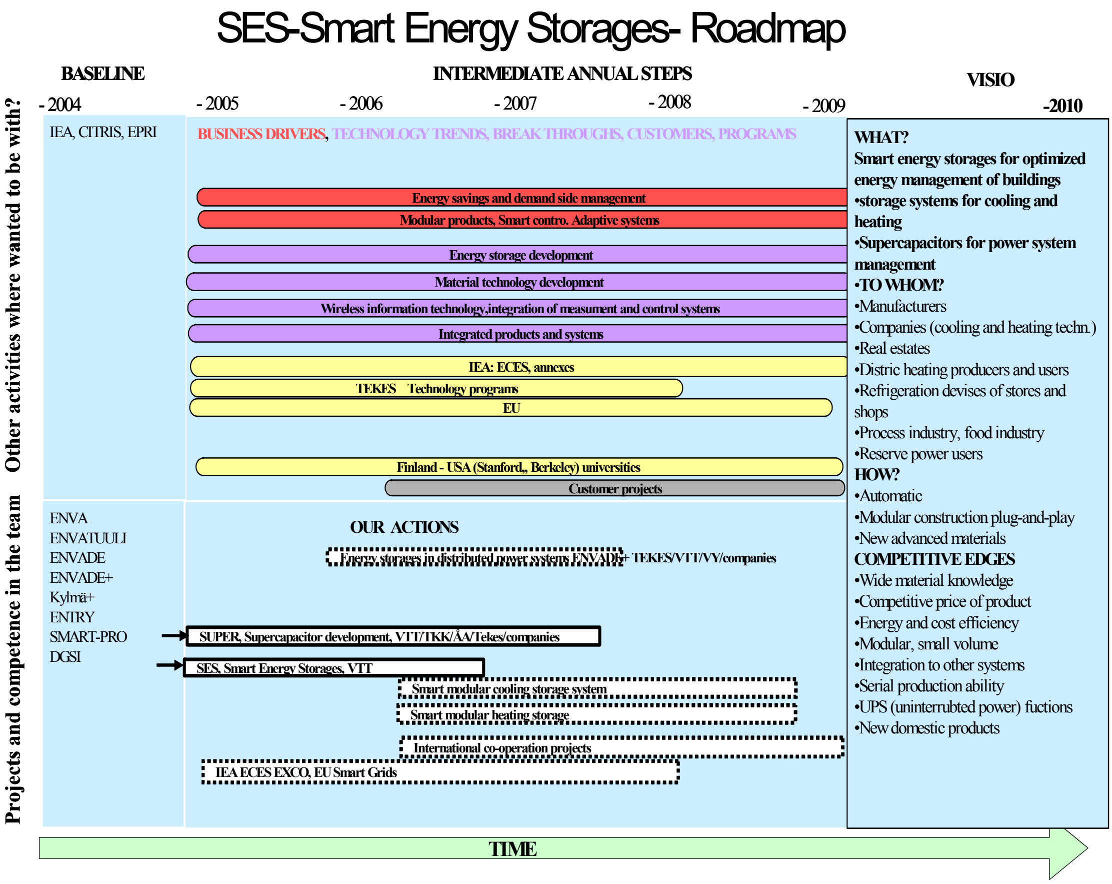


Figure 15. Technology roadmap of Smart Energy Storages in 2004.

Smart Energy Storages (SES) was concentrated on the study of thermal energy storage material and systems, and supercapacitors. Project included phase change material development, thermal energy storage module development and a construction and test of a pilot module, design of a smart modular thermal energy system, study of phase change materials usability in a single family house constructions, simulation and calculation models for VTT House simulation system and a development of a supercapacitor.

In summary, the main strategic steering action adopted in 2004 were

– prioritizing the total simulator capability and readiness emphasized
– energy storages introduced as essential components in distributed energy systems.

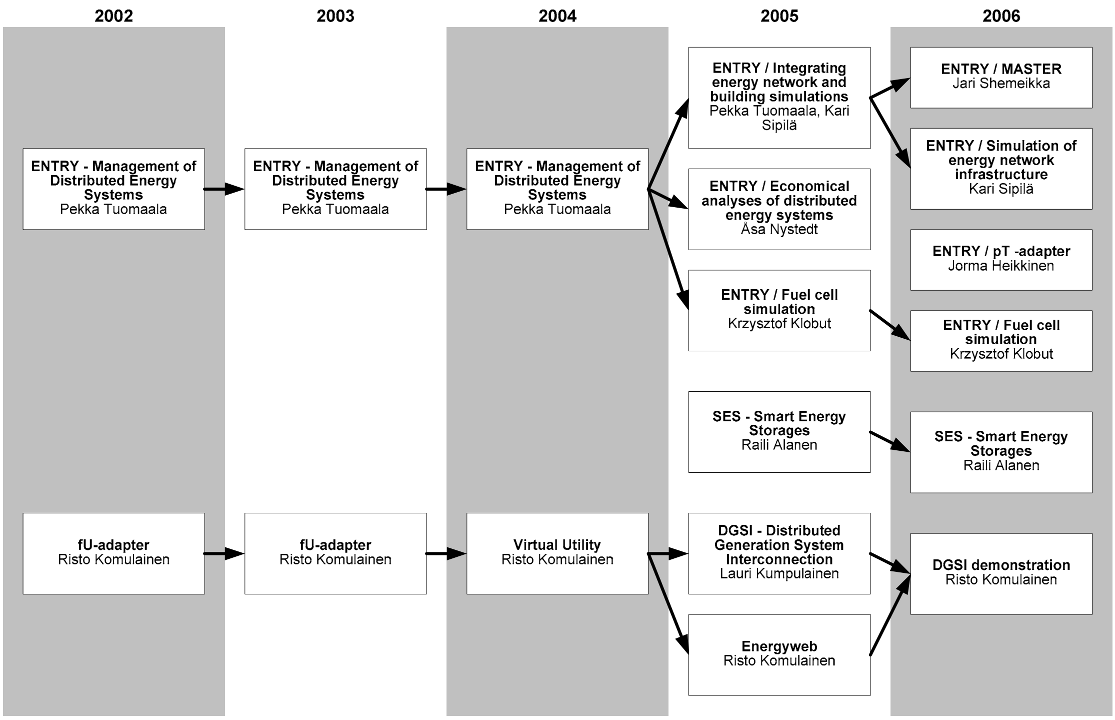


Figure 16. Actual projects flow of topic area Distributed energy.

1.6.3 Embedded Structural Intelligence

The primary, wide goal of the topic area is develop for VTT a strong capability to be an innovative R&D partner for building embedded structural intelligence – together with internationally recognized research partner for the benefit of Finnish and global industry. The major industry sectors are machine, vehicle, and building industries together with respective material, components, and system vendors. VTT's special strengths aspired are multi-technology modeling and simulations as on essential tool and platform, deep understanding and experience on the necessary physics, mechanical engineering, systems engineering and the related ICT. The essential reliability management of the advanced products and systems shall finally ascertain the success of innovations.

The roadmap of Embedded structural intelligence is presented in Figure 17.

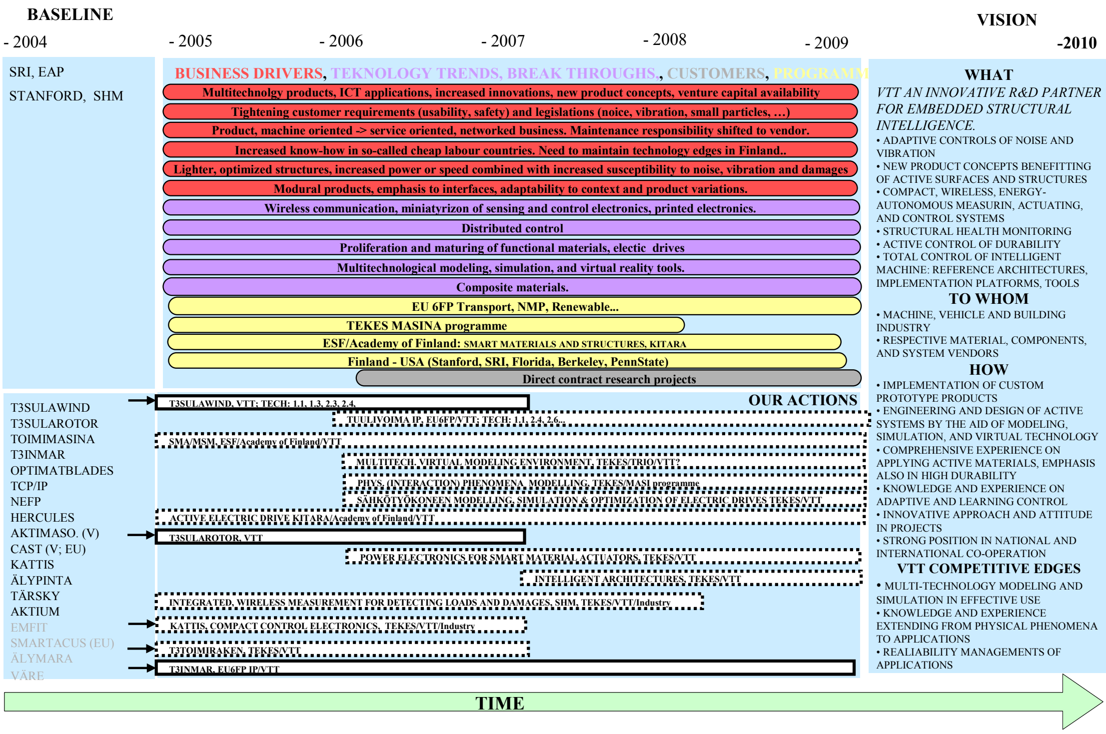


Figure 17. Technology roadmap of Embedded structural intelligence in 2004.

The multitude of diverse requirements of the intended advanced and intelligent products and systems are well understood at VTT, due to past and existing joint and contract based projects. Similarly, contacts to global science have been active, and increasing recently. VTT can also benefit of its multi-science or multi-technology character; intelligent structures shall be extensively complex combinations of many technologies. Also public and private research funding organizations, i.e., EU, Tekes, Academy of Finland recognize the importance of this domain.

There have been many projects at VTT which address the various aspects of the wide topic providing advantageous conditions for allocating challenges across various project types – between self-funded theme program projects and other types.

In the beginning in 2002, we chose target platforms to work on (see also the projects flow of Figure 18): 1) intelligent wind turbine and 2) intelligent rotating machine. Accordingly we set up three actual projects: a) SULABLADE (Developing structural intelligence of a blade of a wind turbine), b) SULATOWER (Developing structural intelligence of a tower of a wind turbine) and c) SULAROTOR (Intelligent control of resonance vibration of industrial rotors). The two wind turbine related projects were merged into one project, SULAWIND (Intelligent wind turbine) in 2003. To extend the applicability of these techniques to more generic mechanical designs, a third project chain was started also in 2003 (TOIMIRAKENTEET). The application domain was extended further in 2004 by joining a large EU-IP project InMAR (Intelligent Materials for Active Noise Reduction). Roughly the same projects combination was kept till the end of the theme program. During 2005 major part of the SULAWIND activities were moved to a starting EU project, called UPWIND.

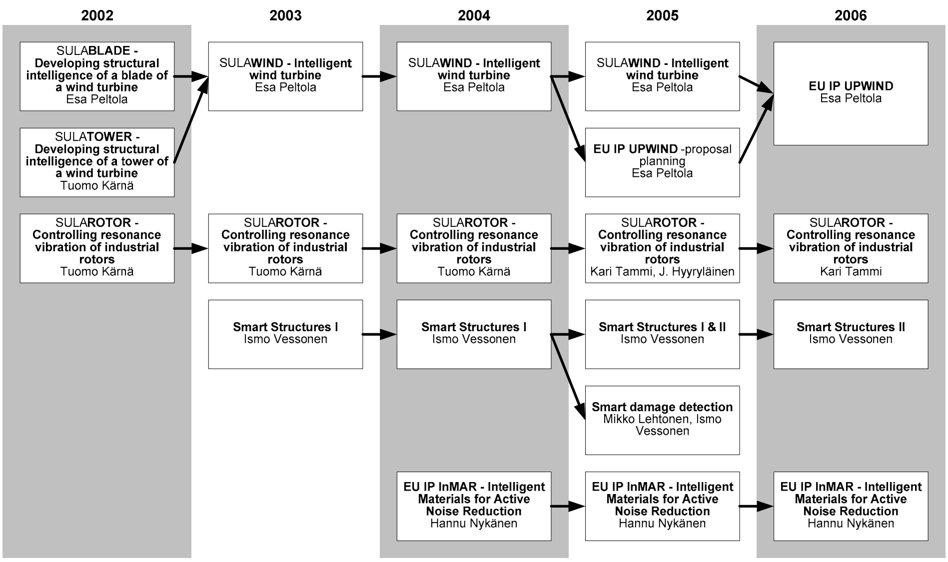


Figure 18. Actual projects flow of topic area Embedded structural intelligence.

In 2001 all projects were funded by VTT alone. TOIMIRAKENTEET was at first co-funded by VTT and Tekes, later on by VTT, Tekes and five partner companies meaning that the project was in the beginning certain kind of high risk project from Tekes point-of-view, and it was later on changed to a high-impact joint project. SULAROTOR was during 2006 funded both by VTT and Academy of Finland meaning that it has been regarded scientifically very high from Academy of Finland point of view (it rarely supports VTT projects). InMAR and UPWIND have been co-funded by EU, by definition.

In the following there is a short description of all the four subprojects. For all of the projects a more detailed description is given in Sections 4.2–4.5 of this publication.

SULAWIND: The expected top-level achievement for SULAWIND project was originally defined as: A new structural concept for future large scale wind power plants. The project has had two focus areas: study of design and virtual modeling of wind turbine’s combined aerodynamic, mechanical, and electrical behavior, and on the other hand developing and testing of technologies for active structural parts to be used in the turbines.

SULAROTOR: The project is striving for adaptable resonance vibration control method for industrial rotating machinery. The aim is to develop and demonstrate active and adaptive control solutions for rotor vibration control. The main objective is to develop an automated system identification – control design – control adaptation procedure for active rotor vibration control. Through better control of structural vibrations it is possible to achieve more design freedom for electric power engines and thus pave the way for novel innovative solutions (e.g. long high speed rotors with overcritical operation).

TOIMIRAKENTEET: The project was first (2003–2004) launched as a joint project between VTT and two university partners (Helsinki University of Technology [HUT] and University of Oulu [UO]), funded by Tekes, the Finnish Funding Agency for Technology and Innovation and VTT. In the 2^{nd} research phase (2005–2007) several industrial partners joined the project. At first the objective was to develop basic know-how on appropriate technologies and implementation of multi-technical smart structures. Later the aim was shifted to creating and implementing innovative prototype solutions for technology challenges taken from industry. In the 1st phase the subtopics were Active joint, Active shell, and Active control. In the still on-going 2nd phase the workpackages are Adaptive mass damper, Adaptive actuator cylinder, Adaptive shell structure, Adaptive vibration isolator and Enabling technologies for adaptive structures.

InMAR: "Intelligent Materials for Active Noise Reduction" is an EU funded IP-project (2004–2008) in 6th Framework Programme. ImMAR aims at realization of intelligent, high performing, adaptive material systems with integrated electronics for noise mitigation purposes. VTT's focus is in the areas of VTT's high competence i.e. on composite and polymer materials, large surface acoustic and vibration actuators, and their application in active noise (and vibration) reduction in cars and infrastructure.

2. Active and Communicative Package Systems

Eero Hurme

2.1 Printed indicators

Thea Sipiläinen-Malm, Eero Hurme, Maria Smolander, Tiina Rajamäki
(indicator development)
Jali Heilmann, Liisa Hakola
(inkjet printing procedures, building a modular research environment)

Abstract

Printing inks containing a certain reactive substance indicating oxygen, and suitable for printing onto plastic materials have been produced. This kind of indicator signals for package leakage and can be used for perishable foods in packages with modified atmosphere. Another type of oxygen indicator has been designed to be activated during the sterilisation process, and is most suitable for medical applications. In addition to oxygen indicators, attention was paid to the concept of freshness indicators. Humidity indicator and ethylene indicator developments were started in the project and, later on, advanced in separate projects. Every indicator system is based on a distinctive chemical reaction. Thus, several active substances were identified and tested, and the most promising systems were chosen for further development. The formulation and design of the ink-jet ink has been carried out. A large number of raw material combinations have been tried out to find a viable system. Preliminary reliability studies in real operational environment in food or medical packages have been performed. Two types of oxygen indicators are under evaluation at potential customers.

2.1.1 Background, starting point and objectives

The project aimed at developing intelligent diagnostic inks and indicator systems printed on the packaging material. The developed optical colour changing indicators could give information on the quality of packed food or pharmaceutical (package leakage/tampering, product spoilage). Special emphasis was put on the development of inkjet printable indicators but also on other printing techniques like flexography. A modular research environment was built for the ink jet printing.

2.1.2 Implementation

The requirements for the indicator printing ink are the following:

- distinctive clearly visible reaction
- can be used in a printing process using inkjet technology
- adherence of ink onto the packaging material, preferably plastics
- shelf-life in storage (the ink must retain its reactivity)
- stability in operation (the indicator must operate at various lightning and temperature conditions)
- suitability for food contact (conformity with food legislation)
- low-price
- an irreversible colour change is usually preferred.

Finding the active substance for the indicator

The principle of an indicator is to expose a reactive substance to conditions (oxygen, moisture, certain temperature, etc., in a sealed package), have the intended reaction occurred which then becomes visible or observable due to colour change accompanied with the reaction. The indicator substance is applied on the inner surface of a food package, it is in its active state prior to or at the point of packaging, coloured or colourless (depending on the colour change mode intended or possible).

Preliminary screening for substances presenting colour change in indicator-reactions was carried out. Various methods for activating the colour substances, when needed, have been studied. For oxygen indicators, a large number of activating systems were examined. The colour change reaction of the enzymatic indicator system has been studied using various types of enzyme in water-borne binder systems. The colour change reaction needs to be sensitive and work well both in solution and when spread on the packaging substrate.

Attaching the indicator onto the packaging material

One critical issue in the project was the attachment of the indicator ink onto the plastic material which most common substrate material. The primary applications for indicators are food and pharmaceutical packages and, therefore, the polyolefins are the most probable surface materials. It was found that, in many cases, moisture was an important feature in the colour development and, in these cases, the printing inks should therefore be water-based, or at least contain some water. In order to prepare a printing ink for plastics, binders are necessary. It has been a challenge to find binder systems which are behaving well in the printer and not clogging the nozzles. Out of several commercial binder systems the suitable ones have been identified. Another challenge in the case of water-based inks is the spreading on the plastic surface. Wetting of the plastic surface by the ink is necessary for good adhesion between the printing ink and the substrate. As the surface tension of plastics is low, corona treatments are needed to improve the adhesion. New binder systems were searched, and a number of new binder systems were found to be printable using a wide variety of solvents (alcohols, esters, etc.). The wetting and adhesion of the solvent based binder systems on polyethylene is remarkably better than the water-based approach since the surface tension of the solvents is much more compatible.

Formulating the indicator bearing printing ink

The active indicator substances need to be added in the binder solution without severe problems. The substances must be printable and they must maintain the capability to change colour in the final dry print. The most crucial part of inkjet printing technology is probably the ink and its physical properties, in particular the viscosity and surface tension. The viscosity should be suitably low, typically below 20 mPa’s but preferably around 10 mPa’s. The surface tension is responsible for the spherical shape of the liquid drop emerging from the nozzle. The wetting behaviour of fluid and nozzle material is important for the spray formation. Inkjet printability correlates with the rheological properties of a polymer-containing ink and, therefore, with the polymer structure, molecular weight, and concentration.

Inkjet devices set certain demands for printing ink, for example the viscosity and surface tension of ink should be on predetermined area. Otherwise the drop formation in a printing head will not work properly. Commercial ink manufacturers take these demands into account and tune their inks to function in a selected inkjet system. This work is often challenging and time demanding because of lack of comprehensive theoretical knowledge, and the inks must also be tested experimentally. This was the case also in this project because different kinds of bioactive components were printed utilising inkjet. One procedure to prevent destroying printing heads was to pre-test the printing head materials beforehand by exposing materials to bioactive ink. After this, it was possible to determine, if the printing ink deteriorates the print head materials by visual inspection. These materials were also sent for print head manufacturer for more comprehensive analysis.

Building a modular ink jet research environment

During the project, a new inkjet printing system was purchased and installed at VTT. Because of the fast development of inkjet technology this research environment was updated several times during the project. A very crucial starting point has been the approach that it should be possible to upscale the research results up to production scale. This is the reason why industrial-scale printing systems were selected.

The system is based on robust and high-quality print heads manufactured by Dimatix (former Spectra). In the study, Nova AAA and SX-128 print heads were used in printing experiments. Nova AAA is the most suitable head for printing functional indicator inks because of the fairlylarge 80 pl drop-size. The experimental inks, which are not yet finely tuned for the commercial print heads, can easily block the ink nozzles of a printing head, so it is beneficial to use print heads, with as large nozzles as possible. Also the nanosilver inks, used in the RFID antenna printing tests, were printed using the Nova AAA head (Chapter 2.5).

The high-quality SX-128 print head is, on the other hand, the most suitable for the printing high-precision 2D codes. The SE-128 print head is not suitable for conductive inks because it can only tolerate pH values near 7 but conductive inks typically have much lower pH values. The other print heads can tolerate pH values in the range of of 1.5 through 9 but the SX-128 can tolerate also harsh solvents such as toluene. Acetone is not recommended to any of the print heads. (See Table 1.)

Table 1. Inkjet print heads at VTT manufactured by Spectra.

Printhead name	**Nova AAA**	**SE-128**	**SX-128**
Image			
Drop size (pl)	80	30	10–12 (adjustable)
Nozzle diameter (µm)	52	38	27
Nozzle count	256	128	128
Resolution (dpi)	up to 450	up to 300	up to 300
Printing temperature (°C)	10–70	10–70	10–70
Suitable ink chemistry	Water and solvent based inks, UV curable inks, PEDOT, metal particle inks (depending on solvent)	Solvent based inks, UV curable inks	Water and solvent based inks, UV curable inks, conductive polymers, OLEDs, LEPs

The printing trials have been carried out with VTT's inkjet printing environment (Figure 19). The printing environment is based on high-quality and robust industrial inkjet print heads with a choice of drop size and compatible ink materials. The printing environment consists of

- inkjet print heads and ink reservoirs
- print head control system
- high-precision xy-table (repeatability 1 µm) for moving (max 0.25 m/s) printing samples
- printing plate can be heated up to 70 °C
- high speed CCD camera for imaging the ink drops from the first microseconds after the printing to several minutes
- high power halogen light source
- personal computers and control units.

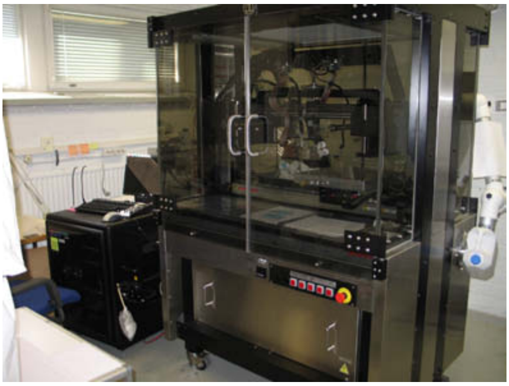


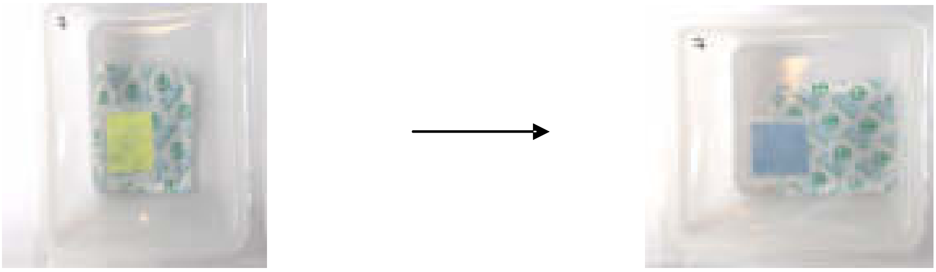
Figure 19. VTT's high-precision printing system.

Also two curing ovens were adopted during the project. The first is an UV-oven meant mainly for curing UC-inks and the second one is a conventional heat oven for evaporating solvents of inks. Also a commercial image analysis system, based both on hand-held and scanner-based devices, were purchased. In conclusion, the present research environment can be regarded as technologically a state-of-the-art environment and unique at least in Europe.

2.1.3 Results

Printable oxygen indicator

In the project various low-cost indicator technologies for consumer packages were developed. Printing inks containing certain reactive substances indicating oxygen, and suitable for ink-jet printing onto plastic materials has been produced (Figure 20) (Heilman et al. 2003). This kind of indicator signals for package leakage and can be used e.g. for perishable foods in modified atmosphere packages. Another developed oxygen indicator was designed for sterilized packages (Figure 21) (Hurme & Rajamäki 2005). This indicator type could be printed on plastic or paper substrate using other e.g. flexographic printing.



Intact package *Leaking package*

Figure 20. Oxygen indicator detecting leak.

printed indicator

indicator after sterilization intact package

indicator after opening the package

Figure 21. Colour change of sterilization type oxygen indicator.

Freshness indicator

Attention has also been paid to freshness indicators. Every indicator system is based on a distinctive chemical reaction. Thus, several active substances have been identified and tested, and the most promising systems have been chosen for further development. The formulation and design of the ink-jet ink has been carried out. A large number of raw material combinations have been tried out to find an effective, reliable and cost-effective system (Figure 22).

Figure 22. Testing indicator substances for freshness indicators.

Ethylene indicator, humidity indicator

The development of ethylene indicator was initialised in the project. Further work is ongoing in another joint financed project. The development of an enzymatic humidity indicator produced a promising indicator concept. Elaboration of this indicator system into an inkjet-printable indicator is proceeding in EU-project SUSTAINPACK.

2.1.4 Industrial and research networking, international position

International research networking has been resulted in the participation in SUSTAINPACK EU-project (Chapter 2.4). Currently new project proposals are prepared for EU 7th framework.

2.1.5 Exploitation and industrial impacts

Basic research findings related to diagnostic ink compositions and knowledge on food/package interactions and volatile analyte compounds correlating with food quality has been further utilized in industrial development projects:

- Development of visual freshness indicator label for fresh packed poultry product (2003). Product has been commercialized 2005 by Raflatac Corp. (Smolander et al. 2003).
- Development of sterilised liquid oxygen indicator for pharmaceutical packages (2004). Product has been commercialised 2006. Subsequent research at VTT had been directed in the development of printable sterilised oxygen indicator. The test runs are currently on-going in two international companies (Hurme & Rajamäki 2005).
- Development of printable visual oxygen indicator (2005–2006), especially for Japanese markets. Product under commercialisation phase in Japan (Sipiläinen-Malm et al. 2005).
- Printable time-temperature indicator (Koivukunnas & Hurme 2003).
- In addition, an EU-funded Collective Research project is on-going: **Integrated Approach to enable Traceability of the Cooling Chain of Fresh and Frozen Meat and Fish Products by means of Taylor-made Time/Temperature Indicators (TTIs)** (Freshlabel) (2005–2007). The consumption of chilled and frozen foodstuffs within the EC is tremendously growing whereas food safety and control are of great concern for the whole consumers' community. Furthermore, a new EC Directive regulating the traceablity of the cold chain of food products will be adopted in 2005. This Regulation will force the introduction of Community controls of the treatment of foodstuffs. The freshness or the spoilage of chilled and frozen meat and fish products is mostly related to temperature conditions during transport and storage. The aim of the project is to optimise TTIs for specific products of the European meat and fish industry and to encourage and train their members in the respective application. The outcome of the project will be the visualisation of the quality and safety of meat and fish products by means of joint application of TTIs. The second aim is to increase the European consumer's confidence in food. The project is funded by EU and industry.

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2.2 Optical coding and detecting systems

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Abstract

It has been predicted that about one billion mobile phones will be sold in the world in year 2007 – and that 90% of these phones will be equipped with a digital camera. So the emerging camera phone technology will be in everyday use for most people in the near future and this development will offer great prospects for the services based on these technology. Two of the most potential application areas of this multi-billion dollar industry of the future are the publication and packaging products, because these items are extensively used in everybody's everyday life. In this project the technologies and the operational environment, in which the new camera phone based applications are developed has been studied. Demonstrators where 2D bar codes can be utilized in information transfer of packages have been built, and a software enabling detection of colour-changing codes has been developed.

2.2.1 Background, starting point and objectives

The most commonly used linear bar code system is the Universal Product Code (UPC) which is one of the most successful standards ever developed. Originally this code was meant to benefit the retail trade but over the years its use has also become common among raw material producers, manufacturers, wholesalers, distribution companies and consumers. This code makes it possible to control many activities of product supply chains and to track and identify products all over the world. The downside of the UPC bar code is that it carries only a limited amount of information, usually only twelve characters. For this reason, the normal bar code cannot include real information but it is rather a keyword or link to a data-base where the information is stored.

A two-dimensional bar code can act as an independent data storage. This means that information can be read wherever a suitable scanning device for the code is available. Other benefits of two dimensional bar codes are small physical size, scalability, big storage capacity and high data density, good correctness of information and high durability. Two-dimensional bar codes can be attached to packages by using stickers or printing them straight onto the packages by means of an ink jet printer.

Two dimensional bar-codes are usually used in the manufacturing sector because more information, even more than a thousand alphanumerical characters, can be included in the code. Every 2-D code includes an independent data-base with total freedom of transportation. This is a great benefit compared to a landline network because the information can be downloaded wherever the product is. Moreover, special encryption technologies can be used, if the information is confidential. Multi-level confirmation technologies can also be added to the 2-D bar codes to ensure that the code will be read right.

2.2.2 Implementation

During this task several literature surveys were done. The topics were:

- Two-dimensional bar codes and how they can be detected and decoded
- Anti-counterfeit methods in packages
- Invisible and reactive inks and their use in packages
- New marking methods in packages
- Functional inkjet printing inks.

The literature surveys contained theoretical and market information, existing applications and future scenarios. On the basis of the surveys, the most interesting and most useful coding and detecting methods were chosen for experimental studies. The coding systems chosen were two-dimensional bar codes and especially one bar code symbology called Data Matrix, invisible inks and color-changing codes. The mobile phone that has an integrated digital camera was used as a detection device.

2.2.3 Results

Experimental studies of new kinds of coding systems, ink jet printers and detectors

The codes investigated in this task were produced with an ink jet printer. For detection a Nokia 3650 mobile phone with an integrated digital camera i.e. a camera phone was used. Camera phone was chosen for a detection device because it is the most likely consumer device that almost everyone will have in the near future. It has been estimated that at the present moment every other mobile phone has an integrated digital camera.

Colour-changing codes

A software that detects a colored square that has frames in two of its edges was developed (Figure 23). The purpose of the black borders of the square is to help the software to find the right square and also tell the right orientation of the square. The software automatically detects the square from the focus area of the camera and takes a picture of the square. After this the software automatically calculates the color coordinates of the square and gives these values to the user. The developed software can also detect squares that are at an angle. The developed software can be used in camera phone for imaging for example indicators. The software recognizes the colour of the indicator and tells the user how much the colour differs from the original colour of the indicator. This information can be used for judging if the food is fresh or not.

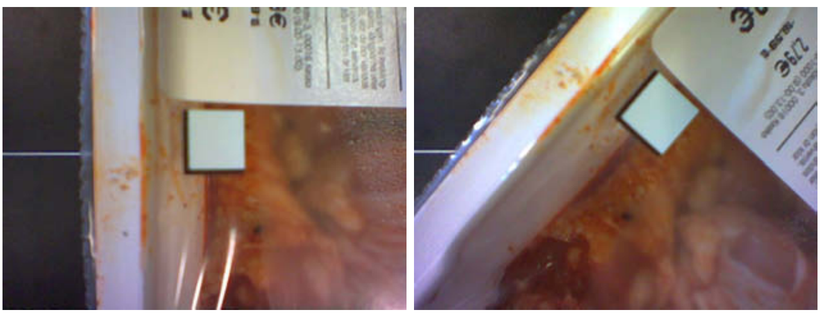

Figure 23. Coloured squares attached to a food package. The pictures are taken with a camera phone. The imaging distance is 6 cm. In the right the camera phone is twisted 40 degrees.

Detection of colour change

The aim of this work phase was to clarify what kind of colour changes could be detected by using a mobile phone equipped with a digital camera. This was carried out by using test fields in which colour coordinate values were changed.

After this, frames of colour fields were taken and the RGB and intensity values of the fields were determined. The RGB values in tests field and in the frames taken with a mobile phone camera are compared in Figure 24. The colour reproduction would be perfect, if the colour values would be linearly same, but this is not the case.

When red colour was examined, it can be noticed, that the values are much smaller than with other colours. Because of this excursion, white colour in nature seemed to be a little greenish in a picture taken with a mobile phone. In this case, the colour of an indicator should be without red colour component, which means that colour of indicator should be in blue, green or blue-green area.

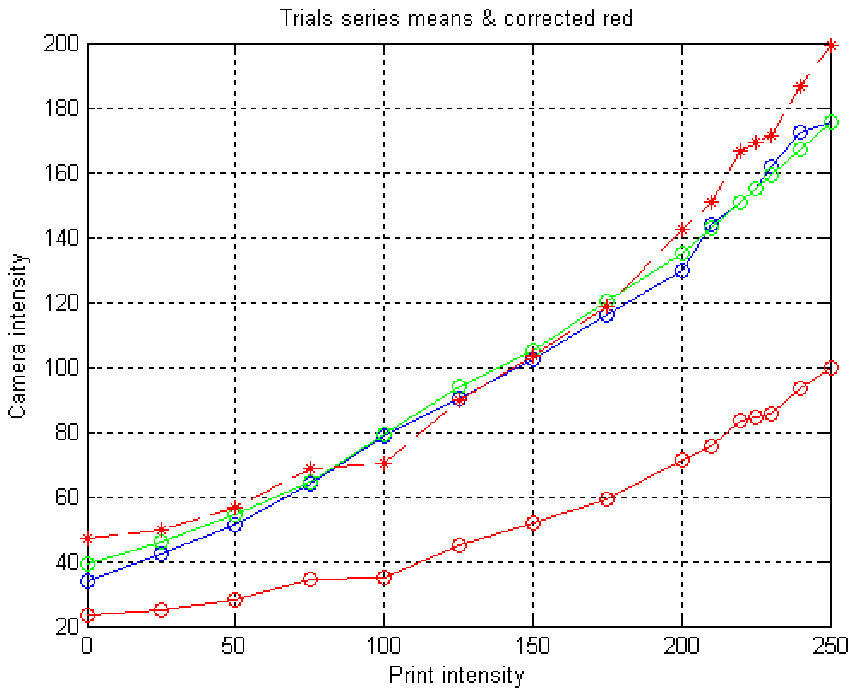

Figure 24. The values of RGB-values in printed test fields and in an image taken by a camera phone. The red line responds the red colour, blue line blue colour and green responds the green colour. By multiplying the values of red colour with factor two (the red line with stars), also the line of blue component responds the other colours.

There are several factors that affect the colour detection, like:

- illumination
- transparency of the indicator field
- properties of camera lens and CCD cell.

Two-dimensional bar codes

Data Matrix code is one of the two-dimensional bar code symbologies. A Data Matrix symbol consists of small black and white squares called cells that are organized in a square matrix. Two edges of the square matrix have black borders that serve as a locator pattern. The purpose of this locator pattern is to help the decoding device to realize the correct orientation of the symbol. The cells are organized according to the encoding standard. As much as 3000 characters can be stored in one symbol.

At VTT Data Matrix codes were imaged with a camera phone. The objective was to investigate the ability of the camera phone to detect two-dimensional bar codes. The goal was also to investigate how a small cell sizes can be detected and how much information can be stored and what limitations the imaging process gives. The code detection and decoding was done with sending the images to a PC software. Also a demo version of a commercial software that works in a camera phone was used. The 2D barcode creator program was used to create 2D barcodes. It was implemented in Matlab on PC platforms. Functionally, the software allows data entering and showing the created barcode on the screen of a personal computer. The length of input data can be up to 64 * 12 = 768 characters.

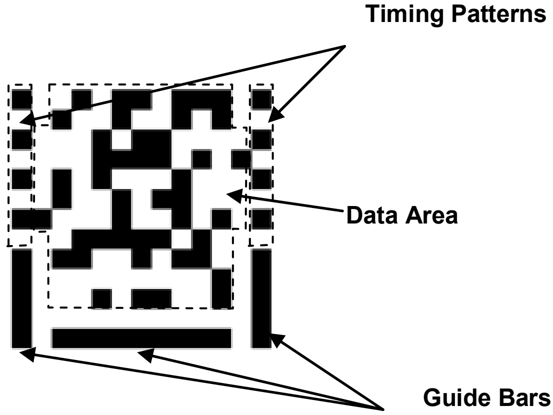

Figure 25. Example of a 2D barcode unit.

The 2D barcode unit (Figure 25) was a 2D matrix code designed for camera phones. It has size 13x13 cells and consists of the following elements: three guide bars and two timing patterns used to locate the code, the data area that is reserved for code information and number of 2D barcode unit. A 2D unit can store between one and 12 ASCII characters (0–255). The code data was protected by a (109,102) Hamming code with 7 additional bits that are used for error detection.

In imaging different camera lenses, imaging distances and both physically and from information capacity different code sizes were used. The results indicated that a camera phone can easily detect quite a small codes, possibly even smaller codes than can be produced with regular office ink jet printers. The results from imaging Data Matrix codes with a camera phone suggests that the smallest cell size the camera phone was able to detect was 0.2 mm, but this was only achieved with particular optics and imaging distance. It can also be concluded that quite a big information amount (64×64) can be detected, but also this depends on the optics. Detecting large amounts of information is difficult because big matrices don’t fit into the focus area of the camera phone. (See Figure 26.)

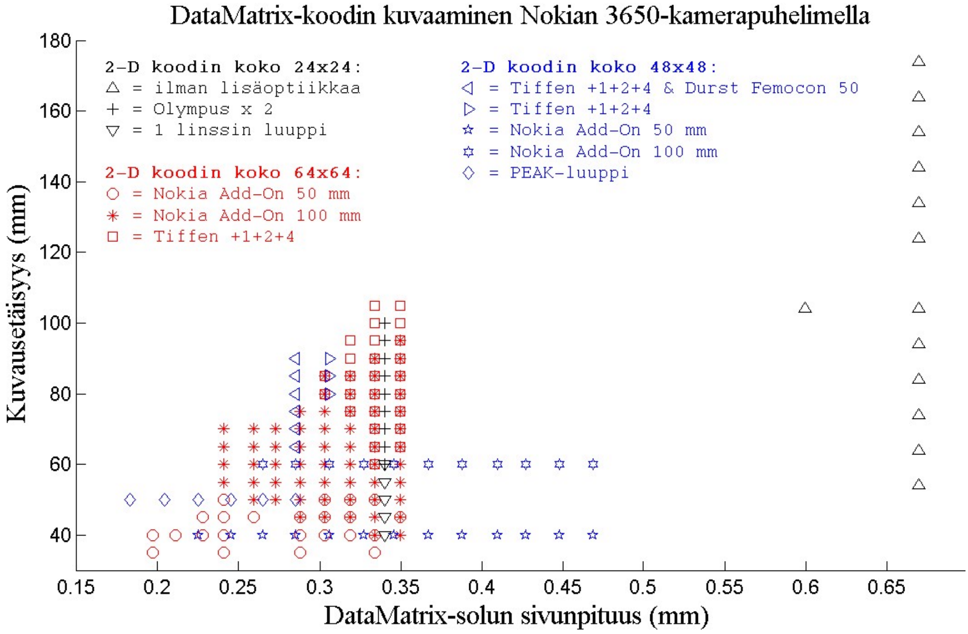

Figure 26. The results from imaging Data Matrix codes with a camera phone.

Invisible codes

There are two kinds of invisible inks: UV and IR fluorescent inks. These inks are invisible in normal light, but fluoresce in different colours when exposed to certain wavelengths of light such as UV or IR light. These inks could be used to print hidden information on packages. This hidden information could include bar codes that only have a relevance to the retail store or someone else during the logistical chain. This hidden information doesn't have a relevance to the consumer so with an invisible ink this information doesn't disturb the appearance of a consumer package. Invisible inks can also be used for anti-counterfeiting. With these inks all kinds of codes or texts can be included in the package. The counterfeiter can't copy these markings or even know if there are any invisible markings in the package.

At VTT a survey of digital presses able to print invisible inks was done. The press manufactures were contacted in order to see and test the presses. UV fluorescing colorant was purchased and an ink jet ink was made of it. The ink was used to print Data Matrix codes both on blank paper and on top of text and graphics. These codes were imaged with a camera phone with a help of an UV lamp. (Figure 27.) It was found out that the camera phone is able to detect also UV fluorescing codes. The text and graphics in the background can, however, disturb the detection process.

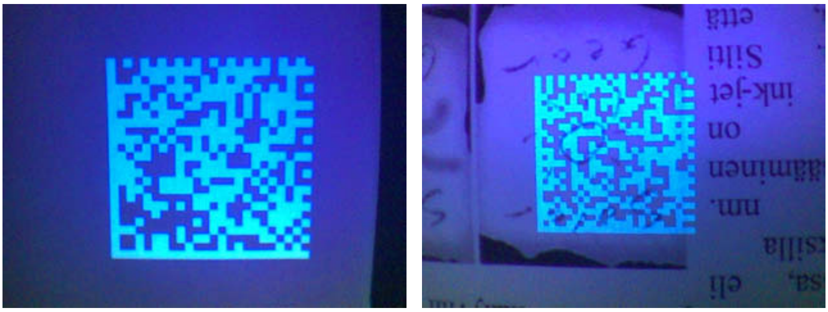

Figure 27. Data Matrix codes printed with an UV fluorescent ink and imaged with a camera phone and an UV lamp.

2.2.4 Industrial and research networking, international position

International research networking has been resulted in the participation in SUSTAINPACK EU-project (Chapter 2.4). Currently new project proposals are prepared for EU 7th framework.

2.2.5 Exploitation and industrial impacts

Research efforts the knowledge created in the sub-project “Optical coding and detecting systems” have been further utilized in the following internal and co-financed projects:

- **Technical innovations and business from functional printing** (Funktiobisnes) (2006–2008). The aim is to develop new technical applications and business models for printed functionality and to find the position of traditional printing plants in the new value chains. The area of printed functionality is defined as printed electronics, optics, displays, bioactive applications, optical codes, hidden codes, special codes, sensors, indicators and others. The existing production chains will be analysed, and the required additional changes and investments in the production processes for new printed functionality applications will be drawn. Laboratory-scale printing trials will be performed on selected materials to demonstrate the selected applications. Based on the results, the final applications will be selected and defined for the pilot-scale trials. The project is funded by Tekes, GTTS, VTT and industry.

- **Ink jet based manufacturing technologies** (2005). The goal was to combine manufacturing of electronic circuits and inkjet technology. The goal was also to develop and demonstrate inkjet based manufacturing technologies for electronics and applications for packaging industry. The project was started by conducting literature surveys that resulted in choosing the ink materials for testing. Based on material testing the demonstration was realized. The demonstration was a working display element that consisted of 6 all-inkjet-printed layers on paper substrate. The project was funded by VTT.
- **Functional inks in inkjet printing** (2003–2004). The goal was to develop inkjet printable conductive inks and to test their potential in making electronic structures, mainly conductors. Suitability of two conducting polymers, polyaniline and polythiophene, to inkjet printing was tested. Polythiophene could be used as a water dispersion and thus it was quite easy to find a solution, which could be printed. Necessary modification of the boiling point was done by adding diethyleneglycol to the ink. Polyaniline inks were dissolved in organic solvents due to the low solubility in water. However, some problems of phase separation still exist even though the ink was printable. In both cases very low solids contents were necessary in order to prevent nozzles from blocking. The project was funded by VTT.
- **Surface proximity assay** (Supra) (2004–2005). The goal was to investigate the potential of inkjet printing to make patterned hydrophobic and hydrophilic surfaces for diagnostic applications. Several inkjet printable inks were made and hydrophobic surfaces were inkjet printed from three of them. It was also investigated if use of particles in the ink or the exposure of the surface to different lasers could result in super-hydrophobic surfaces. Based on literature survey it was also found that inkjet printing is a potential method for all kinds of diagnostic manufacturing, dosing and analysis applications. The project was done in co-operation with University of Turku. It was funded by Tekes, VTT and industry.

- **Hybridmedia as a tool to deliver personalised product-specific information about food** (TIVIK) (2003–2005). A pilot system was developed to deliver personalised food product-specific information to the consumer. The mobile application developed in the project utilises wireless Internet, camera phones and food packages. The consumer can collect the information independent of time and location. A barcode reader software application was also created and patented in the project. This transforms a camera phone into a barcode reader device. TIVIK can also be used with a PC's web browser. The project was funded by Tekes, VTT and Finnish companies.
- **HyperFit** (2005–2007). In this follow-up project of TIVIK, the food diary and related tools are developed further. Physical activity in diary is added. Special attention will be paid to increased incidence of overweight among children and young people. Especially audiovisual media and games are the most natural and appealing tools to deliver information. The project is funded by Tekes, VTT and Finnish companies.

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2.3 SUSTAINPACK EU project – Innovation and sustainable development in the fibre based packaging value chain

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(SP6)

2.3.1 Background, starting point and objectives

SUSTAINPACK is the biggest and most important packaging research project ever undertaken. It is a four year research programme with a budget of €36m. Of this, €19m is being provided by the EU's Sixth Framework Research Programme. The SUSTAINPACK project team is comprised of a consortium of 35 partners from 13 countries, representing packaging research associations, academia and industry. The purpose of SUSTAINPACK is to establish fibre-based packaging as the dominant player in the packaging area within a decade (www.sustainpack.com).

VTT is involved in two sub-projects of SUSTAINPACK: SP1 "Technology Mapping in the Fibre Based Value Chain" and SP6 "Communicative Packaging".

In the Sub-project 1 (SP1) there has been a strong focus on strategic research because the objective is to address real market needs and to ensure that the research sub-projects focus on relevant functions of fibre based packaging. Also the objective is to present and visualise the breakthrough research achieved in the project and to pave the way for future penetration of these packaging into the market by the commitment of packaging users. This is done by identifying supply chain demonstrators which can show the commercial and technical viability of the product solutions identified.

In the Sub-project 6 (SP6) one and two way communicative packaging has been studied. In work package 6.1 "Pro-active communication technology for fibre-based packaging" led by VTT the aim is to develop sustainable technology for wireless communication and information exchange within the distribution chain (information concerning ao. logistic, product quality, surroundings/environment aiming at tracking & tracing, supply chain management, food safety issues, etc.). At VTT the focus of the practical work has been in the development of visual indicator for humidity. Basically two systems have been studied. A visual, fully ink-jet printed indicator based on a chemical reaction and reacting to the presence of elevated relative humidity with irreversible colour change. In another approach the aim is to develop a visual, enzyme-based indicator system for the evaluation of combined humidity-time effect, which can be further linked to the product quality.

Humidity indicators can be used in a number of different applications. Irreversible indicators could be used e.g. as early warning tools of drying in applications where the products are frequently visually inspected. Indicators reacting in an integrating way could be used to evaluate the exposure of the product to certain time-humidity combination in a manner comparable to the performance of time-temperature indicators. Irreversible indicators could be utilised either to indicate the moisture entrapped in the package during packaging procedure or to indicate the storage of the opened package in the presence of too high relative humidity.

In the work package 6.2 “Passive communication technology for fibre-based packaging” VTT has prepared applications based 2D bar codes.

2.3.2 Implementation

Chemical RH indicator

Irreversible visual humidity indicator with specifications listed in Table 2 was the first target of the development work carried out in SUSTAINPACK WP 6.1. The system is based on colour reaction based on two inks originally printed apart each other or partly on top of each other. One ink contains a pH-indicator dye and another ink an acidic or basic solution. Moisture absorption into the sensor system enables the diffusion and subsequent reaction of the inks (irreversible).

Table 2. Basic characteristics related to the visual humidity indicator to be developed.

Requirements for the indicator system	Specifications of the first prototype	Components required for the sensor system
• suitability for food contact • (ink jet) printed • low cost	• visual colour change based on chemical dyes • original status dry (indication of humidity increase)	• humidity absorbing material • humidity/moisture sensitive reaction with visual colour change

The active components of the indicator inks (dye, organic acid, humidity absorbing compound) were chosen on the basis of their performance in hand-coated layers. When the suitable compounds had been found, they were tailored into ink-jet printable inks.

Enzymatic, integrating RH indicator

In the development of the integrating humidity indicator, the idea is that the integrating function is a chemical reaction taking place throughout the storage/ distribution of the packaged product with reaction rate being dependent on the current conditions. We have studied the possibility to utilise enzymatic reactions for this purpose. Typically the enzymatic reactions require the presence of humidity and it was expected that it is possible to tailor the indicator composition in such a way that the humidity is the rate limiting step of the indicator. On the basis of previous background knowledge laccase, an oxidative enzyme with broad substrate specificity has been selected as the active component of the indicator. The performance of this type of indicator has so far been studied using hand-coated layers.

2.3.3 Results

SP1

So far number of different deliverables has been compiled in the sub-project 1. The most recent and important deliverables are

- D1.7: Report on future market needs and SWOT analysis for the European fibre based packaging industry
- D1.8: Technology mapping report
- D1.9 & 1.11: Technology timelines and elaboration of demonstrator concept
- D1.10: New products identified, preliminary market testing of consumer attitudes and maturing stakeholder interest.

The intention of these documents was to provide an insight into the key drivers influencing packaging use, the strengths, weaknesses, opportunities and threats of the paper and board industry, and to provide an initial interpretation of how this might influence the research efforts and outputs of SUSTAINPACK.

The deliverable D1.10 was prepared by VTT. All the deliverables included work undertaken by the sub-project 1 partners: Pira, STFI-Packforsk, A&F, VTT, DTI, ITENE, CTP, PTS, STUBA, Sainsburys and Karlstad University. The aim of this publication was to link the elements of each of the demonstrators back to the technology mapping exercise and consumer surveys. This is important in order to successfully deliver and position research outputs in the packaging marketplace. The section Stakeholder interest focused on industrial partners within SUSTAINPACK. It was agreed that a questionnaire approach would be useful to understand industrial partners' interests and capabilities. The questionnaire was sent by email and some of the industrial partners were also interviewed. Also data has been gathered and analysed for the internal report Understanding Potential Barriers to Nanotechnology. Internal meetings were held for digesting the reports and data.

In addition to deliverables more interactive knowledge sharing has been included in the project. According to the objectives of the project seminars and training sessions should be organised to help knowledge dissemination between specialist researchers in each sub-project area and spreading of an understanding of the total packaging value chain amongst researchers. In the training session Facilitation and Technology Mapping Techniques the objective was to teach tools and skills that were used in the SP1 for technology mapping process, workshops and creative thinking.

The first SP1 dissemination seminar was held 7th June. This took the format of a webcast. Content included the demonstrators chosen by SUSTAINPACK and open call information.

SP6

Chemical RH indicator

The development of the chemical RH indicator has been carried out since the beginning of the SUSTAINPACK project and currently the ink jet procedure for the production of humidity indicators based on two sequentially printed inks has been demonstrated. Optimised procedures for the preparation of the inks have been developed and successfully applied.

According the latest results obtained the sensitivity of the indicators could easily be adjusted by altering the printed test image. For instance the dot size of the printing indicator can be changed. It was seen visually and by instrumental analysis, that the smaller the dot, the faster is the color change (Figures 28 and 29).

In the continuation of the project further improvements on the print quality and indicator performance could be expected by

- improving the compatibility of inks and substrates (analysis on dynamic interactions between ink and substrate surface)
- optimisation of printer settings and printhead parameters
- adjustment of the properties of the indicator inks to the appropriate levels in the final stage of the ink production (e.g. by the use of surfactants, dye concentration).

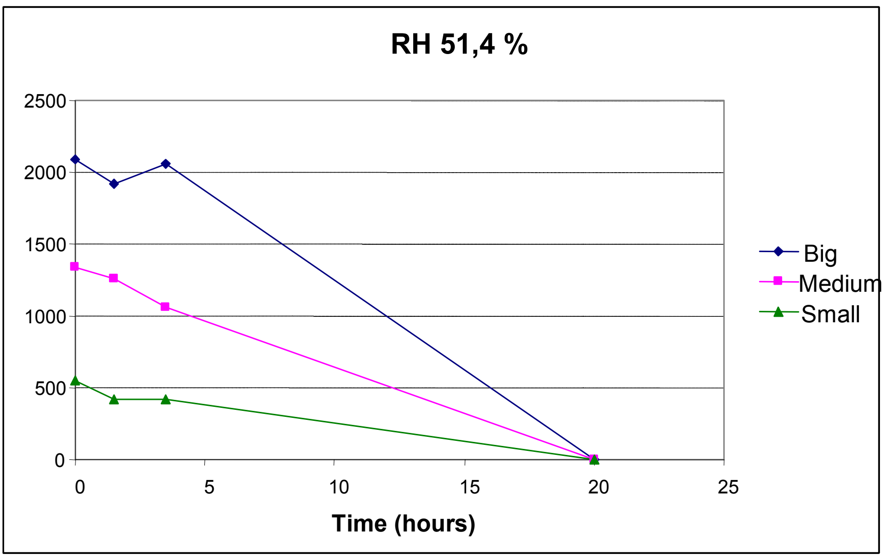


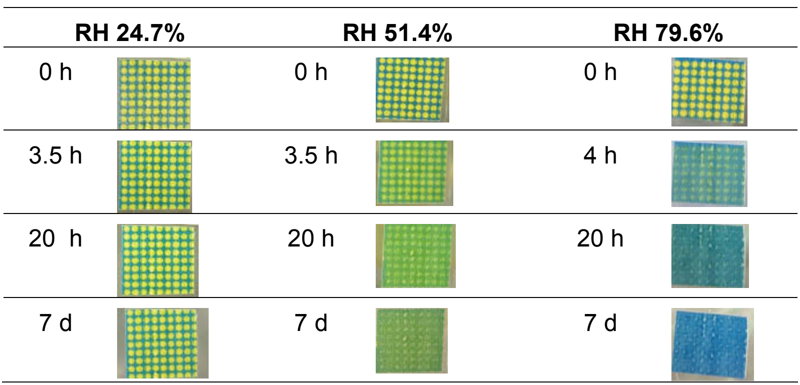
Figure 28. Print quality analysis of the printed RH indicators – the effect of the dot size on the indicator performance in RH 50%.

The humidity indicator will be further tested in connection with the Demonstrator projects of SUSTAINPACK. These Demonstrator projects will set further requirements, which can be used to optimise the performance of the indicators. The Demonstrator projects relevant for the humidity indicator will be the following:

Demonstrator 1: Stronger corrugated box with fibre based cushioning and barrier coated incorporating a RH Indicator/logger

Demonstrator 2: Barrier coated film (O_2 and Water vapour) for snack products, incorporating an RH indicator.

Examples of the indicator performance at different humidities



The effect of the dot size on the reaction time of the indicators in 79.6% relative humidity

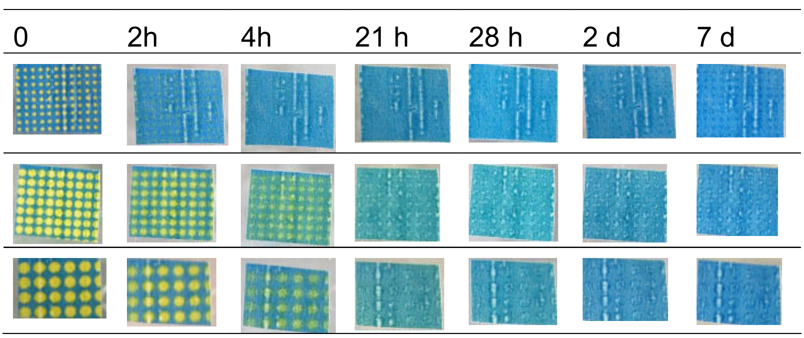


Figure 29. Examples of the performance of the chemical RH indicator. Performance in different RH (upper figure). Performance of indicators with different dot sizes (lower figure).

Visual humidity indicators with text crisp have also been designed and printed for SUSTAINPACK WP6.3 to be used in the consumer study in bread packages to indicate the crispness of the product (Figure 30).

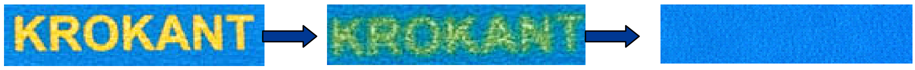


*Figure 30. Chemical RH indicator as a crispness indicator for bread (**krokant** = crispy in Dutch).*

Enzymatic, integrating RH indicator

The development of the enzyme-based, integrating humidity indicators has been initiated and it has been preliminarily demonstrated that an enzyme-based indicator is able to react to cumulative humidity-time effect with slow, visual colour change. If could be seen that in low RH the reaction does nor proceed, but as soon as the indicator is re-contacted with high RH the reaction takes place again (Figure 31). Potential substrates to be used in the indicator, potential indicator structures as well as the compatibility of the enzyme with different humidity absorbing layers have been preliminarily studied. Experiments have been carried out using hand-coated ink layers, but the idea is to develop a printable, enzyme-based composition responding to cumulative effect of humidity and time. Development of reading system based on camera mobile phone is also currently under construction.

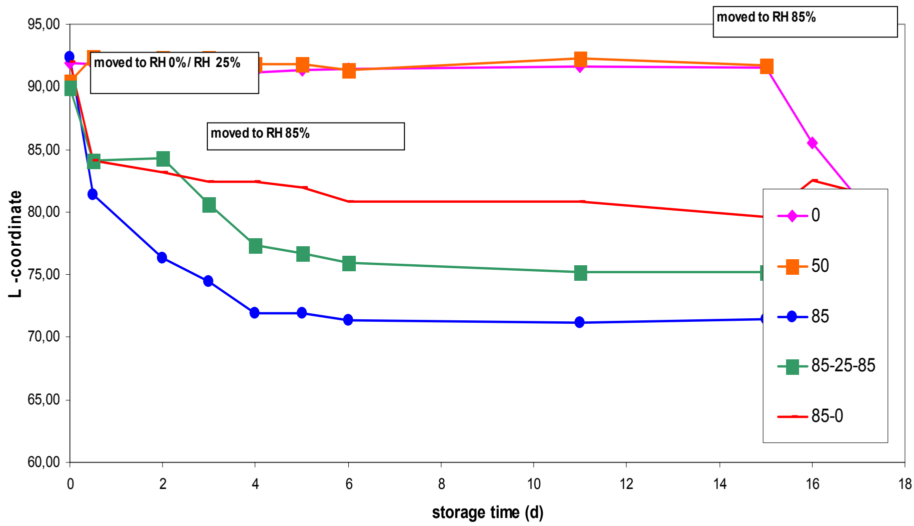


Figure 31. Colour change of an oxidative enzyme based indicator in the presence of different relative humidities.

2D code applications

Two applications are developed in work package 6.2. In the first application, 2D barcodes was utilised in information transfer of consumer packages. This means that on a consumer package is a 2D barcode, which includes consumer information – the selected example was a recipe – was printed using an inkjet printer. After printing the 2D barcode was detected utilising a camera phone and a tailor-made program, which converts the coded information into a readable form in the display of the phone.

The 2D barcode creator program was developed to create 2D barcodes. It was implemented in Matlab on PC platforms. Functionally, the software allows data entering and showing the created barcode on the screen of a personal computer. The length of input data can be up to 256 * 9 = 2304 characters. The application program was implemented in C++ for Symbin OS (versions 6.1 and 7.0). It allows to take images by a mobile phone camera, read the 2D barcode and show code content in a mobile phone display.

In the second application, invisible 2D barcodes was be utilised in anti-counterfeiting of a package. The information in the invisible barcode will be encrypted and needs a special key for the opening of the code. The encrypted 2D barcode creator program is used to create 2D barcodes. It was implemented in Matlab on PC platforms. Functionally, the software allows data entering and showing the created barcode in the screen of a personal computer.

The cipher is substitution cipher. The idea of this method is shifting each character in the entered data (plaintext) using a key chosen by the user. The 2D encrypted barcode creator program is used to create 2D barcodes. The demonstrator was implemented in C++ for Symbin OS. It allows to take images by a mobile phone camera, read the 2D barcode or encrypted 2D barcode, enter a key and show code content in a mobile phone display.

VTT has also developed a technology that embeds ring tone data into 2D barcode. The aim of the system is especially in the packaging applications for special groups. The developed sound system could for example help the use of packages of people with bad sight. The ring tone format is slightly modified RTTTL/Nokring format and contains settings and notes. The 2D barcode contains from units, which have size 13x13 cells and can store about 6 notes. The technology was implemented in use with mobile phone and there is a potential for applications in packaging.

2.3.4 Industrial and research networking, international position

In SUSTAINPACK WP6.1 the development of the visual indicators based on the chemical reaction has been carried out in close collaboration with Xaar and YKI. Construction of the indicators and the printing patterns has been designed at VTT. The basic ink recipies formulated at VTT have been fine tuned by YKI and Xaar. After first printability trials at VTT, the detailed studies on the ink-jet printability have been carried out at printing environment at Xaar. Studies on the indicator performance and print quality analysis have been carried out at VTT.

LCA studies of the indicators developed in this project have been carried out by Itene. Indicators are also currently involved in consumers study carried out in SUSTAINPACK WP6.3 carried out by DTI. Additionally Demonstrator projects involving the chemical RH indicator are currently planned by the SUSTAINPACK consortium.

2.3.5 Exploitation and industrial impacts

Notification of invention and potential subsequent patent application related to the ink-jet printable humidity indicator are currently planned, potentially in collaboration with YKI and Xaar.

2.3.6 References, inventions, patents, academic degrees taken

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2.4 Electrically readable indicators

Mark Allen, Ari Alastalo, Timo Varpula
(printable conductive wiring)
Tommi Riekkinen, Salme Jussila
(electrical thin film indicators)

Abstract

The focuses on “electrically readable indicator” sub-projects have been on the development of printable conductive wiring and electrical thin film indicators. The research work conducted in the first project involved ink-jet printing of conductive wiring using nanoparticle ink, the development of a wireless humidity sensor with polyvinyl alcohol acting as the sensing element and the fabrication and measurement of oxygen deficient titanium dioxide thin-films for room-temperature oxygen sensors. Printing and curing multiple layers led to high enough conductivity for printing functioning RF-coils. A reduction in Q-value of approximately 15% was witnessed between 50% and 100% relative humidity for the wireless humidity sensor and the $TiO_{2-\delta}$ oxygen sensors showed ~15% relative change in conductivity at room temperature when illuminated with UV. The research under the subtitle ‘Electrical thin film indicators’ (2005–2006) was focused on studying such oxygen sensitive materials that involved a change of conductivity rather than a change of color as a function of oxygen exposure. The studied materials were both reactive metallic thin films and organic based thin films and their suitability for food packages was a prerequisite for the utilization. In the beginning of the project a literature survey was made to find out which metals would be the best candidates for oxygen detectors (Ylilammi 2005).

2.4.1 Background, starting point and objectives

Printable conductive wiring

In part of the work reported here, the applicability of ink-jet printed conductive wiring for wireless sensing applications is evaluated. Commercially available metallic nanoparticle ink was ink-jet printed onto various paper and plastic substrates. The printed layer was sintered to form a conductive structure by oven heating. Based on the measured conductivity of sintered wiring, it is assessed whether functioning antennas for RF-based sensors can be printed using this technique. In addition, measurement results for resonator-based wireless humidity sensors with polyvinyl alcohol (PVA) acting as the sensing element, are presented. The conductivity of the PVA layer changes with increasing relative humidity (RH). Since the PVA layer is capacitively coupled to the sensor coil, a change in RH can be detected by measuring the Q-value of the sensor coil.

Also, research work was conducted on developing a room temperature functioning oxygen sensor based on $TiO_{2-\delta}$. Thin film samples with Ti sputtered on a SiO_2 layer were heated in ambient air oven to form a titanium dioxide layer. This way, TiO_2 becomes oxygen deficient (reduced) and conductive. Such oxygen deficient TiO_2 films can act as an oxygen sensor at room temperature. The chemisorption of oxygen captures electrons from $TiO_{2-\delta}$, producing a depletion region on the surface and thus reducing the conductivity.

Electrical thin film indicators

In this work reactive thin film materials for detection of oxygen were examined. These materials can be applied to leakage indicators in packages of food products. A preliminary selection of potential reactive thin film materials was made according to the literature survey written during the project year 2005. The final decision was made on the basis of the experimental work.

Transition metals e.g. Ti, Cr, Ta, Hf, etc. have an inherent tendency to form a native oxide on top of the material when exposed to oxygen or simply air. The thickness of the oxide is generally a few nanometers if the film is thick enough to cover the entire substrate. On the other hand extremely thin films are grown normally in 3D mode. This means that the growing film is composed of material islands giving an ultimate large reaction area to the sensor film. Some organic thin films have also proved to be sensitive to oxygen exposure (e.g. tris 8-hydroxyquinoline thin films used in organic light emitting diodes). So it could be assumed that some organic oxygen indicator films showing a color change would also show a change of conductivity.

The objectives of the research were

- to find out which reactive metals and organic thin films were suitable to be used as an oxygen indicator
- to manufacture sample films by vacuum evaporation and sputtering in the case of metallic thin films and by vacuum evaporation and spin coating in the case of organic films
- to build a test chamber where the samples could be stored in different gas atmospheres (e.g. nitrogen or oxygen).

2.4.2 Implementation

Printable conductive wiring

Cabot's silver nanoparticle ink was printed onto the various examined printing substrates using a printing resolution of 545 dpi (with Apollo 80 pl printhead) leading to the layer thickness of approx. 1 µm after curing (Figure 32). After printing, the samples were transferred to an oven and sintered at temperatures between 100 °C and 200 °C. The substrates considered here include PEN, PET, polyimide, polycarbonate, Siena 250G microporous photobase paper, P 152 CPDG ink-jet paper and HP Brochure & Flyer Paper, Matte.

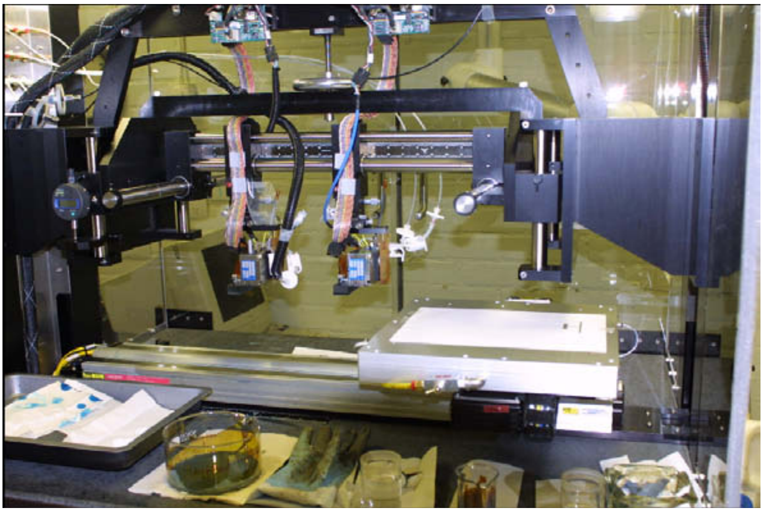

Figure 32. Apollo 80 pl printhead above xy-table at VTT.

The sheet resistance of the printed wiring was measured using the four-point measurement technique at DC. In order to account for the variation in resulting resistance between horizontally and vertically printed wiring (the print head moves in the horizontal direction), a set of ten horizontally and ten vertically printed lines with widths 1 mm, 1.5 mm, 2 mm, 3 mm and 5 mm were printed onto each of the examined printing substrates.

The wireless humidity sensors were prepared by spreading a layer of PVA on the bottom side of the LC-resonators made from aluminum by etching. The humidity sensor was taped to the lid of a hermetically sealed package with the PVA layer facing the inside of the package. The relative humidity inside the package was increased by injecting water through the lid (reference humidity sensor inside package). The frequency dependence was measured with Agilent 8751A Network Analyzer connected to Agilent 87511A S-Parameter Test Set. A two-antenna set-up presented in Figure 33 in which the separate transmitting and receiving antenna loops are positioned orthogonally with zero mutual inductance was used as the coupling element.

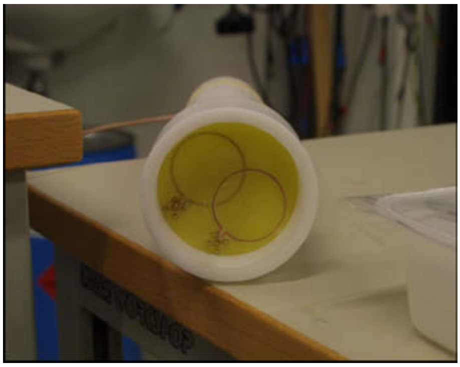

Figure 33. Two-antenna set-up where transmitting and receiving antenna loops are positioned orthogonally with zero mutual inductance.

The $TiO_{2-\delta}$ oxygen sensors were measured in an air-tight chamber with pure nitrogen and instrumental air gas sources connected. The flow rate was chosen to ensure that gas changes inside the chamber sufficiently fast when changing from nitrogen to instrumental air and vice versa, and also to maintain the sample temperature as constant as possible. A UV led with peak wavelength of 370 nm (photon energy 3.36 eV) was used to illuminate the sample. Also a heating resistor and Pt-100 resistor were connected to the measurement frame to enable heating the sample and monitoring the temperature, respectively. The measurement setup is presented in Figure 34.

Electrical thin film indicators

The project implementation can be divided into the following tasks:

- building a measurement chamber (Figure 35) that is suitable for recording the electrical parameters of sample materials
- choosing the oxygen sensitive materials
- manufacturing and measuring the samples.

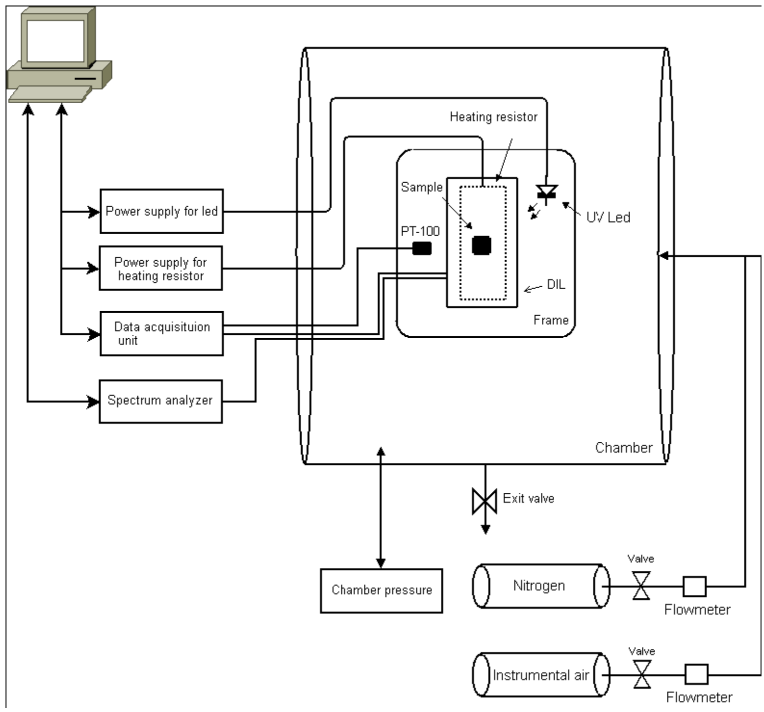

Figure 34. Schematic diagram of the $TiO_{2-\delta}$ oxygen sensor measurement setup.

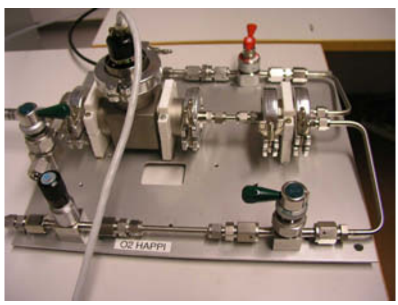

Figure 35. The test chamber where the samples where under testing either in nitrogen or oxygen atmosphere.

According to the literature survey and experimental work titanium was chosen to be a representative candidate of sensor material. Thin titanium films were processed and characterization of the fabricated indicator structures was performed. The metallic titanium films were sputtered on thermally oxidized silicon wafers, 100 mm in diameter. One chamber Sloan DC magnetron sputter system was used. The system was pumped to 1.5 E-7 Torr base pressure to avoid oxygen contamination during processing. Changes of electrical conductivity as a function of time were measured when the samples were exposed to oxygen in air, protective gas and in the dedicated oxygen/nitrogen reaction chamber. Resistance measurements were conducted with a standard four point probe.

The following organic indicator materials were used for testing: brom cresol purple (BCP), brom phenol blue (BPB), pyrogallol, 8-hydroxyquinoline and tert butyl hydroquinone.

2.4.3 Results

Printable conductive wiring

The nanoparticle ink proved to be rather compatible with all the examined printing substrates. Though no pre-treatment other than wiping with IPA was carried out before printing, the ink spread evenly over the substrate leaving smooth and sharp edges (Figure 36). The coated paper substrates completely absorbed the ink immediately after printing leaving the samples dry to touch.

Figure 36. Cabot's nanoparticle ink printed onto polyimide substrate.

Half of the printed samples on paper substrate were oven cured at sintering temperature of 100 °C for 10 minutes while the rest were left untreated (raw). The measured sheet resistance is presented in Figure 37. Huge differences in conductivity exist between the different paper printing substrates. Best results were obtained with Siena 250 G with sheet resistance below $R_{\square} < 100\ m\Omega/\square$ after heat treatment.

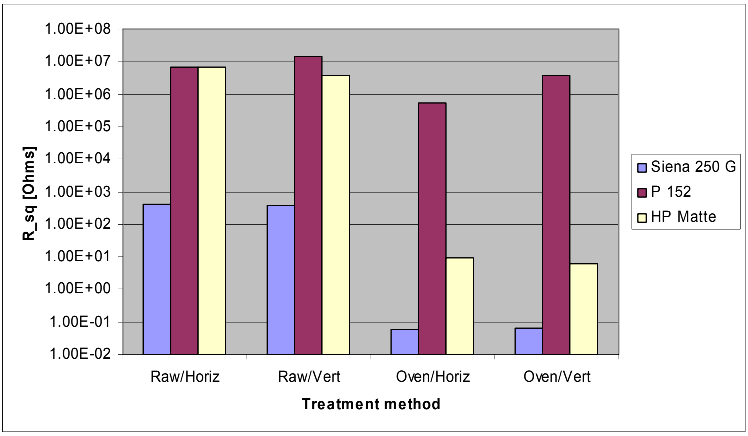

Figure 37. Conductivity of wiring printed onto coated paper substrates.

The samples printed onto plastic substrates were oven cured at two different temperatures. In Figure 38, long drying time refers to samples cured for 120 minutes at approx. 120 °C while short drying time refers to heating at 200 °C for 8 minutes. Generally, horizontally printed stripes have slightly lower sheet resistance than vertically printed stripes and short drying time at higher temperature appears to result in somewhat higher conductivity than with long heat cure at a lower temperature.

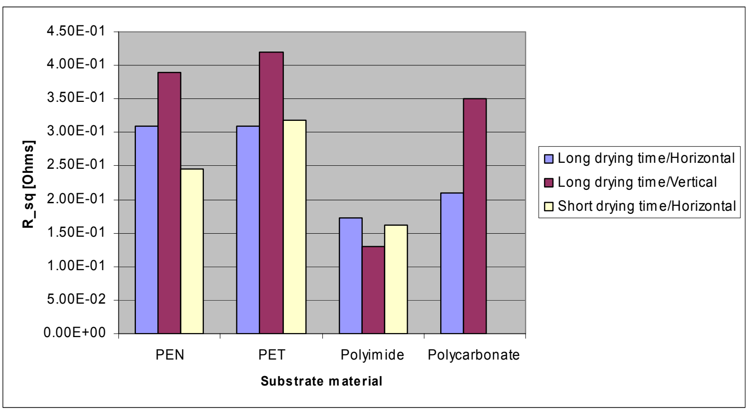

Figure 38. Conductivity of wiring printed onto plastic substrates.

It can be concluded that sheet resistance $R_{\square}$ ~ 100 mΩ/□ can be obtained by printing and curing one layer. Simulations and measurements have proven that this level of conductivity is enough to print functioning antennas for UHF frequencies, but RF coils for sensors with inductive read-out will result in having too low Q-value. This problem can be overcome by printing and sintering multiple layers. Functioning coil antennas with three printed layers have been demonstrated at 13.56 MHz.

The measured Q-value of the wireless humidity sensor as function of relative humidity is presented in Figure 39. A rather large reduction in Q-value was witnessed between 50% and 100% RH. The resonant frequency remained approximately constant.

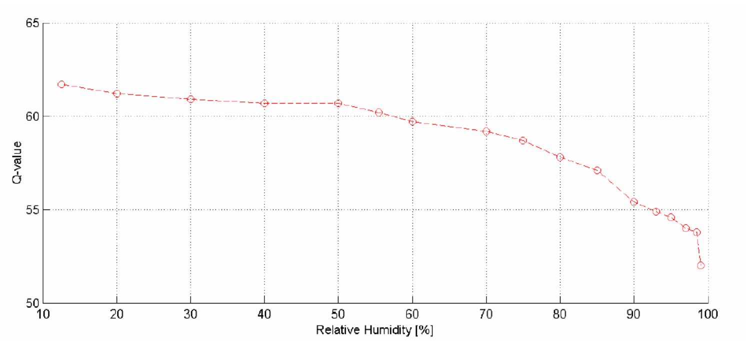

Figure 39. Q-value as function of relative humidity.

When illuminated with UV, the $TiO_{2-\delta}$ oxygen sensors showed a clear response even at room temperature (~15% relative change in conductivity) when measured alternately in pure nitrogen and instrumental air (Figure 40).

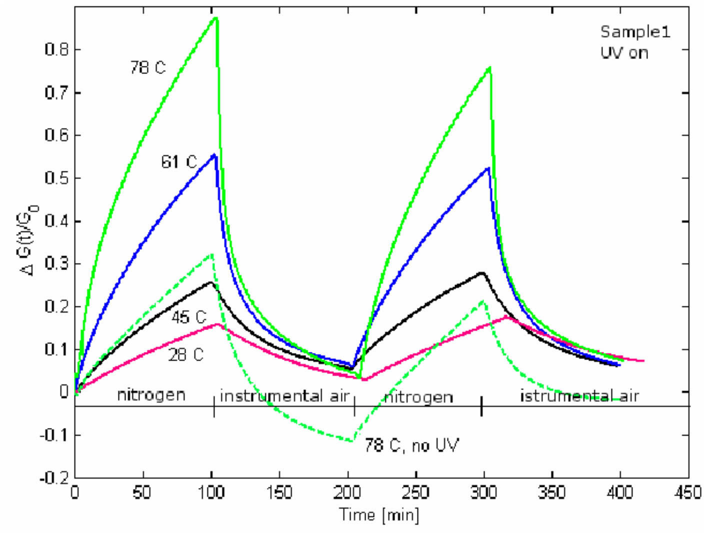

Figure 40. Relative change in electrical conductivity of $TiO_{2-\delta}$ oxygen sensor.

Figure 41 presents the oxygen sensor response at room temperature when pure nitrogen and room air with moisture are varied. The response of the sample was very similar to nitrogen vs. instrumental air measurements. The measurements showed reversible oxygen response of 15% under UV-illumination at room temperature.

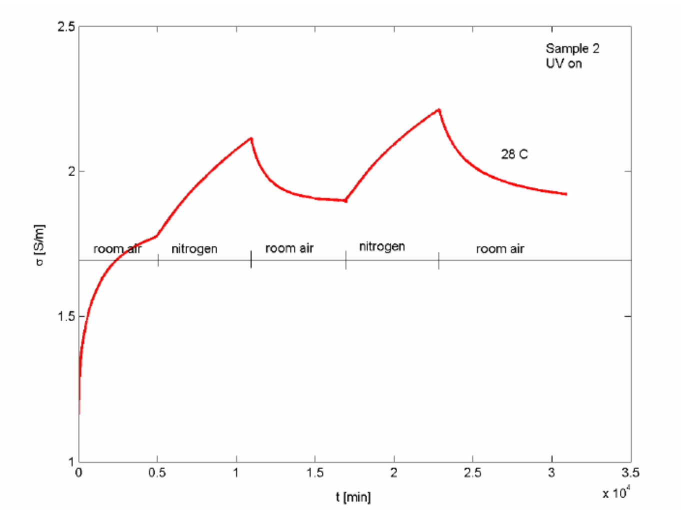

Figure 41. Conductivity of $TiO_{2-\delta}$ sensor when exposed alternately to nitrogen and ambient air.

Electrical thin film indicators

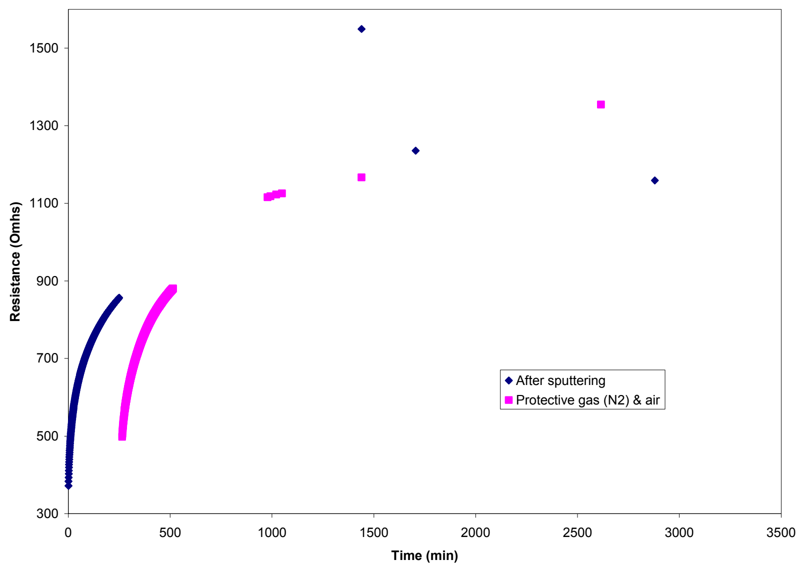

Figure 42. Oxidation reaction of nominally 2.25 nm thick titanium thin film in air.

As an example the oxygen response of nominally 2.25 nm thick titanium thin film is shown in Figure 42. After breaking the vacuum the samples were exposed to air for three minutes before starting the measurement and sealing again into protective gas. The resistance change is strong in the sample measured after sputtering, see Figure 42. Also the reaction in the sample stored for 4 h 25 min in protective gas before the measurement is strong. The oxidation tendency of the films is so highly vigorous that the oxidation takes place regardless of protective nitrogen gas in the pressurized chamber. As a conclusion it was noted that thin metallic films can be applied to oxygen detection since a clear change in conductivity is observed when the film is exposed to oxygen. However, the high reactivity sets challenges to the protection procedures of the material prior to the actual use of the sensor.

The most promising organic materials for oxygen indicators proved to be pyrogallol and brom phenol blue films (Figure 43) by showing a distinctive decrease of conductivity as they were exposed to oxygen. For instance the conductance of the drop cast pyrogallol sample decreased from 2.3 uS to 0.1 uS during 15 hours. The vacuum evaporation of these materials proved to be difficult due to the unknown material parameters (acoustic impedance, density) so the samples were usually made by spin casting or drop casting method.

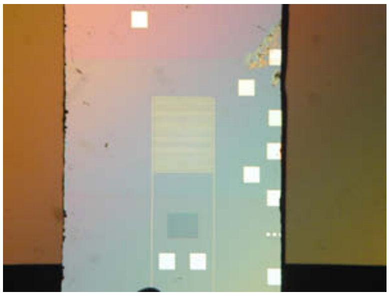

Figure 43. Vacuum evaporated brom phenol blue film on gold electrodes having a distance of 50 micrometers.

2.4.4 Industrial and research networking, international position

Research networking inside VTT was quite efficient since some special equipment situated only in Micronova building was now available for other groups (e.g. the plasma etcher).

2.4.5 Exploitation and industrial impacts

It can be anticipated that the additional value of various consumer packages having electrically readable indicators is noticeable. Such indicators can be exploited in many parts of the logistics chain e.g. in shops and warehouses were large amounts of packages are transported and it is impossible to check all of them manually.

The research in the sub-project "Electrical thin film indicators" started in 2006 and thus is at an early stage. The results are, however, promising and it can be predicted that several types of electrically readable indicator structures will appear in packages in coming years and so they will also have a clear industrial impact.

Research efforts the knowledge created in the sub-project "Printable conductive wiring" are being further utilized in the following co-financed projects and industrial commissions:

- The work has been closely related to VTT's internal project PRINTF on printed H_2S sensors to detect spoilage of poultry. This work is continued in the Tekes-funded "**Printed RFID Sensor Solutions**" project (2006–2007). The project focuses on printed RF rectifiers and modulators for fully printed passive and semi-passive RFID tags; integration of printed sensors and standard RFID platforms; efficient active wireless sensor technology able to directly communicate with standard RFID readers.
- The results of the sub-project, for example, on printable resistive oxygen sensors contributed to acquiring funding from the Technology Industries of Finland foundation for 2007–2009.
- The sub-project has facilitated initial developments of a new low-temperature sintering method for which a patent application has been filed (Patent application FI 20060697) and which is to be developed further in new Tekes, EU and contract-research projects that are currently under preparation.
- **PRINTAG** project aiming at to develop and demonstrate printable electrical coding systems and RFID technology. The project is financed by Tekes, VTT and industry.
- The knowledge created in the sub-project about printed antennas has been carried over to the ongoing **Interconnections for Smart Cards** project (2005–2008). The project develops technologies for reliable interconnections in thin contactless smart cards as well as technologies of die stacking for cards with increased functionality and memory capacity. VTT's work is concentrating on the technologies for thin contactless cards. The project is financed by Tekes, VTT and industry.

2.4.6 References, inventions, patents, academic degrees taken

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2.5 Logistics – Increasing intelligence in supply chains

Antti Permala, Ville Kotovirta, Henrik Huovila,
Pekka Maijala, Hannu Salmela, Harri Hiljanen

Abstract

Efficient and reliable supply chain is important to trade and industry. The wireless data transfer technique and sensor technology enables significant development of the supply chain. New technology can change the business process models and can give speed to the growth of the e-logistics. The overall objective was the development and integration of an intelligent measurement and control system for the transport supply chain. The IT architecture of intelligent monitoring equipment was created in the project. The architecture showed the complexity and demanding nature of these systems. Information platform for supply chain and network applications is missing. Now when companies try to pilot and implement RFID identification, the lack of architectures is slowing or preventing this development. The automated data transfer between companies is still a barrier. The project described possible solutions for information architectures for supply chain monitoring. A case study dealing with temperature in a food chain showed that even this simple task is challenging in today's supply chains. Identification is a prerequisite for automated monitoring. Automated identification of transport units, pallets, roller

gages etc. is becoming common within next years. This will even down the way to intelligent packaging. Electronics industry as well as paper industry is already using data logger type monitoring technologies in their supply chains. Food industry will follow, partly due to the new legislation. The challenge is to introduce wireless and real time solutions.

2.5.1 Background, starting point and objectives

Intelligent package is a package that monitors its own condition, makes intelligent conclusions and communicates wirelessly in the supply chain. The system is based on an active package and automated and interactive communication and is able to monitor location of the package and to indicate of the condition such as temperature, humidity, acceleration or electric discharge (EMI/ESD). Intelligent package enables better control of the logistics, management of exceptions, analysis of information and automation. In addition to the package, a transport unit or warehouse module is needed. This module transmits and saves data and also keeps record on packages. The package communicates with Bluetooth in the transport unit or warehouse level. The transport unit communicates with GSM/GPRS technology to a control centre. The package sends a message to the control centre if alarm limits (e.g. temperature is not within given limits) are exceeded.

The overall objective was the development and integration of an intelligent measurement and control system for the transport supply chain:

1. The basic part of the system is the package, which contains the measuring system, processor, memory and wireless communication. The package (such as pallet or roller cage) is able to perform measurements, transmit the data, operate independently and manage the sensors.
2. In addition to the package, a transport unit or warehouse module is needed. This module transmits and saves data and also keeps a record of the packages. The package communicates in our demo device with Bluetooth in the transport unit or warehouse level. The transport unit communicates with GSM/GPRS technology to a control centre. The package sends a message to the control centre if alarm limits (e.g. temperature is not within given limits) are exceeded (Figure 44).

3. The transport unit does not necessarily have a constant GSM connection available. Because of this, processing capacity and memory capacity is required both for the package and the transport unit. This guarantees that the information is stored until the communication link is once again available and the data is transmitted.

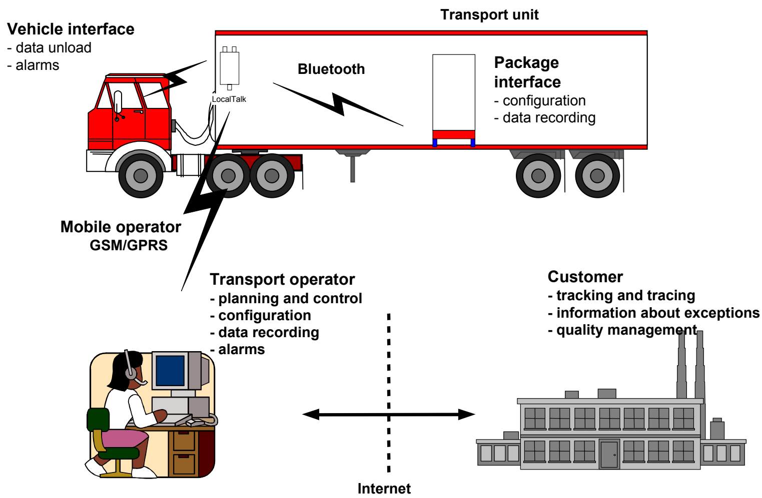

Figure 44. Layout of the system and interfaces.

Benefits

The system enables better control of the supply chain because the location of the package is better known and in the differing conditions one can quickly intervene. In case of problems the responsibilities can be identified more clearly. The system makes the monitoring of the situation of the commodities to be transported possible at a totally new level and produces significant cost savings due to reduced human labour and increased control. In the longer run systems like this can change the logistics business models and can stimulate the growth of e-business.

The proposed system enables new functions related to the development of logistics. Among others, this could include data mining and the statistical analyses of the location and other measured characteristics of the packages. The effectiveness of the logistics is increased when the analysis can show in which part of the supply chain the packages are delayed. Furthermore, for example, the automation of work processes and customer inquiries becomes possible.

IT architecture for package and supply chain

The vision for freight transport telematics architecture describes the freight transport target that should be reached after the issues defined in the architecture have been accounted for:

- Real time information about the location, contents and conditions of identified shipments, goods items, parcels and transport vehicles can be collected in a controlled manner.
- The collected information can be combined with planning information and refined appropriately to be used during various parts of the process and distributed efficiently and timely to actors.
- By collecting, refining and distributing information efficiently organisations can boost their goods transport logistics processes, lower their operational costs and improve their portfolio of logistics services.

The hierarchy of tracing includes handling of the track and trace data of transport means (local), the logistics service operator, the supply chain operator, the user of the track and trace data (for example, a customer) (Figure 45).

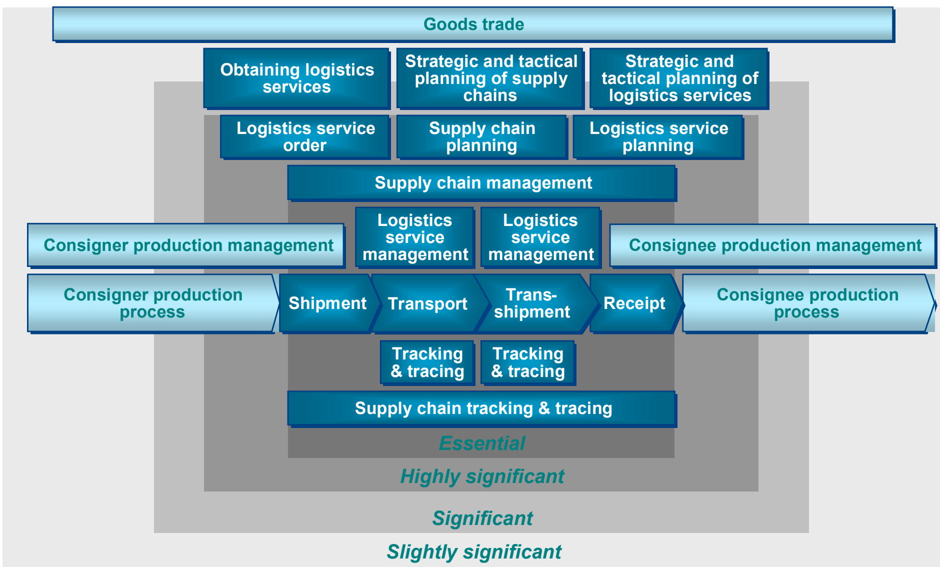

Figure 45. Application area of the telematics architecture of the goods flow and the significance of processes from the point of view of the objectives of the architecture (source: Granqvist et al. 2003).

The intelligent package can be used to control the process, for example information about the arriving package into a terminal (ETA estimated time of arrival) and to manage the deviations. Central parts of the logistics concepts are the following:

- Vehicle information systems which are based on the CAN bus and different connected "boxes". The focus is the control of the information of the truck (consumption, the driven distance etc.).
- Fleet management which culminates in transport control systems and big transport companies.
- Control of the freight; the supply chain and the viewpoints of the delivery sender and receiver.

2.5.2 Implementation

Case electronics industry

In the electronics industry the objective is an intelligent package and logistics system which will meet the growing demands of the electronics industry also in the future when the packing density of the integrated circuits and the malfunction sensitivity increase (the line width to become smaller). The packages have to give as good a protection as possible against all the stresses during the transport and handling. This requires on the one hand, active protection properties from the packing and on the other hand, the know-how and control of the supply chain. The target system makes the real-time collecting of the stresses and strains possible during the logistics so that it will be possible to track the damaged products and to direct corrective actions at as early a stage as possible. The collected information can be used for the optimisation of both supply chain and packages to minimise the malfunction risk.

The intelligent logistics outline that is developed in the project is adapted by studying the product deliveries of the companies that operate in the value network of the electronics industry. Different logistic chains have been examined with a pilot-device – for potential ESD risks, among others. Also with the companies developing packing materials and solutions and delivering it has been examined functionality of the new materials and packing concepts.

Case food industry

In the transport of foods different small units such as roller cages, plastic boxes (Transbox, bread boxes etc. producer-specific boxes), pallets and other boxes are used. Still the acute target for the development is the automatic identification of the units and products based either on a barcode or on the RFID techniques.

In food transports the monitoring of conditions is needed for example for the follow-up of temperature and moisture. Furthermore, the traceability of products in the supply chain is important if there are mistakes in production or transport conditions which necessitate manufacturers to withdraw their products. When the conditions of the chain are known, the history of mistakes can be clarified more effectively than at present. The monitoring must cover the whole chain – transport, handling, terminals and storage – seamlessly from production to consumption. The mere observation of the transport will not be enough if the product will stand for hours on the loading bridge before being transported to the warehouse. The supply chain is multi-phased containing a manufacturer, wholesale, retail, all transports and storages. For export and import there are still more stages and portals.

The pilot measurement of temperature in one food supply chain showed that even so simple task like this is very demanding. The systems to transfer information between customer, numerous suppliers and subcontractors do not exist. The same problem is seen in RFID pilots.

2.5.3 Results

Status of development at the end of the project

New element from customer side has been the risk management of supply networks. This has directed the development work also for logistics concept development. The latest version of equipment has based on sensor network with Bluetooth interface (Crossbow® MICAz). MICAz is a 2.4 GHz, IEEE 802.15.4 compliant Mote module used for enabling low-power, wireless sensor networks. Connection to network is through Bluetooth enabled mobile phone or laptop PC. (See Figures 46 and 47.)

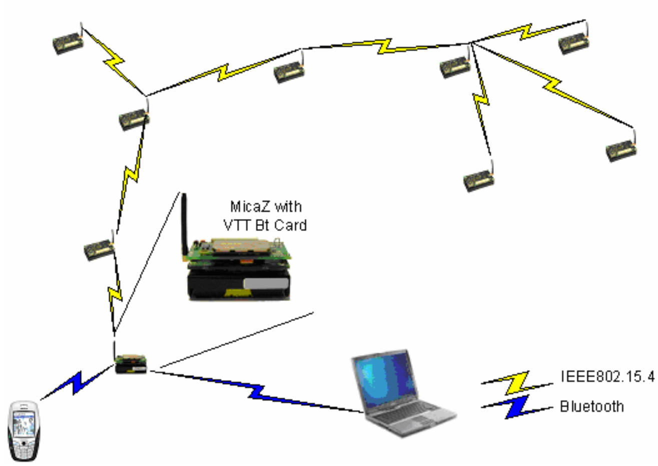

Figure 46. An example of a test measurement.

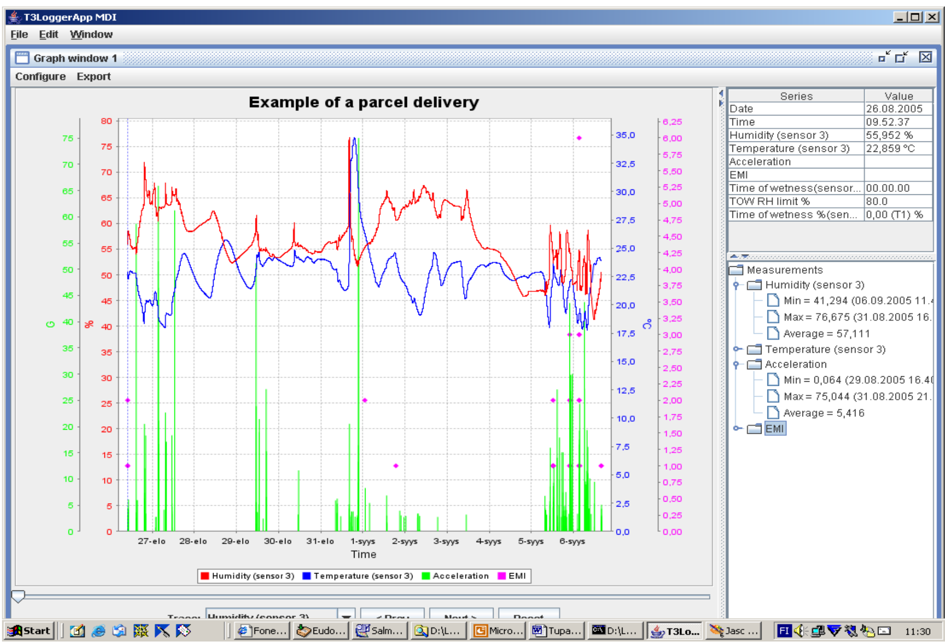

Figure 47. An example of output.

A demo equipment was built consisting of the following parts: the iPAQ pocket PC which simulates the package device, Laptop PC as a vehicle device and Desktop PC as a device for transport control. The connection between iPAQ and

Laptop is carried out in Bluetooth and between Laptop and Desktop with GPRS. Demo has the following features (Figure 48):

- The start is manually performed.
- The user can choose the continuing or an alarm follow-up.
- The programme depicts the results as graphs.
- Simulated temperature and acceleration, furthermore simulated location information with GPS.
- If there is no connection, usage is of the Datalogger type.

Figure 49 gives an example of a test measurement. The graph gives the temperature, humidity and ESD values for the transport chain of circuits.

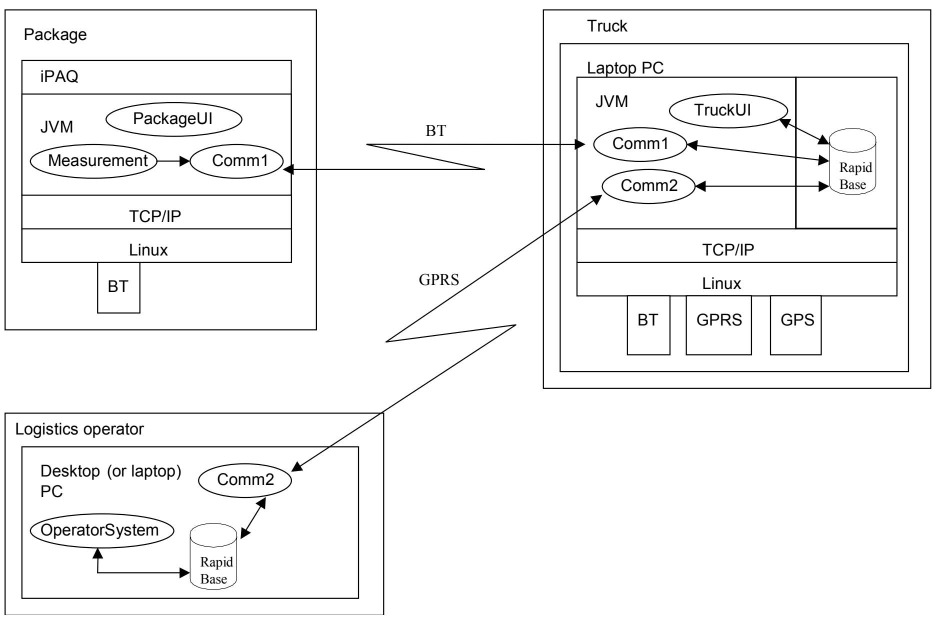

Figure 48. Demo architecture.

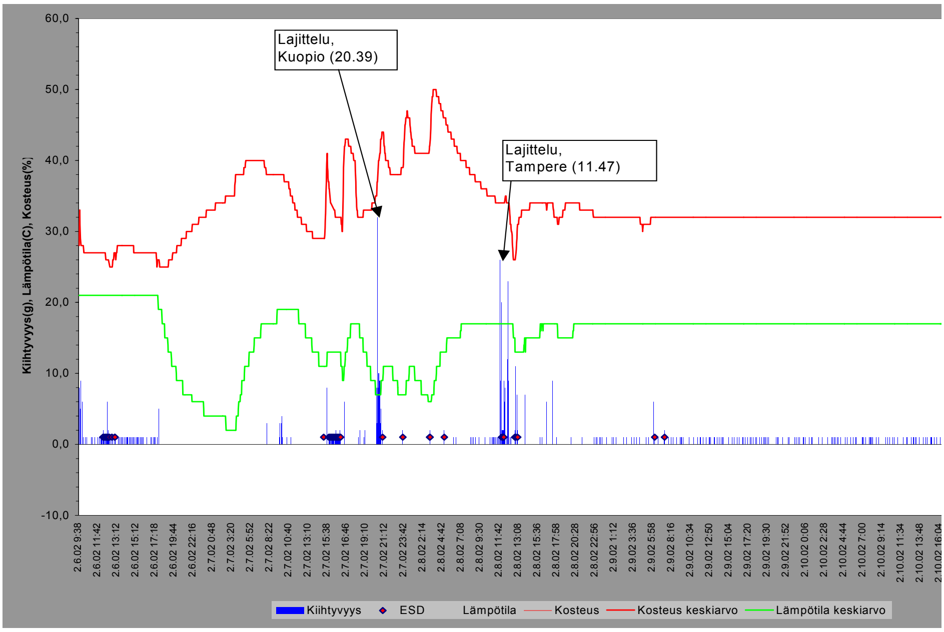

Figure 49. Example of desired output.

2.5.4 Industrial and research networking, international position

- ECTRI – European Conference on Transport Research Institutes
- PROMIT – Promoting Innovative Intermodal Freight Transport – EU Coordination Action

2.5.5 Exploitation and industrial impacts

Follow-up projects based partly on the theme:

- Risk management in logistics networks – Industrial R&D project
- Management of security critical supply chains – Industrial R&D project
- Intelligent logistics system – Military R&D project
- Monitoring of environmental conditions and data transfer in supply chains and in production plants – an industrial case study
- RFID identification in logistics processes – Industrial R&D project.

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3. Distributed Energy

Raili Alanen

3.1 ENTRY – Management of Distributed Energy Systems

Krzysztof Klobut, Jari Shemeikka, Pekka Tuomaala, Kari Sipilä, Jorma Heikkinen

Abstract

The basic idea of a distributed simulation environment has been presented and elaborated in a new context, in which building energy simulators and district heating network simulator are hydraulically and thermally linked from the power plant via the district heating network to the internal room conditions in buildings. The models and software employed in this task were either developed originally or reshaped and adapted within the frames of this project. An economical evaluation tool was developed and analysis was carried out considering different heating systems operated in a group of houses connected to a district heating network. Heat trading was evaluated as a new business concept, which assumes that small scale producers are allowed to connect the network, and it was found technologically feasible. However, a transition from the current monopolistic business environment to a new and liberated heat market is a prerequisite. A model for a selected distributed co-generation technology, solid oxide fuel cell system, has been created and integrated with building simulation software. The ICT-architecture was defined to assure the stability of the distributed simulation environment. Considerable effort was spent to sustain a generic approach when defining the requirements. **The main delivery of the project is an alpha-prototype of a software tool capable of performing the challenging task of simulating operation of the whole energy supply chain simultaneously. As far as we are aware, this has not been achieved anywhere else.** Limited results obtained so far confirm the applicability of the approach. Test cases demonstrated that the convergence control is the critical part of the architecture.

3.1.1 Background, implementation and results

Conventional combined heat and power generation (CHP) used in large power stations is a process where heat (generated as a by-product of electricity production) is captured and delivered by means of district heating network to heat buildings. In recent years smaller CHP prototypes have emerged (e.g. fuel cells, Stirling engines) and the concept of decentralisation of energy systems has become a subject of research. In this context, mini- or micro-CHP solutions scaled down for a single building come to the focus. The main objective of this project was to develop tools to enable a versatile analysis of the entire energy supply chain covering the source (remote or local), distribution system and utilization of heat in buildings.

Over its entire lifespan the project was carried out in a number of sub-projects that can be grouped in three complementary parts focusing on:

- background, collection of digital data and economy analysis
- distributed co-generation technologies (micro-CHP, fuel cell)
- coupling of building's internal and external networks in simulation.

The main obtained results are as follows:

- Alpha prototype of coupled software was developed capable of mastering the distributed simultaneous simulation of the whole energy chain; this is a **brake-through achievement**.
- Models for district heating network and substation heat exchanger were developed and adapted.
- A system level of fuel cell model was developed and incorporated in building's energy simulation.
- Economical evaluation was carried out considering different heating systems operated in a group of houses connected to a district heating network.
- Heat trade was evaluated as a new business concept and technological feasibility was found.

Industrial and research networking, international position and exploitation

Figure 50 and Figure 51 show how in the year 2004 we saw the drivers, trends and future development of distributed energy and how we planned to respond in research projects, also in the future (see "our research efforts" in Figure 51).

Currently, on the domestic level, there are separate confidential industrial assignments going on in this field. In addition, networking with private companies, and other research organisations is strengthening via technology programs funded by Tekes in the field of distributed energy systems (DENSY) and building services (CUBE) promoting the technology transfer from theory to the practice, see listing of the projects below. Integrated software prototype is being further developed within the frames of newly established SIMANTICS-project. Preparation for demonstration of fuel cell system is in the scope of the new large project SOFC-Power 2007–2011 that is in the final phase of preparation. This project has international collaboration connections (within present Framework Program FP6 and soon starting FP7 of European Commission) and will belong to new Tekes funded technology program on fuel cells.

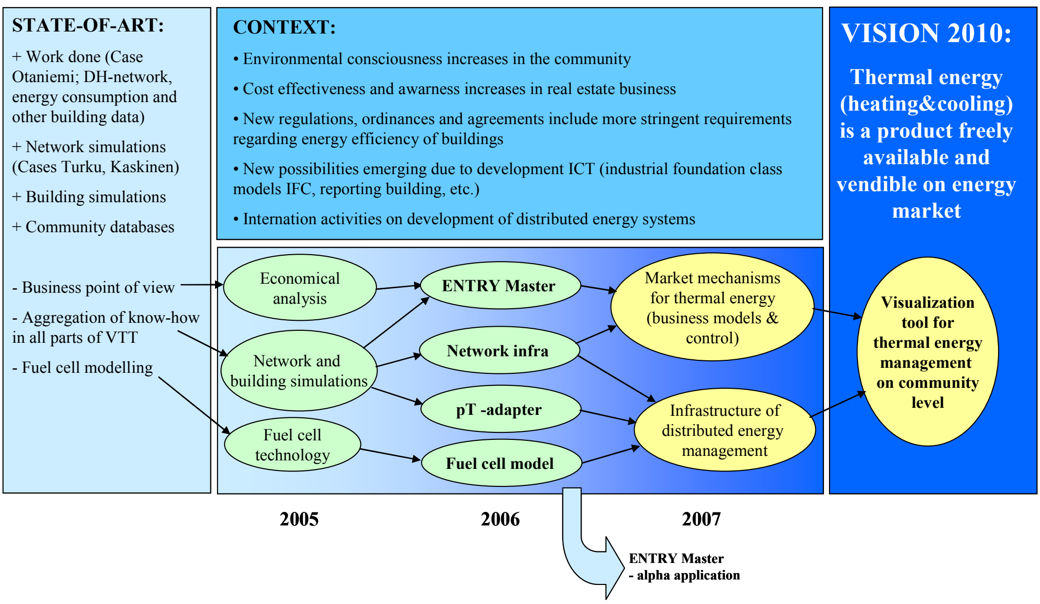

Figure 50. Roadmap for management of distributed energy systems (as recognized in the year 2004).

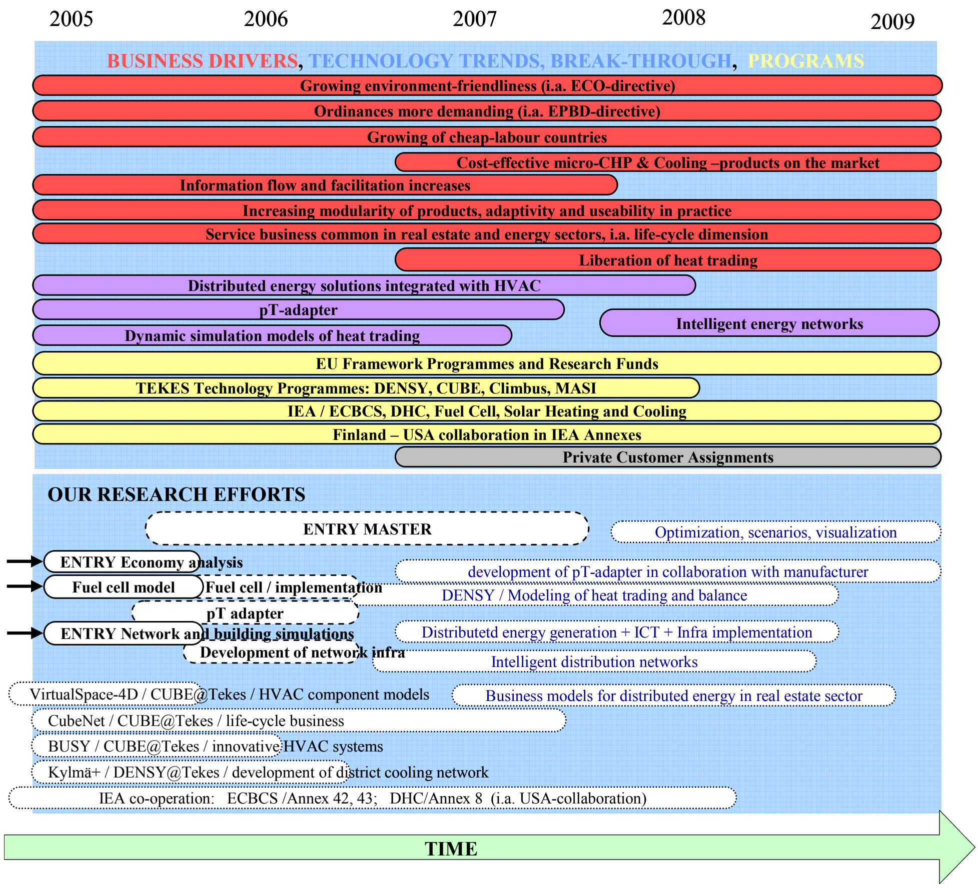

Figure 51. ENTRY projects on the map depicting other related projects and business drivers and trends (as recognized in the year 2004).

International co-operation has been established and continued mainly within the frames of International Energy Agency, Implementation Agreements on

- Energy Conservation in Buildings and Community Systems (ECBCS), Annex 42 and its planned follow-up, Annexes 37, 43 and 49
- District Heating and Cooling (DHC), Annex VII and VIII.

The following listing covers the largest executed or on-going research projects with connections to ENTRY project:

– Hydrogen Energy Foresight in the Nordic Countries. Co-operation project funded by Nordic Industry Fund.

- District heating distribution in areas with low heat demand density. IEA/DHC Annex VIII.
- A Comparison of Distributed CHP/DH with Large Scale CHP/DH. IEA/DHC Annex VII.
- Building Energy Analysis Tools. Participation in Experts Group. IEA/ECBCS Task 22.
- FC-COGEN-SIM. The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems. IEA/ECBCS Annex 42.
- SUNTool – Sustainable Urban Neighbourhood Modelling Tool. International project funded by EU Commission DG TREN.
- COMBI (Integrated use of fireplaces and HVAC systems). Co-operation project funded by Tekes.
- Pienet CHP-laitokset ja kaukolämpö (Small CHP-plants and district heating). Project within DENSY Technology Program (funded by Tekes).
- DO2DES – Design of Optimal Distributed Energy System. Project within DENSY Technology Program (funded by Tekes).
- (KYLMÄ+) Alueellisten sekä rakennusten kylmä- ja lämpöjärjestelmien yhteiskäyttö (Simultaneous operation of cooling and heating in buildings and local energy systems). Project within DENSY Technology Program (funded by Tekes).
- HETRA – Technical Features for Heat Trade in Distributed Energy Generation. Project within DENSY Technology Program (funded by Tekes).
- BUSY – Innovative future BUilding SYstems (Tulevaisuuden innovatiiviset talotekniikkajärjestelmät). Project within CUBE Technology Program (funded by Tekes).
- CUBENet – Talotekniikan tulevaisuuden elinkaaripalvelut (Future concepts of life-cycle service of HVAC) Project within CUBE Technology Program (funded by Tekes).
- Virtual Space 4D (Sisäolosuhteiden hallinta). Project within CUBE Technology Program (funded by Tekes).
- SIMANTICS (Simulation Based Knowledge Management in Engineering Lifecycle). The first follow-up project emerging from the results of ENTRY.
- Domestic confidential assignments from Turun Uunisepät Ltd and Tulikivi Ltd.

References, inventions, patents, academic degrees

The ENTRY project produced a number of academic and scientific achievements:

- one doctoral dissertation
- 3 thesis for the degree of Master of Science in Technology
- 16 journal and conference publications; all listed in the context of the following project descriptions in a greater detail.

3.1.2 Distributed energy from technological and economical point of view

3.1.2.1 Technological approach

Recent technological development has shown that combined heat and power generation is possible, not only in large power stations, but also locally. A distributed CHP-unit can serve one building or a group of them. If enough heat and electricity can be generated locally within the building, dependency from external networks is reduced. Otherwise, the missing part should be delivered to the building and the surplus part should be stored or transferred out of the building.

One key issue when evaluating future trends of distributed energy systems is the infrastructure of the whole thermal energy supply chain, both from technological and economical point of view. The ENTRY project focused on these aspects, as well as management of distributed (thermal) energy system, and the primary aims were

- to define, analyse and develop <u>concept models of building service systems</u> (BSS) compatible with distributed energy systems
- to develop <u>methods and tools for life-cycle management</u> of the whole thermal energy chain – from production to consumption – utilising modern ICT platform
- to develop <u>expert service products</u> for design, implementation, and control of distributed energy systems.

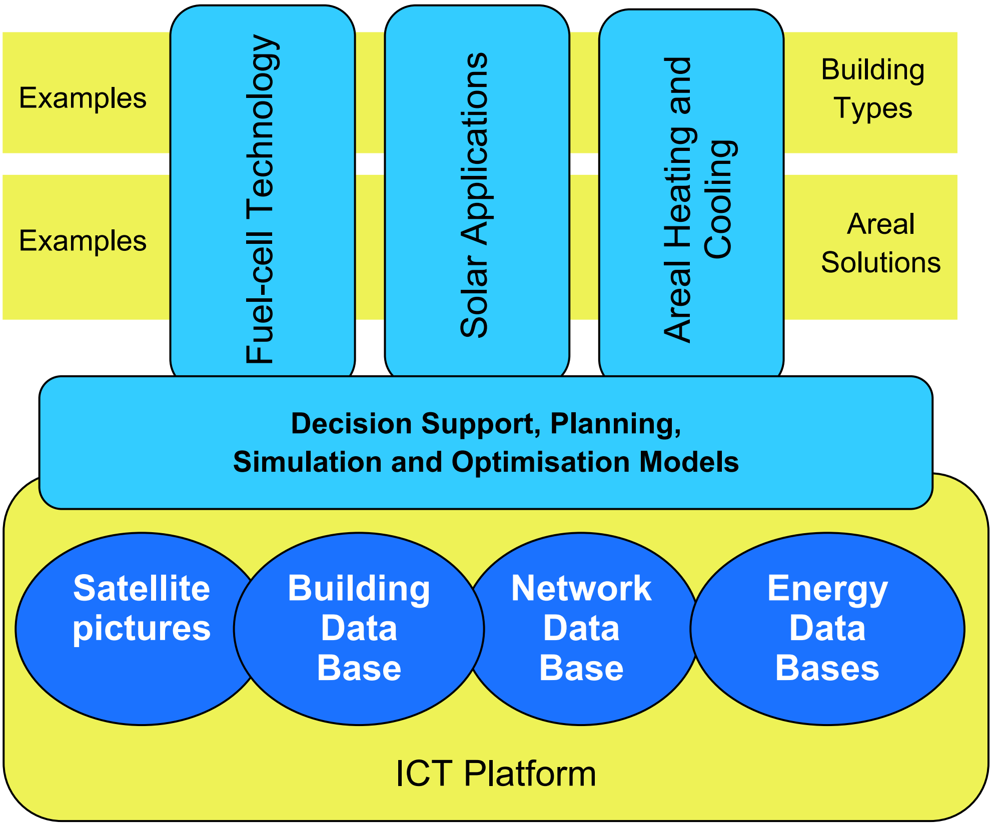

Figure 52. The adopted research approach of the entire ENTRY project.

All research activities related to this subject were coordinated according to Figure 52. One starting point was to collect all available data of a group of buildings to be able to test and demonstrate alternative concepts of distributed energy systems. Therefore, satellite pictures, buildings data, district heating network data, and energy consumption data were collected from Otaniemi area as a raw material for the ICT Platform to be developed.

Among other things, the collected building data from Otaniemi area included building locations, building volumes, and heating methods. Most buildings are connected to a district heating network, and the underlying substation connection information was also collected.

Measured data related to building level energy consumption (both heat and electricity) and water consumption were collected from the period of five years. This raw data makes enables calculation of quantitative energy saving potentials and energy economy estimations in alternative energy management concepts.

Figure 53 shows the detailed structure of the Otaniemi area district heating network. In addition, all other necessary input data (i.e., pipeline dimensions, network elevation data, pumping stations) for simulations of the district heating network were collected. This network information, together with the building level data, enables thorough simulations and analysis of the whole energy supply system with realistic thermo-hydraulic interaction between the district heating network and the regional building stock. Finally, this realistic interaction is one key issue when comparing the conventional and futuristic concepts.

During the project, several simulation models were developed for decision support, planning, simulation, and optimization purposes. On building level, a ***VTT Talo*** (*VTT House*, developed at VTT) application was the most important simulation tool producing necessary thermo-hydraulic data for interaction between the district heating network simulations. New simulation and calculation features were also developed (e.g. a new heat exchanger model for alternative substation concepts and floor-heating model for more realistic transient thermal response of building) for ***VTT Talo***. In addition, special models of fuel-cells as well as an economy analysis tool for comparing alternative heating options were developed and are explained in the following of this publication.

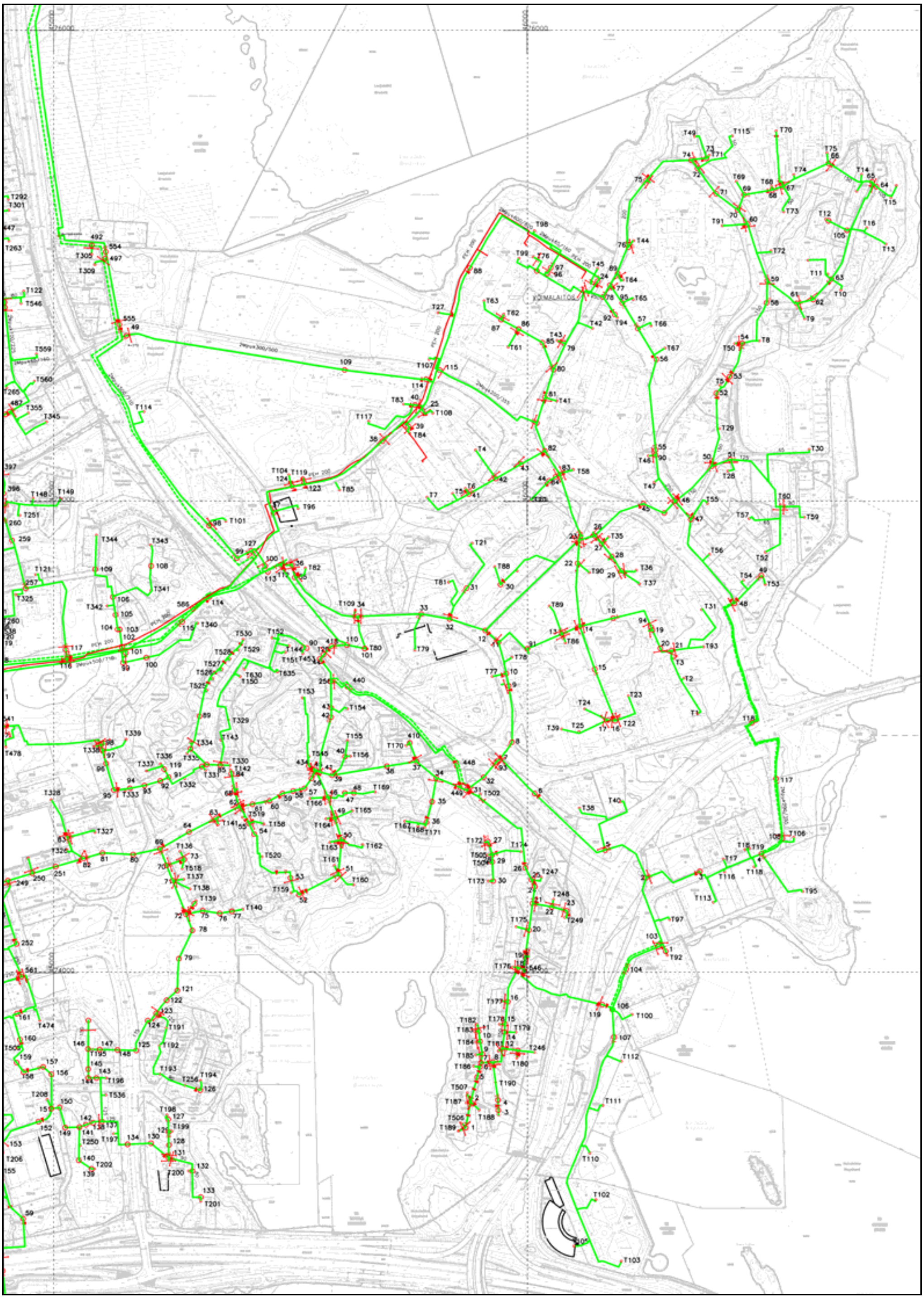

Figure 53. District heating network data from Otaniemi area.

3.1.2.2 Economical approach

Cogeneration systems (CHP) provide both useful thermal energy and electricity generated from a single source such as fuel oil or natural gas. From the technological viewpoint, potential for the application of micro-CHP in the residential sector seems promising. However, reliable information about the prices of the micro-CHP units is not yet widely available. Technical solutions are still in a developing stage. Prices are expected to decrease in the future, when technology develops further and is followed by increase of production and demand.

The main objective of this research was to evaluate the competitiveness of micro-CHP plants, when compared with the current heating solutions used in the residential sector. Technologies such as fuel cells and Stirling engines seem promising for small scale cogeneration for residential buildings in the future and have therefore been used in this research. The other heating techniques used in the comparison were fuel-oil heating, district heating, ground source heat pump heating and electric heating.

A new calculation tool was developed. Information regarding costs of different heating plants was collected and saved in the data base of the tool. The total costs of each heating method were calculated separately for each heating plant, but using the same approach in which present value of each heating type is expressed as a function of time. The total costs include: construction stage investment costs, annual energy costs, fixed annual basic fees and service and maintenance costs during a life time of 30 years. The ranking of different heating generation methods according to the costs (from lowest to highest) were district heating, electric heating, ground source heat pump heating, Stirling engine, fuel cell and oil heating, see Figure 54.

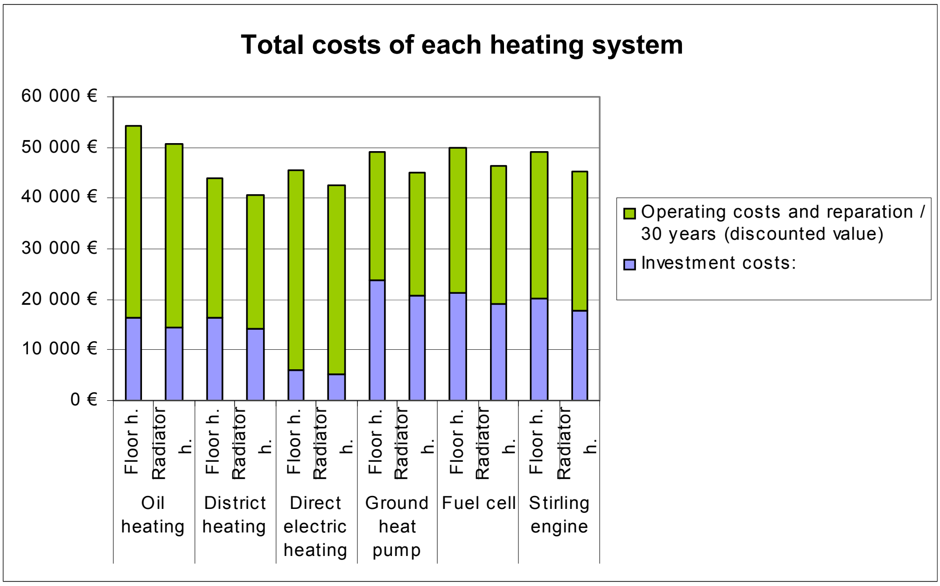

Figure 54. The total costs of different heating systems. The total costs are divided into the investment costs (blue) and operating and repair costs (green). The operating costs are generated during a period of 30 years and they are calculated into present value (5% annual discount rate was used).

A sensitivity analysis was also performed to determine the effects of considerably higher electricity and gas prices and doubled maintenance costs. The investment price of devices for the fuel cell unit and Stirling engine needs to be 7 500 € and 7 000 €, respectively to be competitive with electric heating. If the electricity price increases by 2 cents, the competitive price for investment of devices is 16 500 € for both micro-CHP units. Even at today's prices, the micro-CHP unit is a serious alternative in the Nordic climate, when all the investment costs of devices are considered. However, with an increase in electricity prices there is the possibility that micro-CHP units will be more cost-effective than electric heating. (Jahn 2005.)

3.1.2.3 New service and business concept – heat trading

When comparing alternative technical solutions of a distributed energy system, a new level (above the ICT Platform) of methods and tools is needed for decision support, planning, simulation and optimization, and analysis. Figure 55 presents a general structure of simulated and studied network of thermal energy supply chain of a community.

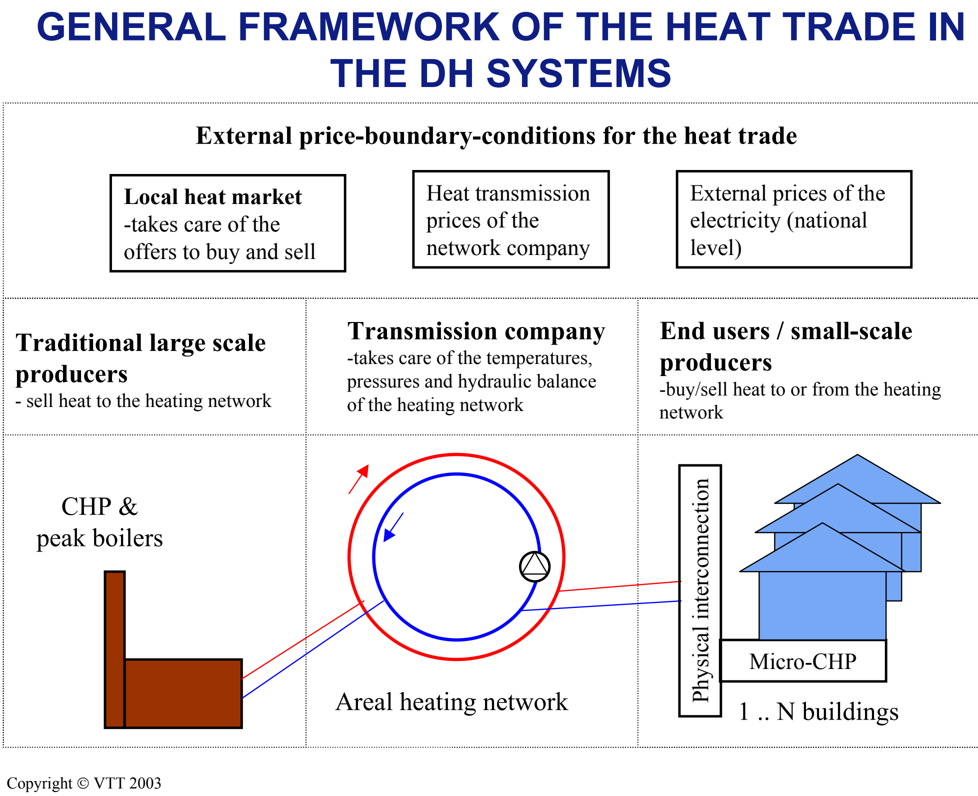

Figure 55. Schematics of heat trading concept for the heating networks.

Liberated heat market would operate mainly like a liberated electricity market in Nordic countries with the exception that heat market would be limited by a local district heating network. There are producers, customers, a network operator and a system operator as exists in the electricity market. Physical actors are the traditional large scale producers that sell heat to customers connected to the district heating network, and the end users, that would also be small-scale producers using a micro-CHP or a boiler. They would buy heat from other producers or sell heat to customers through the network. The liberated heat energy market will also need the transmission-network-company that takes care of the temperatures, pressures and hydraulic balances of the heating network.

A balance-sheet operator is also needed to coordinate the heat contracts between producers and customers as well as to take care of reserve capacity, spot and future markets and billing.

The requirements for the district heating network design in the heat trading context are an aspect that still requires further attention. Our simulations showed that temperature changes were occasionally quite rapid in some parts of the network. They were caused by stagnation of flow in some loops of the network, where flows come from different directions. Small producers seem to bring more time-varying factors into the system. This might lead to a new district heating network design approach where temperature variations can be minimized. (Sipilä et al. 2005.)

The transfer of energy from the building for utilization elsewhere is a relatively new option. Transfer of electricity from local generation site to the grid has already been introduced in the market (windmills, photovoltaics). The study performed within ENTRY project brings a new perspective to the issue of decentralisation of energy production by exploring the possibilities of trading not only electricity but also heat. This was done by simulation using a case of limited population of buildings connected to the district heating network. Eight different scenarios were elaborated (marked as A through G in Figure 56) regarding the degree of decentralisation and operating strategies of local micro-CHP systems. Energy consumption of the community was computed for each hour of the year and the annual consumption in different scenarios is depicted in Figure 56.

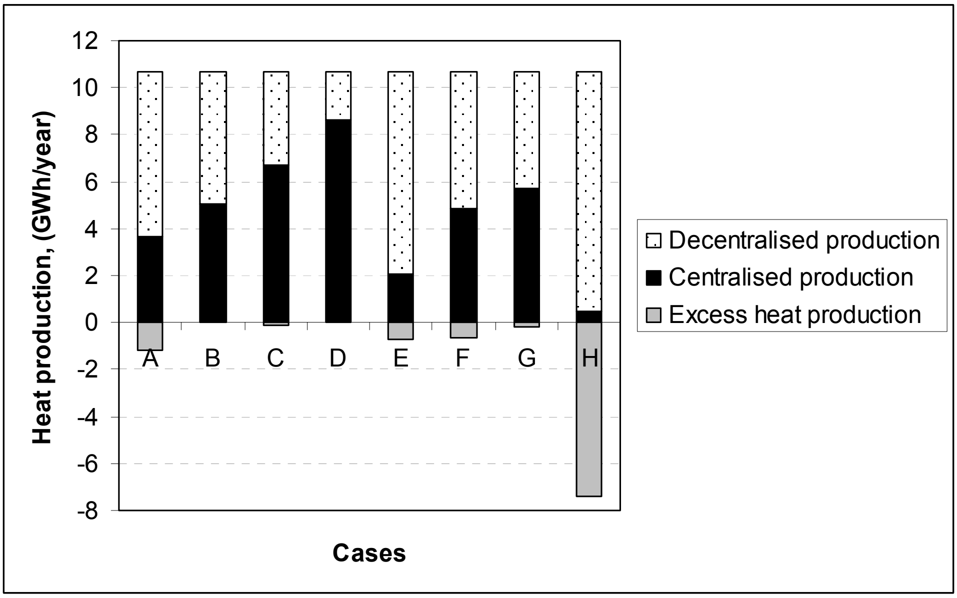

Figure 56. A summary of the net heat from the centralised production, decentralised production and excessive heat production (decentralised) for eight different studied scenarios (Nystedt et al. 2006).

Our limited simulations showed theoretically that heat trading could be a functional way to develop decentralised energy systems. There is a potential advantage to be utilised when buildings with consumption profiles different in shape and/or timing are connected through a district heating network. However, it is unlikely that this potential could be utilised by simply providing micro-CHP plant to every building. More advanced dimensioning and control strategies in different buildings (with and without micro-CHP), and maybe a new district heating network design, are needed to obtain the optimum heat demand/supply match and network performance. A possibility to use a thermally activated cooling in the district heating network could be considered as a supplementary measure for utilization of the excess heat in summer. (Nystedt et al. 2006.)

3.1.2.4 Conclusions

The main achievements and findings are the following:

- Digital data regarding maps, buildings, their energy consumption and district heating network of Otaniemi area were collected.
- Economical evaluation tool was developed and analysis was carried out considering different heating systems operated in a group of houses connected to a district heating network.
  - Even at today's prices, the micro-CHP unit is a serious alternative in the Nordic climate, when all the investment, operation and maintenance costs of devices are considered.
- Heat trading was evaluated as a new business concept and technological feasibility was confirmed.
  - In a certain analyzed case community 19–96% annual energy demand could be provided by distributed generation; in optimal case it was 81% (excess heat generation was minimized to 7%).

3.1.2.5 References

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3.1.3 Application of co-generation in buildings

3.1.3.1 Technologies of the distributed cogeneration

Properties of different reduced scale co-generation systems are related with the technological solutions used. Typical features of power plants based on gas or diesel engines are: low costs, high efficiency, wide power range and ability to run on different fuels. Internal combustion engine power plants are modular, i.e. standard units can easily be combined. Their disadvantages include noise and high emissions.

Gas turbines consist of turbine itself, generator and compressor to compress supply air. Advantages of gas turbines are small size and reasonable costs.

However disadvantages include poor efficiency at part load and high temperature of flue gas (400–600 °C).

Stirling engine differs from internal combustion engine by the fact that cylinder is closed and combustion process takes place outside of it. External combustion process provides a possibility for application of different fuels, but efficiency of electricity generation remains relatively low. Advantages of Stirling engine, when compared with internal combustion engines, include stable combustion, low noise and emissions and longer maintenance intervals.

Advantages of fuel cells are: high efficiency (also at part load), low noise and emissions. Disadvantages are very high costs and fuel quality requirements.

In Table 3 an estimation is given regarding how well different technologies fit different types of buildings in terms of application as distributed energy generation systems. Outcome of the analysis shows fuel cell technology as quite promising for distributed application in buildings.

Table 3. Estimated technical applicability of different technologies to different buildings (Valkiainen et al. 2001).

Building type	**Gas and diesel engines**	**Gas turbines**	**Stirling engines**	**Fuel cells**
Single family house	-	--	++	++
Attached row house	+	-	++	++
Apartment house	+	-	+	+
Office building	+	-	-	+
Hotel, spa, etc.	++	+	-	+
Green house	++	+	--	+
Small industry: workshop, sawmill etc.	++	++	--	+

Fitting category: -- very poor - poor + good ++ excellent

A fuel cell system includes not only the fuel cell stack but also

- a fuel processor to allow operation with available hydrocarbon fuels
- a power conditioner to regulate the output power of the cell and where necessary convert it to alternating current
- an air management system to deliver air at the proper temperature, pressure and humidity
- a thermal management system to remove heat from the stack and to transfer heat among various system components and, in some cases
- a water management system to ensure that water is available for fuel processing and reactant humidification.

The low-temperature stacks include polymer exchange membrane cells (PEMFC) and phosphoric acid cells (PAFC). They require extensive fuel processing and yield thermal energy at a low temperature. The high-temperature stacks, molten carbonate cells (MCFC) and solid oxide cells (SOFC), are more flexible in their fuel requirements and yield thermal energy at a higher temperature. All four types have similar requirements with respect to power conditioning.

Among different types of fuel cells, the high temperature SOFC cells seem particularly attractive due to wide power range of application.

3.1.3.2 Matching fuel cell with building

There are a number of strategies possible to control the operation of the fuel system applied in building. An optimal choice of strategy depends on energy consumption profile of the building and on energy prices. Energy consumption of typical household is presented in Figure 57. Figure 58 shows the time series of different energy means consumed during one day. Changes in electricity demand are usually very fast, when compared to changes in thermal demand. Maximum electrical power demand is high, but the total amount of electricity is relatively small when compared to thermal demand. Figure 58 shows monthly heat and electricity demand of a Finnish single-family house. Both demands are almost equal in the summer, but in the winter, the heat demand is more than triple the electricity demand.

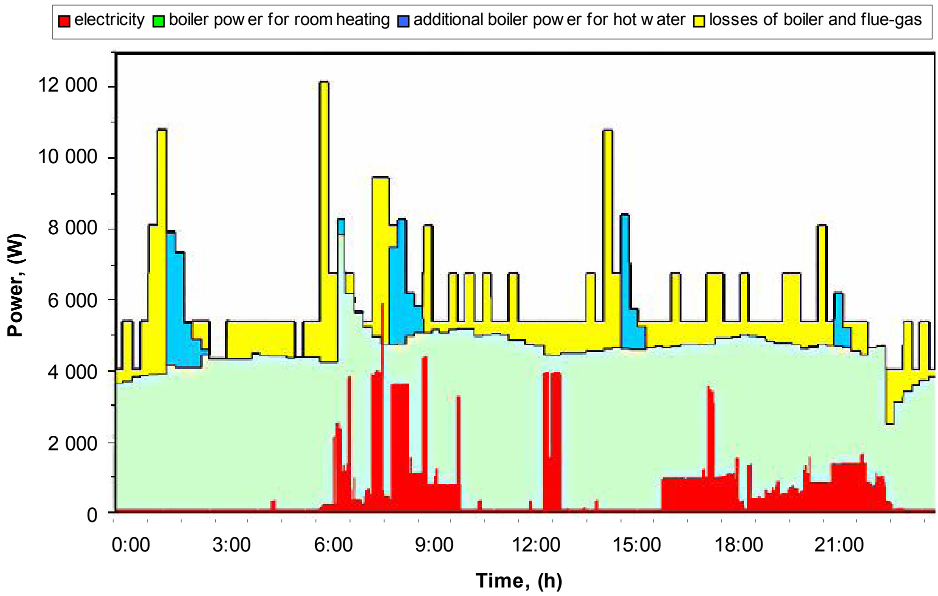

Figure 57. Demand of gas (for heat and hot water) and electricity of one household in Germany, 19th January, outside temp. < 10 °C (reworked from original by Birnbaum & Weinmann 2003).

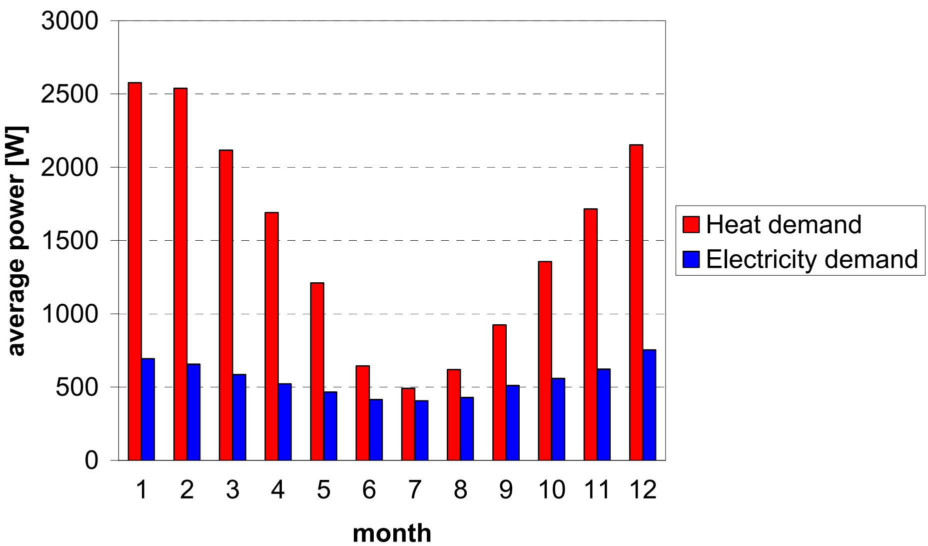

Figure 58. Monthly average electricity and thermal demand of a typical Finnish one-family house (Jahn & Shemeikka 2004).

The figures indicate how challenging a building environment is for fuel cell operation. It is probable that a single strategy might not be sufficient to satisfy the needs of the building during entire year. Currently, only little is known about building and fuel cell interaction during dynamic operation. Computer simulations could be used to address the problem. However, most of the current fuel cell models are designed for material and product testing and they employ very short time-steps. Thus, models require heavy computing, which makes them unsuitable for the year-round building energy simulation.

3.1.3.3 New approach to model fuel cell system

Many fuel cell and cogeneration component models have been developed with the intention of modeling microscopic or high-frequency phenomena, e.g. changes in fuel concentration within a fuel cell. Such models are not suitable for incorporation into building simulation. Most component models continue to be coded for a particular simulation tool and portability remains a problem; dedicated component models require translation and a re-write before being suitable for use in another simulation code. In addition to an expanding number of simulation codes, over the last decade the range of systems encountered in building simulation has also been increasing. Given the fact that micro-cogeneration is a relatively new phenomenon and that there is an inevitable time-lag between the evolution of the technology and the development of building simulation models, there are as-yet relatively few fuel cell or cogeneration models that have been specifically developed for building simulation.

In preparation for the new IEA/ECBCS Annex 42 FC-COGEN-SIM (2004–2007) international collaboration effort, the existing fuel cell models have been reviewed. Based on this work it can be summarized that none are “ideal” candidates for inclusion in building simulation tools: all have some form of shortcoming such as a lack of validation, incomplete modeling of some aspect of performance, over-complexity, over-simplification, etc. It was concluded that model development work needs to be undertaken within the annex with regards to developing component models suitable for domestic systems simulation (< 10 kW), which incorporate dynamics, are adaptable and are capable of running with multi-fuels and (very importantly) have been extensively validated. (Kelly 2005.)

As mentioned previously, the fuel cell stack itself is only a single component within a complex energy conversion system. Figure 59 illustrates one possible system configuration of an SOFC cogeneration device. Besides the fuel cell stack (shown in grey), the system might include an afterburner to combust unreacted fuel; an air filter and pre-heater; a fuel desulfurizer, pre-heater, pre-reformer, and reformer; and water preparation. A compressor may be required to supply pressurized fuel, while a blower will likely be present to supply air to provide oxygen to support the electrochemical and combustion reactions. A pump may also be required to supply liquid water for steam reformation purposes. A battery could be used for buffering the fuel cell stack's DC electrical production and for meeting load transients, and the system will include a power conditioning unit to convert the electrical output to AC. All SOFC-cogeneration systems will include a heat recovery device that transfers the heat of the hot product gases to the building's HVAC system. Some systems may include an integrated auxiliary burner that is activated when the fuel cell cannot satisfy the building's thermal loads. With that all in mind, a system level model of a fuel cell was proposed by combining input and output for each component in such a way as to assure that overall energy balance for system presented in Figure 59 would be fulfilled.

The mathematical model developed by Annex 42 for simulating SOFC-cogeneration devices is extensively documented in (at least by intention) an unambiguous fashion. It discretizes the SOFC-cogeneration device into nine control volumes (e.g. the fuel cell power module, the gas-to-water heat exchanger) and provides energy balances for each. Detailed methods and equations are provided to calculate the terms of these energy balances, such as the air and fuel supply rates, the electrical conversion efficiency, and the heat exchange between the hot product gases and the water stream that delivers the thermal output. (Beausoleil-Morrison et al. 2006.)

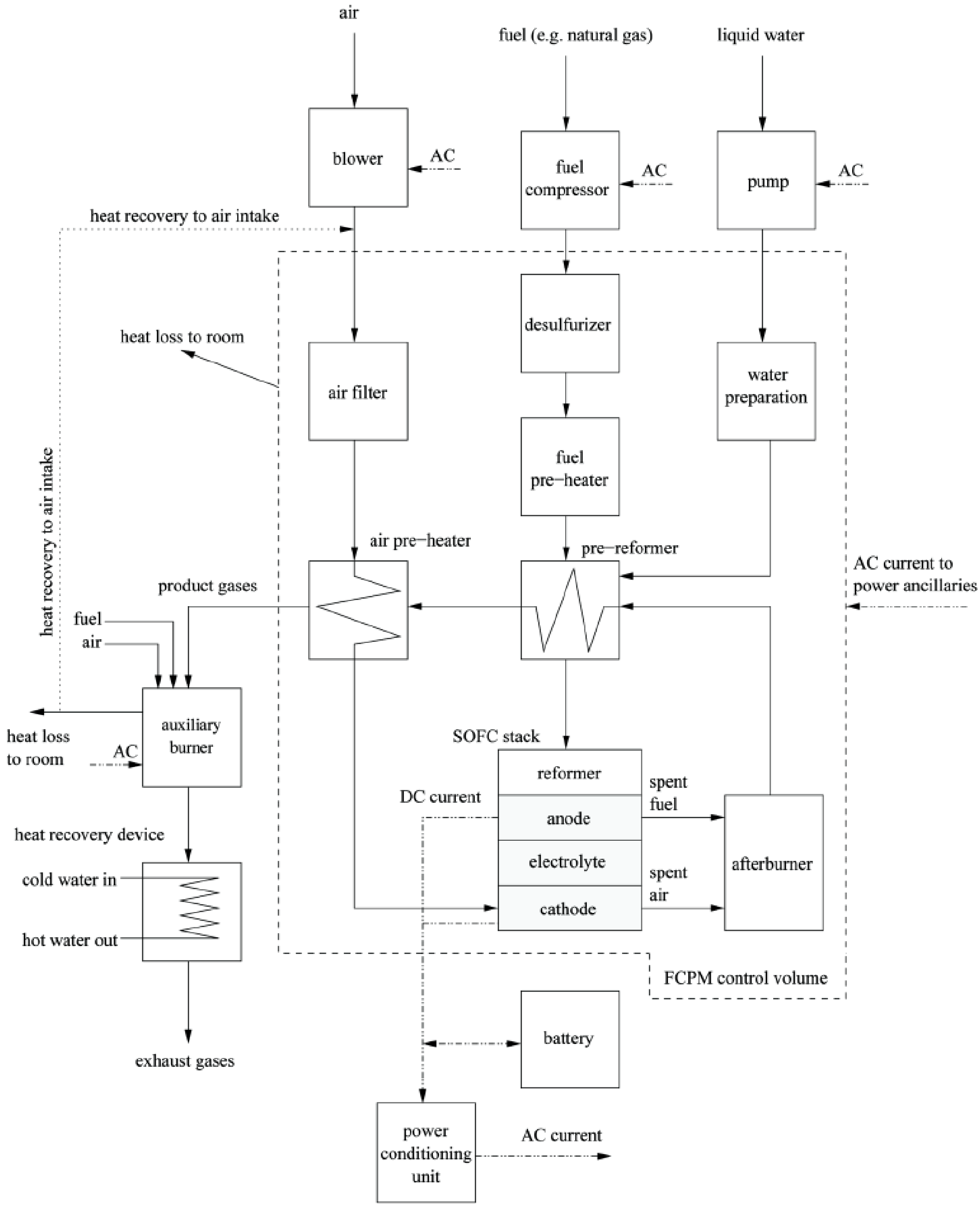

Figure 59. One possible system configuration of a SOFC-cogeneration device.

3.1.3.4 Integration of SOFC model with building simulation and validation

Our objective was to create a tool to enable consideration of interactions between building and fuel cell system. This was done by implementing a simplified, yet realistic fuel cell model into a building energy simulation.

An approach described in previous section was used for a system level model where a control volume boundary is assumed around a fuel cell power module. Interior of the power module is regarded as a 'black box'. The cell model provides a link between inputs and outputs of the 'black boxes' in the system model. This approach allows for easy modifications whenever needed. The system level model has been integrated with the building energy simulation tool IDA-ICE (Indoor Climate and Energy) using Neutral Model Format (NMF) language.

Further details of the model and implementation process can be found in (Vesanen et al. 2005).

The mathematical model of SOFC has been independently implemented into five simulation platforms within the frames of Annex 42 cooperation. The platforms were ESP-r, EnergyPlus, IDA-ICE, TRNSYS and EES. This provided a unique opportunity to apply inter-model comparison testing to diagnose the internal sources of errors. VTT participated in this effort with own IDA-ICE implementation. The opportunity is unique because the same mathematical model has been implemented into all five programs. As such, all ambiguity in equivalencing program inputs can be eliminated and all predictive differences can be attributed to either errors in the mathematical solution of the models or to coding errors (bugs). (See Figure 60.)

A suite of inter-program comparative tests has been created to examine the five (and future) implementations of the Annex 42 SOFC-cogeneration model. Each test case is carefully constructed to isolate specific aspects of the model and is described in sufficient detail. The validation comprises the total of approx. 100 different test cases. Some of the experiences were reported in a conference publication (Beausoleil-Morrison et al. 2006). It is planned to complete the whole series by the end of year 2006.

The next step is the validation of the mathematical model itself through empirical testing, which will be the subject of future papers.

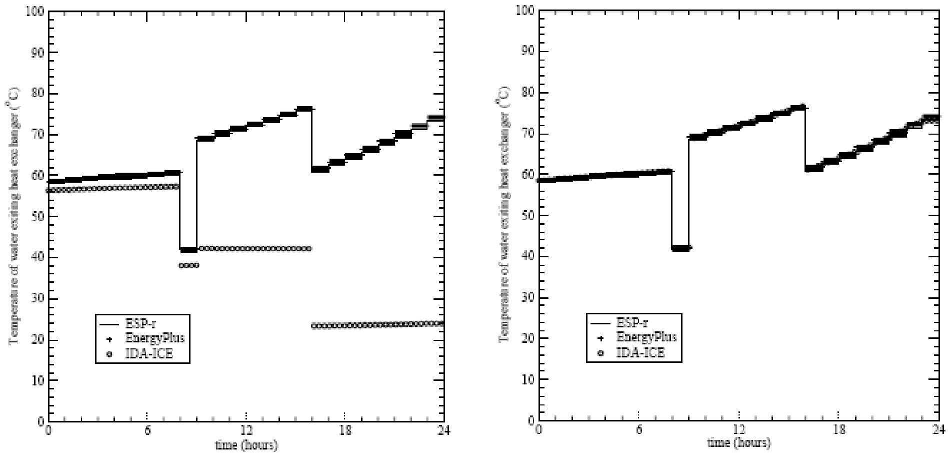

Figure 60. Example of bug detected (left) and repaired (right) in IDA-ICE implementation in one of the test cases.

3.1.3.5 Conclusions

A model for a SOFC fuel system has been created and integrated with building simulation software. Other models have been and are currently being developed by other research groups to study fuel cell operation in a building, but as far as we are aware, the model presented in this report is the only one integrated with IDA-ICE. In the next phase, model validation will continue within Annex 42 co-operation and empirical validation is considered if measured data becomes available.

In the future, some indicators should be added, e.g. costs of electricity and gas, to enable evaluation of the equipment and different system combinations. Models for the ancillaries and heat recovery require improvement. Models for the battery and heat storage system are to be added. The final goal is to create a comprehensive but flexible model, which could serve as a reliable tool to simulate operation of different fuel cell systems in different buildings.

3.1.3.6 Literature

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3.1.4 Coupling of building's internal and external networks

3.1.4.1 Simulation of district heating and cooling networks

District heating network

A system for simulating flows, pressures and temperatures in district heating pipeline network was developed (Figure 61). The system was implemented both in Matlab and as a stand-alone application with C++. The solution is based on the pressure loss in a single pipe. Pressures and flows in the whole network are then solved iteratively with the Newton-Raphson method. Typically less than ten iterations were needed to achieve a satisfactory accuracy.

Temperature simulation is done with finite element method. Transient simulation of temperatures in different parts of the network is possible. This has great importance in for example analyzing periods when consumption increases rapidly, as it often does in office districts in the morning. Also a version of the program was developed, in which the static equilibrium temperatures in all pipes are computed.

The program also features the possibility to add booster pumps and artificial circulation in the network. The user can specify any number of power plants for which a certain order of operation is defined. Data can be input e.g. as hourly values, from which intermediate values are interpolated.

The system can be easily integrated into other programs as a C++ library or through a special interface in Matlab. With commercial programs this is difficult. As an example it has been used in network optimization and integrated into heat flow modeling for buildings. The system has been tested against commercial network simulation software and good agreement of the results was achieved.

It has also been used in real design of planned district heating networks. In Figure 62 an example of pressure simulation is shown. Normally the longest period that has been simulated is one week because the consumption pattern tends to repeat itself from one week to the next. Time consumption of flow simulation is proportional to the square of network size, whereas heat simulation is linearly proportional to the network size. Depending on the network size, simulation of one week may take from 20 minutes (100 pipes) to 2 hours (400 pipes) on a normal PC.

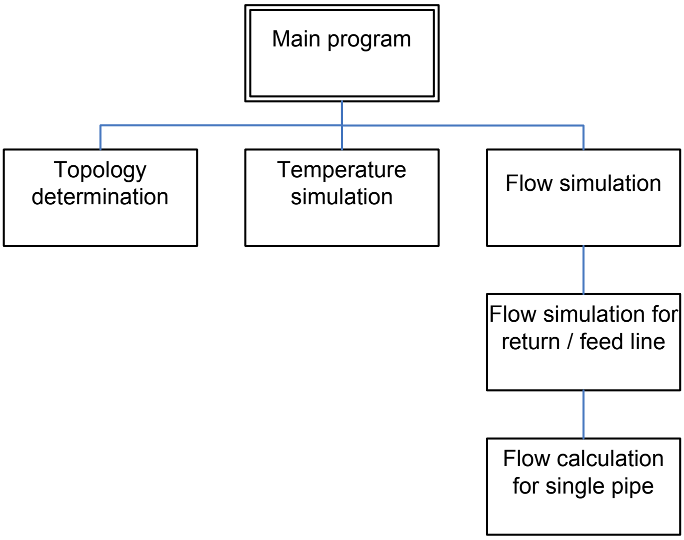


Figure 61. The functional structure of the network simulator. The main program calls temperature and flow simulation subprograms. The same code is used for simulating both feed and return lines. Topology determination examines the network to figure out how many loops there are and whether all parts are connected.

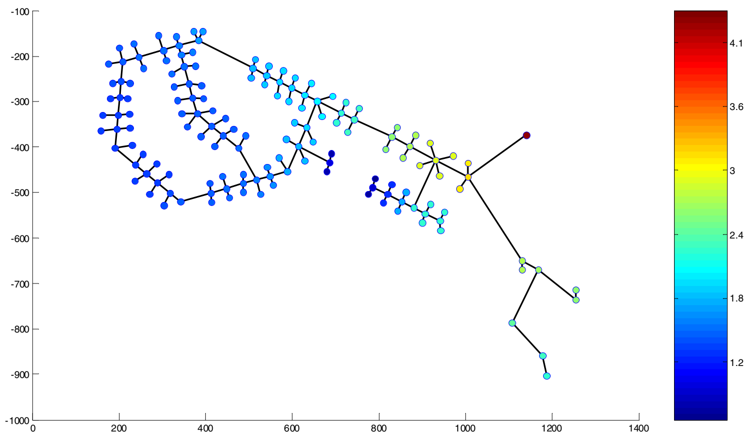


Figure 62. An example of pressure simulation for a small district heating network with the network simulator. The color indicates pressure differences at consumers in bars. The xy-coordinates are given in meters.

District heating pumps are located normally at the CHP plants and feed only boiler plants. When pipelines are long, booster pumps must be used due to otherwise too high pressure level at the beginning on pipelines. DH-networks are normally designed for 1.6 MPa pressure. If heat transfer distance exceeds 10–15 km, an extra pump capacity is needed in the network. Pump capacity and pressure level can be saved by distributing part of the capacity to the district heating network i.e. using pressurizing stations as boosters.

Distributed pump capacity was studied. The main objective was to find out if total cost of pumping is cheaper when the pumping capacity is distributed to the network and the maximum pressure level of the network can be reduced. Also important question is how to control distributed pump stations in varying pressure conditions, especially if there are loops in the networks. At the present stage of the study it seems that total savings are not high but more research is needed regarding the influence of the location and control strategy of the pumps.

District cooling using water or carbon dioxide

The district cooling network model is based on the district heating model presented above. The changes made in district cooling model using water as heat transfer medium are minor, but modeling a carbon dioxide based network is somewhat more complicated. The name ‘district cooling’ indicates that heat is not transferred *to* but extracted *from* the consumers. When calculating the consumptions, a constant temperature difference (i.e. the temperature rise of primary water) over consumer connection is used. The temperature levels in district cooling are significantly lower than in district heating (typically close to 8 ºC in feed pipes and 15 ºC in return pipes).

The district cooling process using carbon dioxide as a heat transfer medium is presented in more detail in master’s thesis (Rämä 2006). The main idea is to take advantage of phase change energy and thus increase the heat transfer capacity (J/kg). Also the fact that carbon dioxide has low viscosity results in lower pressure drop than in water system and makes it possible to reduce the diameter of pipes in the network, which decreases the required investment. This is the main advantage in using carbon dioxide as a heat transfer medium. The disadvantages include uncertainties concerning the behavior of two-phase flow in a system including altitude differences and high pressures, peaking at approximately 40 bar. Higher pressures require more durable and thus more expensive pipe material, but with only 20% more expensive pipes carbon dioxide network remains an attractive investment. Natural gas pipes are readily available and meet these demands.

The district cooling process using carbon dioxide can be described as follows; liquid carbon dioxide is pumped through the network to the consumer where it evaporates. After the consumer carbon dioxide flows back to the plant where it is condensed and pumped back into the network.

The design and operation of the network depends on how much carbon dioxide is evaporated at the consumer. If all of the carbon dioxide is evaporated and two-phase flow is not wanted in return pipes, the resulting vapor should be superheated to avoid condensation. The heat transfer coefficient of carbon dioxide drops sharply when vapor concentration exceeds approximately 80–90% in typical flow conditions. After this point, the size of the required heat exchanger grows significantly. In the district cooling process studied in master's thesis, the evaporation is stopped at 80% which results in two-phase flow in return pipes. In the feed pipes, two-phase flow is avoided by super-cooling liquid carbon dioxide before it is pumped into the network. Liquid CO_2 slightly warms up while it flows in the feed pipes. In the return pipes, CO_2 is in saturated condition and thus the temperature decreases with the pressure drop. The temperature drop is much larger than in feed pipes. In the proximity of 0 ºC, a pressure drop of 1 bar means approximately a drop of 1 ºC in temperature. (Figure 63.)

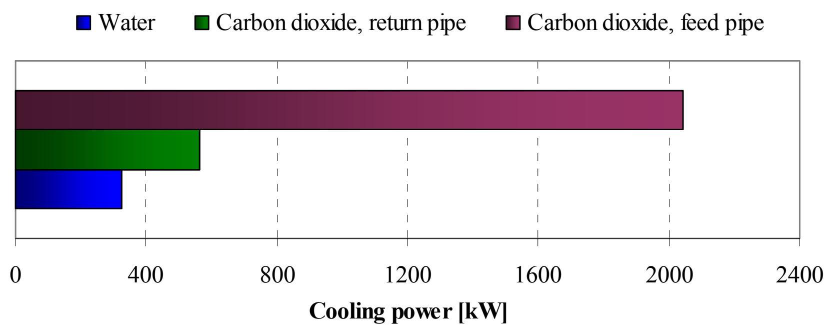


Figure 63. Cooling power of water and carbon dioxide flowing in a DN 100 pipe with a pressure drop of 1 bar/km. At the consumer, 80% of carbon dioxide is evaporated at 0 ºC and the temperature difference of water is 8 ºC.

Consumptions are calculated using a fixed amount of evaporation and the temperature of carbon dioxide at the consumer. The cooling effect of super-cooled carbon dioxide before it reaches the saturation point is discarded as it is insignificant compared to the cooling effect of evaporation heat.

The pressure drop in feed pipes is calculated as in a normal one-phase flow using the physical properties of carbon dioxide. In return pipes, Müller-Steinhagen–Heck (1986) correlation is used to calculate two-phase pressure drop. It uses as variables the quality of carbon dioxide (vapor concentration) and one-phase pressure drop in a situation where the flow is either gas or liquid.

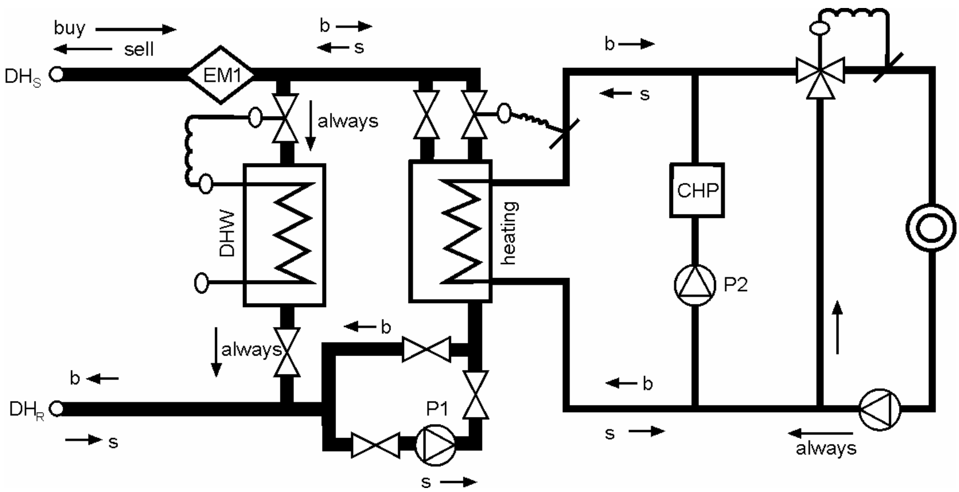
The quality changes of carbon dioxide flow in return pipes are calculated by constructing an energy balance between two points in network. Since the quality of carbon dioxide leaving the consumers nodes is set, they are used as starting points in the calculation.

3.1.4.2 Model of heat exchanger in district heating substation (pT-adapter)

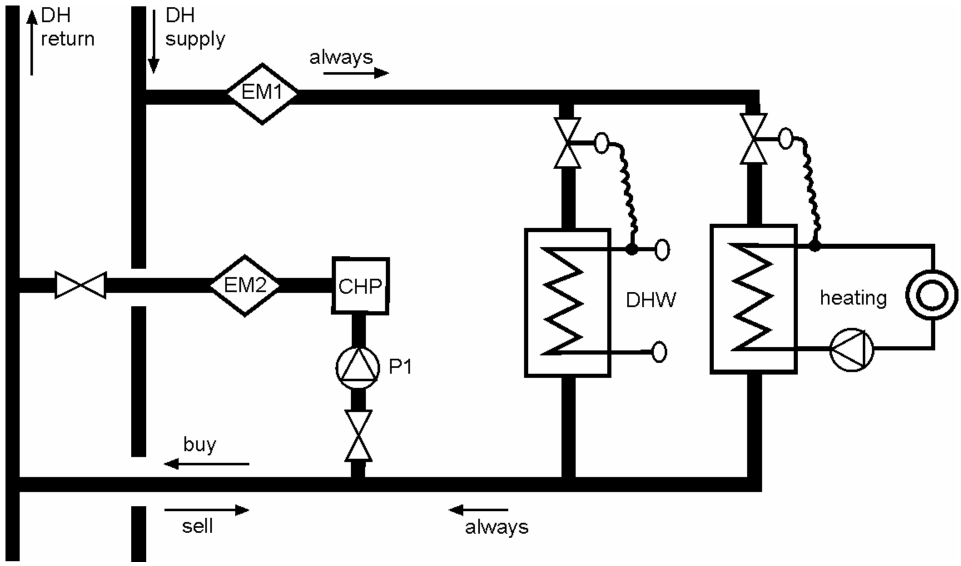
The building heating system as well as the eventual local heat generation system is connected to the district heating network by means of a substation. The main components in a substation are the heat exchangers but also pumps, pipes, valves and controllers are needed. The possibility to sell heat from the building into the whole network sets new requirements for the substation because the water flow and the heat flow will reverse during the selling mode of operation. From the modeling point of view they are just the temperatures and pressures at the coupling points that ultimately determine the heat and mass flow and therefore the substation model is called a pT-adapter.

There is a limited number of various connection schemes in Finland pre-elaborated for certain types of buildings. None of the existing solutions takes into account the possibility of heat generation on site. Therefore, four possible connection schemes shown in Figure 64 were developed and their pros and cons were analyzed. The substation version *d)* in Figure 64 that connects the small scale heat producer in the building via a heat exchanger was finally chosen to be used in the system simulations. This connection has advantages over the other versions, it does not bring any changes to the standard modular substation, it is a safe solution for the user (no water leaks) and to the district heating network (no gas leak problems). Furthermore, it is easy to control, suitable for new installations as well as to renovations, and maintenance of the CHP unit does not cause any problems for the district heating operation.

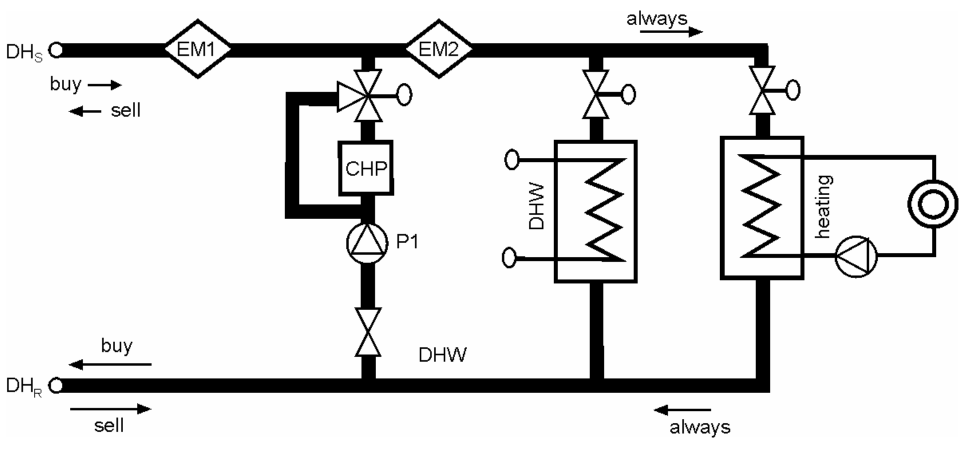
In general, we found out that the physical connection will need standardized rules, in which the quality and the performance of the connection unit are unambiguously defined, same way as the current Finnish Energy Industries / District Heating Department's (earlier Finnish District Heating Association) guidelines do for the district heating substations.



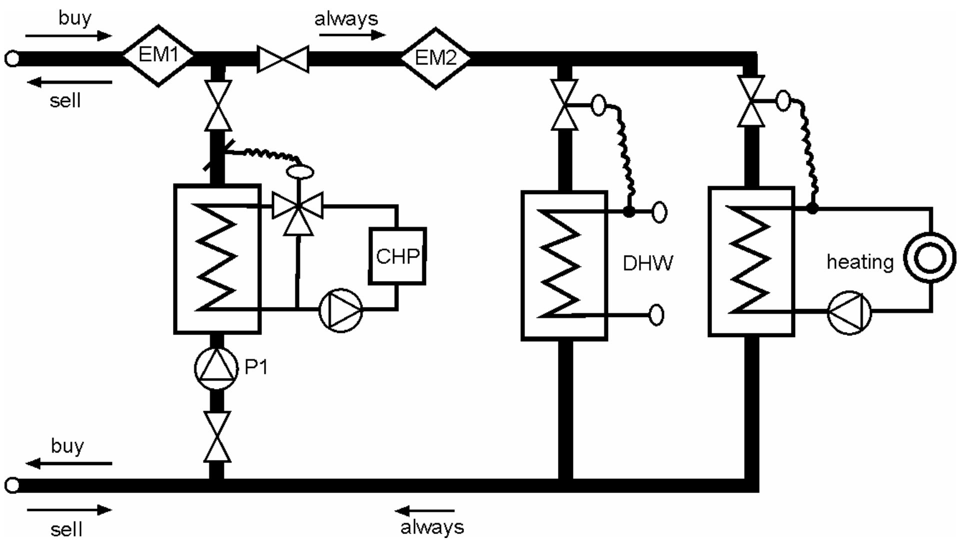
a) CHP unit connected directly to the consumer's heating network. The standard district heating substation had to be revised to include two extra by-bass lines and a pump.



b) CHP unit connected directly to the district heating return pipe. No changes are necessary for the standard district heating substation but the pricing of the sold heat is complicated.



c) CHP unit connected directly to the district heating network. This is a simple connection but involves risks for water and gas leakages.



d) CHP unit connected indirectly to the district heating network with a heat exchanger. This is a safe connection that was chosen for the coupled energy simulations.

Figure 64. Four possibilities to connect a small scale combined Heat and Power unit (CHP) to the district heating (DH) network. DHW = Domestic Hot Water system, EM = Energy Meter, P = Pump, heating = building heating system. (Sipilä et al. 2005.)

Most of the substation components existed already in the VTT House building simulation environment except a computational model of a heat exchanger. A dynamic simulation model for a counter-flow heat exchanger is easily implemented by connecting thermally the two heat exchanging flow channels and dividing them into a number of successive elements, in order to take into account the variable temperature difference between the two streams in different parts of the heat exchanger. But it was found that a large number of elements is needed if good predicting accuracy is required: about 40 elements are necessary to compute the heat power within 2% accuracy, see Figure 65. This means that the VTT House model will have 40 additional computing cells to accommodate the heat exchanger elements, which makes the solution computationally heavy. The error comes from the multi-zone network model convention that the temperature of the outgoing flow from a room is the same as the room temperature, as depicted in the right-hand part of Figure 65.

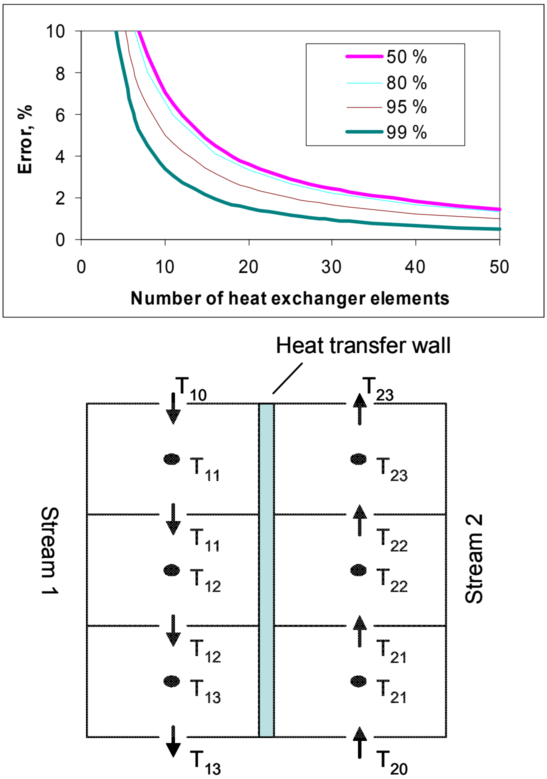


Figure 65. Number of required heat exchanger elements to predict the steady state heat power at specified accuracy, depending on thermal effectiveness. The second independent variable, the capacity ratio of the two streams is 0.5, representing a typical maximum value for district heating exchangers. The error decreases slightly with decreasing capacity ratio.

A more accurate modeling option is to use conventional equations for thermal efficiency of a counter flow heat exchanger but then we lose the transient behavior inside the heat exchanger. This is usually not a major restriction because normally plate heat exchangers are used, which have a low mass and a small water volume and therefore this kind of modeling is preferred.

To accurately simulate the behavior of commercial counter-flow plate heat exchangers, we need to know the product data, namely the heat transfer correlations and pressure loss correlations of the flow channels. A new method was developed to extract this data from the results of the manufacturer's simulation program, or from measured results. Then it is possible to size the heat exchanger for the simulations based on the design heat power and pressure losses, the result being the size and number of the heat transfer plates, as shown in Figure 66. All this information is subsequently needed when the heat exchanger is used in the actual simulations.

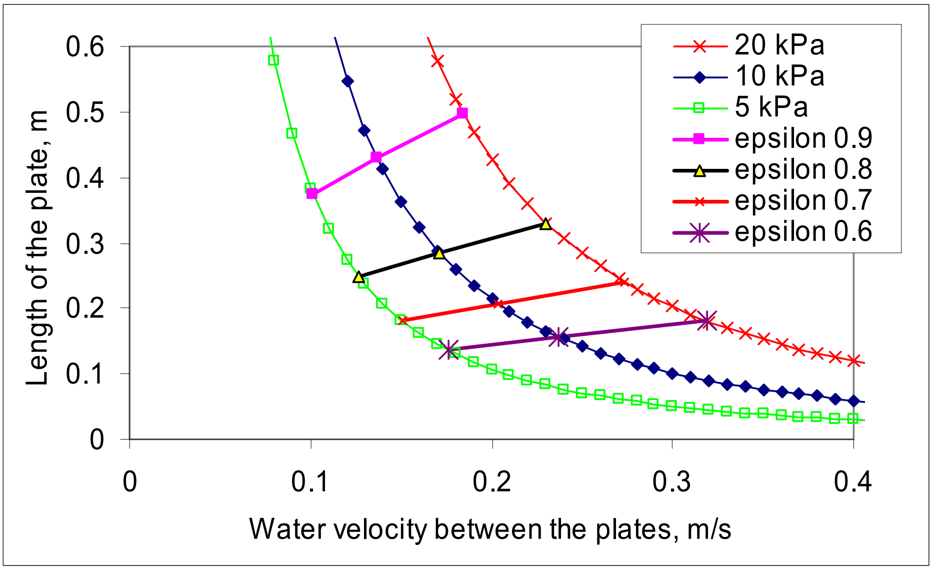


Figure 66. Plate heat exchanger sizing for district heating. The intersections of the efficiency and pressure loss lines determine the plate dimensions and the water velocity. The number of plates depends on the required design heat output. The heat transfer and pressure loss properties have been extracted from the manufacturer data.

Conclusions

The indirect scheme to couple the local heat and power unit to the district heating network was chosen for the simulations because of its simplicity and safety. There are two options to model the heat exchangers in the substation: the dynamic model is computationally heavy whereas the static one may lose some very fast transients. A method was developed for extracting the necessary heat exchanger information from the manufacturer provided data.

3.1.4.3 Coupling of DH-network with building's energy simulation (EntryMaster)

Abstract

The distributed generation as a whole, as suggested here needs new type of analysis tools to design and to optimize the energy chains from the power plants (both large and small scale) to the consumption points. Traditional large scale production-consuming environment is less complicated than distributed and can be handled with separate modeling and simulation tools with sufficient accuracy. The suggested distributed generation environment needs new tools to handle the challenging multi-production and multi-consuming phenomena in the transmission networks to enhance the quality of the design and optimize the use of the energy system. Today, there does not exist any tools to handle the energy system as a whole. The distributed production-consumption simulation environment is very computing-intensive, even though it could be modeled. There is also an obvious need to have a solution to connect existing separate modeling tools together and which delivers the simulation results in reasonable computing time.

A totally new approach for dynamic coupled energy simulations was created. This approach contains a generic software engineering design that enables interaction and communication between different simulators. The design is generic and is meant be used to connect whatsoever simulators together. The solution has been tested by connecting a district heating network simulator with a building energy simulator. The approach has the following properties and benefits:

- The heart of the solution is the coordinating middleware program named *Master*, which acts as a conductor of the "simulation orchestra". The Master handles certain important tasks from the simulation point of view:
    - interaction between simulator components and synchronization of the simulation calculations
    - convergence handling.

- The connection between simulators and Master utilizes standard technologies (SOAP, WebServices), which enable certain general validity of the solution in the Internet environment.
- It is possible to solve a larger integrated application than before by using standard desktop computers. The computing intensive simulations become faster and they enable totally new dynamic simulations for the energy system (in our test case: buildings and district heating networks) as a whole.
- The simulators can be run on different platforms (for example: Linux, Windows).
- The coding effort is reasonable: (1) add the plug-in layer or software wrapper into your simulator, and (2) add some functionality derived from the architecture and service rules.

The pilot application was a community in Nordic climate (a district heating network together with buildings). The pilot covered both the hydraulic and the thermal flows in the networks, as well as, the indoor climate conditions in the buildings. The selected simulator components used:

- an integrated district heating network simulation (hydraulics) and a simple power plant model, both implemented in Matlab at VTT
- VTT House for the building thermal energy (indoor climate) and the internal distribution network simulation (hydraulics).

First test simulations indicated – without any fine tuning – that a simulation covering one year of a town operation (buildings together with district heating network) could last less than a week of calendar time. This simulation could have taken several weeks of computing time, if modeled traditionally. The time-lapse is due to the better architecture which now allows the various simulator programs to be run on separate computers connected via Internet.

It was found out that the convergence control of the whole simulation is the critical point of the simulation architecture. Typically, when the differential equations are solved in different simulators, the most common way to handle the stability is to control the length of the time-step. We also adopted the idea of "black-box", which means that the simulator gives public only the inputs and outputs necessary for the communication. The internal parts of the simulator are encapsulated. It was also found out that there are two kinds of convergence problems in this framework: (1) internal and (2) external. By ‘internal’ we mean the convergence inside the individual simulator and by ‘external’ the convergence between all simulators in the environment. To enable the open architecture, it was found out that the simulator has to be responsible for the following up of the changes of its own critical interface-variables and also, the simulator has to inform the Master, if it has itself convergence problems. These major service requirements have to be fulfilled to handle the internal convergence and to give the Master the possibility to control the external convergence, which is enabled through the roll-back feature. The major finding and service rule was that the simulators have to be able to roll back to enable the Master to control the stability. The roll-back feature means the simulator’s ability to reverse the simulation to previous successful time-step, when required by the Master. It is perhaps challenging to apply this sophisticated architectural approach in the building simulation tools available on the market today. We are not aware of any existing simulator with the ability to roll-back readily available.

General description of the approach

The basic idea of our simulation environment is defined in Figure 67. The simulation environment consists of building simulators and their connections to the district heating network. The interaction between programs and the synchronization of the simulation is performed by the Master-program. The Master is responsible for handling the data exchange, the project data and the other simulation specific features between the simulator services. At the same time, the approach allows new simulators to be added or plugged in later on (marked shadowed in Figure 67).

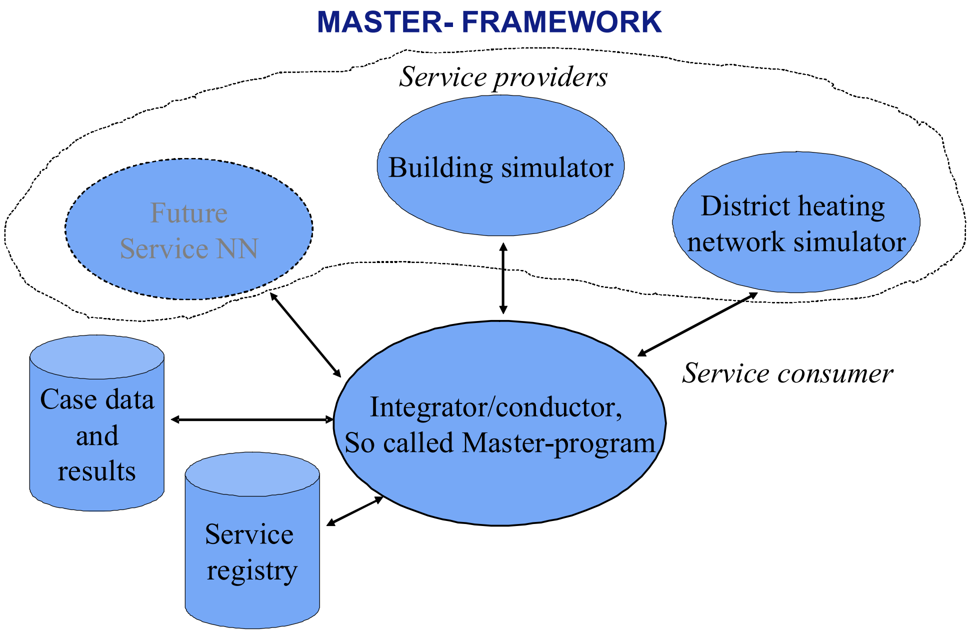


Figure 67. The framework of connections between the building simulator and the district heating network simulator. There can be several simulator-instances running on their own hardware, but for simplicity reasons there is only one of each in the figure. The connections between different actors (marked as two-headed arrows) are implemented on the WebService technology. By definition, all actors must have a WebService-interface.

The so-called service-oriented architecture approach was used to govern the challenging environment where various tasks are performed by different computers using different software. The architectural design contains the definitions of the interfaces and rules how the data, events and callbacks are handled and also the definition of the so called Master-program, which acts as a coordinating middleware between simulator components. The architectural approach for the distributed simulation is presented in Figure 68.

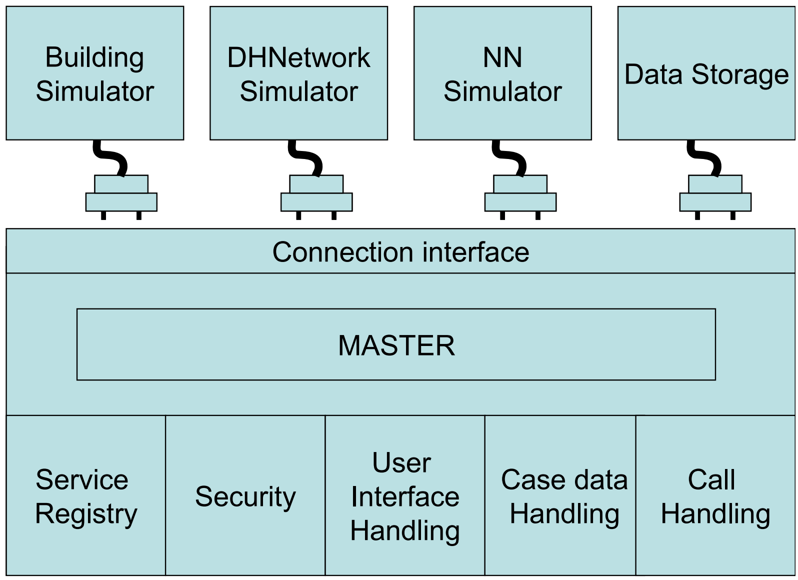


Figure 68. The architectural approach for the distributed simulation. The data exchange is enabled with the help of the Web service-technology and XML. The data exchange and the connection between the services in our architecture are implemented on the Web service technology, which enables the use of the Internet-based distributed simulation platforms.

The elements of the crucial Master-framework are the following:

a) **Service Registry**-module which contains the locations and book keeping of the available simulators. The service registry is a simple Web Services/SOAP interface to a database with little additional logic. The interface of the registry provides two SOAP methods, one for reporting a simulator's state and one to query for free simulators. When a simulator is started, it automatically reports itself to Registry. The simulator periodically re-reports its state so that Registry knows it's alive. The simulator's timestamp is updated by the registry every time it makes contact. When a simulator-instance is shut down, it immediately notifies Registry.

b) **Security**-module, which contains the authentication and the encrypting or decrypting mechanism of the calls between various distributed components. All interaction between different services and components is encrypted-decrypted, if necessary, and passed through security module in the Master. The Master framework contains two-key methodology securing the data exchange. The security settings can be put in the background if there is a need for high performance of the simulation and if the LAN-network used is secure, for example isolated by a firewall.

c) **Graphical User Interface** handling-module (initial Master program and also simulators' user interfaces. Every simulator component can send its own http-based Graphical User Interface, if requested to show the status of the simulation, changing the case data etc.

d) **Case Data** handling-module (project data for the buildings, district heating network, etc.). Every simulator component has its own free XML-based data format, which can be delivered via connection interface. The case data is stored in a database, which can be local or distributed into the Internet.

e) **Call handling**, which enables the roll-backs and non-synchronized calls and retry, if call fails. The data exchange or the service requests may fail because of the nature of the Internet. The Call handling has the book keeping of created threads and the service calls sent to the simulators or other service providers. If some service call failed, the same service call can always be resend if necessary. This module contains also the logics for the time-outs so that the service calls won't be repeated forever. The intelligence of the roll back-methodology is governed in this part of the Master environment. The roll back feature means the simulators ability to restore the previous successful time-step state. Basic assumption is that simulator components are black-boxes. The internal knowledge of the simulators' phenomenon will be capsulated behind the simulators' interface. Every published variable in the simulators' interface has to be able to follow up the changes of its own during the external time-step. At the same time the changes have to be compared to the convergence criteria set and the Master has to be indicated, if limits are exceeded. Each simulator has to be able to roll-back to the previous successful time-step, if requested. In Entry Master a two-way convergence handling methodology is implemented: (1) limit the time-step length, and (2) roll-back the simulation. The simulators inform the Master if "in trouble" and suggest a new better external time-step from each own point of view. The Master picks up the simulators' "in trouble"-requests and rolls back the simulation to the previous successful external time-step.

The system level use case analysis of the approach to find out the service rules

The use case definition of the Master middleware is presented in Table 4.

Table 4. The system level use case of the basic program flow and interaction between simulator components and the Master-program.

Actors:	(1) User of the simulation environment (*human*), (2) Service registry (*system*), (3) Master (*system*), (4) district heating network simulator(s) (*system*), (5) building simulator(s) (*system*), (6) Data storage (*system*).
Preconditions:	Master program is open and the simulation case (district heating network and its connections between buildings) is defined by the user and is ready to simulate, communication network is alive.
Basic flow of communication between different actors:	1. User starts the simulation. 2. Master asks available simulation services that meet the case from the registry, registry allocates the services and gives the web-addresses where the available services are located. 3. Master sends the project data to the services and calls the initialization for each simulator, simulators reply when the init is OK. 4. Master runs the simulation, for each required time step. 4.1 Update inputs and outputs between simulators. 4.2 Run the individual time step, wait for the response for each simulator, roll back and try with a shorter time-step if necessary for the convergence. 4.3 Collect the simulation results and save to the data storage. 4.4 Communicate the simulation status and results to the user. 5. Master ends the simulation and releases the allocated simulation services. 5.1 The simulators are terminated and the service registry is updated.
Post conditions:	The simulation data is stored and the simulation environment is ready for the next simulation.
Exceptions:	1. The service registry is not available or enough free allocations does not exist. 2. User aborts the simulation. 3. The convergence cannot be found regardless of several roll-backs (for-ever-loop exception). 4. The individual simulator service crashes (time-out or crash-notification from the simulator). 5. The communication network (Internet/LAN) goes off. 6. A service call between Master and simulator fails – retry invoked.

The so-called 'use cases' are commonly used in software engineering, and they are part of the well-known standard UML (Unified Modelling Language). Use Cases are used as a method for describing the program flow and its participants – so called actors – during a certain task, in the early phases of a software development life-cycle. The use case is supposed to be defined with a language or notions familiar to end-users or doman experts, without too many information engineering or implementation specific terms. The use case analysis was utilized to find out the important features of the service architecture developed.

The sequence diagram, which gives a picture of the interaction between different actors, derived from the use case is presented in Figure 69. This diagram shows the basic flow of events in program interaction.

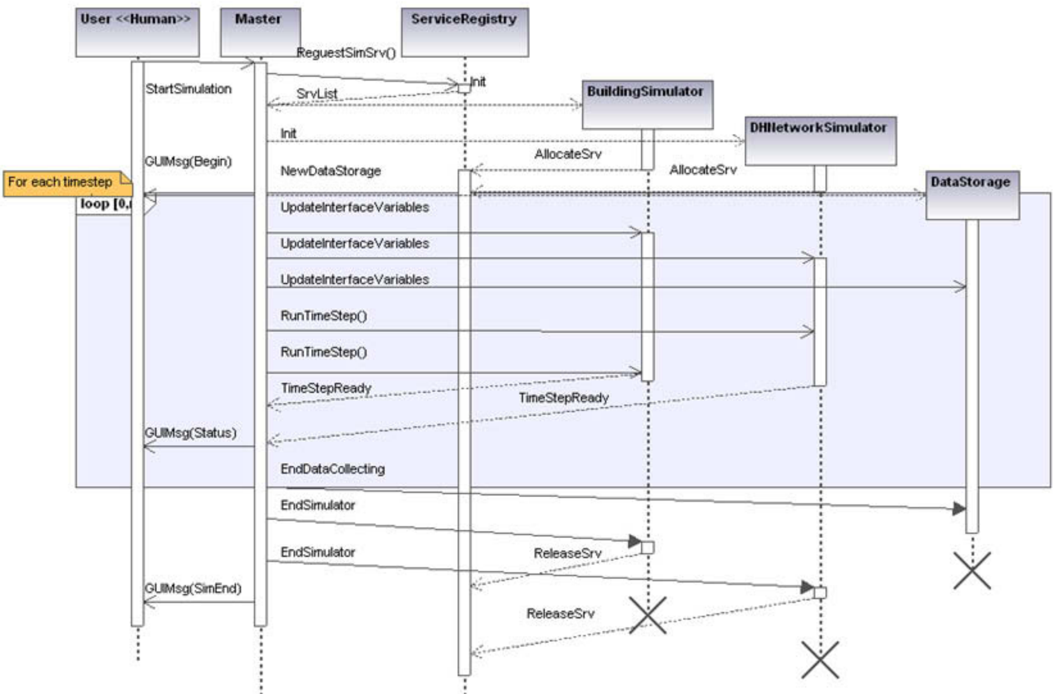


Figure 69. The sequence diagram derived from the use case. The security level has been left out to simplify the diagram.

3.1.4.4 Conclusions

The basic idea of a distributed simulation environment has been presented and elaborated in new context, in which building energy simulators and district heating network simulator are hydraulically and thermally linked from the power plant via the district heating network to the internal room conditions in the building. The models and software necessary to perform this task were either developed since the beginning or reshaped and adapted within the frames of this project.

The necessary ICT-architecture was defined to handle the environment stability under consideration of different requirements (convergence, data exchange, security). Considerable effort was spent to sustain a generic approach when defining the requirements.

The main delivery of the project is an alpha-prototype of a software tool capable of performing challenging task of simulating operation of the whole energy supply chain simultaneously. As far as we are aware, this has not yet been achieved by anybody else.

Limited results obtained so far confirm the applicability of the approach. Test cases demonstrated that the convergence control is the critical part of the architecture. The main finding was that all simulators connected to the architecture have to be able to roll back when necessary to a previous successful time-step without collapsing the whole simulation.

3.1.4.5 Literature

Publications produced in the project

Ikäheimo, J. (2004). Cost optimization of district heating network design. Proceedings of the 9th International Symposium on District Heating and Cooling. Helsinki University of Technology, Espoo 2004. Pp. 149–157. TKK-ENY-20. ISBN 951-22-7209, ISSN 1457-9944.

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Sipilä, K., Ikäheimo, J., Forsström, J., Shemeikka, J., Klobut, K., Nystedt, Å., Jahn, J. (2005). Technical features for heat trade in distributed energy generation. VTT Tiedotteita – Research Notes 2305. Espoo: VTT. 111 p. ISBN 951-38-6731-5; 951-38-6732-3.

Rämä, M. (2006). Hiilidioksidi kaukojäähdytysverkon lämmönsiirtoaineena (Carbon Dioxide in District Cooling. In Finnish.) Thesis for the degree of Master of Science in Technology. Espoo: Helsinki University of Technology.

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McGovern, J., Ambler, S.W., Stevens, M.E., Linn, J., Jo, E.K., Sharan, V. (2004). A Practical Guide to Enterprise Architecture. Prentice Hall.

Müller-Steinhagen, H., Heck, K. (1986). A simple friction pressure drop correlation for two-phase flow in pipes. Chemical Engineering Process Vol. 20, No. 6, pp. 297–308.

3.2 SES – Smart Energy Storages

R. Alanen, J. Heikkinen, J. Keskinen, A. Laitinen,
M. Rämä, K. Sipilä, L. Wikström

Abstract

Energy storages have been seen as a key component for the further implementation of distributed energy in the EU and other countries. Most of the problems in power quality, distribution reliability and peak power management can be solved with energy storages. In spite of a keen development of different kind of energy storages during latest ten years it is still a need of smart, cost effective and efficient thermal and electrical storages. In the research project "SES – Smart Energy Storages" it has been concentrated on the research and development of thermal energy storage systems and supercapacitors. The two-

year project included study and modification of phase change materials (PCM) and materials for supercapacitors, development, simulation, building and testing of cold storage base module, definition of intelligent modular cooling storage system, study and simulation of PCM materials as a part of building elements of single family houses, and building and testing of supercapacitors. For simulation it was also defined new modules on VTT House simulation platform. The project included international co-operation in IEA ECES executive committee, in WG 4 (Generation and Storage) of European Technology Platform Smart Grids and a researcher exchange with the University of California, Berkeley.

3.2.1 Background, starting point and objectives

Energy storages have been internationally seen as a key component for the further implementation of distributed energy (Figure 70). Most of the problems in power quality, distribution reliability and peak power management can be solved with energy storages. Energy storages give new possibilities for demand side management, and for customer level energy cost control.

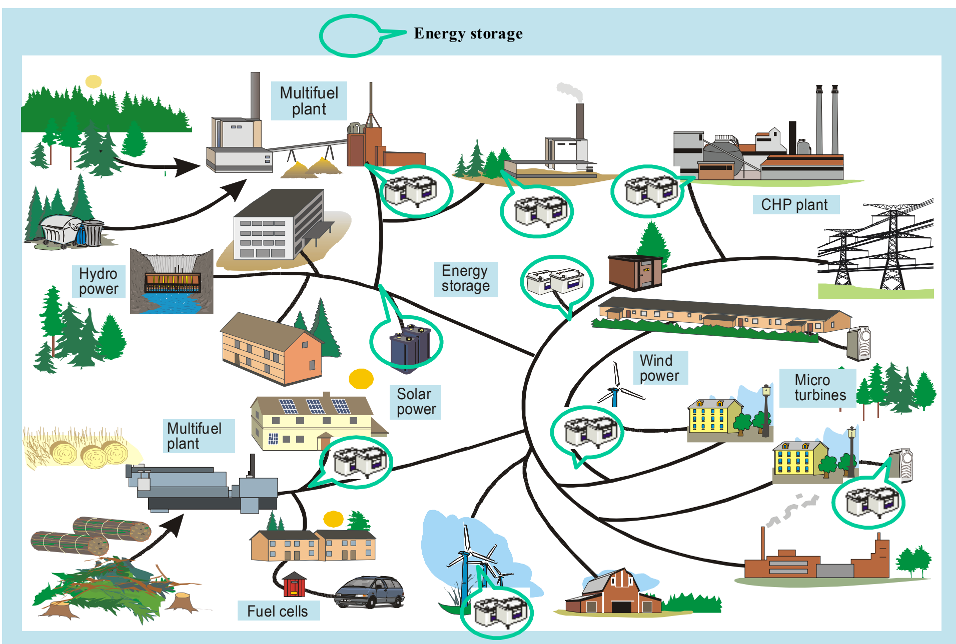

Figure 70. Energy storages in a distributed energy system.

Cost effective, smart energy storages give new potential for building energy management especially when they are used in combined heat and power (CHP) production systems such as fuel cells and micro turbines. Energy storages give possibilities to manage uncontrollable power production in renewable energy production systems such as photo voltage and wind power systems. Uninterruptible power delivery can be essential even in single family houses for example when they are used as a home office with computer systems or they has critical medical equipments that could be more common in near future.

In spite of keen development of different kind of energy storages during latest ten years it is still a lack of smart, cost effective and efficient thermal and electrical storages.

3.2.2 Implementation

This two-year project focused on two main areas of energy storage technology, to develop smart modular thermal energy storage for buildings using phase change materials such as waxes and saline solutions, and supercapacitors that can used for example to manage short power interruptions and as a ride-trough power source before reserve power production system starts up. A technology roadmap for the project is presented in the following figures (Figures 71 and 72).

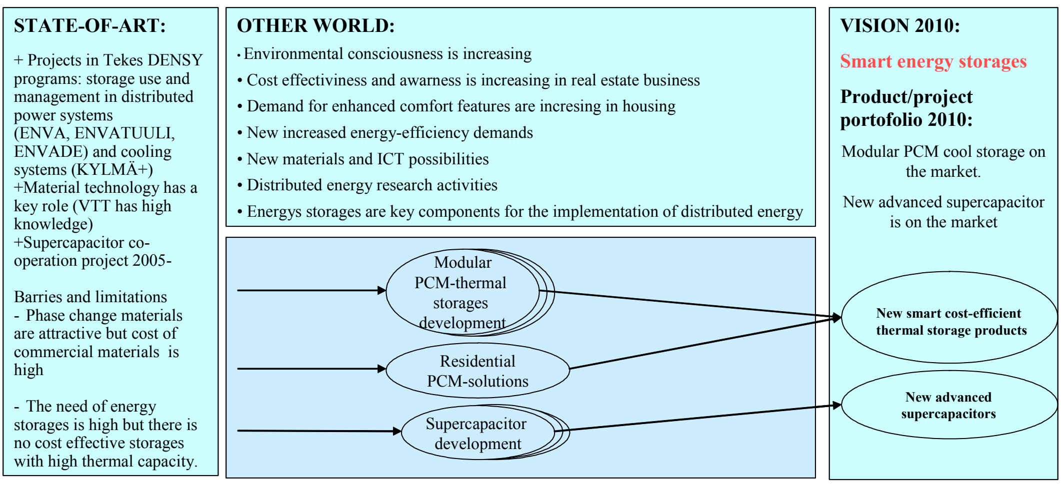

Figure 71. Smart energy storages project, main roadmap.

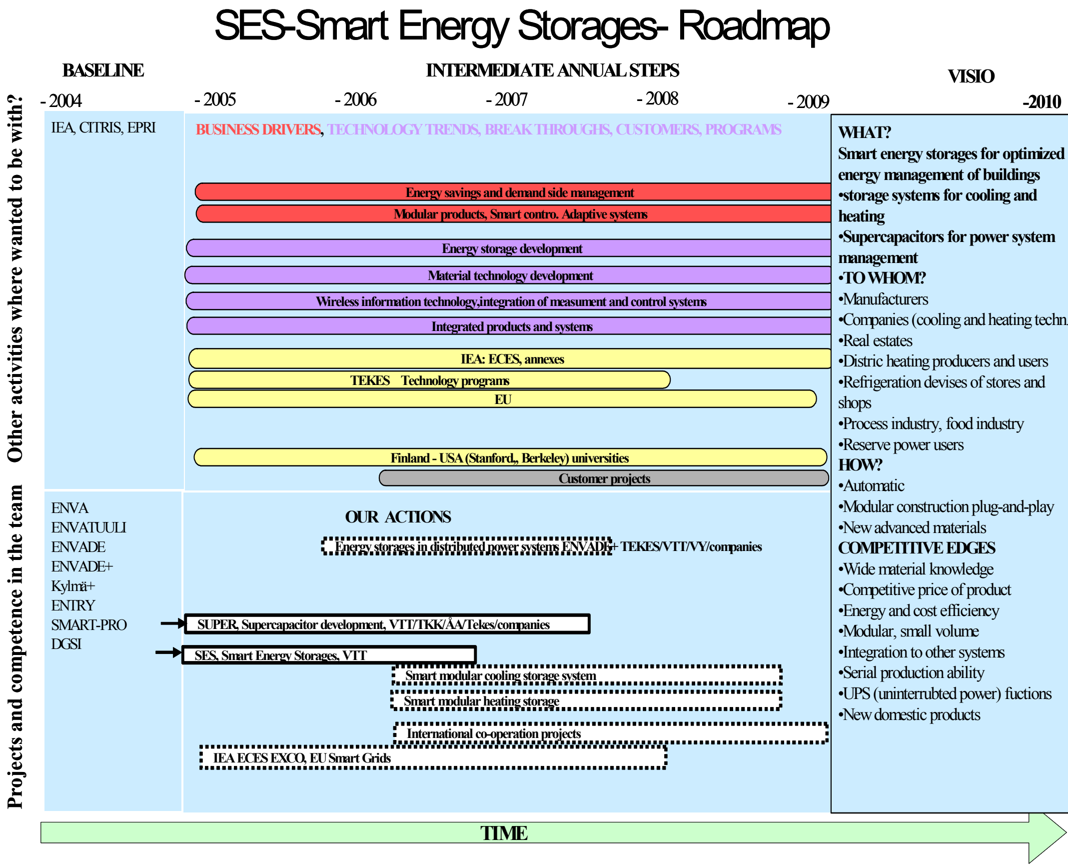

Figure 72. SES projects and other projects, business drivers and trends (as recognized in the year 2004).

Project included phase change material development, thermal energy storage module development and a construction and test of a pilot module, design of a smart modular thermal energy system, study of phase change materials usability in a single family house constructions, simulation and calculation models for VTT House simulation system and a development of a supercapacitor.

3.2.3 Results

The main results of the project are the following:

– Test system for energy storage material test was developed.
– Different materials for heat and cold storage were evaluated and tested.

- To improve thermal conductivity and stability it was developed and tested different types of wax-based thermal energy (heat) storage constructions.
- Simulation and calculation system for defining and sizing thermal energy storages was defined.
- A pilot module for heat storage was developed, built and tested.
- A smart, module based thermal energy management system for buildings was designed and simulated.
- Different kinds of supercapacitor materials and structures were evaluated, defined and tested.

3.2.4 Industrial and research networking, international position

This project completes the energy storage research work of several research projects (ENVA, ENVATUULI, ENVADE, ENVADE+) done by VTT co-operating with several Finnish companies. Research co-operation in these projects has happened for example with Vaasa University or Helsinki University of Technology.

The project included also international co-operation, participation in IEA ECES executive committee, in WG 4 (Generation and Storage) of European Technology Platform Smart Grids and a researcher (Raili Alanen) exchange with the University of California, Berkeley (VTT–Tekes project BECIT). VTT also participated in IEA ECES NATO Advanced Study Institute on Thermal Energy Storage for Sustainable Energy Consumption (TESSEC) in Turkey and in EcoStock 9th International Energy Agency Thermal Energy Storage Conference, in Stockton, New Jersey, USA.

3.2.5 Exploitation and industrial impacts

R&D work continues in two co-operation projects. The co-operation project "Developing super-capacitor" started in 2005. It has been financed by Tekes, five industrial companies and VTT. This theme project has been done in cooperation with Helsinki University of Technology (HUT) and Åbo Akademi University. Based on the thermal energy project experience and knowledge, it has started in 2006 a project "Heat and Cool Accumulators in Vehicles, Lämpö- ja kylmäakut kuljetusvälineissä" where the research goal is to develop thermal energy accumulators for vehicles. The project will be done in cooperation with Helsinki University of Technology (HUT) and it is financed by Tekes, VTT and eight companies.

3.2.6 Thermal energy storage system

Energy storing for heating and cooling is one of the most traditional energy storage applications which importance is increasing because of the increasing thermal loads in buildings and requirements for better load management, because of increasing energy cost and also environmental issues.

3.2.6.1 Thermal energy storage materials

Thermal energy can be stored as sensible heat, latent heat and chemical energy (Figure 73).

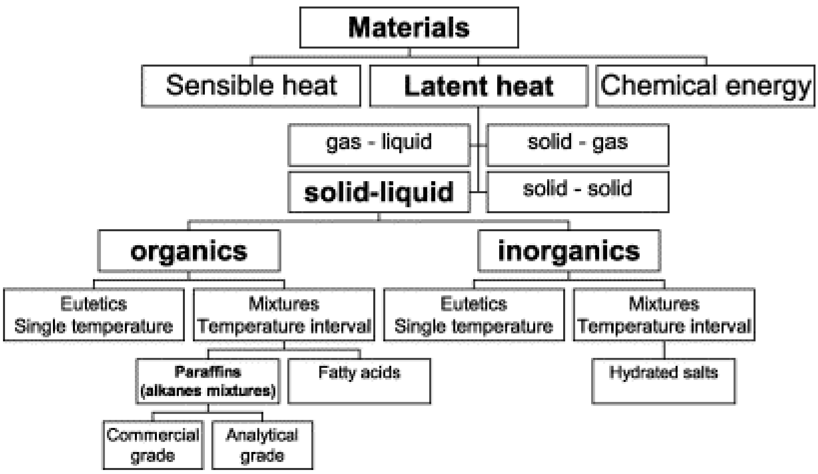

Figure 73. Classification of energy storage materials (Zalbe et al. 2003).

Phase Change Materials (PCM) are commonly used to store thermal energy. While PCM undergoes a phase change a large amount of thermal energy is stored or released. Traditionally used thermal storage material is water (sensible heat) or water/ice or water/snow (latent heat). Water is an inexpensive material and it has good heat transfer characteristics. However, water storage needs a large volume because it's low energy storage capacity. Unlike conventional storage materials, many latent heat PCMs change phase (their melting point) absorbing large amounts of heat without getting hotter. Besides the large latent heat the melting point of the PCM should also be in the range of operation, it should have high thermal conductivity, it should melt congruently with minimum super cooling (the melting point of a material is found well above it's solidification point) and be chemically stabile, non-corrosive and non-toxic. PCM should also be low in cost.

In this project it has been studied paraffins, salt hydrates, fatty acids, sugars and different kind of eutectic mixtures that typically have good energy storage capacity and stored energy can be delivered in a sufficient narrow temperature range that can improve the storage system performance. They can have also disadvantages such as high cost, heat transfer problems, limited long term stability or they (salt hydrates) can increase the corrosion of materials.

The low thermal conductivity is a problem with almost all phase change materials in most of the applications. Increasing the thermal conductivity is necessary in cold and heat storages to decrease the charging and discharging times. Increasing the thermal conductivity was studied with paraffins with thermally conductive structures and fillers. The best thermal conductivities were achieved with thermally conductive structures such as foamed aluminium and zinc. The foamed aluminium increased the thermal conductivity of paraffin from 0.25 W/Km to 3.4 W/Km and foamed zinc to 3.7 W/Km. The weak point of foamed aluminium and zinc is their high price. The thermal conductivities of some combinations are shown in the Table 5.

Table 5. Thermal conductivity of paraffin with different thermally conductive structures and fillers.

Sample	**Thermal conductivity, W/Km**
Paraffin	0.25
Paraffin + Al -foam	3.4
Paraffin + Zn -foam	3.7
Paraffin + Al -honeycomb	2.1
Paraffin + steel wool	0.5
Paraffin + Al coil ships (10 vol-%)	2.5
Paraffin+ SEBS + graphite	1.0
Paraffin + carbon fibre felt	0.5
Paraffin + carbon fibre fabric	0.6

Some thermally conductive structures were tested in the laboratory scale test storage with paraffin based phase change materials. The discharging time was halved with addition of aluminium coil chips (2.5 vol-%) compared to the pure paraffin PCM. The discharging time was at the same level with the commercial heat exchanger which was also tested in the laboratory test storage, Figure 74.

Thermally conductive fillers were also tested. The density of the fillers is high and they tend to sediment while the PCM is in a molten phase. In the use of fillers the PCM needs to be thickened for binding the fillers to the PCM. The thickening was done with SEBS (styrene-etylene-butylene-styrene).

a) b) c)

Figure 74. a) Laboratory scale thermal energy storage / testing system, b) different kinds of paraffins and c) thermal conductivity measurement system.

3.2.6.2 Cool storage system

The need of cooling power in buildings has typically large variations during the day, as shown in Figure 75. Instead of designing a refrigeration system for the maximum cooling load, a cool storage is an attractive option for covering the peak cooling need. The cool storage system shifts cooling energy to off-peak periods which means that the refrigeration system can be smaller, it can run longer periods of time at full load, make use of lower outdoor air temperature at night-time and perhaps use cheaper night electricity rates. This peak shaving cooling technology also helps to reduce the rise of electrical power demand of power stations during the hottest summer hours.

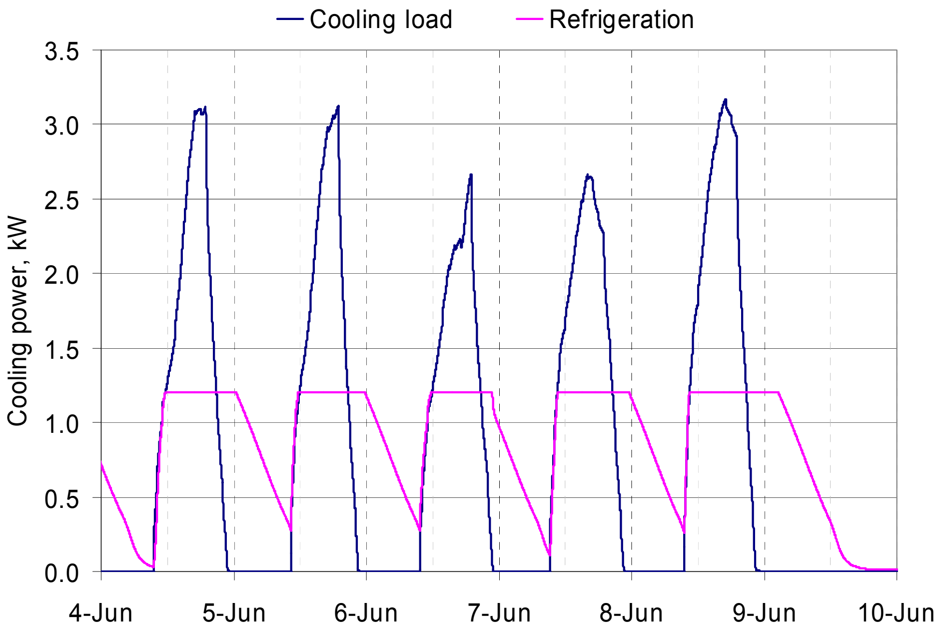

Figure 75. Cooling load of an office during a hot summer week. The basic cooling need up to 1.2 kW is supplied by the refrigeration system and the rest is covered with a PCM cool storage. The refrigerator is working night-time to charge the cool storage.

Phase Change Materials (PCM) are an attractive option to be used in cool storages because they are able to store large amounts of energy in a small volume within a small temperature range, compared with sensible heat storage materials as liquid water. The cool storage temperature in a system shown in Figure 76 typically varies between 5 °C and 14 °C during the charge and discharge cycles of the day. The purpose of the storage is to bridge the temporary gap between the cooling need and supply.

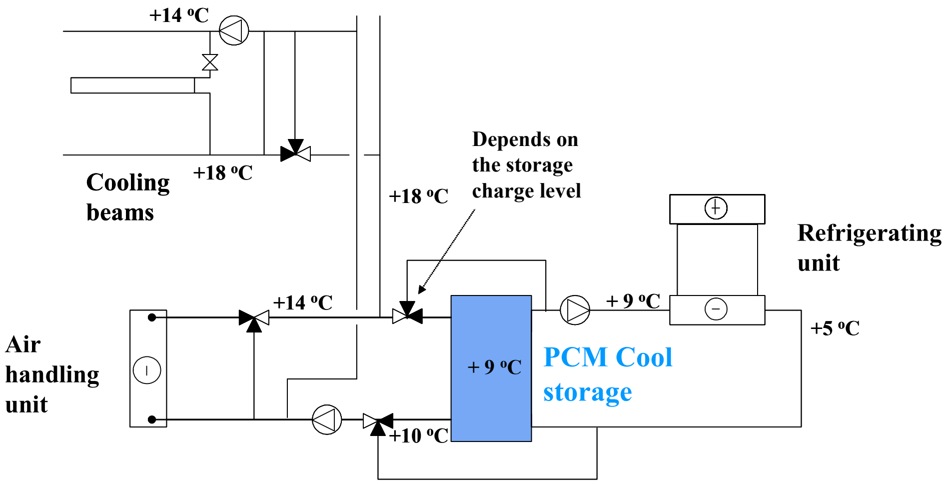

Figure 76. Temperature levels in a typical building cooling system incorporating a storage. The cooling energy produced by the refrigerating system is used in the cooling beams in the rooms and in the central air handling unit. The storage is bypassed when it is not needed.

The design of a PCM cool storage is a challenging task, from technical as well as from economical point of view. The capacity of the storage and the amount of the required PCM material is quite straightforward to determine. But to predict the time behavior of the thermal power during the charge and discharge periods one needs a numerical model for the whole storage. Such a model was implemented into the VTT House building simulation environment. In the model, the phase change material can be in the form of plates or tubes, the heat transfer medium flowing outside the PCM. The model was validated against known analytical solutions as well as against numerical results found in literature.

For the cool storage the phase change temperature was desired about 8–10 °C. Paraffin based phase change materials were given a priority because their latent heat is moderate, they are chemically stabile and non-corrosive and they have no supercooling. Paraffins are commercially available in many temperature ranges and the price is reasonable. For the prototype cool storage module commercial materials (Rubitherms RT6 and RT9 and EPS Ltds PlusIce A8) were first tested using Differential Scanning Calorimeter and the laboratory scale thermal energy storage.

A prototype for a modular PCM cool storage was built inside a commercial 300 liter hot water tank shown in Figure 77. The phase change material paraffin is inside aluminum tubes. Paraffin is modified to increase the heat conductivity to about 0.8W/mK. The tube diameter was optimized to fit for the typical daily charge/discharge periods and for the typical temperature differences between the water and the PCM. The size of the storage itself was chosen for practical reasons like transportation through doors.

Figure 77. The prototype of a modular PCM cool storage with water inlet/outlet port ready for test measurements.

Water flows very slowly through small triangular spaces between the tubes in the direction of tubes. The design yields effective heat transfer between the water and the tube in the laminar flow regime, still at low pressure loss. An example of cooling power in a test is shown in Figure 78. The measured power is smaller than the computed power because part of the water bypassed the PCM tubes even if the space between the tubes and the tank wall was filled with polyurethane. The most striking feature of the cooling power output in Figure 78 is that the cooling power decreases rapidly, to the half during first 30 minutes and therefore does not fit well into the cooling power requirement which typically increases during the day.

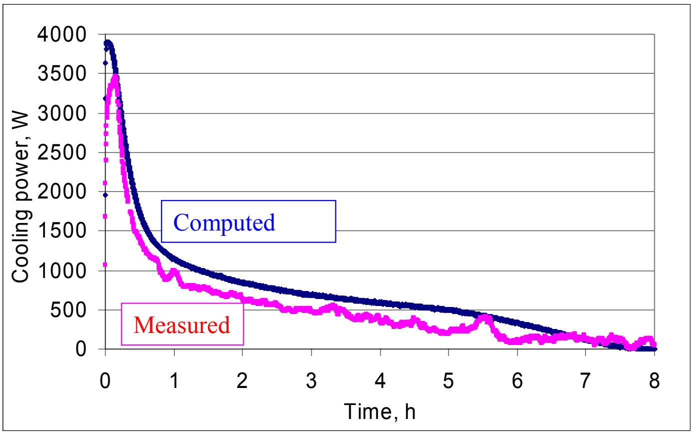

Figure 78. Measured and computed cooling loads provided by the prototype cool storage at fixed water flow rate and constant inlet temperature. The measured power is smaller than the computed power because of water bypass.

It turns out, however, that by regulating the water flow rate it is possible to cover increasing cooling needs as well. The whole cooling system and building simulations were performed with an enhanced cool storage that prevents water bypass. A simulated result of the cooling need in the office and it's coverage by the storage was already shown in Figure 75. In addition to cooling power the temperature level is an important indicator for the performance of a cool storage. Figure 79 shows that the storage outlet temperature ("In" Figure 79 during the discharge period) remains at a suitable a level for the cooling beams in the air conditioned rooms.

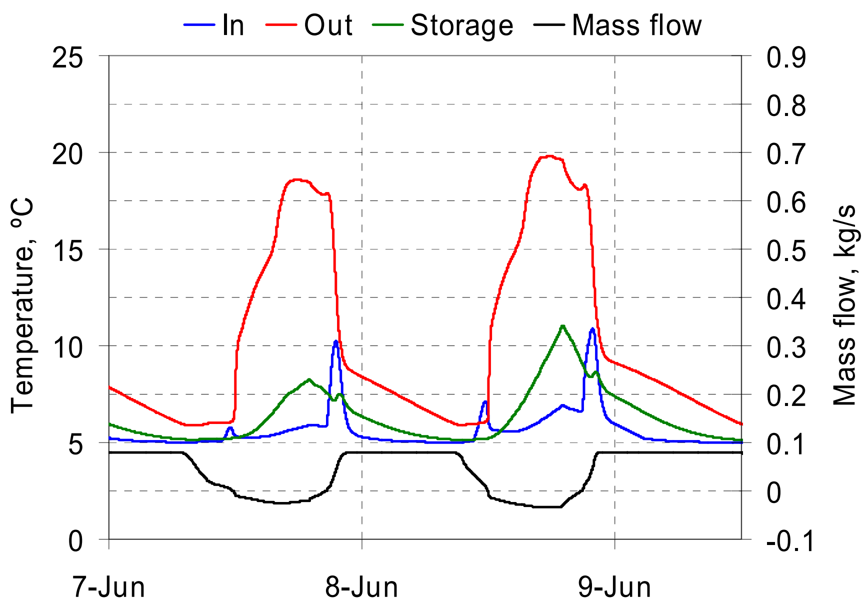

Figure 79. Inlet, outlet and middle storage temperatures and the water flow rate in the PCM cool storage during two hot summer days. "In" refers to the inlet end of the storage during the charge phase (positive mass flow). The mass flow direction is reversed during the discharge phase.

The intelligence of the PCM storage and the cooling system originates from the proper sizing and packaging of the PCM material to fit to the time behavior of the cooling need in the building. The control system discharges the storage only when needed and uses the excess refrigeration power to charge the storage, until the temperature sensor detects that the storage is full.

A more intelligent control system could make use of an available weather forecast information service to decide how much loading is necessary during the night to minimize the use of the refrigeration. To achieve this it would need reliable information on the status of the storage, which can be provided by monitoring the temperatures inside the PCM tubes.

In addition to peak shaving, the PCM storage can be used as a buffer to allow the refrigerator to operate mainly at ideal efficiencies. At some point the refrigerator can even be shut down and let the storage alone to provide the necessary cooling power.

Usually many PCM storage modules are needed to cover the cooling demand in a building. The control system could make decisions concerning which units to charge or discharge based on the storage status, e.g. some units can be kept as a reserve to be discharged only when needed.

3.2.6.3 Heat storage

The phase change temperature for heat storage had to be about 90°C and the latent heat was required to be over 200 J/g. The latent heat of commercial phase change materials in the wanted temperature range is lower than desired. To achieve higher latent heat some sugars and Acetamide were tested with DSC for the heat storage purpose. The DSC test results are shown in the Table 6.

Table 6. Melting temperatures and latent heats of Acetamide, Erythritol, D-sorbitol, Maltitol and Xylitol tested with DSC.

	T_m, °C	Latent heat. J/g
Acetamide	80	208
Erythritol	118	346
D-sorbitol	97	175
Maltitol	149	170
Xylitol	94	253

The latent heat of D-sorbitol and Maltitol were lower than required. Acetamide melted at 80 °C and the latent heat was 208 J/g but Acetamide was ignored because of its carcinogenic effects. Erythritol and Xylitol were studied further. Both of them tend to supercool. To prevent the supercooling different nucleating agents were tested with both sugars. The supercooling of Erythritol could be decreased about 70 °C with the nucleating agent with a similar crystal structure as Erythritol, Figure 80 With and without additives Erythritol melted at same temperature, 119 °C. The latent heat of melting was 346 J/g without nucleating agent and 330 J/g with nucleating agent. The crystallization occurred at 32.7 °C with pure Erythritol and the latent heat was 223 J/g. With the addition of nucleating agent the crystallization temperature was increased to 100 °C, at the same time the latent heat of the crystallization was 303 J/g.

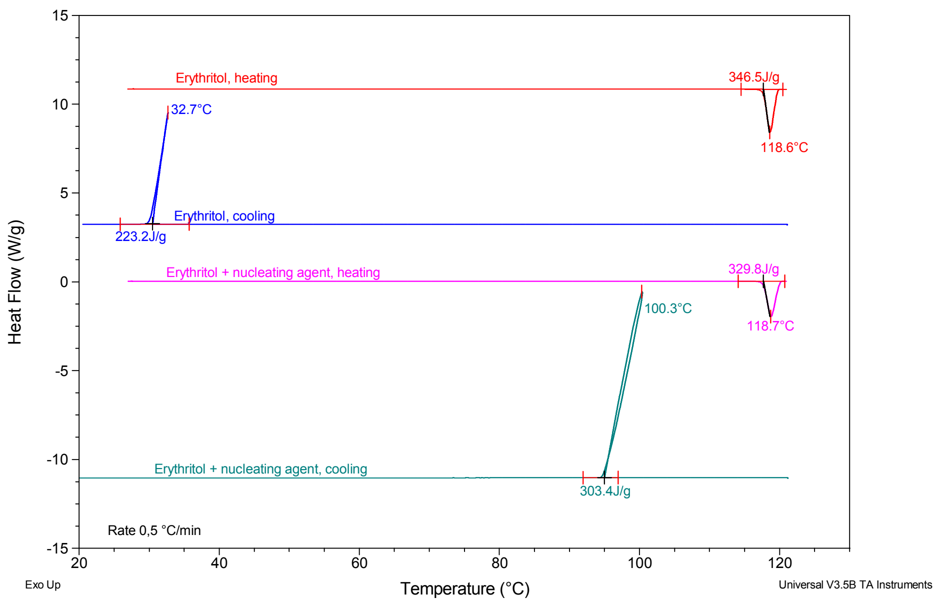

Figure 80. DSC measurements of the Erythritol with and without a nucleating agent that was used to prevent the supercooling effect.

The same prototype storage that is used for cooling purposes is here used as the domestic hot water storage. The simulations were carried out with VTT House computer software. The simulated case network is presented in Figure 81. The simulated case consists of a hot water storage filled with phase change modules, heating element (3 kW), loading pump, temperature control system and one shower.

In this project a cool storage prototype module was not built. The goal was to use same mechanical construction for the heat and cool module.

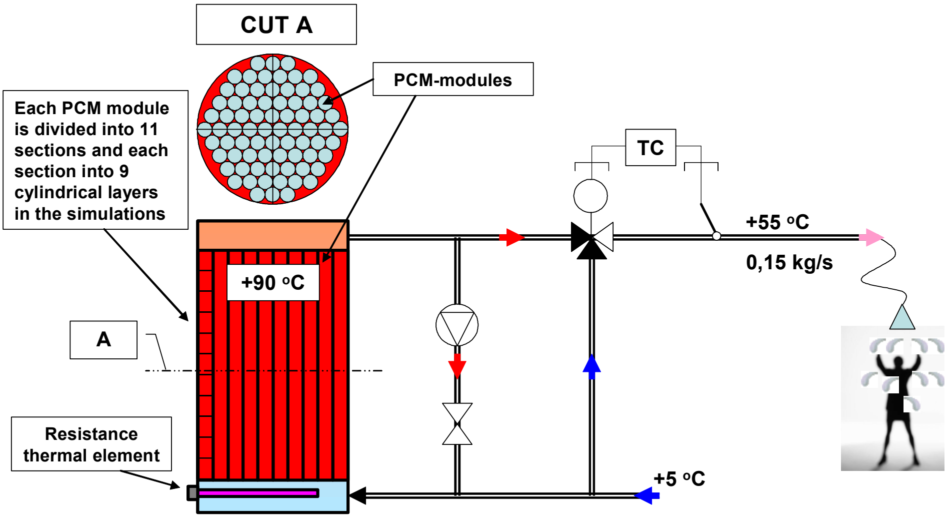

Figure 81. Simulated hot water storage with PCM modules. Circulation pump is used only during loading of the storage and during other times the valve in this pipe is closed.

In the following examples of the simulations, the PCM modules were filled with commercial paraffin based phase change material (Rubitherm® RT 80) which is suitable for the case study because of the decent melting temperature range (71–86 ºC). The simulated hot water usage profile is shown in Table 7 where also total water and used heat energy are presented. Two samples of the simulation results are presented in Figures 82 and 83.

Table 7. Hot water profile and used heating energy.

Time, h:min	**Water flow, kg/s**	**Duration, min**	**Water volume, litres**	**Energy (5 -> 55 °C) kWh**
7:00–7:05	0,15	5	45	2.62
7:30–7:40	0,15	10	90	5.24
17:00–17:05	0,15	5	45	2.62
20:00–20:07	0,15	7	63	3.67
22:15–22:30	0,15	15	135	7.86
Total		**42**	**378**	**22.00**

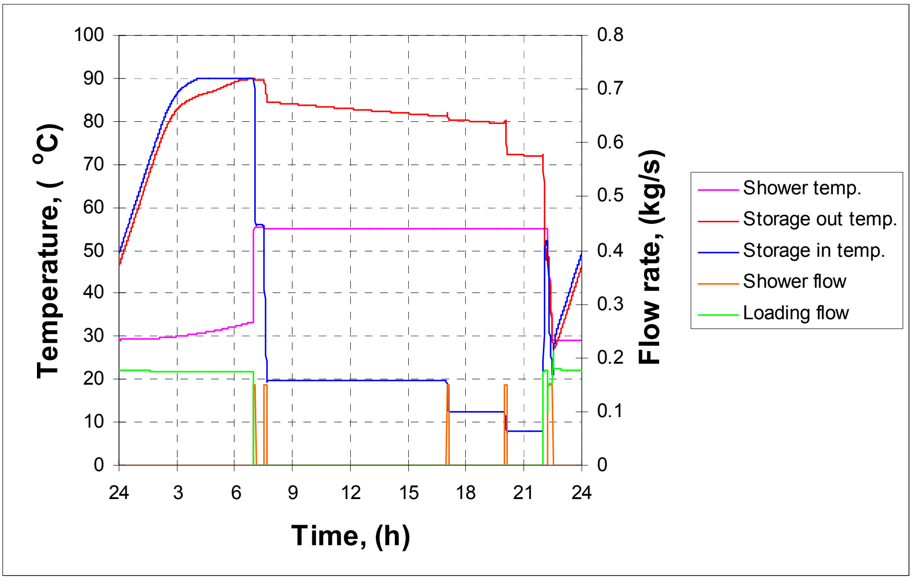

Figure 82. The temperature of the shower flow stays in its set point (55 ºC) until the last draw (22 o'clock) when the capacity of the PCM storage runs out.

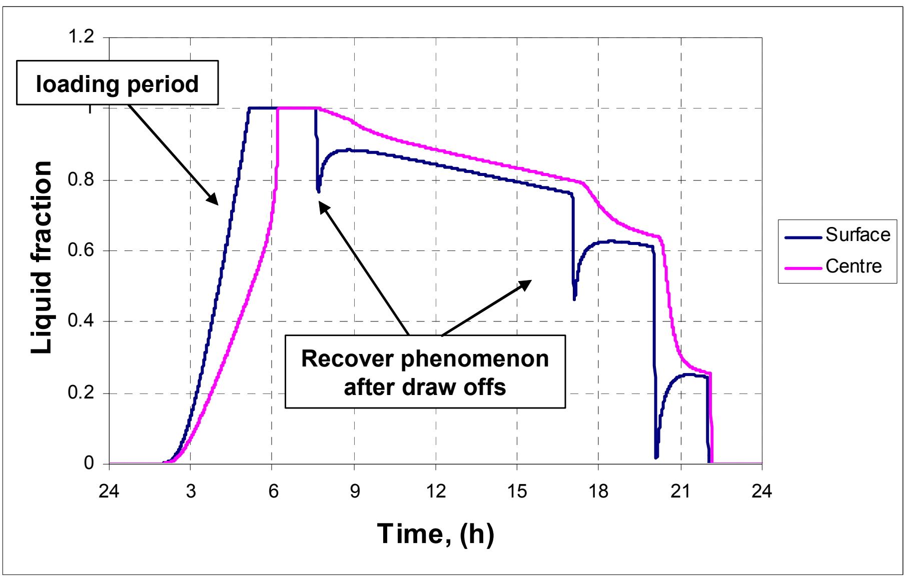

Figure 83. Liquid fraction of the surface and centre points of the last section of the PCM module. When the liquid fraction is 1, the PCM in that particular point is in liquid state. A clear recover phenomenon of the PCM can be seen after the draw offs.

The results illustrates that the typical loading time (cheaper electricity price between 22–7 o'clock) and loading power (3 kW) that are used in Finland are enough to charge the storage. The other conclusion is that the capacity of the simulated PCM storage used in the case study is too low compared to the conventional water storage due to too low latent heat of fusion of the used phase change material. The recover phenomenon of the surface layer of the PCM module after the shower draw offs in figure 3 can be explained by a dynamic effect where the heat of the inner parts of the module melts again part of the already solidified material.

3.2.6.4 Simulation system

In this research program a special dynamic building simulation software, VTT House, were used and further developed to include the features of phase change materials (PCM). The developed characters of the dynamic simulation tool where:

- PCM module to be used in heating or cooling buffer storages
- integrated PCM construction to be used with building heating and cooling simulations.

Some samples of the developed user interfaces of the VTT House is presented in Figures 84 and 85 and particularly the developed PCM module instance.

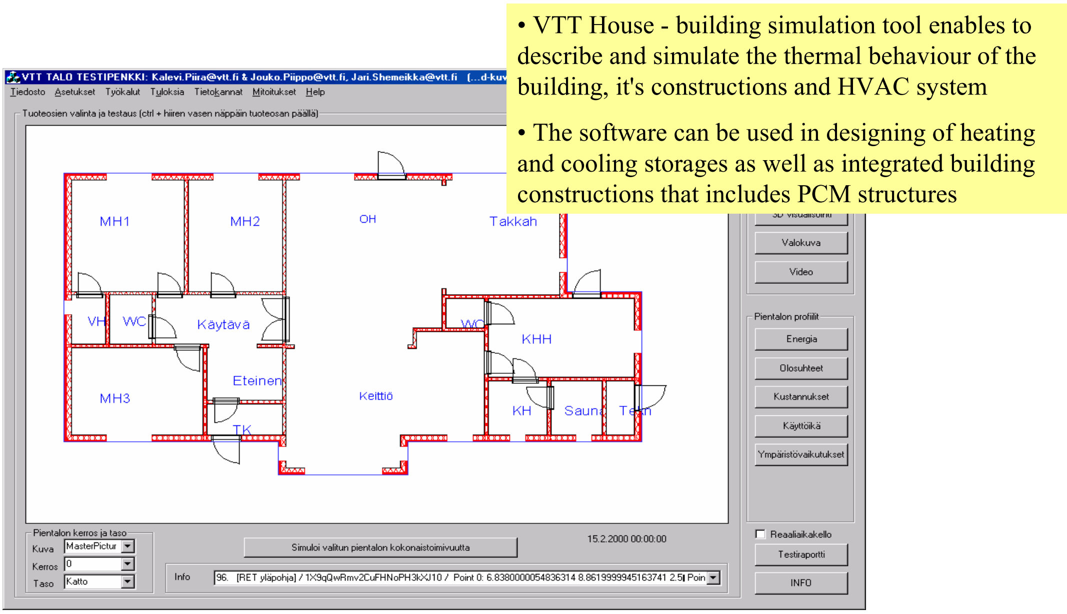

Figure 84. Main user interface of the VTT House building simulation software. On the screen there is a shot of a simulated detached house.

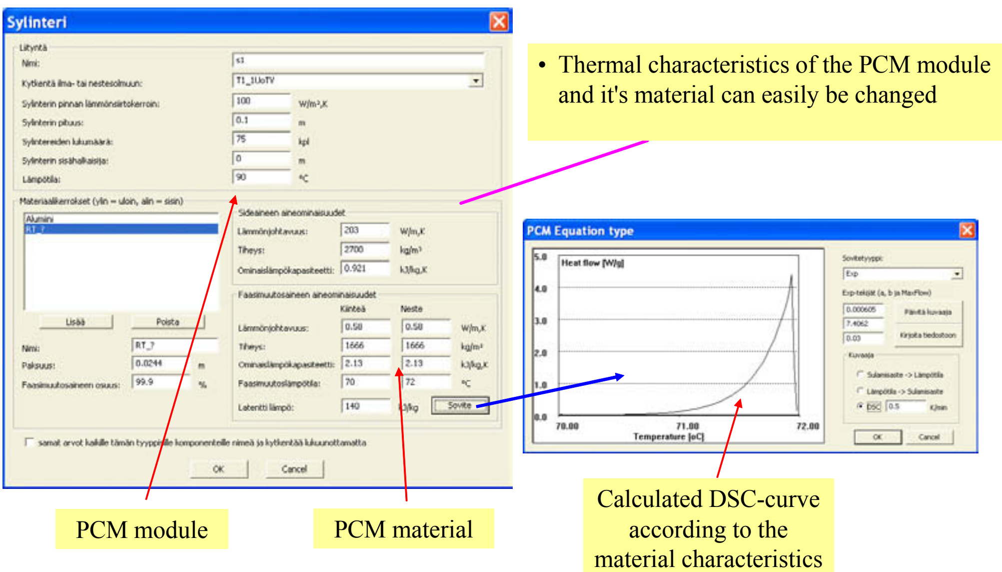

Figure 85. A view of the PCM module user interface of the VTT House building simulation software. On the screen there is a shot of a simulated heat storage module and its material.

In the project it was built simulation tools on VTT House simulation platform to be used in developing and designing smart PCM energy storage systems for heating and cooling applications. The tools have been used to test three PCM applications:

1. The effect of PCM material integrated into building constructions. In this case the phase change material were integrated into the plaster board of the indoor side of the walls and the effects on the indoor air temperature and on the heating and cooling energy demand were examined. This case is not included in this paper but in short the results proved that the use of PCM boards is advantageous in damping the temperature fluctuations of the room temperatures during summer and winter conditions with lower energy demand (heating energy savings were < 2%).
2. PCM storage buffer for domestic hot water production in which case the conventional hot water storage works pretty well owing to the large temperature difference of the water that can be utilized. The most potential use of PCM in building heating and cooling storage applications is in systems where the competing water storage works with small temperature difference.
3. A PCM storage module for peak shaving of the building cooling load. Prototype storage was built and tested. Simulation of the storage together with the building and the cooling system showed that the storage is able to cover variable cooling needs when properly controlled. The modular principle of the storage allows great flexibility in controlling the charge and discharge periods.

3.2.6.5 Conclusions

The importance of the advanced thermal energy storages is seen worldwide and keen research and development is continuing for example in Japan and Germany. Thermal energy storages play an important role in heating and cooling systems for different reasons: 1) to compensate for the high energy production power to meet the lower power need of the consumption (buffer storage), 2) to compensate for the low production power to meet the short period of high power demand (peak load reduction) and 3) to utilize occasional energy sources to be used at different time.

The development of well working PCM heat storages necessitates the development of well working materials with high enough latent heat of fusion. For example a stability of a thermal storage is a key issue and therefore the standardization of PCM and the testing of PCM-based products is essential important for the future development and implementation of new products.

This two year project for thermal energy storages can be seen as an important prerequisite for new research and development projects that will have benefits of VTT's increased knowledge of phase change materials, their features and behavior for heating and cooling purposes, modular thermal energy storages and systems. The research work of thermal energy materials and storages continues for example in the ongoing project "Heat and Cool Accumulators in Vehicles" that includes research and implement of phase change materials for heating and cooling storages in vehicles.

3.2.6.6 References, inventions, patents, academic degrees

Zalbe, B., Marin, J., Cabeza, L. and Mehling, H. 2003. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Applied Thermal Engineering, Volume 23, Issue 3, February 2003, pp. 251–283.

During the project two VTT inventions related to the PCM storages were done.

3.2.7 Supercapacitor development

3.2.7.1 Background

Supercapacitors (ultracapacitor, electrochemical double layer capacitor) can be used as an energy storage. Their performance is between conventional capacitors and batteries when power and energy densities are considered. Because of the high power that can be obtained from supercapacitors they can be used in applications where relatively high peak power is needed. These include e.g. vehicles and wind power plants. Even if supercapacitors have very high power density (1000–10000 W/kg) and long cycle life (> 500 000 cycles) the energy density is still about tenth of the energy density of lead acid batteries.

However, a keen material development has produced new type materials such as nanomaterials that can give possibilities to increase energy density. In this project it has been concentrated to study possibilities and develop new types of supercapacitors with increased energy density and overall performance.

The supercapacitor structure is shown in Figure 86. Basically the component is an electrochemical device in which two capacitors are formed on the interface between electrodes and electrolyte. The electrodes are typically made of active carbon having large specific surface area (1000–2000 m^2/g). The electrolytes can be water based or organic. Water based electrolyte limits the voltage to slightly above 1 V. With organic electrolytes the voltage level can be increased to above 2.5 V. The energy stored in a supercapacitor is related to capacitance and to the square of voltage.

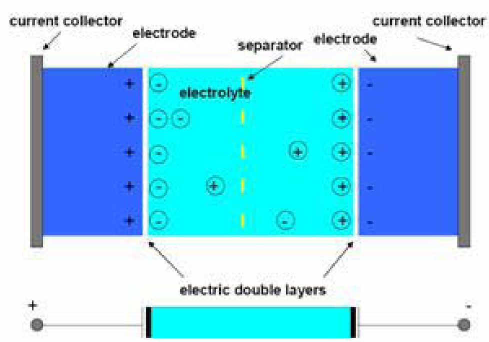

Figure 86. Schematic structure of a supercapacitor.

3.2.7.2 Research topics

The work related to the theme (ÄLY-teema) has been done in two projects. The cooperation project has been financed by Tekes, five industrial companies and VTT. In this project cooperation has been done in with Helsinki University of Technology (HUT) and Åbo Akademi University. In the project financed completely by the theme work has been focused to components that partly behave like batteries and partly like supercapacitors.

Particular topics have been:

- Carbon electrodes having very high specific surface area (carbon powder/carbon cloth)
  - Improvement of electrical conductivity to minimize losses
  - Advanced electrolytes
- Completely polymeric dry supercapacitor
  - Economic manufacturing method for thermally stable polymer electrolyte
  - Optimization of chemical or electrochemical synthesis for the production of polyaniline or other conductive polymer
- Power electronics for supercapacitors (HUT)
  - Voltage balancing in series connection
  - Voltage stabilization during charge and discharge
- Supercapacitors with non-symmetrical structure
  - Ni- and Li-containing electrodes
  - Improved energy storage capacity with higher voltage.

3.2.7.3 Results

Activated carbon with liquid electrolytes

Different activated carbon powders have been used for processing supercapacitor electrodes. Some tests have also been done using a cloth made of activated carbon. Mechanically relatively strong electrodes have been made with polymer binder. With organic electrolyte the measured specific capacitance values have been of the order of 20–40 Farads per 1 gram (measured in a capacitor having two electrodes). Beside capacitance also series resistance, leakage current and energy efficiency have been defined.

Electrochemical characterization procedures for supercapacitors using voltammetric measurement and impedance spectroscopy have been developed at Åbo Akademi University. Commercially available supercapacitors were measured and the results showed the methods were reliable. A voltammetric measurement method was tailored for characterizing the active surface area of carbon powder and electrodes.

Commercially available supercapacitors have been tested electrically using Arbin supercapacitor test station. This device was applied also for measuring self-made components. The commercially available supercapacitors and those made in the project have been compared. The comparison shows that the specific capacitance of the commercial components has been surpassed whereas leakage current levels should still be improved.

Polymer electrodes and electrolytes

Polyaniline electrodes have been synthesized electrochemically onto carbon cloths. Tests show that specific capacitance can be appreciably improved with polyaniline. Specific capacitance of over 70 F/g has been achieved. The synthesis process for sulfonated polyetheretherketone (SPEEK) electrolyte film has been developed. The film presents good mechanical stability when dry. According to thermal tests the SPEEK film is more stable at high temperatures than PTFE based Nafion. Capacitors having Nafion electrolytes have been constructed. In these capacitors carbon cloth was used as electrodes. The capacitance values measured have been 34 F/g which is slightly better than the ones reported in the literature.

Hybrid supercapacitor

A nickel hydroxide electrode has been constructed. It was used as positive electrode (anode) together with active carbon cathode. The obtained discharging behavior was different from typical supercapacitors: during discharging the voltage remained relatively constant whereas in symmetric supercapacitors the voltage decreases linearly with constant current.

Power electronics

At Helsinki University of Technology a survey has been made of balancing circuits and dc-dc converter topology. The balancing can be done using either passive or active solution. According to the literature survey the best topology for the dc-dc converter seems to be a solution based on a half-bridge, although the most suitable implementation for each application must be evaluated separately. Frequency responses of commercially available supercapacitors have been studied. A Master's Thesis has been done (Isola 2006). In this Thesis work the charging characteristics of one Maxwell PC10 supercapacitor has been studied and features found are worth of further study, which may be realized later in a form of improved supercapacitor models. An approach of utilizing power electronics with supercapacitors for energy storage was presented.

Surveys of supercapacitor structures

Two surveys have been done: one of the patent situation concerning supercapacitor structures and one of hybrid supercapacitors having lithium containing electrodes. The electrical behavior of lithium containing components is between supercapacitors and batteries. The energy capacity can be considerably increased although compromises with obtained power and lifetime must be accepted. One commercially available lithium-based hybrid supercapacitor was tested.

3.2.7.4 Utilization of the results

The technology that is developed during the project can be used in industrial manufacturing of supercapacitors or their raw material. The experience of supercapacitors and power electronics obtained from the project is essential when supercapacitors are applied in energy storage systems.

3.2.7.5 Publications produced in the project

Isola, E.-M., Kyyrä, J., Bergelin, M., Keskinen, J. 2006. Models of Supercapacitors and Their Charging Behavior. European Symposium on Supercapacitors and Applications. November 2006.

Isola, E.-M., Kyyrä, J., Seppälä, P., Keskinen, J., Bergelin, M. Submitted. Supercapacitor Model for Circuit Simulations, 12th European Conference on Power Electronics and Applications, EPE 2007. Aalborg, Denmark, 2–5 September 2007.

Keskinen, J., Kauranen, P., Bergelin, M., Johansson, M. 2006. Supercapacitors with activated carbon powder and cloth electrodes. European Symposium on Supercapacitors and Applications. November 2006.

3.2.7.6 References, inventions, patents, academic degrees

Isola, E.-M. 2006. Power Electronics for Supercapacitor Based Energy Storage. (Tehoelektroniikkaa superkondensaattoreihin perustuvaan energiavarastoon.) Master's Thesis. Espoo: HUT / Sähkö- ja tietoliikennetekniikan osasto. 64 p.

During the project a VTT invention related to supercapacitors was done.

3.3 DGSI – Distributed Generation System Interconnection

Risto Komulainen

3.3.1 Background, starting point and objectives

The ultimate goal of the project is DG (Distributed Generation) system interconnection (DGSI). That is a novel, intelligent and modular network interconnection unit of consumer/power producer in a distributed power network. The focus in first two years was to create a two-way communicating and controlling interface, the so-called fU-adapter that is the core part of DGSI. The fU-adapter project dealt mainly with the interconnection of fuel cells (DC) with inverter connection, and a wind power unit with AC or inverter connection.

In 2004 and after the technology roadmap activities an expanded project DGSI was started with the focus on the intelligent control system concept of the "Virtual Utility". The idea was to control and connect the distributed producers to the customers, while preserving the network stability and power quality both in the normal loading and in fault conditions. New network solutions, such as, microgrids, adaptive intelligent protection, and modern system control principles (forecasting, communication solutions, demand side management etc.) have been studied.

Later on the microgrids concept was investigated more carefully. By using that concept, the original objective – easy interconnection procedure – might be possible to realize in the longer run, because a microgrid may act as a single connection node for the supply network despite its internal structure. The concept was indented to be simulated and tested in the real testing environment facilitated by the parallel project (Tekes-DENSY MULTIPOWER). Due to delays in that project, these verifications have been postponed.

3.3.2 Implementation

The fU-adapter part of DGSI started in November 2001. At the same time planning of the national technology programme, Tekes-DENSY (2003–2007), was underway. The ideas developed for DGSI were imported, as far as possible, also into the DENSY program. Due to the common goals, VTT was capable of extending the funding base to several projects, directly inside the theme program and closely linked. The set of projects is summarized in Figure 87. Special emphasis has been put into the distribution network, simulation and modelling and network control issues.

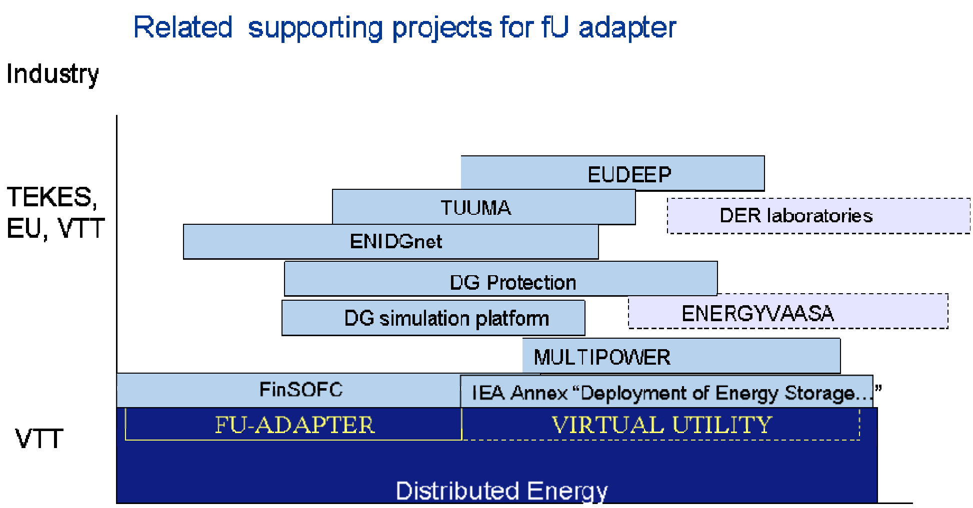

Figure 87. Distributed generation projects aiming at the ultimate goal (theme projects and, linked projects).

A wider project DGSI was designed to research the new control system concept, where the present distribution system adopts more and more distributed generation. Solutions of this project were simulated and, later on, they will also be tested in the new laboratory environment of VTT at Espoo. The change in focus was considered relevant after the aforementioned technology roadmapping activity.

As a case study, the fuel cell interconnection concept was simulated and the complete set of testing requirements was collected for the further discussion with the Finnish distribution operators (HELEN, E.ON...). Functionality of traditional protection concepts together with distributed generation, as well as, control problems (voltage and frequency control) were studied in several simulations. The Microgrids concept was investigated as a new possibility to connect several moderate units into the network so that some of the actions required today by network operator could be eliminated or to make them easier.

3.3.3 Results

Main results are as follows:

- definition of interconnection requirements and testing procedures
- definition of fuel cell interconnection unit concept
- different level of simulation models
- verification of the functionality (by simulations).

Several national and international research problems and projects related to DG has been generated, see Figure 88. Many impacts can be seen such as:

- Combination and increase of the knowledge inside VTT
- Activation of external R&D projects together with industry
- National DG research program DENSY aligns well with our TRM, as well, as, with the European Union research activities.
- Possibilities for interconnection of different simulations for the complete production and operation processes (e. g., mechanical and electrical interactions, distribution network behaviour)
- Finnish industry and other organisations are well represented in these medium and long-term projects. Protection relays, network management systems, metering, fuel cell and windmill units, power electronics, storage

systems, as well as, the business and operational processes are of interest in these projects. VTT is a major research party in these presented projects.
- National DG testing site to Espoo will be finished in one of these generated projects.

3.3.4 Industrial and research networking, international position

Networking with research organizations (HUT, VU, TUT, LUT) and selected industrial partners in Tekes-projects (such as SVK pool, TUKES, ABB, Fortum, Merinova, Vacon, VAMP, Verteco, Wärtsilä, HELEN), and other network organisations.

Several cooperation projects in different forums (national, Nordic and EU) have been generated and VTT has been partial or major actor in these projects (FINSOFC, DG Simulation platform, DG Protection, PAREE, Envatuuli, ENIRDGNet, EUDEEP, TUUMA, CODGUNet, MULTIPOWER).

3.3.5 Exploitation and industrial impacts

Based on concepts of interconnection in fU-adapter, the interconnection of SOFC fuel cell unit has been realized. Realization of the concept and equipment is based on existing components, cost optimization is not included. Only the cost factors in interconnection have been addressed. Also the interconnection of different generation units of MULTIPOWER environment and control system solutions are based on the generated concepts.

3.3.6 fU-adapter

Interconnection solution

The focus of fU adapter was to create a two-way communicating and controlling interface. This would enable the intelligent control of the distributed production and the grid, preserving safety and high power quality for an end-user. The requirements and acceptance testing procedures for such an interconnection are not available today. Thus, distribution network operators are reluctant to allow small power producers to be connected to the network. Interconnection is in many cases difficult, expensive and case dependent, and there are no standards. To help in this problem, the goal is to get a cost-effective interconnection unit and energy storage solution and to keep the present high power quality. The fU adapter has modern characteristics like wide communication ability, protection, metering of power and other quantities, adaptability into different network situations, power quality control, and so on.

A universal solution is too ambitious because of the needs of different production and distribution network technologies, so we focused on two case studies: fuel cell unit (later FC) with DC and inverter connection, and wind power unit with AC or inverter connection. Moreover, the testing requirements have been developed in the projects.

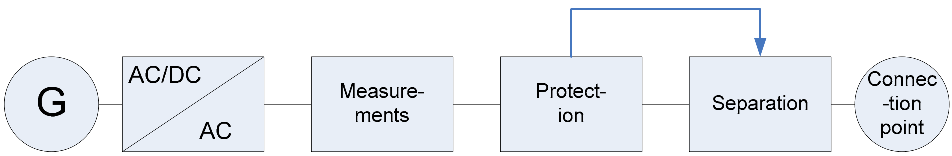

Figure 88. General interconnection concept.

Simulation models

Modelling of the *whole wind power process* from wind to the distribution network. For the electrical part of the total system, see Figure 89.

By this model we can simulate, for example, the forces and stresses in the basement, when there is voltage drop in the power network.

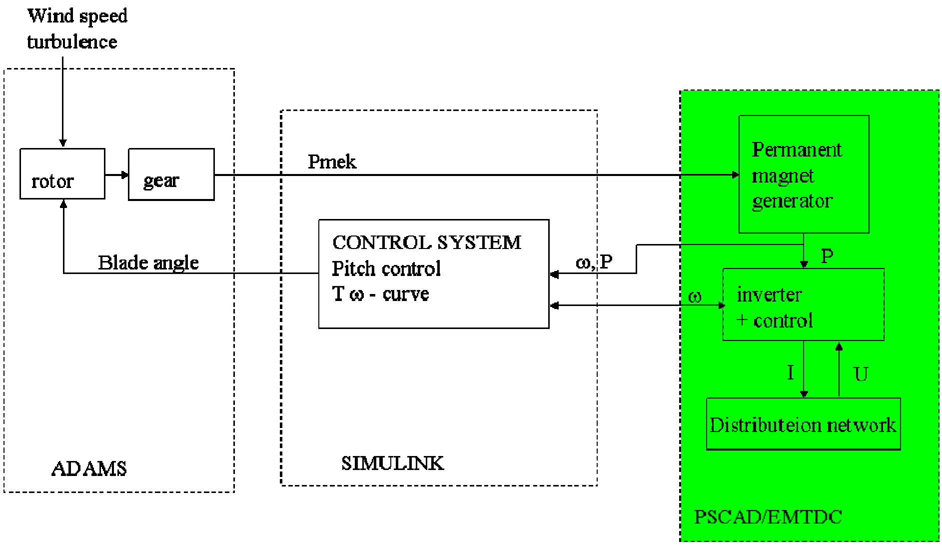

Figure 89. Technology trends. Different technical sections of the wind power process model.

FC system interconnection concept is described in Figure 90.

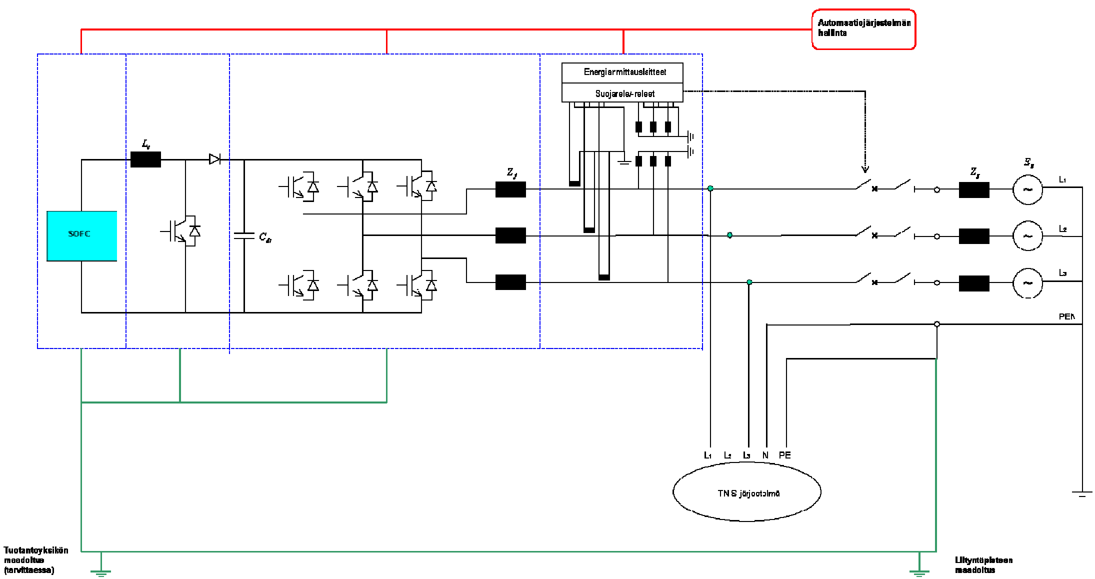

Figure 90. FC interconnection solution.

Modelling and simulation of protection solutions and their functionality and impact to the power quality.

Definition of testing procedures for interconnection unit and its requirement in the common project with a linked project FINSOFC (Clean World theme program).

Activities in the birth of national DENSY program

The national technology program, Tekes-DENSY, as well as, the respective European Union research activities aligns well with our research agenda.

Several national and international research problems and projects related to distributed generation have been brought up. Finnish industry and other organisations are well represented in these medium and long-term projects. Protection relays, network management systems, metering, fuel cell and windmill units, power electronics, storage systems as well as the business and operational processes are of interest in these projects. VTT is a major research party in these presented projects.

National DG testing site to Espoo will be built in one of these projects.

In the EU level, VTT is in many cases asked for participating in DG related projects as a Finnish partner.

International and national networking

National networking:

VTT, several disciplines: General DG system; distributed network technology; interconnection; control and monitoring systems; SCADA systems; energy markets
Helsinki University of Technology / Power station automation
University of Vaasa: Energy logistics, business opportunities
Tampere University of Technology, Lappeenranta University of Technology

International networking:

EU Tentative network for DGnet www.dgnet.org
ELFORSK/SE, SINTEF/NO, ELTRA/DK

3.3.7 DGSI – General Virtual power system

Scope of the project

The focus of DGSI in the third year was to develop further the "Virtual Utility" concept in such a way that it controls and connects the productions to the customers while preserving the distribution network stability and power quality, both in the normal loading and in fault conditions. New solutions, such as microgrids, storage, adaptive intelligent protection and modern system control principles (forecasting, communication solutions, demand side management...) will be addressed. (Figure 91.)

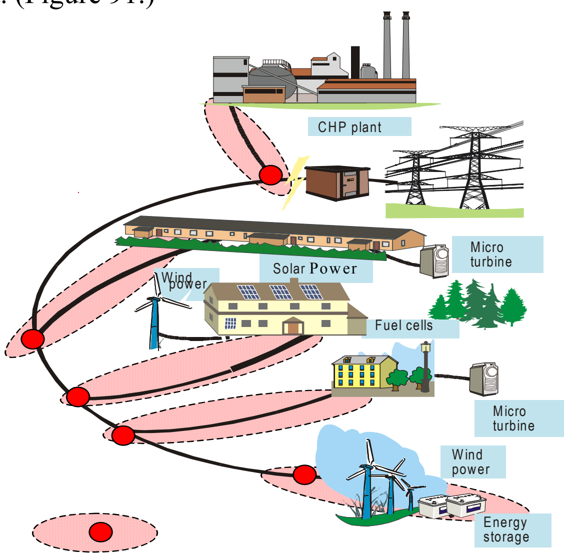

Figure 91. DG-system interconnection units (DGSI) in low-voltage DG network.

The Virtual Utility consists of several functionality models and parts, such as

- power interconnection unit (FU-adapter)
- external power flow management (between unit and distribution network)
- autonomous network condition (islanding) management
- proactive protection management
- assisting functions for network operators
- customer-side internal energy flow management
- service and maintenance functions.

Construction and links to the other projects in the same field is described in Figure 92, where tasks are defined as follows:

1. GD-network interconnection with basic functions. Cost-effective FU-adapter unit.
2. Requirements for the management of local energy resources in DG systems (PAREE).
3. Study of microgrids in the islanding operation.
4. Description of the differences of the traditional and DG systems protection. Safety improvement by loss mains protection.
5. Study of forecasting procedures. Study of communication needs and possibilities (wireless communication) between consumer/producer and network operator.
6. Preliminary study of special characters in customer-side internal power flow.
7. Follow up the activities in this field.

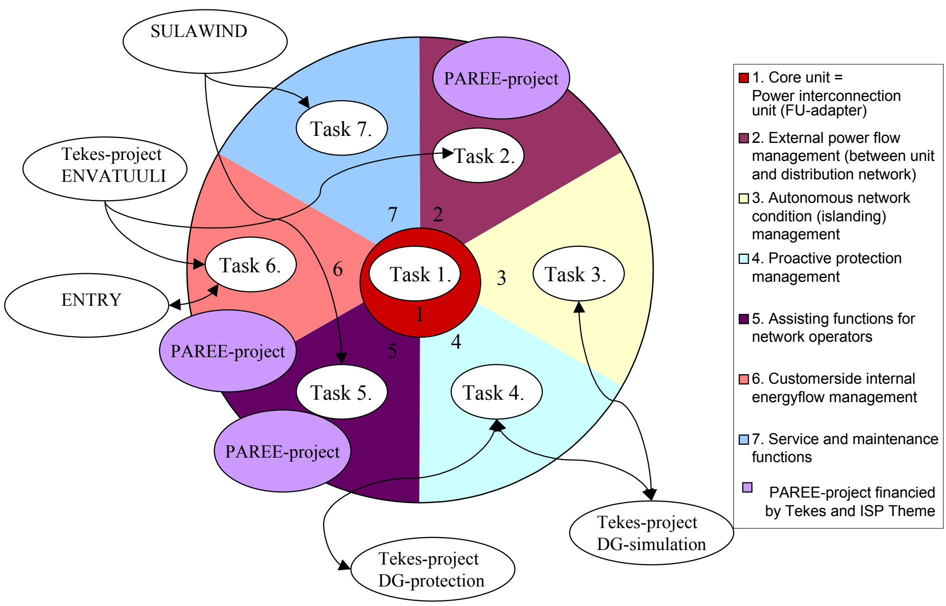

Figure 92. Tasks and supporting projects for DGSI-functional modules.

Tasks are as follows:

1. The cost structures (of fU-adapter) and estimation of the interconnection costs.

2. Development of the power flow management concept and specification for the control systems (in the PAREE-project).
3. Study of the features of the microgrid systems. Define of power quality improvement possibilities (islanding) by a microgrid concept, basics and simulations.
4. Identification by simulation the problems of traditional protection in DG systems. Study of different loss of mains protection methods in different cases (also in generated DENSY project).
5. Study of communication requirements and co-operation with the SULAWIND-project (the TCP/IP-project). Study of forecasting possibilities for system efficiency improvement.
6. Preliminary study of special characters in customer-side internal power flow and energy storages.
7. Follow up the activities in this field e.g. in the SULAWIND-project.

In the project, the interconnection concept was split into the requirement based functional modules and costs that were asked from the component manufacturers. For practical reason, there were three different sizes of distributed generation interconnection cases. Management concept was studied in the separate theme project PAREE (Control of local energy resources in distributed energy system) (Valkonen et al. 2005) together with wide internal VTT group. Microgrids research was started and as a part of it the graduate thesis was done (Microgrid-structure as a part of a distributed energy system). Functionality of microgrids and general distribution network during the faulty situations was studied in the special generated DENSY project (Kumpulainen et al. 2006) and also in the thesis. Communication requirements and solutions were studied in a separate generated DENSY project TCP/IP (The data communication requirements and capabilities of the management of distributed energy resources) (Lemström et al. 2005). Customer-side internal power flow was not studied in this project.

Results

Cost factors are dependent on the existing requirements. In the following figure (Figure 93), the functional requirements are presented.

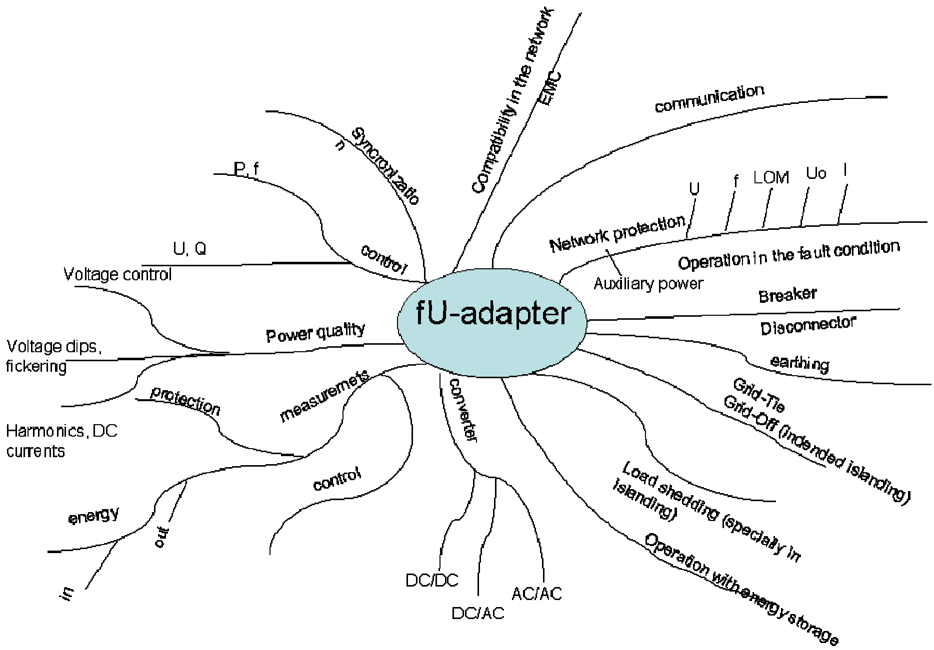

Figure 93. Functionality requirements of the interconnection.

As a result, the interconnection of small units is today expensive, if only the general components are used. Costs may be tens of percents of the total costs. So we need much further development work for dedicated and functionally highly integrated product to get the costs lower.

Microgrids concept is in theory a vital possibility for getting more benefits from the distributed generation in the distribution network. Today it is however forbidden to run the public network in the islanding mode but it may become possible. At least in USA they consider microgrids structure to be a cornerstone of the future distributed energy network concept. The general structure is presented in the following figure (Figure 94).

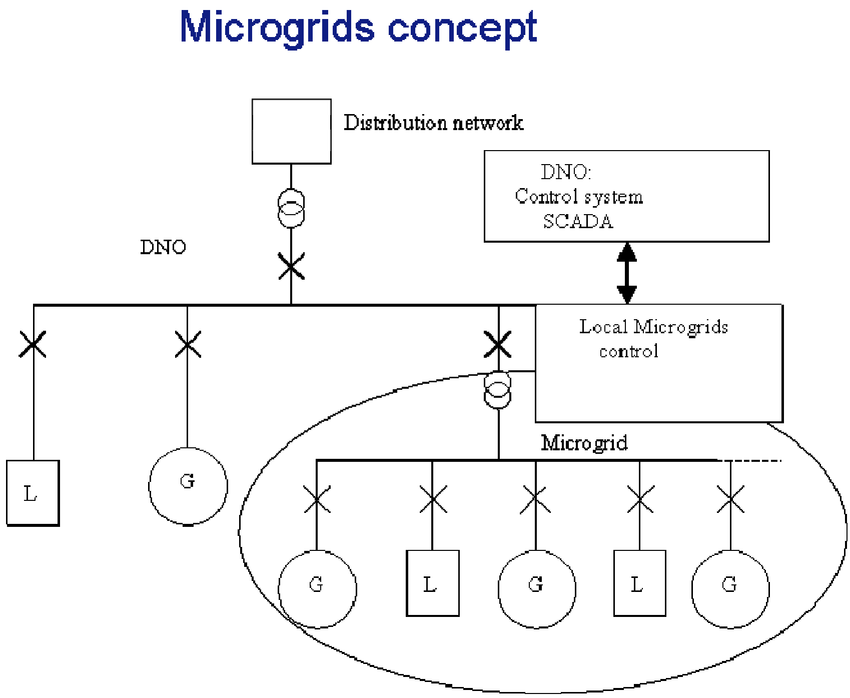

Figure 94. Microgrids structure.

3.3.8 Energy web

Energy web

Today, consumer can easily get the interconnection to the network. Interconnection of small generation units should be as easy. It should be a kind of plug-and-play method to add a producer into the network. A distribution network operator sets in many cases high requirements for interconnection because it is responsible for the power quality, reliability of supply, and safety of the whole system. In the future, the customer should be able to take and/or feed in energy with the distribution network.

In the connection point, the future interconnection device and concept must be able to fit to the system by:

– to be able to adapt to the control, safety and protection requirements, as well as, to the communication interface

– a unit has to be able to adjust the state of production according to the state of network system and the delivery contract. Participation to the voltage and frequency control, fault ride through ability and also the production restriction possibilities may be required for energy balance in the network.

In the Energy web or Active network concept, separate units may actively participate into the functions of the system. Solution requires the next generation ICT-solutions and increased data communication ability because all the equipment must be aware of the state of the total system.

Microgrids concept can be a solution to the problem because a network operator sees the network as one connection node with agreed parameters and functionalities. In addition to this, the microgrid operation system must be able to cooperate and exchange information with the major network control system.

Project concept (DGSI) with the microgrids research is according to the following figure (Figure 95).

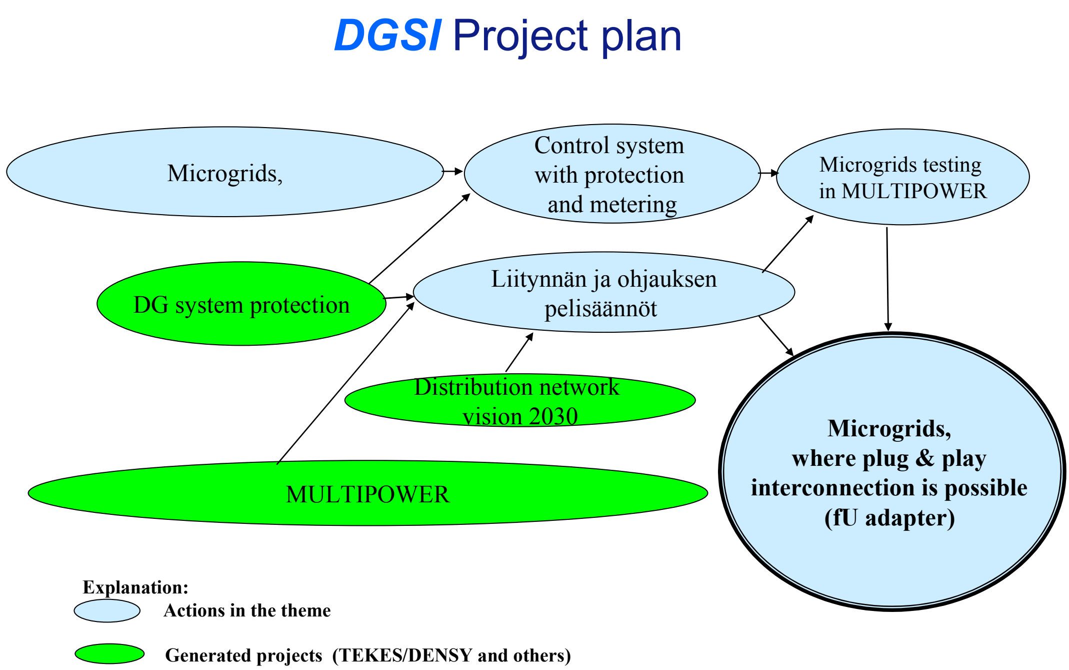

Figure 95. DGSI project plan.

In this project, requirements of the control system and the behavior of the microgrid in the transition state (disconnection from the supping network) were studied with different simulations. Also the need for the storage and its impact to the power quality was studied. A graduate thesis was finished in this phase of the project.

Control system and validation simulations for test environment (MULTIPOWER)

In the ENWEB project, we started to plan and build a new microgrids concept with its necessary control and communication solutions. The microgrids control and protection behaviour study by simulation has been continued.

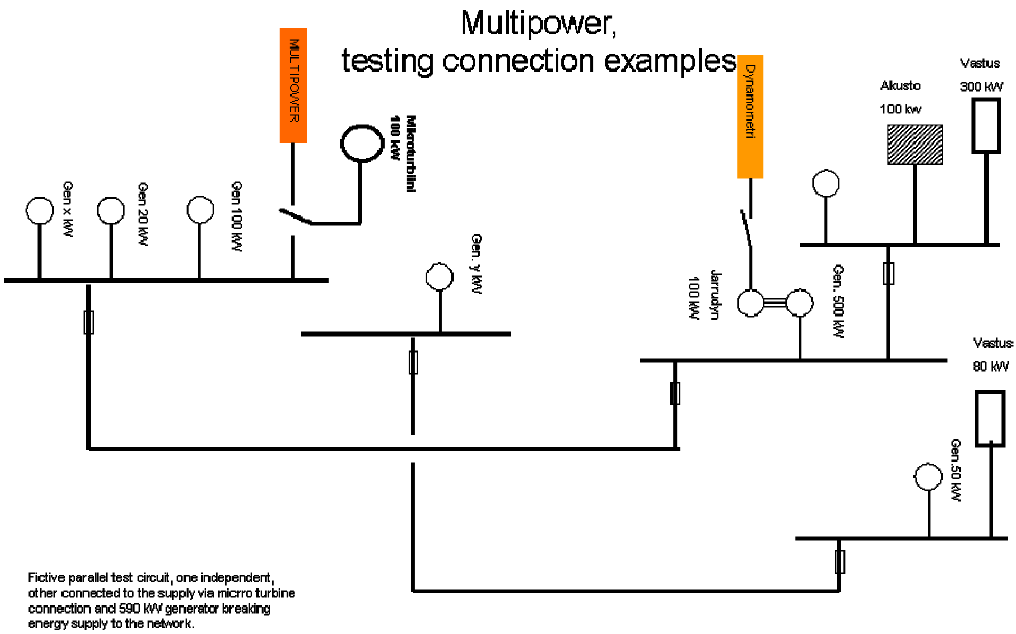

Figure 96. MULTIPOWER environment.

In the subsequent project, MULTIPOWER, the Microgrids and interconnection concepts are taken account so that these can be tested, when the environment will be ready (Figure 96). A simulation network of the testing environment was build for calculation of behaviour of the system under test. At the same time, the simulation tool may be validated against the measured data. Unfortunately, the completion of testing environment was delayed, and the real tests shall be performed later on when the necessary environment is ready.

The next figure describes the test environment MULTIPOWER at a certain VTT building in Otaniemi (BK5).

Results

Microgrids with its behaviour can ease the connection of small generation units into the network. The operation limits and characteristics in microgrids connection node can be defined and so that the network operator is not so dependent on the individual small unit inside a microgrid. The following figure (Figure 97) gives an example about the voltage of a connection node during transition into the islanding mode for microgrid.

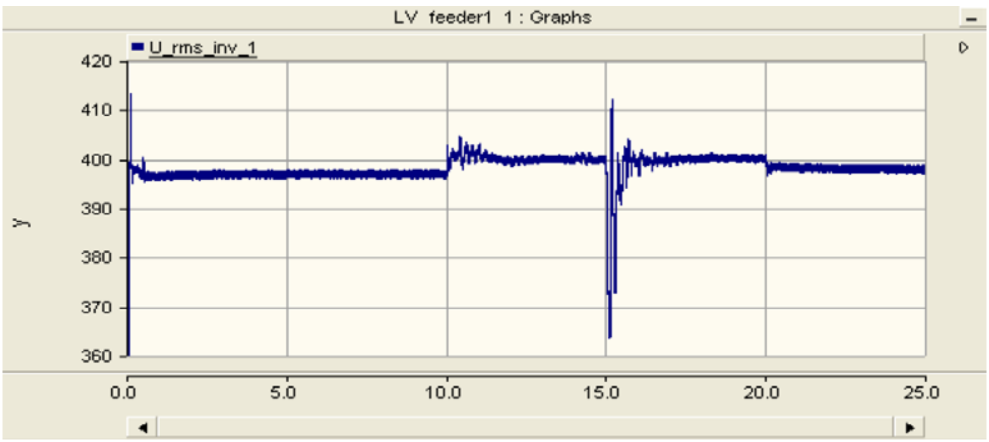

Figure 97. Voltage in connection node of a microgrid.

A simulation model of the testing environment MULTIPOWER has been developed, so that the results can be verified in the future by the real measured data.

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4. Embedded Structural Intelligence

Ismo Vessonen

4.1 Topic description

4.1.1 Objectives and visions

Finnish or European machine and vehicle industry are looking for new business and product concepts to maintain and gain competitive edge. From technological point of view, the huge steps taken forward especially in information technology and modern materials technology can give opportunities for innovations. With co-operative research VTT's multi-disciplinary know-how can be combined to catalyze the innovation process and to promote the utilization of new technology in the products of conventional machine industry.

At the same time the businesses are moving from product orientation to extended product or service orientation, i.e. appropriate performance, capability or reliable operation is sold and bought. Customers optimize the overall cost-effectiveness of an investment, which brings under consideration the whole life-cycle, from product idea through design, manufacturing, after-sales, decommissioning and recycling. Data, information and knowledge, generated in products and processes are rapidly transferred to almost anyplace via information networks, and are fuel for the new service businesses. This new service oriented business model calls for innovative intelligent products which will also be in the future an important cornerstone of industry competitiveness. Integration of novel and conventional technology combined with innovation capabilities are becoming critical keys to success.

Embedded structural intelligence means incorporating an appropriate set of sensing, active reaction, decision making, and communication capabilities into mechanical structures in order to achieve optimum performance in all operating conditions – even in conditions unknown at the time of product design. Minimization of life cycle costs is an important objective. The research topic Embedded Structural Intelligence is about studying the implementation of product or component level intelligence.

Embedded intelligent technologies enable novel structural concepts intended to implement the required functionality and are a way to make the most of the properties and the information content of a structure or machine. One important feature is also the capability of the product to independently adapt its operation according to changing conditions. An intelligent product or structure shall be simple in design, well-performing, cost-effective, reliable, easy to use and environment-friendly. The aim is to save material and energy. The abilities to diagnose, make decisions, tune operation, fix and heal problems and damages i.e. to adapt are important. The overall usability is improved by the aid of communication ability.

The speed of product development cycles is constantly increasing. Possibilities to conduct technology developments striving for innovations and technology leaps along with the actual product design are limited. The new technological ideas, concepts and solutions have to be ready-to-go and reliable in order to be accepted for commercial use.

4.1.2 Activities

In the beginning in 2002, we chose target platforms to work on (see also the projects flow of Figure 98): 1) intelligent wind turbine and 2) intelligent rotating machine. Accordingly we set up three actual projects: a) SULABLADE (Developing structural intelligence of a blade of a wind turbine), b) SULATOWER (Developing structural intelligence of a tower of a wind turbine) and c) SULAROTOR (Intelligent control of resonance vibration of industrial rotors). The two wind turbine related projects were merged into one project, SULAWIND (Intelligent wind turbine) in 2003. To extend the applicability of these techniques to more generic mechanical designs, a third project chain was started also in 2003 (TOIMIRAKENTEET). The application domain was extended further in 2004 by joining a large EU-IP project InMAR (Intelligent Materials for Active Noise Reduction). Roughly the same projects combination was kept till the end of the theme program. During 2005 major part of the SULAWIND activities were moved to a starting EU project, called UPWIND.

In 2001 all projects were funded by VTT alone. TOIMIRAKENTEET was at first co-funded by VTT and Tekes, later on by VTT, Tekes and five partner companies meaning that the project was in the beginning certain kind of high risk project from Tekes point-of-view, and it was later on changed to a high-impact joint project. SULAROTOR was during 2006 funded both by VTT and Academy of Finland meaning that it has been regarded scientifically very high from Academy of Finland point of view (it rarely supports VTT projects). InMAR and UPWIND have been co-funded by EU, by definition.

In the following there is a short description of all the four subprojects. For all of the projects a more detailed description is given in Sections 4.2–4.5 of this publication.

SULAWIND: The expected top-level achievement for SULAWIND project was originally defined as: A new structural concept for future large scale wind power plants. The project has had two focus areas: study of design and virtual modelling of wind turbine's combined aerodynamic, mechanical, and electrical behaviour, and on the other hand developing and testing of technologies for active structural parts to be used in the turbines.

SULAROTOR: The project is striving for adaptable resonance vibration control method for industrial rotating machinery. The aim is to develop and demonstrate active and adaptive control solutions for rotor vibration control. The main objective is to develop an automated system identification – control design – control adaptation procedure for active rotor vibration control. Through better control of structural vibrations it is possible to achieve more design freedom for electric power engines and thus pave the way for novel innovative solutions (e.g. long high speed rotors with overcritical operation).

TOIMIRAKENTEET: The project was first (2003–2004) launched as a joint project between VTT and two university partners (Helsinki University of Technology [HUT] and University of Oulu [UO]), funded by Tekes, the Finnish Funding Agency for Technology and Innovation, and VTT. In the 2nd research phase (2005–2007) several industrial partners joined the project. At first the objective was to develop basic know-how on appropriate technologies and implementation of multi-technical smart structures. Later the aim was shifted to creating and implementing innovative prototype solutions for technology challenges taken from industry. In the 1st phase the subtopics were Active joint, Active shell, and Active control. In the still on-going 2nd phase the workpackages are “Adaptive mass damper”, “Adaptive actuator cylinder”, “Adaptive shell structure”, “Adaptive vibration” isolator and “Enabling technologies for adaptive structures”.

InMAR: “Intelligent Materials for Active Noise Reduction” is an EU funded IP-project (2004–2008) in 6th Framework Programme. ImMAR aims at realization of intelligent, high performing, adaptive material systems with integrated electronics for noise mitigation purposes. VTT’s focus is in the areas of VTT’s high competence i.e. on composite and polymer materials, large surface acoustic and vibration actuators, and their application in active noise (and vibration) reduction in cars and infrastructure.

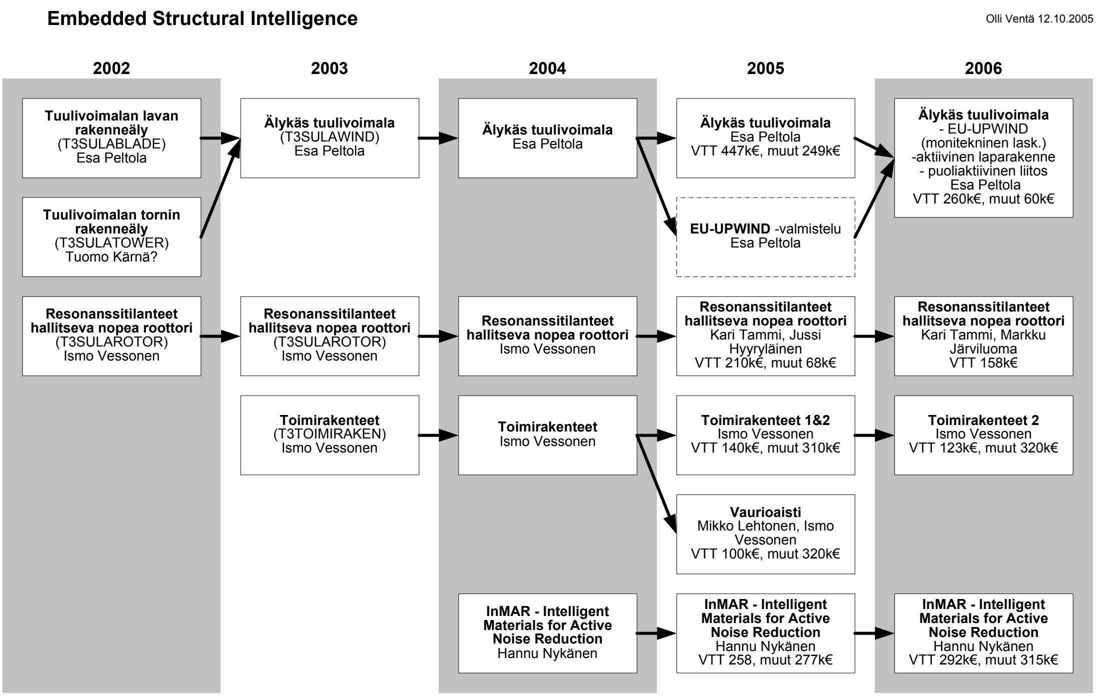

Figure 98. Project structure of the topic area Embedded Structural Intelligence.

4.1.3 Approach

The main goal of the topic area Embedded Structural Intelligence is to develop know-how to design and implement cost-effective, intelligent and adaptive structures for machine and vehicle industry applications.

More detailed technological objectives and their motivation are in the following (projects involved given in parenthesis):

1. **Know-how and tools for integration design of multi-technical systems using functional virtual prototypes. (SULAWIND)**

The aim is to promote the simulation based design process of intelligent concepts and structural solutions using functional virtual prototypes. These comprehensive simulation models should be able to model the whole chain of physical behaviour (also fast dynamic phenomena) from external loading through mechanical structure and associated interaction phenomena all the way to the driven system. A special emphasis is given to the development of such models for electro-mechanical machine systems including electric grid connection. The case machine for this study is a wind turbine. The utilization of this kind of model include design and optimization of e.g. active subsystems for vibration/durability/shape control, condition monitoring systems and fault identification, overall plant control etc. The application potential of the developed know-how is wide in intelligent control design of electric power generating systems, in electrically driven machines, in future electric vehicles etc.

2. **Intelligence embedded in composite materials and structural joints through integration of functional materials systems. (SULAWIND, TOIMIRAKENTEET)**

Active composite materials

The objective is to develop and demonstrate lightweight active composite structures, which are capable, through smart structural design and integrated functional material systems, of reacting to internal or external stimuli with an appropriate response.

Fibre re-enforced plastic (FRP) composite and sandwich structures were selected as starting point for the study because of the relatively easy tailoring possibilities of FRP's and of manufacturing technology that supports embedding of sensors, materials based actuators and control systems. The aim is to find novel structural vibration/noise/durability/shape control concepts, with which it is possible to meet the future requirements for reduction of weight and energy consumption. The focus is on Shape Memory Alloys (SMA) based shape control of FRP-beams and structural panels (generic structural elements).

Active structural joints

To develop and demonstrate concepts and devices for implementing structural joints capable of (semi-)actively controlling stiffness and damping properties of the joints. The focus is on the concepts of active friction joint and active stiffness controlled spring element.

This kind of (semi-)active approach offers a great potentiality to realize cost-effective embedded structural elements to change dynamic properties and responses of a structure without continuous energy input and complex control systems. Functional materials such as piezo ceramic (PZT), SMA as well as new materials like magnetorheological elastomer (MRE) and a novel temperature controlled epoxy material are in major role in this study.

Development of modelling capabilities to include behaviour of functional materials in design models is an important part of research in both of these tasks. Special features of controlling functional material systems are also considered.

3. Adaptable resonance vibration control method for rotating machinery (SULAROTOR)

The main focus is on studying self-tuning, fully-active and adaptable control methods for controlling rotation related periodic vibration of industrial rotor systems. Self-tuning capability of the control is essential in order to make the control design more effective and to enable adaptation to various product variations due to differences in dimensions, accessories, design, and operation environment. On-line adaptability is needed to guarantee performance in varying operating conditions. In a typical real world case, the changes in vibration state are not predictable and the system has to be intelligent in order to handle also the unexpected situations. The developed procedures are meant to be, to as large extent as possible, independent of the application under control, and thus several other industrial applications, outside rotating machine industry can benefit from the results.

4. Active noise reduction by utilizing multifunctional materials (InMAR)

Especially the automotive industry in Europe anticipates knowledge-based, multifunctional materials or intelligent material systems as one of the key factors for the realization of future requirements and legislations. One important requirement is energy efficiency, which from structural point of view leads to requirement for lighter structures. The structural weight of cars has been significantly reduced over the last decades but the total mass has increased due to higher safety, comfort, and functionality requirements.

One of the challenging tasks in the future is to overcome this contradiction by introducing new, intelligent material systems that enable a multi-material, lightweight design that enhance emission, safety, comfort, functionality, and reliability standards by means of actively controlled structural behavior. Both sustainable development and the addition of higher functionality in products is best pointed up by noise-optimized product design. It is well known that lightweight structures tend to vibrate more easily and radiate noise on a higher level. Special effort must be made to compensate for the higher noise level. This often leads to additional mass which, in turn, nullifies the lightweight design. In the future, noise-optimized products can only be achieved by applying active noise reduction concepts based on intelligent materials that allow for a lightweight design and higher functionality with respect to noise control.

4.2 SULAWIND – Intelligent Wind Turbine Components and Structures

Jaakko Heinonen, Tomi Lindroos, Esa Peltola, Mikko Lehtonen

Abstract

The activities have been broadly divided into two different approaches: modelling of the wind turbine's aerodynamical, mechanical and electrical

behaviour and, on the other hand, development, laboratory testing and modelling of technologies of active structural parts to be used in the turbines.

An adaptive wing profile was designed, manufactured and tested. Novel tools for designing, modelling, and manufacturing of composites with embedded SMA actuators were developed and demonstrated. Patentability evaluation of the developed composite technology is ongoing.

Several stiffness control concepts utilizing actuator property of Shape Memory Alloys (SMA) have been developed. A 3–5 fold on/off type stiffness increase has been demonstrated with these devices. One patent application on studied concepts has been deposited. Several numerical studies on an offshore wind turbine structure are made in order to study application potentiality of adaptive components.

A multidisciplinary-modelling environment has been developed and is used in power system dynamic studies of wind farms. Active duration and load control algorithms have been included and demonstrated in the developed models.

The research activities of five research groups in three institutes have been combined. The groups have established networks with several researchers with different expertise in Europe and USA. Some results have been taken into use in other projects with industrial involvement. Many results have much wider applicability than just wind energy.

4.2.1 Background, starting point and objectives

The use of wind power is doubling every 2 to 4 years worldwide. The cost-effectiveness has grown mainly due to the increased size of turbines. There is an interest of doubling or quadrupling the rated power. The growth in size and the increasing requirements call for new structural concepts together with advanced materials and also for more adaptive solutions. In order to reach the targeted weight reduction, better control of the turbine, such as advanced blade pitch control, advanced generator control, airfoil shape control or their combination, has to be developed. Being successful here would contribute to larger step changes in the development of wind technology.

The operating environment in offshore is much more hostile and complicated compared to onshore common today. The turbines in offshore are exposed to severe climatic conditions. The turbines must also be designed to operate with less maintenance. The large offshore wind farms must be more adaptive towards the requirements and needs from production scheduling and grid operation.

The rapid increase of the use of wind power in many countries has led to tightened requirements for the turbines regarding grid disturbances. This calls for both new fast means of control and good knowledge and better modelling capabilities on the interaction of the network disturbances and wind turbines.

Lightweight and effectively load bearing shell structure is a common structural solution in many vehicles, machines and devices. Fibre re-enforced plastic (FRP) composite and sandwich structures are selected as the starting point for the study. From the smart structures point of view, such lightweight structures are particularly interesting because their mechanical properties are relatively easy to tailor (fiber orientation, stacking of fiber layers, asymmetry etc.) for particular needs. Moreover, their manufacturing enable embedding "intelligent technology" like functional materials based actuators and sensors and control systems into the structure.

Many active composite structures apply shape memory alloy (SMA) actuators. Also piezoelectric actuators have been applied but, due to the very small motion amplitude of piezo actuators, their applicability to wind turbines are limited. Three main directions of use of SMA's can be seen: to improve the strength of the structure against shock loads, to control the shape of the structure and to control the stiffness of the structure for vibration control.

The international research activity dealing with active FRP composites and embedding structural loading and damage detection measurements into composites is rather vivid. The potentiality of tailored lightweight composites combined with embedded sensing and active functionality is widely noticed in many research efforts abroad.

Intelligent materials and systems have been developed mainly for aviation industries, machine industries and for the mitigation of damages in civil structures due to earthquakes. VTT has been active in these areas, too. VTT has long experience in the technologies required in the present project such as: vibration and durability control, modelling and simulation methods, wind technology for harsh environment. VTT's customers have growing market positions in wind turbine components and technology. Their position can be further strengthened by successful application of embedded intelligence in wind turbine components. The results can be applied also in other areas such as mobile work machines, vehicles and construction industries.

The overall objectives of the project are

- to develop intelligent components, structures and control systems for active vibration and durability control of wind turbine, which are cost-effective and enable the continued growth in the size of wind turbines
- to develop intelligent material and control technologies, which can be embedded in to lightweight composite materials, steel structures and joints in these structures.

A simulation environment incorporating hierarchic modelling of the wind farm, individual turbines, intelligent subsystems and interaction with operation environment is needed. This is necessary for the design of intelligent subsystems and brings the design of wind power plants to a new level.

4.2.2 Implementation and results

The structure of a wind turbine is suitable for demonstrating many technologies. Also system level simulation and control of an active wind turbine or a wind turbine farm from the electric net point of view is an important goal of the project. Embedding active structures to system level simulation models is needed for facilitating true active control of wind farms.

Thus the project has started from two very different approaches: on one hand, the turbine and wind farm operation and, on the other hand, the development of active structural parts. Joining these two very different domains of modelling and simulation is a challenging task. The progress in the project has already reached to the point that total success is evident.

The activities have thus been divided into two main parts:

- new materials and structural components to develop components using functional materials and having new properties like shape control, vibration damping etc.
- hierarchic modelling to study the benefits of the active components and structures with respect to load and vibration control.

The main results are presented according to this decomposition.

Adaptive composite materials and structures

In the SULAWIND project the manufacturing and integration of SMA's in laminates to actively control the shape of the laminate structure has been in focus. Also vibration control has been tested. The passive materials have been studied in a parallel Optimat Blades, linked project at VTT. Both lines of work are continued in the EU-IP (6^{th} Framework) UPWIND, a large European project on Integrated Wind Turbines. The research work of SULAWIND is directed on implementation and demonstration of active functionality in generic structural shell elements (common in many applications).

The project has produced generic advantages in the form of increased know-how on practical issues in applying functional materials, as well as, more generally applicable control methods and tools for numerical design studies of functional materials systems and active structures. These can be utilized in many fields of engineering. Especially generic is the created know-how on flow control by controlling the shape of a shell surface.

Modelling

Shape memory alloys (SMA) are a special group of metallic alloys which exhibit a shape memory effect meaning that a component of SMA deformed at a low temperature will regain its original undeformed shape when heated to a higher temperature. Typically a SMA wire actuator is first elongated in its so-called martensitic state, resulting in large pseudoplastic strain, and then heated to a so-called austenitic state. Heating removes (recovers) the pseudoplastic strain and the actuator shortens. This shortening can occur against load and the actuator thus produces a displacement, etc. If a monolithic NiTi wire actuator is completely fixed at both ends, it can produce a stress of about 800 MPa. Usually the maximum stress in monolithic actuators is designed to be below 200–300 MPa to avoid thermal fatigue and ensure long service life. Features of the thermomechanical behaviour of SMAs include for example:

- Strong nonlinearity.
- Strong coupling between thermal and mechanical effects. For example stress shifts the transformation temperatures and thus more heating is needed to obtain strain recovery.
- Large hysteresis.
- Difference in behaviour between tension cycling, compression cycling and tension-compression cycling.

The behaviour of SMA wires embedded eccentrically inside a composite beam was calculated. It was shown that embedding reduces the strain recovery drastically because the matrix restricts the strain change of the wires. As the volume fraction of the wires is relatively small, this leads to very high elastic stresses in the wires. Elastic stress over the plateau stress causes stress induced orientation of the martensite variants and thus works against strain recovery. This slows the strain recovery down enormously and reduces also the achievable strain recovery. High stress also shifts the transformation temperatures according to the Clausius-Clapeyron equation and thus more heating is needed for transformation and strain recovery.

It was shown that the sleeve method is preferable for shape control but the fatigue effects of the internal transverse load created by the wires pushing the sleeve wall in bending must be considered. Fully bonded wires should be used only for stiffness control of relatively flexible composites. Even then the strain recovery is very slow. In structural FRP laminates with embedded fully bonded NiTi wires the achieved strain recovery obtained is usually below 0.5%. This is very little compared to the 6–8% strain recovery of free wires.

Manufacturing

The manufacturing route of adaptive SMA composites has only a few differences to traditional manufacturing of fibre reinforced polymer composites. The most challenging procedure is the embedding of the SMA wires into the structure. Integration is always some kind of compromise between maximum force generation and structural integrity. By using a large diameter wire it is possible to generate high force volume ratio but also local stress concentration can be increased to relatively high level and lead cracking and delaminating of the structure.

Basically two different approaches are used in manufacturing of SMA composites: the first is based on mechanical sleeve where SMA wires were attached inside and the second, more sophisticated method is based on adhesive joint between the SMA wire and the matrix. One can notice that the adhesive joint is very critical on the stress levels and temperatures of the SMA wires.

In this study a more advanced method to manufacture SMA composites was developed. The method is a combination of mechanical sleeves and adhesive joining. In Figure 99 a typical layout of the adaptive composite based on embedded SMA wires is presented. Patentability evaluation of the developed technology is ongoing.

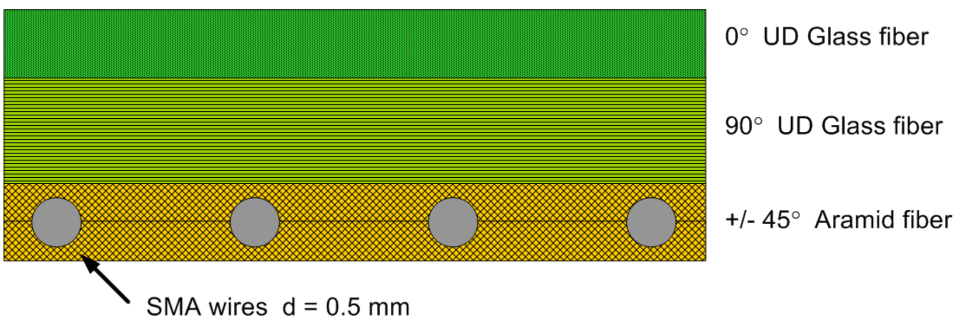

Figure 99. Typical layout of the SMA composite cross-section. SMA wire volume fraction ~2%.

Measurements

The mechanical system introduced in this paper is a glass-fiber reinforced plastic wing profile (wind turbine blade cross section). The profile is 700 mm long, 100 mm wide and the laminate thickness is 3 mm. The profile and its main parts are shown in Figure 100. The shape memory alloy actuators are embedded inside the laminates. There are separate actuator wires for upper and lower surfaces. The camber of the trailing edge can be adjusted by activation of the actuators. The global shape of the profile will also change. During the operation, the actuators are activated simultaneously. The actuators are activated resistively using electric current. The amplitude of the shape change depends on the heating power. The trailing edge of the wing profile bends downwards when the actuators are heated. Cooling returns the original shape of the wing profile. Vertical support seen in Figure 101 is relatively rigid and the shape of the leading edge will not change.

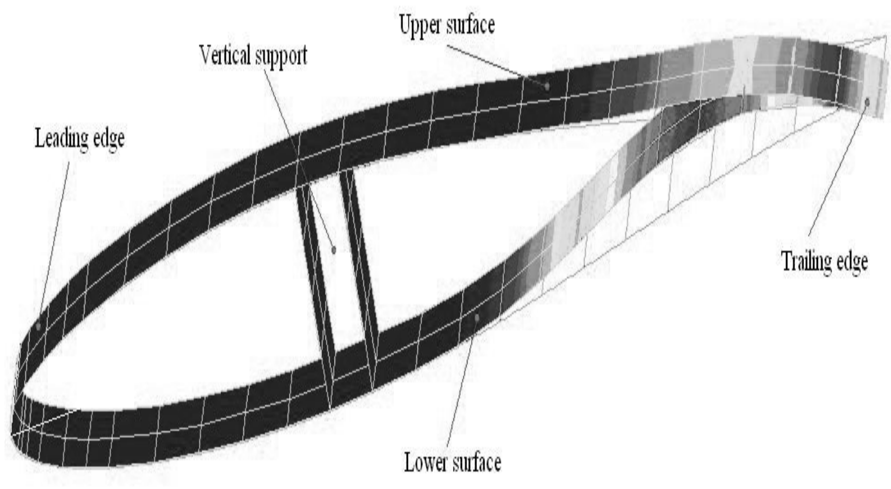

Figure 100. The adaptive wing profile.

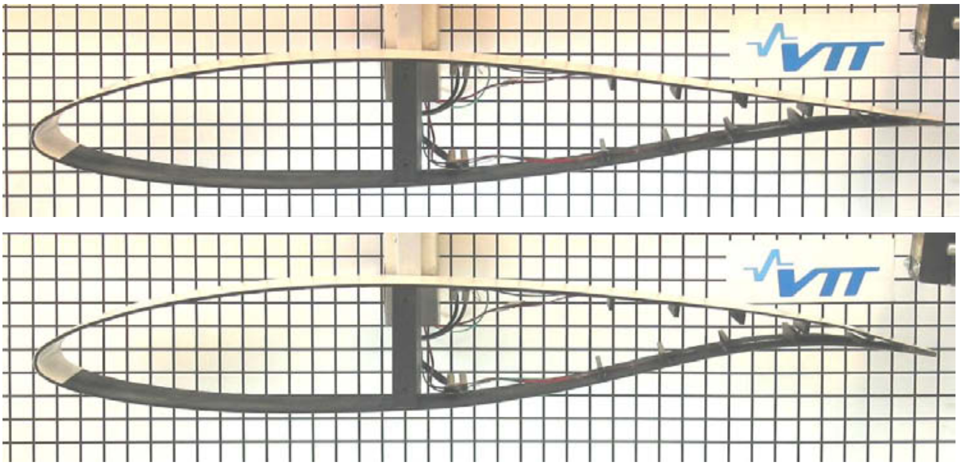

Figure 101. The wing profile and the test setup. Upper picture: non-active state, lower picture: activated state.

The wing profile shape change was studied first. The maximum real displacements of the selected points on the surface were measured using three laser distance sensors and two strain gauges. Surface temperatures were measured using two thermocouples. The maximum temperature was set to 70 °C. The actuators inside the structure should be fully activated (SMA should be austenitic) at ca. 60 °C. The behaviour of the wing profile and the locations of the laser distance sensors are illustrated in Figure 102.

The shape control system was primarily developed for research and demonstration purposes. The performance of the system was measured in laboratory conditions. There were no external loads or disturbances present. The shape control performance was evaluated by measuring both response times and achieved accuracy in several cases.

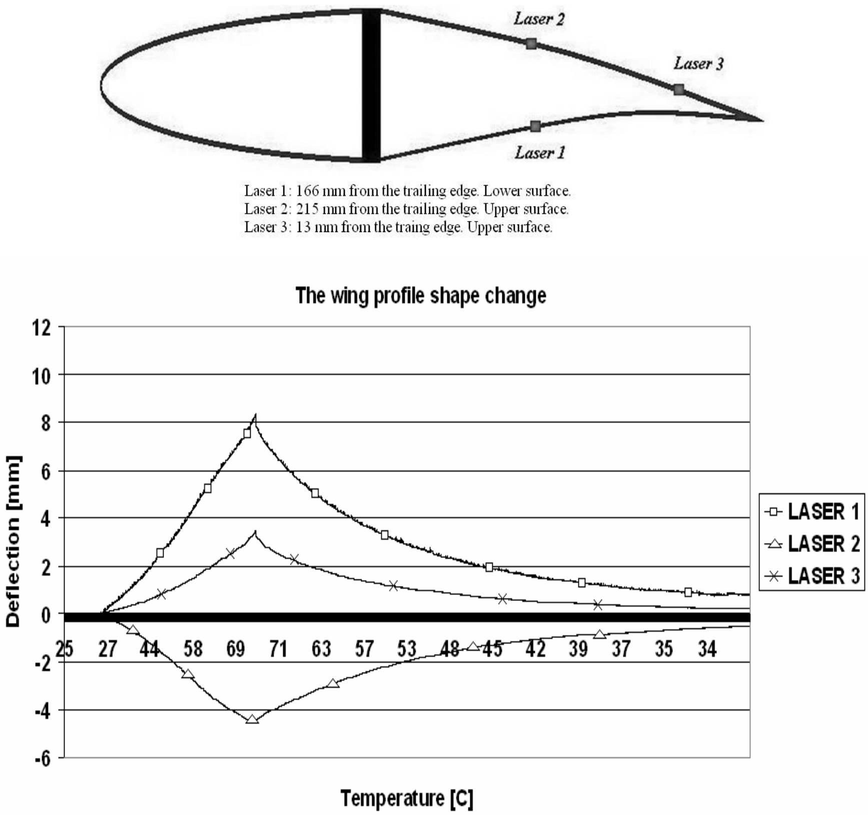

Figure 102. The behaviour of the wing profile and the locations of the laser distance sensors.

Conclusions

An adaptive wing profile was designed, manufactured and tested. New tools for designing and manufacturing of SMA composites were developed and demonstrated.

The performance of the system was measured in laboratory conditions and it worked much as expected. The developed control system worked accurately enough for the shape control of the wing profile.

It should be noted that real loadings were not present in the laboratory tests. In a real application the volume fraction of SMA wires should be higher for the actuation to be able to function against external loads (flow). The future work will concentrate on development of the modelling tools and the manufacturing technologies to industrial level. The task to prepare a large scale wing profile (1 m slice of a real scale wind turbine blade) is underway will be ready to wind tunnel tests in the beginning of the next year.

Semi-active vibration control

A semi-active device supporting a structure or machine at its base or as a part in a structural joint can be utilized to isolate vibrations. In a semi-active isolator, the stiffness or damping can be controlled during operation. Changing the stiffness of the support device can be exploited by moving the eigenfrequency of the system to bypass the resonance. Reliable control of the support device requires monitoring of a critical point of the structure and knowledge about the frequency response of the system. This kind of adaptive isolator can change operation conditions according to dominant loading, thus, resulting in improved vibration isolation capability compared to passive systems. Undesired vibrations can be reduced in different loading conditions, i.e., a large frequency range is covered.

Several different concepts were studied to develop new type of vibration isolators including development of numerical models for semi-active control. The idea of studied semi-active concepts was to change the kinematic boundary condition in the horizontal direction of the device to adjust its vertical stiffness. Two novel concepts were selected for further analysis and experimental demonstrations:

- a circular metal frame (ring) with a horizontal SMA spring behaving as an actuator
- an axial elastomer spring attached with a circular SMA support ring as an actuator.

The feasibility of the semi-active vibration control to a off-shore wind generator were studied by Mroz and Kärnä (2005) and Graczykowski and Heinonen (2006).

Frame spring

The main idea of the controllable device was to change its boundary condition to adjust the stiffness. The selected construction for the device was a circular frame or ring. While the ring is pushed vertically it behaves as a spring. During the compression the ring expands horizontally, as shown in Figure 103. Restricting the deformation in the horizontal direction, the stiffness of the frame in the vertical direction becomes higher due to confinement. The change of boundary condition was applied by an SMA string that adjusts the gap between the frame and confinement. To change the boundary condition, the gap is closed by warming up the SMA.

Experiments with various metal springs and SMA wire configurations were conducted. Controllability was evaluated using stiffness ratio between the stiff and soft mode operation. Measurements indicated average stiffness ratio values typically from 3.4 to 4.1. Although the theoretical value that takes into account the compliance of the SMA string is 6.0, the achieved controllable stiffness range is large enough for many applications.

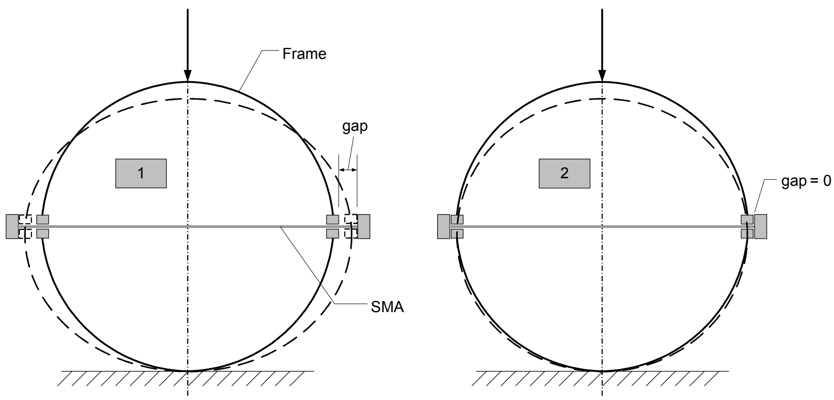

Figure 103. Boundary condition of a frame spring adjusted by a SMA string controlling the gap. The frame is acting in soft mode on the left (mode 1) and in stiff mode on the right (mode 2). The original state is shown by solid lines, and the deformed state by dashed lines.

Elastomer spring

The idea was the same as in the frame spring: to change its boundary condition to adjust the stiffness. The selected construction for the semi-active isolator consisted of two parts, a cylindrical elastomer and an SMA actuator. A circular support ring made of SMA was used as an actuator, which was attached to the outside of a cylindrical elastomer spring. The change of boundary condition was controlled by the gap between the elastomer spring and constraint, as shown in Figure 104. While a cylindrical block of the elastomer is compressed in the vertical direction, it expands in the horizontal direction (perpendicular to the load). Restricting the expansion, the axial stiffness in the loading direction becomes higher. The operation mode, stiff or soft, was selected by controlling the temperature of the SMA actuator which controls the phase composition of SMA.

Dynamic loading tests were carried out to verify the feasibility of the semi-active device. The temperature control of the SMA constraint was applied by an external air blow system in which the air temperature and flow were controlled. The control system was rapid to heat up the SMA from soft to stiff control. Owing to the relatively large heat capacity of the isolator and surrounding parts, the cooling needed much more time. A faster cooling system was developed after these tests enabling rapid control from stiff to soft mode. The maximum stiffness ratio achieved was 4.5.

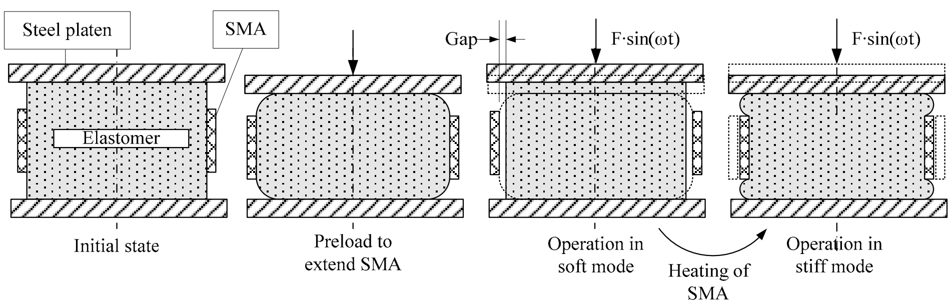

Figure 104. Principal sketch of operation modes of the semi-active device. After preliminary adjustments by preloading, the device acts in two operation modes: soft and stiff.

Applications

Vibration of slender offshore structures, like offshore wind turbines, subject to the dynamic actions of drifting sea ice is a good example where adaptive vibration can be utilized. As a basic solution, these structures will have a conical waterline geometry that prevents the most severe problem known as self-induced vibration due to level ice. It is proposed that the remaining vibrations can be solved by additional control devices. Numerical studies are made on an offshore wind turbine structure. First, the dynamic excitation caused by sea ice was modeled (Figure 105). Second, the prospects of using either a passive or a semi-active tuned mass damper (TMD) were studied. Third, the idea of smart cone based on semi-active vibration isolators, was developed. Four, an application for inflatable adaptive bumper was developed.

Moreover, in a separate study the effect of semi-active stiffness and damping control devices, located at the foundation of a wind turbine, were studied.

Smart cone

Cone-shaped structures installed on off-shore towers subjected to ice loading aim at inducing bending failure of the ice sheet. Since the total interaction force acts normal to the structure's surface, the slope of a cone introduces the vertical component of the loading. As the ice sheet comes to the contact with cone, both horizontal and vertical components increase; the horizontal component, which causes the tower vibration, produces compression, and the vertical component produces bending in the deforming ice sheet. When the value of the vertical force achieves a certain level, the ice sheet fails by bending. The idea of the "Smart Cone" is to further decrease the horizontal reaction acting on the tower and inducing vibrations, without changing the vertical component responsible for the bending failure of ice. (Figure 106.) This could be achieved by introducing new cone – tower interface as shown on Figure 107.

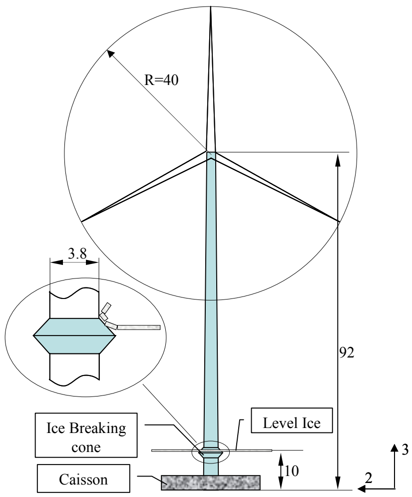

Figure 105. Major dimensions of the wind turbine selected for the simulations.

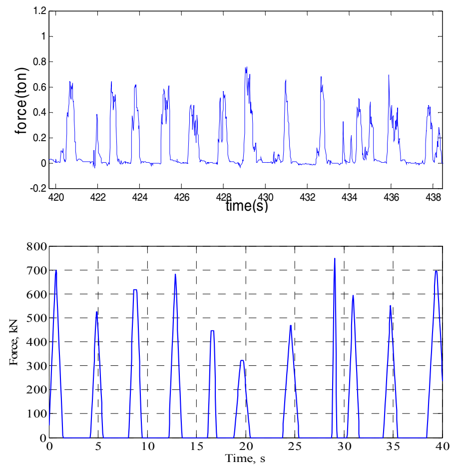

Figure 106. Top: Measured ice forces versus time. Bottom: Sample of generated horizontal ice loading data in time space.

The numerical studies indicated that the performance of a passive TMD device is significantly reduced when the dynamic excitation changes from harmonic to a narrow band random force, which is typical loading in wind turbines. The errors that often occur in the frequency tuning could be compensated by controlling the stiffness of the damper. The calculations indicate the in the case of narrow-band random excitation, the damper's performance is reduced by 10% to 25% if the tuning error is 10%. The amount of benefit that can be achieved by a stiffness controlled arrangement is thus quite small. For harmonic excitation the benefits can be significantly higher.

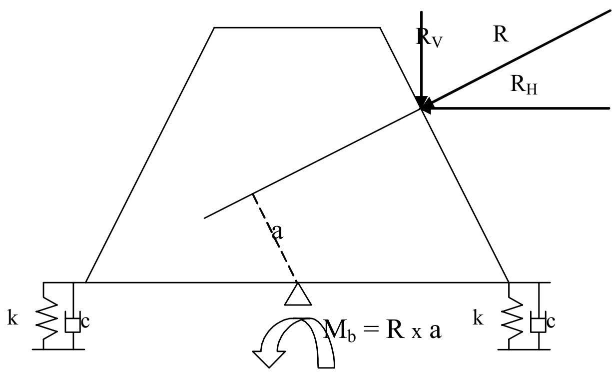

Figure 107. New cone – tower interface.

Inflatable adaptive structures

Collisions of small ships are one of main dangers for the offshore wind turbines. Using inflatable structures surrounding the tower on the water level is a possibility of effective protection. Modelling of such structures was based on interaction between solid wall and fluid enclosed inside. Inflatable structures can be adapted to various impact schemes by adjusting initial pressure and controlling release of compressed air by opening piezo valves. A ship collision with 2D model of wind turbine tower protected by pneumatic structure was simulated (Figure 108). Numerical analysis was performed using ABAQUS/Standard and ABAQUS/Explicit. Performed feasibility study proved that inflatable structures can protect wind turbine tower and ship against serious damages.

The goal of applying pneumatic structures is mitigating of the response of both ship and wind turbine tower. In particular, inflatable structure helps to dissipate the impact energy, minimize forces acting on the ship, decrease stresses arising at the location of the collision and mitigate vibrations of the tower.

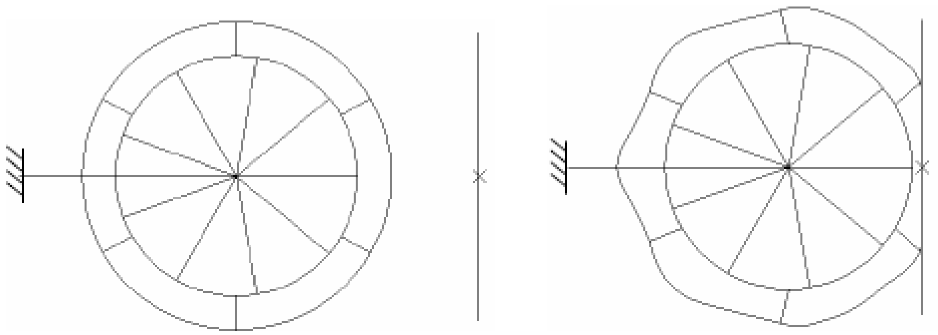

Figure 108. Collision modeled by contact: initial state and resulting deformation. A 2D model of describes dynamic properties of wind turbine at water level implemented with inflatable rubber tanks.

Semi-actively controlled support structures

A smart connector element containing parallel spring and dashpot has been implemented into ABAQUS/Standard as an user element. The spring stiffness and the dashpot damping are adjustable and they can be non-linear. The user can choose the input parameters for the control and they can be solution dependent. For instance, the displacement response (amplitude and frequency) of the hub can be used as an input parameter for the control.

Dynamic finite element analysis of the wind power station with smart connector elements were aimed to find out how and how much the stiffness needs to be changed and how it depends on the excitation frequency and the eigenfrequency. The excitation frequency is first monitored and analyzed during the harmonic vibration to determine the frequency. The control algorithm needs the excitation frequency as an input value to know how the stiffness is adjusted.

With proper stiffness control the root mean square of the displacement amplitude is mitigated from 7% to 35% in all test cases. The ratio between the initial stiffness and target stiffness was from 0.1 to 10.

Hierarchic simulation tools

Hierarchic modelling of the wind turbine

A hierarchic model of the wind turbine, including wind turbine structure and aerodynamics, actuators, grid and control system for turbine control, as well as, for control of active components has been developed.

Commercial tools for aerodynamic and mechanical modelling, as well as, for electro-magnetic modelling are nowadays in common use. In case of wind power modelling, however, turbine dynamics is usually studied with a fairly simple model of the power system – and, vice versa, aero elastic properties of the wind turbine are fairly simple or non-existent in network studies. In this project, a new approach has been brought forth in which the best parts of different tools are used jointly. The approach and the codes developed can naturally be used for other electromechanical systems than wind turbines as well.

The set of tools and data that are used in wind turbine modelling are shown in Figure 109. The mechanics of the turbine are modelled with multi-body systems code ADAMS. This complex model includes 3D-wind field and flexible parts such as blades, tower, drive-train etc. Wind turbine design is assisted with a special NREL produced package ADAMS/WT.

The aerodynamics is modeled using the code Aerodyn. Aerodyn runs as a separate program, which takes blade angles as input from ADAMS and sends calculated output forces back. Aerodyn uses three dimensional wind field to calculate the forces induced by the wind and the blade profile.

The control system of the turbine that regulates blade pitching, yawing and generator characteristics is modelled in Matlab/Simulink. Simulink is very suitable for modelling complex control systems. Simulink makes it possible to add blade pitch control, yawing, vibration control, generator control and other systems to the dynamic turbine model.

The electrical components and events of the turbine and the network are modelled in PSCAD/EMTDC. In addition to being tried and tested the choice of ADAMS and PSCAD/EMTDC is explained by the fact that these tools are already in frequent use at VTT. Also these models are used by industries.

For appropriate power system modelling it is practical to use software which is developed specifically for that purpose. Simulink has a power system blockset named SimPowerSystems that can be purchased separately. In this project, however, a separate program, namely PSCAD/EMTDC, has been chosen because of the good experience of it at VTT. Simulink works then as a platform for connecting the electromagnetic simulation into the mechanical simulation.

Different models and tools working simultaneously enable to study, which mechanical phenomena are transferred to the electrical side, the influence of network disturbances to the mechanical side, the impact of control actions and development of new control strategies, indicators that can be used for condition monitoring purposes, new technical solutions and materials in order to reduce harmful forces and events on for example drive train etc.

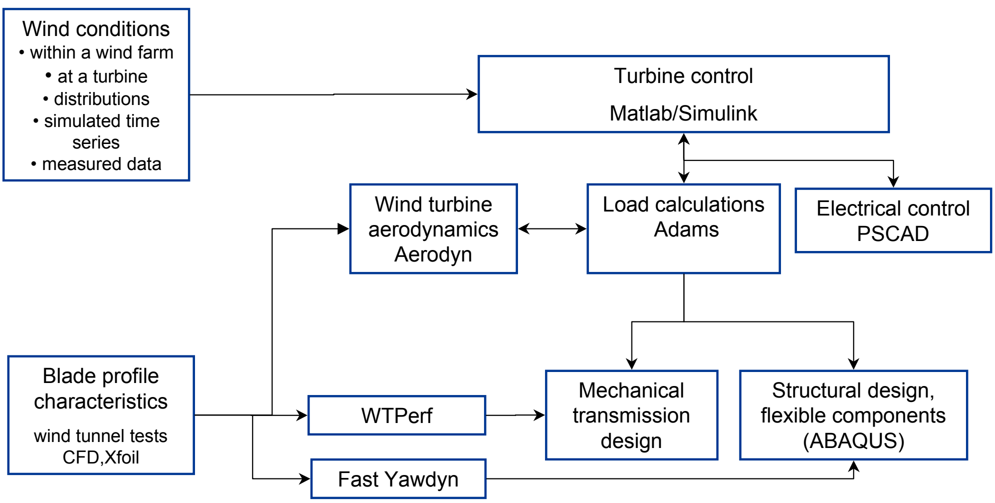

Figure 109. Wind turbine modelling environments with relation to the structural design.

An example of cause-effect chain describes the principle of the adjoint simulation. The chain starts from the power system as a network fault created in

PSCAD/EMTDC. This affects the generator and through a change in the electrical torque, the mechanical side of the turbine. PSCAD/EMTDC passes the change in torque to ADAMS through Simulink. ADAMS returns the new shaft speed to Simulink, which sends it to PSCAD/EMTDC. The dependence between the electrical and mechanical parts works similarly the other way around. For example wind speed or wind direction change can be seen in the network simulation as power fluctuations. Data exchange between the simulation programs can be seen in Figure 110.

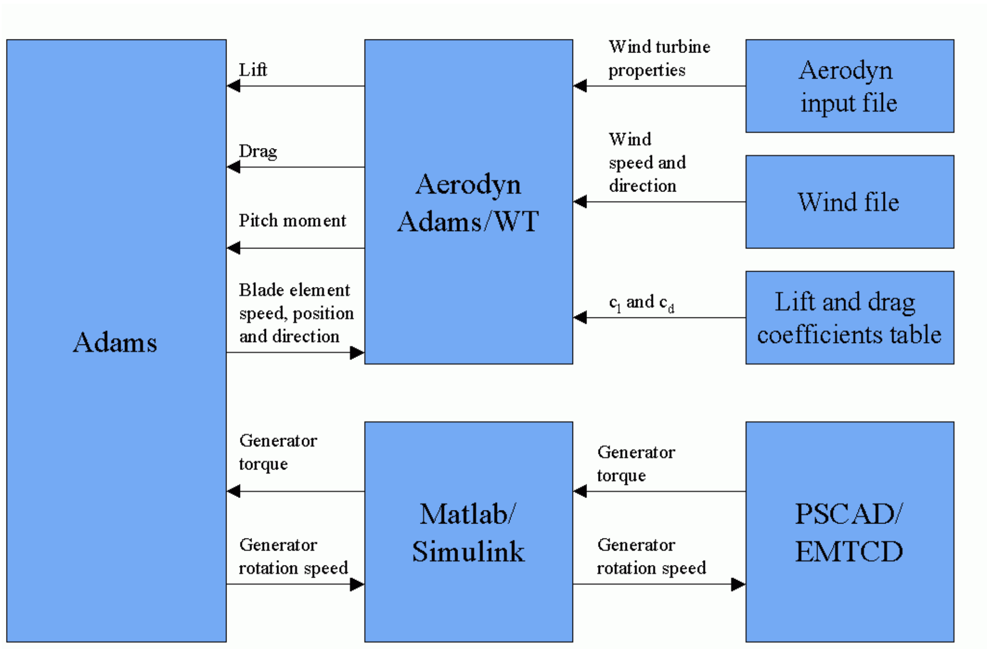

Figure 110. Data exchange between simulation programs.

Further, the purpose of the project was not solely in the integration of the three programs, but also to support development of mechanical models to be used in connection with PSCAD/EMTDC in power system studies during disturbances as well as better modelling of network disturbances in ADAMS-Simulink.

Demonstration of an active control of load and fatigue

The active duration control of wind turbine tower has been demonstrated using the developed virtual model (Figure 111), which shows the developed Matlab/Simulink model.

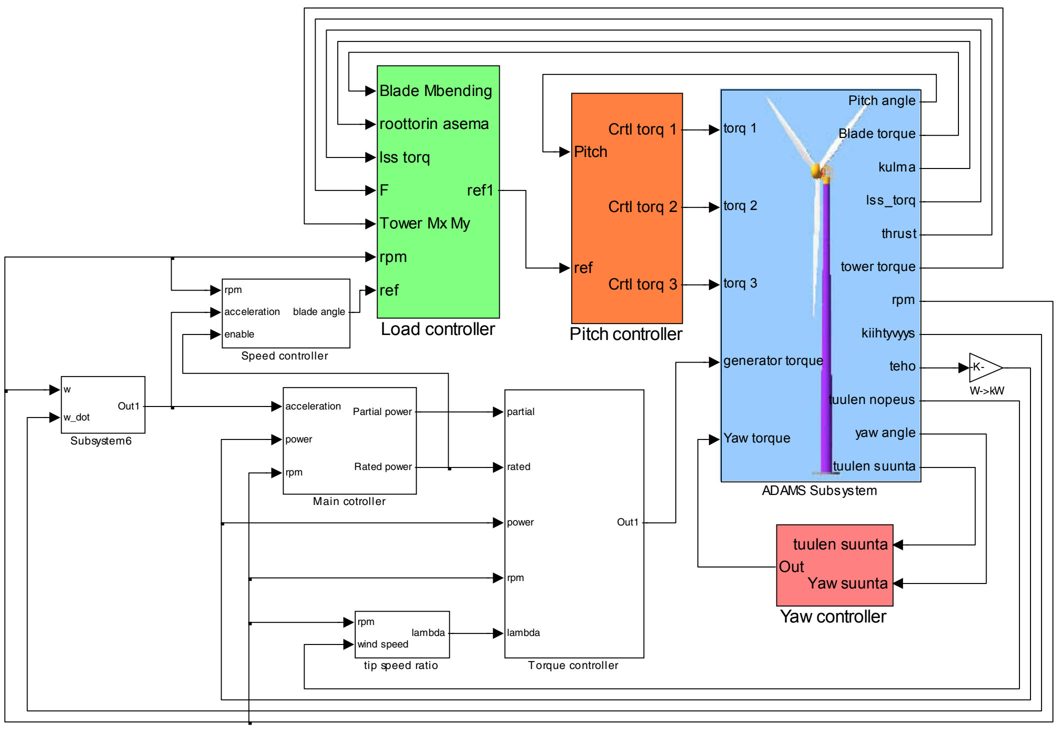

Figure 111. The active durability control of wind turbine tower.

Among other control requirements, the demands of active duration control to the communication needs of wind turbines are studied in a co-funded project within the DENSY-research program.

4.2.3 Industrial and research networking, international position

The research group prepared and coordinated three proposals for EU 6th framework program. The proposal Mitigation of Sea Ice Impacts on Wind Energy Converter Structures (MIWECS) was submitted under the heading New and advanced concepts in renewable energy technologies. The proposal Control of Environmental Actions on Structures (CAST) was submitted to the call FP6-2003-IST-2 dealing smart structures. The proposal Integrated Project Integrated Wind Turbine Design (UPWIND) was submitted to the call FP6-2004-Energy-3. Industrial participation was included in the projects.

More specific networking internationally includes e.g.

- within composite materials research especially in wind turbine blades: Technical University of Delft, Riso National Laboratory, Energieonderzoek Centrum Nederland (ECN), Vrije Universiteit Brussels
- within Intelligent systems in wind turbines: Technical University of Delft
- within Smart material applications in structures: Institute of fundamental technology research Poland
- modelling of wind farm and wind turbine dynamic behavior: SINTEF Norway, Chalmers Sweden.

National networking with technical universities and companies has been done within the frameworks of MASINA- and DENSY-technology programs of Tekes.

4.2.4 Exploitation and industrial impacts

An industrial pre-feasibility study on the manufacturing of the blades revealed that the anticipated considerable weight reduction cannot be achieved by applying only new materials and constructions alone. The continuation of the study in a separate industrial project is under consideration. In order to reach the anticipated weight reductions, better control of the turbine, such as advanced blade pitch control, advanced generator control, airfoil shape control or their combination, has to be developed and utilized.

A 3-year co-funded project on Dynamic models of wind farms parallel to the project has been started as part of Nordic co-operation. Industrial interest to the project has been shown both from technology suppliers, wind turbine owners and grid companies.

The improved modelling facilities are also directly utilized in ongoing projects dealing e.g. with the loading of the wind turbine in icing conditions. The modelling of various control functions of a modern wind turbine has required co-operation with industry. Thus the developed tools are anticipated to be applicable in further design of the turbines and their control systems. The chosen approach to combine different simulation tools enables the combination of VTT's tools to customer's own software without the need of transferring sensitive information. The approach can be applied in other electro-mechanical applications than wind turbines such as diesel power plants, paper mills etc.

Further development plans include the development of active durability control system based on continuous operation and load-monitoring systems including distributed and intelligent subsystems and intelligent control and condition monitoring of a wind power plant in an industrial project.

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4.3 SULAROTOR – Intelligent control of resonance vibration of industrial rotors

Kari Tammi, Markku Järviluoma

Abstract

The project focused on active vibration control solutions for rotating machines including system identification together with vibration problem identification, control synthesis and algorithm implementation, actuation and measurement issues related to the topic. The motivation for the project came from the identified trends towards high-power smart machines, capable of adapting to different operating conditions. The solutions were developed in order to control machine dynamics during machine operation. The control of machine dynamics makes it possible to optimise machine's work-process quality, machine's durability, or its ergonomics.

In the technical perspective, the main results of the project were the development of new identification and control methods together with the experimental validation. Different algorithms were compared and the design aspects of an active system were discussed in the project. Other results of the project are refined customer focus, networks founded among scientific community and industry, and publicity in the form of several articles and two thesis works.

4.3.1 Background, starting point and objectives

The SULAROTOR project has dealt with rotor identification, wireless measurement technologies for rotors and particularly, active vibration control of rotors. The project objective has been to develop and to demonstrate an automated and integrated system identification, control design, and control adaptation procedure for an active vibration and durability control system. The project objective and its focus are important because several heavy rotating machine manufacturers exist in Finnish industry and those manufacturers have started to add smart features in their products.

Then why vibration control of rotors is important? Generally speaking, rotating components are often a major source of excitation in machines. Those excitations may be harmful to machine quality, durability or ergonomics, for instance. By means of active vibration control, the effects of excitations may be mitigated. More specifically, the critical speed has been a restricting factor in rotating machines design because today's variable-speed rotors with conventional journal or rolling element bearings are often designed to operate in sub-critical range. Their maximum speed may be limited to less than one third or one half of the critical speed. This is a common practise for variable-speed rotors used in industrial machinery. The reason for limiting the speed is to avoid an excessive dynamic response that can reduce the process quality, shorten the life of machine components, or cause disturbances in the environment of the machine. A simple specification is to restrict the speed of operation so that the rotation harmonics do not coincide with the bending resonance. Restricting the speed of rotation is an effective way to control responses, because the mass unbalance excitations are proportional to the square of rotation speed. This design philosophy leads to relatively heavy structures and robust machines with a restricted operating range.

Constant-speed rotors with conventional bearings can be designed to be super-critical in order to achieve a higher speed and thus a higher power. The critical speed is usually crossed rapidly but continuous operation at the critical speed is not allowed. This is the case with turbo machinery, large power generators and high speed pumps, for instance. Such a design leads to a higher power density with respect to machine mass than for sub-critical machines but also to a restricted operating range.

The choice between a variable-speed or a constant-speed machine and the choice between lower or higher power output brings with trade-offs to the designer. The trade-off problem is often solved by suggesting different products for each purpose: heavy sub-critical products with a wider operating range, and lighter super-critical machines with a restricted operating range. Figure 112 represents a classification of rotating machines: the restrictions lead the design to flexible variable-speed machines with a lower power output, or constant speed machines with a higher power output. For heavy industrial machines, a tailored product must be designed for each purpose.

Active Magnetic Bearing (AMB) technology has offered one solution for this problem. The technology is rapidly gaining ground in high-speed pumps and compressors. The active vibration control concept studied in the SULAROTOR project aimed to offer a similar solution for heavy industrial rotors on conventional bearings where AMBs are not necessarily applicable. The concept is believed to offer a solution for the problems explained. It is designed to be an add-on device that may be applied to virtually any rotating machine. The benefits of application are found in performance, process quality, life-cycle of components but also in a wider product line based on the same basic product.

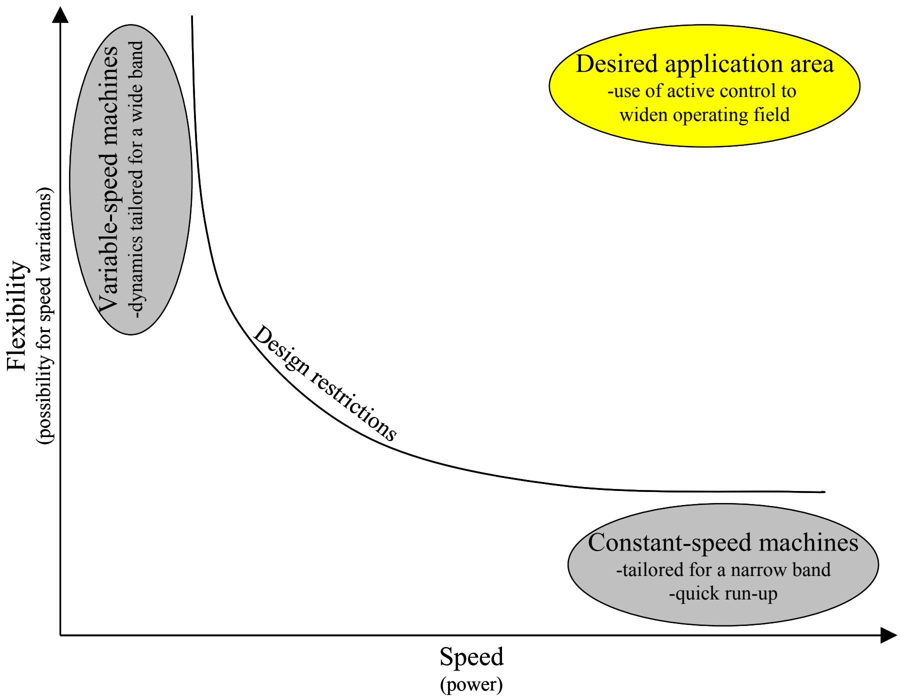

Figure 112. Active vibration control solutions are designed to help in covering new operating areas.

Before the project SULAROTOR, VTT had shorter research projects on active control systems for different machines. All those projects were application-oriented and know-how on active systems was spread in VTT. One aim of the project was to collect this know-how and study a generic solution for vibration control. The idea a retro-fit active control system concept was born in the beginning of project. During its first years, the project was focused on identification and control methods, and the development of the retro-fit concept. The customer focus was broad.

Later on, the customer focus was refined because first applications were assumed to be found in electrical machines. Also, the development of new measurement systems was seen important. This focus has been kept until the end of the project and activities regarding electrical machines are actually continued after the project.

4.3.2 Implementation

In order to cover whole design path from system (and vibration problem) identification to the implantation of control algorithms, the project efforts were divided into two sub-efforts: 1) identification and wireless measurement technologies developed mainly by VTT in Oulu, 2) active control research and practical implementations performed by VTT in Espoo. In Espoo, a test rig for the research was constructed (Figure 113). The test rig was exploited for testing the identification and control methods. The development of the test rig was supported by High Speed Tech, Ltd.

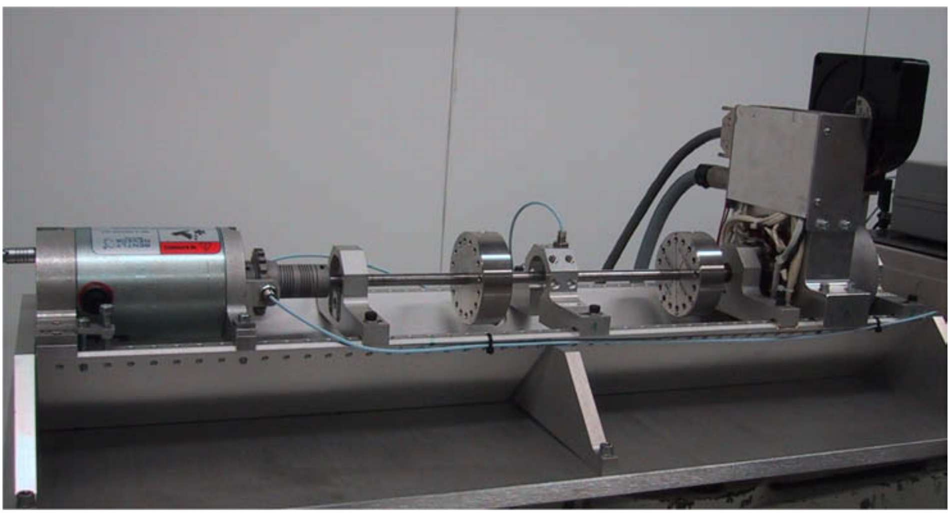

Figure 113. The test rig: the driving motor (left), the rotor with the disks, and the actuator (right) (the same figure will be published in the Mr. Tammi's doctoral thesis).

The aim was to develop an active vibration control concept for vibration problem solving in industrial machines. The concept was based on the retro-fit electromagnetic actuator. The research work aimed to cover the complete design path from problem definition and system identification to design and tuning the active control algorithms.

As mentioned above, the research was directed towards electrical machines and measurement technologies by the end of the project. A consortium was founded and a project called Active Control of Rotor Vibrations in Electrical Machines (ACRVEM) was initiated. These arrangements were justified by the discussions with VTT's customers. The use of electromagnetic inter-action in electrical machines showed a great application potential and a research consortium was founded around the topic. The effort was also supported by ABB.

A feasibility study exploring the implementation issues of an active system was performed. The feasibility study showed that an active system can provide significant benefits in terms of performance and is applicable for several types of machines. The study also showed that sensor systems required by active control may pose challenges in final applications. Based on this finding, new wireless measurement technologies were explored during the last year of the project.

4.3.3 Results

The technical results of the SULAROTOR project comprise findings regarding theoretical backgrounds of identification and control algorithms, implementation of algorithms on a practical system, and the development of the wireless measurement system. In this section, examples of technical part are reported. The reader is advised to explore the references in case of further interest.

The examples presented here must be understood as details. In total, the major achievements during the project were the following:

- development of theoretical and practical know-how on rotor dynamics, active vibration control and system identification
- definition of the customer focus for the active vibration solutions considered
- initiation of research activities on electrical machines

- publication of one licentiate's thesis and one doctoral thesis (will be finalized in early 2007), another doctoral thesis work has been started in 2006
- publication of 18 articles including 11 papers published in scientific conferences or journals (2 of those to be finalized in 2007)
- establishment of a network among known researchers on the field of smart machines
- establishment of VTT's role as a significant player in that field.

As a conclusion: the research effort has created know how for VTT, defined the customer focus, and helped to initiate further efforts towards that focus. In addition, the project enabled VTT's researchers to network internationally and to enhance their skills on smart machines.

For example, the comparison of mass unbalance compensation algorithms showed significant differences between two feedforward control algorithms and one learning algorithm (Figure 114). The algorithm called Convergent Control was found the best-performing method for the purpose. The responses with the adaptive FIR filter with LMS adaptation algorithm were the second smallest. The learning repetitive control algorithm suffered fluctuation as a function of rotation speed.

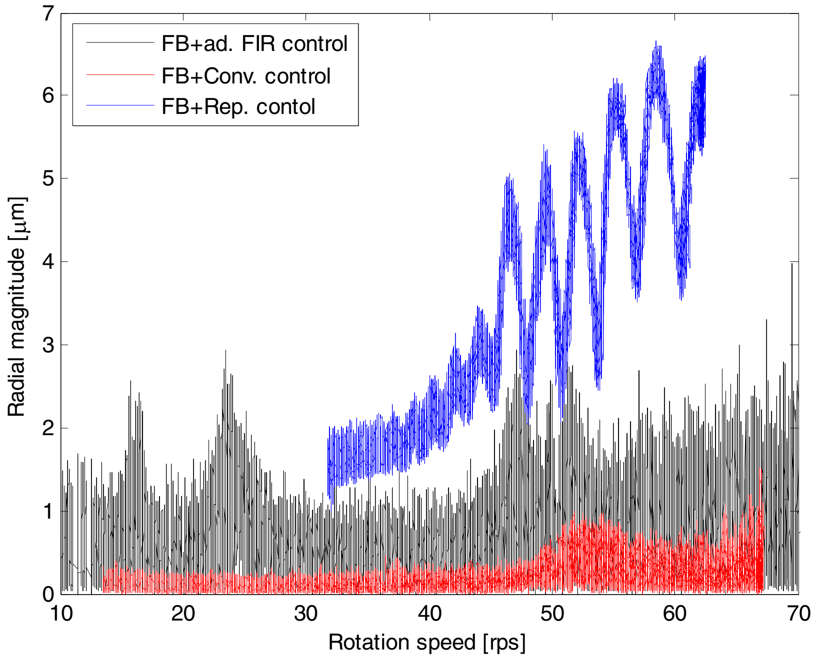

Figure 114. Responses measured with three different mass unbalance compensation algorithms (the same figure will be published in the Mr. Tammi's doctoral thesis).

As another example, two identification methods were developed for the rotor identification: adaptive filtering identification and so called Disturbance Tolerant Identification (DTI). Figure 115 shows an identification result achieved with DTI compared with an ordinary identification method. The new method enabled the rotor identification during operation.

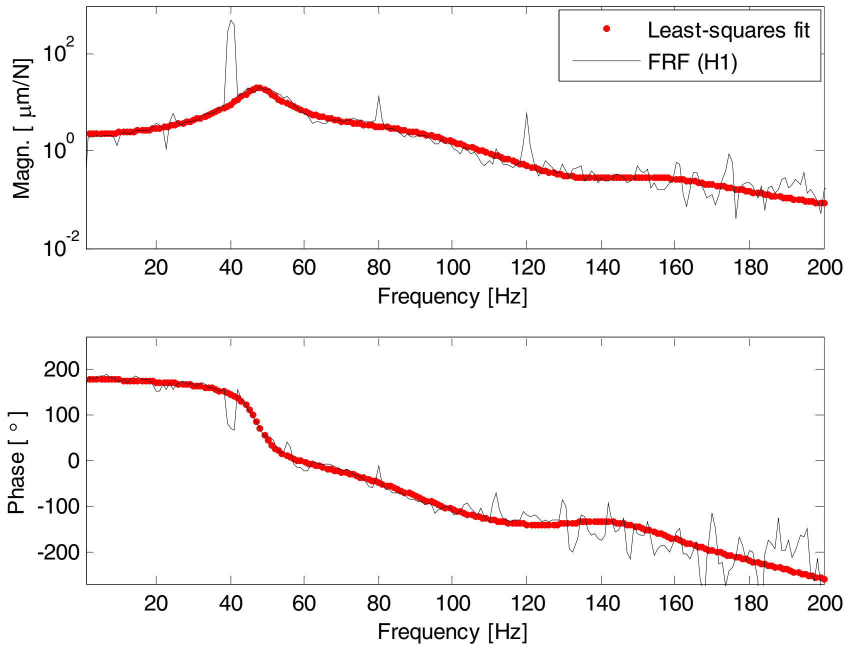

Figure 115. The disturbance tolerant identification method with least-squares fit was able to exclude false peak due to rotation (the same figure will be published in the Mr. Tammi's doctoral thesis).

Figure 116 shows the wireless measurement system. It has an integrated transmitter-amplifier module to be attached to a rotating object. The module is capable of measuring four channels up to 4 kHz sample rate. The measured data can be filtered and sent to a receiver up to a sample rate of 500 Hz. The receiver can be plugged into a PC via the USB port. Currently, the set-up has been demonstrated to work with rotating speed up to 30 Hz.

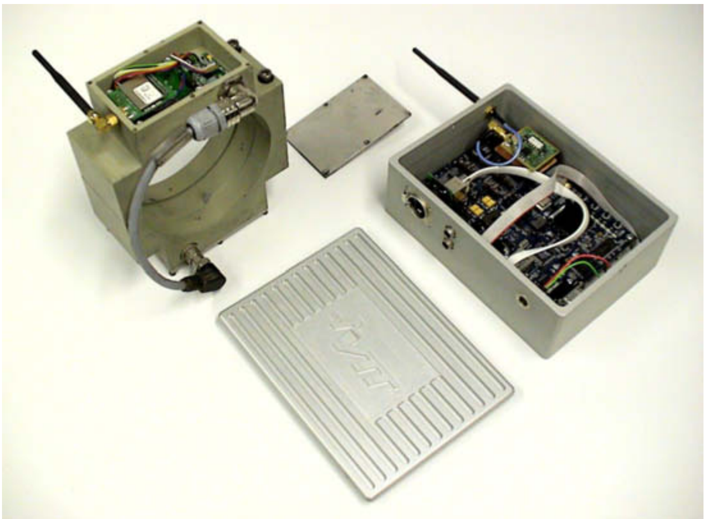

Figure 116. The wireless measurement system developed: the transmitter on left and the receiver on right.

4.3.4 Industrial and research networking, international position

The publications have made VTT known as an actor dealing with system identification, active vibration control, and new measurement technologies. The SULAROTOR project had a significant impact in making VTT known in scientific community.

Industrial network

High Speed Tech, has participated in the project by designing an electromagnetic actuator for control and offering their software for research use. The motivating factor has been in the quest of new business areas for electromagnetic actuator systems.

Wärtsilä has participated in the project by offering their point-of-view about future rotating machines. In addition Professor Matti Kleimola, former CTO of Wärtsilä Corporation, has contributed by mentoring VTT's researcher in order to refine the customer focus of the research.

ABB has contributed by providing their point-of-view on future's electrical machine concepts. Currently, experts from ABB act as advisors for the continuing project (ACRVEM).

University network

Helsinki University of Technology has been frequent partner with VTT. The Control Engineering Laboratory and the Laboratory of Electromechanics carry out research together with VTT on active control of rotor vibrations in electrical machines (ACRVEM).

University of Sheffield has participated SULAROTOR project by offering their expertise on learning control algorithms. In practise, this has meant open discussion on research topics and common publications with VTT.

North Carolina State University (NCSU), USA and VTT plan together future's initiatives on new electrical product concepts for smart machine. The first action is Mr. Tammi's researcher exchange at the NCSU from March 2007 to May 2008.

Universities from Northern Sweden have made an initiative on a Nordic centre of excellence on rotor dynamics. In the centre of excellence, VTT is asked to bring the know-how on active control of rotor vibrations and electro-mechanics.

4.3.5 Exploitation and industrial impacts

The presented identification or control concepts have not yet been directly exploited by an industrial customer but the wireless measurement systems have been exploited. In addition, the know-how and experience on identification and control has been exploited in industrial assignments. Typical assignments have been feasibility studies of smart systems for machines, or concept creation assignments for next-generation machines, etc.

Major impact has been the creation of the network between industrial and university parties. The exploitation of the network is a challenge of the future.

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4.4 InMAR – Intelligent Materials for Active Noise Reduction

Hannu Nykänen, Samu Aalto, Pasi Kosonen, Tomi Lindroos, Esa Nousiainen, Jukka Tanttari, Seppo Uosukainen, Marko Antila, Jari Kataja, Velipekka Mellin, Ari Saarinen

Abstract

During the last decade fundamental research on smart structures using intelligent materials has raised industrial interest. One of the most challenging application field is noise and vibration control. The strongly coupled phenomena vibration and noise limit the design of highly advanced and efficient lightweight structures. To face the challenge European Union has granted funding for the Integrated Project Intelligent Materials for Active Noise Reduction – InMAR as the key European Union funded project in the area of Intelligent Materials within the FP 6.

VTT's main focuses in InMAR project are in

- developing novel concepts for vibroacoustic properties of light weight composite materials

- developing new large surface structural and acoustic sensor-actuator pairs for sound transmission control
- developing new local feedback control methods, especially for multi-channel active sound transmission loss control
- implementing active sound profiling for car interior sound quality control
- applying the developed materials, actuators and control methods in passive design, and in active systems in car sound package design and elevator wall sound transmission loss increase.

The first realization of novel composite panel concept at VTT is a GFRP panel with striped core made of two different materials. The panel shows up to 10 dB better sound insulation compared to the reference (homogenous stiff core) panel. Two types of polymer material based actuator-sensor elements have been developed together with Panphonics Oy, one for active structural control and the other for active acoustic control of sound transmission loss of panel type structures. Development of multi-channel digitally adjustable analog control system is carried out for the active systems e.g. utilising large surface polymer actuators. The developed FPAA prototype controller contains an FPAA unit board and a microcontroller. The prototype controller system has been tested in active car sound package mock-up with large surface polymer actuator-sensor pair with up to 9 dB improvement in the target frequency band with broadband acoustic excitation. Local feedback control system gives possibilities to tune and increase the sound insulation of the sound package at selected frequencies giving flexibility for the sound insulation design of car sound packages and other panel like structures.

4.4.1 Background, starting point and objectives

Background of the project

During the last decade fundamental research on smart structures using intelligent materials has raised industrial interest. One of the most challenging application field is noise and vibration reduction in civil engineering, machine tools, automobiles, trains, and aerospace engineering. The strongly linked phenomena, vibration and noise, limit the design of highly advanced and efficient lightweight structures. With the upcoming demand of highly efficient, emissionless lightweight structures and increased standards for any type of emission, new intelligent materials systems are needed to allow both highly damped and controllable, as well as, light but durable structures for any type of high-tech application.

To face the challenge European Union has granted funding for the Integrated Project Intelligent Materials for Active Noise Reduction – InMAR as the key European Union funded project in the area of Intelligent Materials within the FP 6.

Objectives

Facing the market and political drives or demands for higher added value, as well as, eco-efficient and sustainable products and processes, industry is giving up its resource-based approach towards sustainable and knowledge-based concepts. By enhancing the efficiency, functionality, and quality of not only high-value products but also of quotidian mass products, totally new design concepts and guidelines are being considered and, therefore, traditional approaches are reconsidered or even abandoned. Particularly, the automotive industry acts as a forerunner for innovations in Europe. It is expected that knowledge-based, multifunctional materials or intelligent material systems act as one of the key factors for the realization of future requirements and legislations.

In realizing a breakthrough in sustainable development, the industry strives for enhanced lightweight design and reduced emission of all kinds. But the application of enhanced lightweight designs using existing design rules contradicts with the requirements of low-noise emission, safety, functionality, comfort, and reliability. As an example, the structural weight of cars has been significantly reduced over the last decades but the total mass has increased due to higher safety, comfort, and functionality requirements.

One of the challenging tasks is to overcome this contradiction by introducing new, intelligent material systems. Both sustainable development and adding functionality to products is best pointed up by a noise-optimized product design. It is well known that lightweight structures tend to vibrate more and radiate noise on a higher level. The higher noise levels often call for additional mass which, in turn, compromises the lightweight design. In the future, noise-optimized products can only be achieved by applying active noise reduction concepts based on intelligent materials that allow lightweight design and higher functionality with respect to noise control.

4.4.2 Implementation and results

Research on intelligent material systems addresses the design of intelligent materials, the embedding of electronics and the design of control strategies for broadband noise control. According to the different research aspects, the fundamental research in InMAR is divided into three technology areas: intelligent material systems, system integration and life-cycle of these materials and systems. This trisection also reflects the evolutionary progress in the development of intelligent material systems. Within these technology areas intelligent material systems has been designed and characterized, simulation and manufacturing technologies developed according to the problems defined in the application scenarios.

The design of the system is complicated by the fact that the control of multichannel systems for broadband noise reduction is computationally very demanding, and requires heavy signal processing. The reduction of computational complexity and hardware implementation of certain parts of the algorithm have a direct influence on the possibility to achieve the desired goals and has been taken into account in the overall design process.

VTT's focuses and key results in InMAR

VTT is not participating in all sectors of InMAR. VTT's main focuses are in

- developing novel concepts for vibroacoustic properties of light weight composite materials
- developing new large surface structural and acoustic sensor-actuator pairs for sound transmission control
- developing new local feedback control methods, especially for multi-channel active sound transmission loss control
- implementing active sound profiling for car interior sound quality control

- applying the developed materials, actuators and control methods in passive design and in active systems in car sound package design and elevator wall sound transmission loss increase.

Novel, radical concepts to control vibroacoustic properties of light weight composite panels

For this work VTT's research team has concentrated on stiff, lightweight three-layer sandwich panels, which have load carrying capability. The focus has been on the panels of 20...25 mm thickness and 8 kg/m^2 surface mass range. Traditional methods to enhance sound insulation or other vibroacoustic properties of this kind of panels are

(i) mass increase in the form of heavy, limp layers or
(ii) damping using, for instance, constrained layer techniques.

In present work radical novel concepts based on thick plate flexural wave dynamics have been developed. In thick plates, the flexural wave is a mix of bending waves and transverse shear waves. The central idea in the developments is the controlled use of the transverse shear deformation to construct panels having:

(iii) dynamically floating sub-panels using for instance discrete stripes of soft core material
(iv) to construct panels with inherent waveguide or diffraction properties using functionally graded materials.

The more specific developments are (Figure 117):

1. ***Striped panel***: soft-stiff striped core.
2. ***Chessboard panel***: soft-stiff cores for dynamically floating subpanels.
3. ***Active chessboard panel***: Freezing the vibration of floating subpanels using structural actuators.
4. ***Diffraction panel***: Control of wave propagation for creation of silent zones using dynamic stiffness gradients.

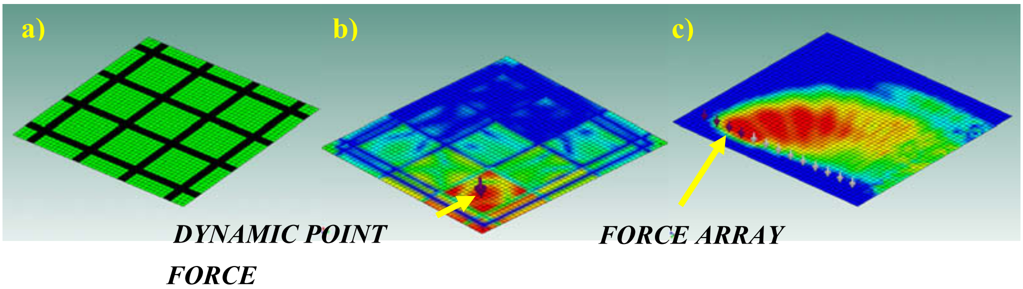


Figure 117. Conceptual approaches to enhance sound insulation or other vibroacoustic properties of lightweight sandwich composite panels; a): A chessbord panel with crossing soft core stripes; b): 2D-filtering effect in a chessboard panel excited by a point force; c) Diffraction effect due to stiffness gradient in a panel excited by an arry of point forces.

All these concepts are manifestations of <u>Hamilton's principle</u>, the inherent law of an elastic system to minimize its potential energy.

The first realization of the <u>striped panel</u> is already manufactured and tested. The panel shows up to <u>10 dB better sound insulation</u> compared to the reference (homogenous stiff core) panel (Figure 118). The first realization of the <u>chessboard panel</u> is in the manufacturing process and will be tested in early 2007. Also preliminary FE-models of all designs have been developed. <u>The unique concepts will be further developed by VTT funding (resolution concerning the invention 006100).</u>

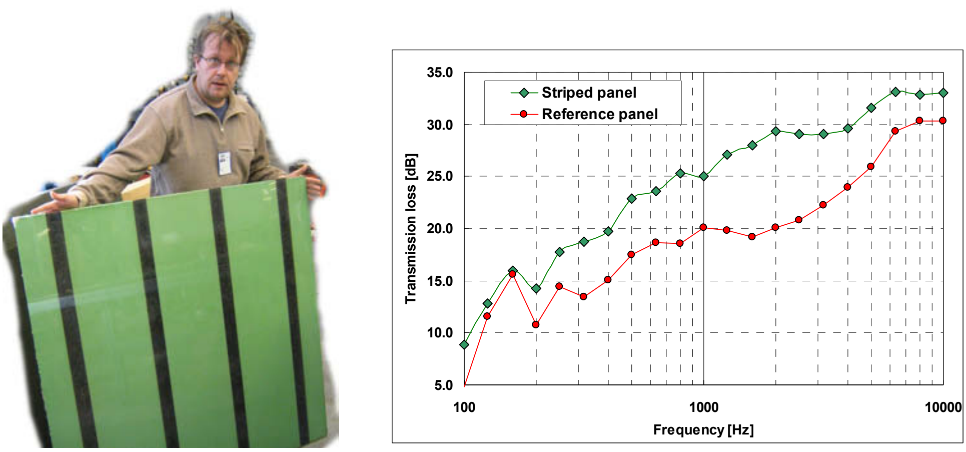


Figure 118. Striped panel and the imporvement of sound transmission loss of striped panel compared to reference panel.

Actuator and actuator-sensor elements

Large surface piezo driven composite actuator panels and two types of large surface polymer material based actuator-sensor elements have been developed by VTT in InMAR project. Piezo panels have been developed by VTT alone and polymer actuator-sensor elements together with Panphonics Oy. One of the actuator-sensor element types has been developed for active structural and the other for active acoustic control of sound transmission loss of panel type structures. As the acoustic actuator-sensor elements consist of two commercial G1-panel elements, one acting as an actuator and the other (with minor modifications) as a sensor, they are not described here in detail, but only referred to as G1 actuator-sensor pair (G1-ASP).

Piezo driven panel actuator is intended for low frequency sound production for sound quality control in car interior. For active sound control inside vehicles the actuators must be capable of producing relatively high sound pressure levels. Flat loudspeakers would be ideal for use in vehicles, where they would require little space and could be placed near passengers. However, flat loudspeakers typically tend to exhibit poor low frequency characteristics. The aim of this part of InMAR work was to develop acoustic actuator with the operating frequency band of 50–250 Hz. The measurements inside cabins indicated that an ideal actuator should be able to produce approximately 100 dB sound pressure level at 50 Hz frequency at one meter distance from the actuator.

Five slightly different actuator structures utilising Macro Fibre Composite driving units were modelled, manufactured and tested. By this way the behaviour of the MFC driving units and effects of the structure were studied. Main goal of the iteration work were to construct more precise dynamic model of the actuator structure.

The final prototype structure consists of 400 mm x 400 mm glass fibre reinforced composite plate where three MFC piezo driving units are placed on the centre line (Figure 119). Non-active areas of the plate are stiffened with sandwich structure.

Figure 119. Piezocomposite actuator based on three MFC actuators. Dynamic behaviour of the element was measured with laser vibrometrer.

The basic idea of the developments work was to design the structure so that the first eigenmode is located near the lowest operating frequency and that way increases the amplitude of the plate at low frequencies.

Modelled results were compared to laser vibrometer measurement (Figure 120). After iteration process relatively good correlation of the modelled and measured results was achieved. The actuating plate was modelled by using plate elements with approximated boundary conditions. Because of the complicated nature of the joints between actuating plate and test frame also a solid model of the whole system (plate and frame) was constructed. Even if the material parameters were measured as precisly as possible there is some deviation in the natural frequencies especially at high frequencies. This is propably due to the fact that exact modelling of the joint is difficult and on the other hand manufacturing and assembling of the panel has always some inaccuracies.

It can be easily seen from laser vibrometer measurements that sound radiation of the second and third eigenmode are poor because of the movement of the certain parts of the panel are in antagonist phases. By using a more rigid frame it would be possible to avoid higher resonance modes in the operation frequency range.

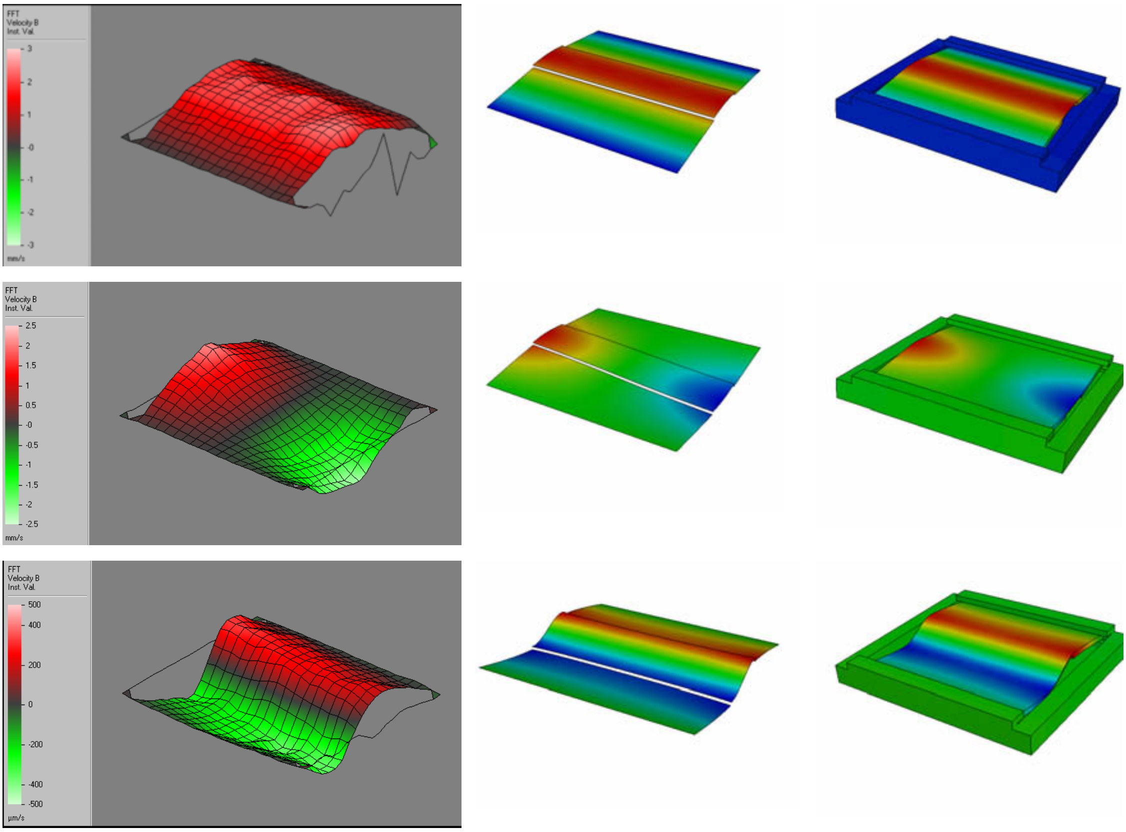


Figure 120. The lowest measured and analyzed (FEM) eigenmodes of the actuating plate.

Based on earlier experiences the development work of the low frequency high sound pressure eactuator were known to be very challenging. Even if the high amplitude values were reached the acoustic performance was detected to be insufficient. The main reason for insufficient performace was high harmonic distortion of the element. Only 80 dB sound pressure levels were achieved when harmonic distortion was kept under 5%. More optimization work of the structure is needed to achieve original requrements.

The principle of the structural element (so called Elastic Mass Actuator, EMA [Figure 121]) has been developed already in an earlier national Finnish project EMFiT, the core new development done in InMAR is the design of the new driving unit for the mass actuator (Generic G3 Actuator or Elastic Actuator in

Figure 121). The VTT work has concentrated on modelling and simulation of this novel driving unit.

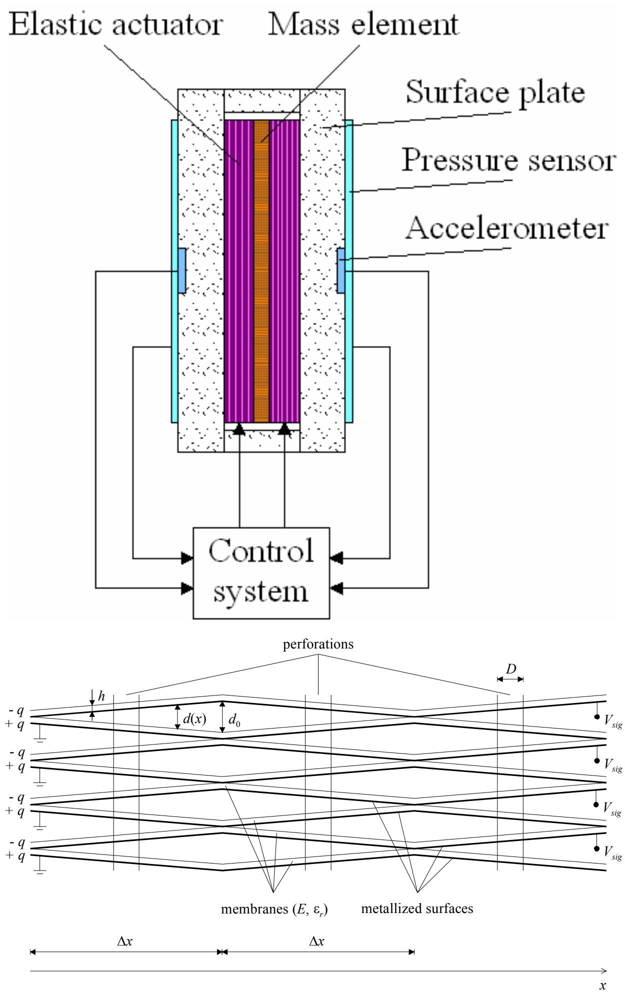


Figure 121. Elastic Mass Actuator (EMA) concept (left) and the microstructure of the new driving unit (Elastic actuator, right).

Matlab programs have been developed to simulate the static and dynamic response of the Generic G3 Actuator element, one elastic actuator of the EMA. Simulations show that the sensitivity of the element can be increased by increasing the number of membrane layers, by decreasing the Young's modulus, increasing the density and decreasing the thickness of the membrane material, by increasing the width of the salmiac pattern, and by decreasing the air gap thickness between the layers. As examples, the effect of the number of layers and the membrane thickness to the amplitude response of the actuator is presented in Figure 122. Every means to increase the sensitivity either increases the harmonic distortion, or has other adverse effects or limitations. The distortion, being mostly composed of the second harmonic, cannot be decreased below the level determined by the excitation mechanism and the proportional amplitude response. The distortion can be decreased at high frequencies by increasing the number of layers, by increasing the density of the film material, and by increasing the diameter of the holes. There are no means to decrease the distortion substantially at low frequencies. The preliminary simulations of the whole EMA show, however, that the symmetrical mounting of the two elastic actuators at both sides of the mass element causes the harmonic distortion to vanish almost to an insignificant level.

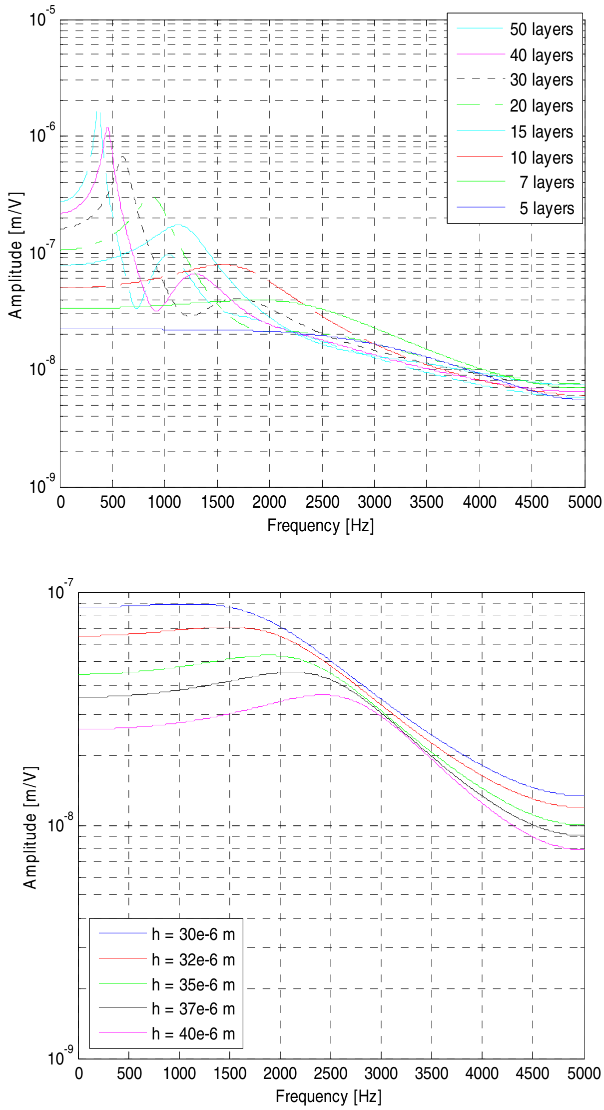


Figure 122. Amplitude response of the Generic G3 Actuator, number of layers (left) and membrane thickness (right) as the parameter.

Control method development

The development of a multi-channel digitally adjustable analog control system is carried out in InMAR and other related projects. The final system is based on FPAA (Field Programmable Analog Array) technology. Such control systems are good candidates for controlling the active sound insulation systems which are based on feedback control principle and in which the loop delay must be minimized.

The developed FPAA prototype board contains an FPAA unit and a microcontroller. Using the prototype board, multi-channel systems have been constructed for the active car sound package setups. The principal realisation and the usage of the system are presented in Figure 123. Only one channel of operation is shown in this diagram, but the system is capable of controlling 4 channels simultaneously.

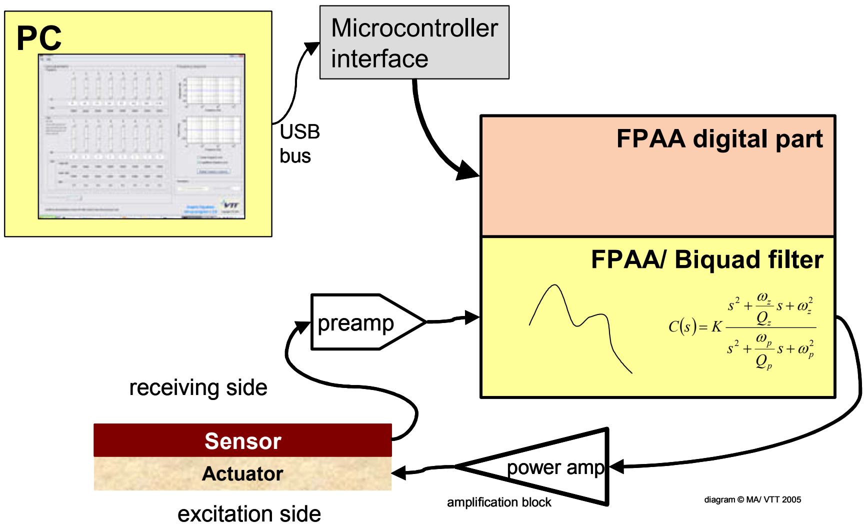


Figure 123. VTT's FPAA-based control system, principle.

The four channel system consists of 2 FPAA boards (giving totally 4 inputs and 4 outputs), the USB-SPI converter microcontroller board, enclosure, power supply and the optimisation software. Both boards are internally connected to the USB-SPI converter which translates the USB messages from the host PC to suitable form for the FPAA units. The data transfer between the host and the target is done via the USB bus. An optimiser program is used for calculating the optimum control for each channel.

The optimiser program has been developed especially for the control parameter calculation for the different feedback controller types, including the FPAA technology. The optimiser is based on genetic algorithms and random search optimisation method. The program is also used for data download to the digitally controlled analog units. The parameters for all the 4 channels can be downloaded in one pass. The optimiser-downloading program has been written in MATLAB and compiled to a stand-alone graphical user interface (Figure 124).

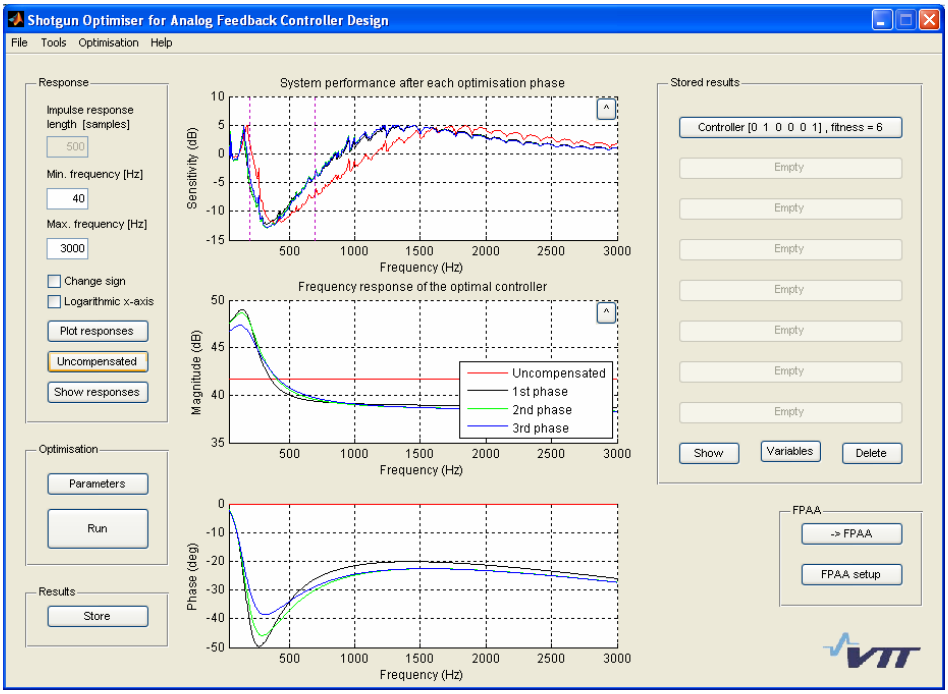


Figure 124. Screenshot of the optimiser tool.

Active sound profiling

The design of a passenger vehicle's cabin sound quality for all operating conditions is a complex task. The challenge is to implement hardware capable of yielding the required results without compromising other attributes, e.g. emissions, fuel consumption, exterior noise, weight, cost etc. In most cases this will be possible only using Active Noise Control (ANC) technology. The aim in this area within InMAR has been to demonstrate the possibility of shaping the engine order components of the interior sound field with an ANC system.

At VTT, a model for the performance simulation of the psychoacoustic controller, including algorithm and hardware has been developed. This model allows the effect of algorithm and hardware modifications on the performance and required calculation power to be modelled.

VTT has also been in charge of the loudspeaker and sensor technologies in this task. Lightweight polymer material based flat panel loudspeakers and piezo-driven composite panel loudspeakers have been investigated for the purpose, but the investigations showed that their low frequency performance would not allow the whole frequency range of interest to be controlled. Therefore, conventional dynamic loudspeakers were installed into the roof liner and an additional bass loudspeaker was placed in the trunk of the vehicle to allow control at engine idle frequencies. (Figure 125.)

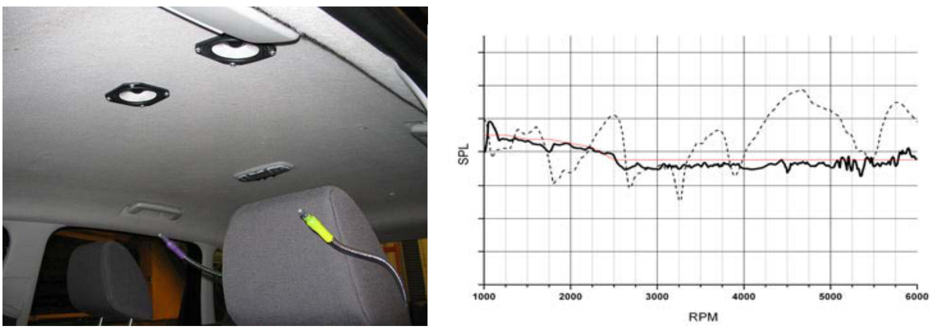


Figure 125. The loudspeakers of the Active Noise Profiling system installed in the roof liner above driver's head position, the error microphones mounted to the headrest (left) and the system performance in laboratory measurements (right). Dashed line: sound pressure level of an engine order without active control. Solid line: with control. Target level is shown with thin red line.

VTT has also been responsible for complete systems integration, system optimization and laboratory tests of the final system. The complete system was tested in laboratory at neutral gear operation, and the test results showed good performance with some minor deficiencies.

Active sound package

The car sound package mock-up consists of a steel plate with a layer of insulation material and the G1 panel based actuator-sensor pair. The size of the test package was 500 × 600 mm. The steel plate is 0.7 mm thick and the thickness of the insulation layer is 20 mm. The G1-ASP contains one G1 panel actuator, and one G1 panel element which was used (with slight modifications) as a sensor element. There was a small air gap between elements with the total thickness of approximately 10 mm.

The influence of the G1-ASP on the increase of the car sound package mock-up was **tested in an opening** between a semi-anechoic chamber and a small sending room at VTT. The size of the opening is approximately 900 × 900 mm. Small aluminium plates were added to the G1 actuator and sensor panels in order to tune the mechanical resonance of the panels. The objective was to move the resonance to a lower frequency away from the attenuated band. The mass of each additional plate was about 100 g. (Figure 126.)

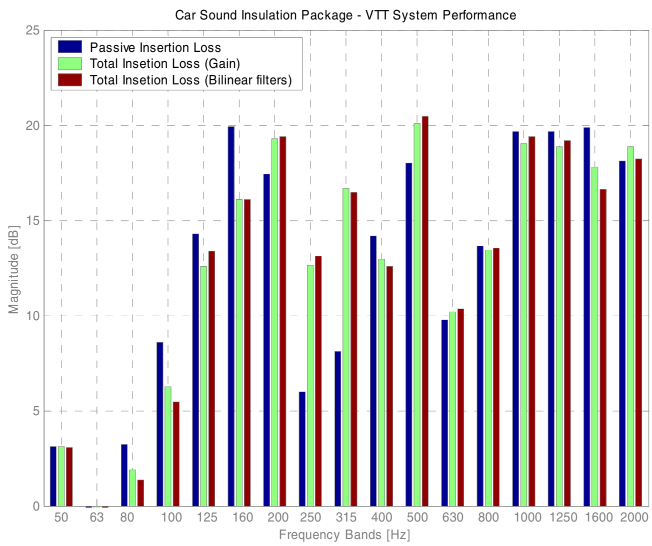
Figure 126. Scheme of the test setup for the testing of active sound insulation of a car sound package mock-up (left) and the evaluation microphone positions approximately at 1 m distance from the sensor panel on the receiving side (right).

The objectives of the testing were to **determine the passive, active and total insertion loss of the mock-up**. With active systems passive insertion loss (IL_P) is defined as the case where the (active) sound insulating structure is installed but not yet actively controlled. Insertion loss is referred to as total insertion loss (IL_T) when the active control is on. Active insertion loss (IL_A) is then the difference between the total and passive insertion loss and shows how much the active control improves or deteriorates the passive insertion loss.

The **primary acoustic excitation** was white noise. The excitation level on the sending side was approximately 100 dB. Of the four evaluation microphones one was placed near the steel plate on the sending side. The other three microphones were placed approximately 1 m from the sensor element at the receiving. The average of the three receiving side microphones was taken as the evaluation result.

One-channel FPAA analog feedback controller was used to control the active operation. The objective was to control broadband noise at frequency band 200…800 Hz. First, a simple negative gain block was used as the controller. Also more complicated controller structures with two bilinear filters (1st order filter with one zero and one pole) were designed. With the bilinear controller, no significant difference compared to the negative gain was achieved. This implies that the frequency response of the system has an optimal shape for feedback control.

Results indicate that, using active control, the sound transmission loss has been increased at 200, 250, 315 and 500 Hz 1/3 octave bands. Maximum improvement is approximately 9 dB. Some deterioration has occurred at 1/3 octave frequency bands below and above the improved bands and also at 400 Hz band. Maximum deterioration is about 4 dB. (Figure 127.)



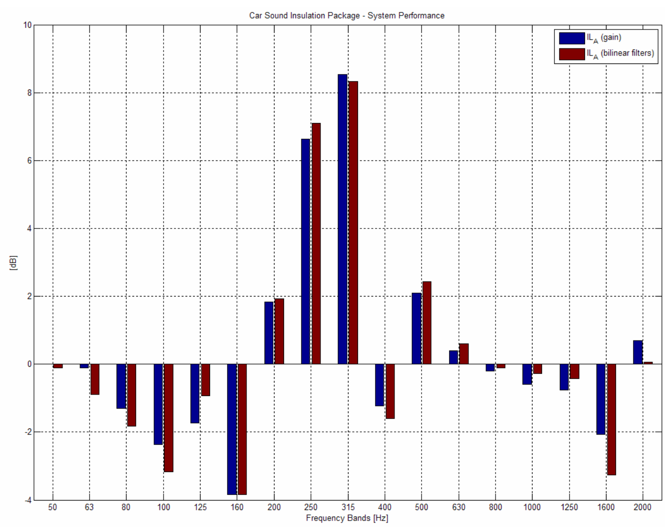


Figure 127. Passive and total insertion loss of the active car sound package mock-up with one-channel FPAA feedback controller (two different cases, left) and the calculated active insertion loss (right).

As can be seen in the test results, it is possible to achieve remarkable passive and active sound insulation increase in the car sound package mock-up using active system. Local feedback control system gives possibilities to tune and increase the sound insulation at selected frequencies, unfortunately at the expense of some decrease in sound insulation at other frequencies. Furthermore, it is quite interesting to note that the active operation works best when the passive insertion loss is at its worst. If this is a just a coincidence in this case, or more generic property of the system, will be studied further during the rest of the InMAR project.

Active elevator wall

Sound transmission loss of elevator wall has been studied theoretically and experimentally. Most of the theoretical efforts have been concentrated on the development and simulation of the elastic mass actuator EMA. Experimental efforts have been divided to the measurements of single and double wall structures by using Micromega actuators and DVF (direct velocity feedback) control system and to the measurements of basic properties of EMA-actuator. (Figure 128.)

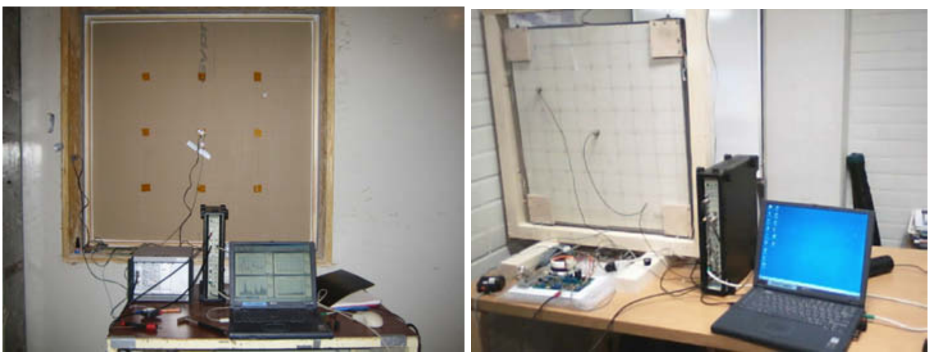


Figure 128. Measurement set-ups for transmission loss and EMA-actuator measurements.

At single frequencies it is possible to increase the sound transmision loss of wall structures by active means, especially single constructions (Figure 129).

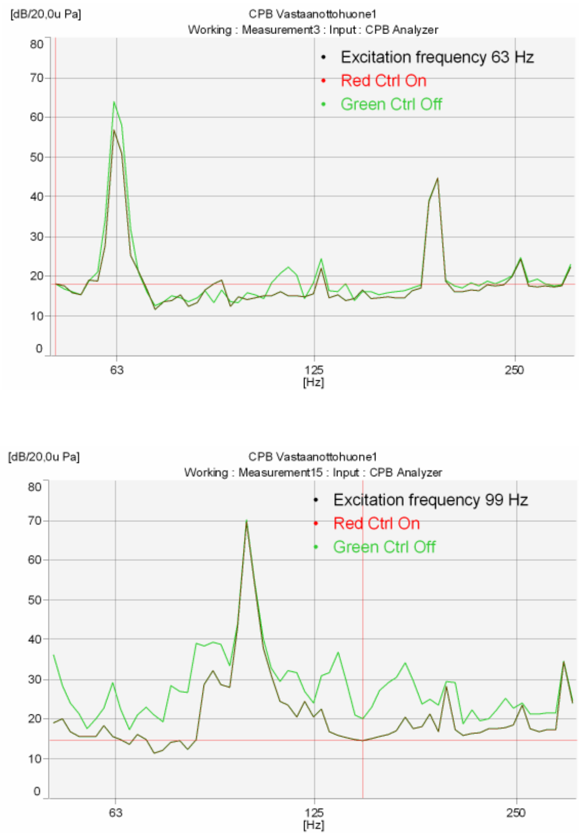
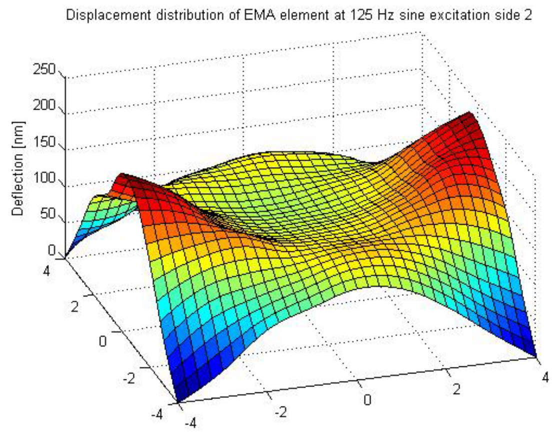


Figure 129. Measured sound pressure level in receiving room by using active control: single and double structures.

The displacement and phase distributions of EMA-actuator are quite flat at the center of the actuator and at low frequencies (Figure 130). The velocity amplitude is still quite low especially at lower frequencies. The element seems to be suitable to the elevator wall sound transmission loss application when some of the properties of the element will be modified in the next generation of the actuator.



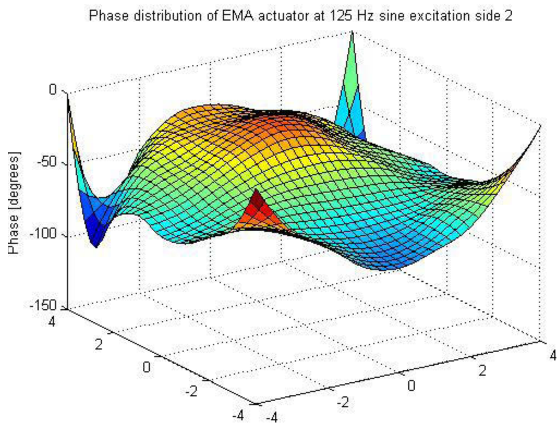


Figure 130. Measured displacement and phase distributions of EMA-actuator at 125 Hz.

4.4.3 Industrial and research networking, international position

Along with the realisation of InMAR project VTT has closely networked with several important industrial and research entities.

In composite material and polymer material based actuator and sensor development the most important partners have been Royal Technical University (Kungliga Tekniska Högskolan, KTH) in Sweden, and Budapest University of Technology and Economics (BUTE) in Hungary and, at industrial level, Panphonics Oy in Finland.

In control system development VTT has worked closely with University of Twente and TNO (the Netherlands), FhG-ITWM (Germany), ISVR (UK) and, at industrial level, with TechnoFirst (France) and ERAS (Germany).

The most important partners of cooperation to apply the developed technologies are Ford Europe (Germany) and Rieter Automotive (Switzerland) both in active noise profiling and in active sound package development and Schindler (Switzerland) in active elevator wall development.

However, there are numerous other InMAR project partners with which VTT has been in contact and exchanging ideas and research results giving excellent collaboration possibilities in the future.

In most focus areas, in which VTT is working, a leading position at European level have been gained, especially in the area of improving sound transmission loss utilising polymer material based large surface acoustic actuators (so called Active Acoustic Barrier Control concept). This reflects also VTT's international position, though in Smart Structure development utilising structural elements and control U.S. research and practical applications in general are more advanced than in Europe.

4.4.4 Exploitation and industrial impacts

The industry and the supporting, highly innovative SMEs expect from their participation new design tools, guidelines, and possibilities to vibro-acoustically optimize their products with respect to exterior and interior noise. Research organizations and universities are a vital factor in this progress by providing and enhancing the enabling technologies in a manner to which the industry and SMEs can adapt. It is the natural interest of research organizations and universities to generate generic knowledge in key technologies and to exploit these together with the industry as a reliable and equal partner.

In Table 8 below is summarised the expected exploitable results, which have been creaeted by VTT alone or by VTT together with other partners.

Table 8. Overview table of VTT's expected exploitable results.

Exploitable Knowledge (description)	**Exploitable product(s) or measure(s)**	**Sector(s) of application**	**Owner & Other Partner(s) involved**
Method to predict and experimentally validate the vibroacoustic behaviour of generic sandwich composite panels.	Vibroacoustically optimised sandwich composite plates for different applications.	Manufacture of transport equipment, building and construction.	VTT (owner)
Method to design low frequency acoustic piezo-composite actuators.	Low frequency acoustic piezo-composite actuators.	Manufacture of motor vehicles.	VTT (owner)
Method to optimise large surface acoustic and structural polymer material based multilayer actuators, sensors, active elements and systems.	Polymer material based large surface acoustic and structural actuators, sensors and active elements.	Manufacture of transport equipment, building and construction.	VTT (owner) KTH, BUTE (development), Panphonics (manufacturer of active elements)
Method to design and optimise digitally adjustable and networked analog local control electronics for active feedback systems.	FPAA-based networked local control electronics for active feedback systems.	Manufacture of transport equipment, building and construction.	VTT (owner)
Complete ANC feedback system model with emphasis on electronics.	System model and optimization tool.	Manufacture of transport equipment, building and construction.	VTT, ITWM, UTW (owners)
Method to design and optimise active sound package for cars and other vehicles.	Active sound package design	Manufacture of transport equipment.	VTT (owner) Rieter (development and manufacture of active sound packages), Panphonics (manufacturer of active elements for sound packages)
Sound Quality emphasized ANC.	ANC system model taking SQ issues into account.	Manufacture of transport equipment, building and construction.	VTT (owner), Ford, ISVR
Method to optimise the integration of large surface structural polymer material based active elements in building elements for sound transmission loss increase.	Well sound insulating light-weight walls for buildings.	Building and construction.	VTT (owner) Panphonics (manufacturer of active elements for building acoustic applications)

4.4.5 References, inventions, patents, academic degrees taken

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Tanttari, J. & Nousiainen, E. 2005. Considerations on the SEA-modelling of sandwich plate structure. Akustiikkapäivät 2005, Kuopio, Finland, 26.–27.9.2005. 6 p. (In Finnish.)

4.5 Smart structures (TOIMIRAKENTEET)

Ismo Vessonen

Abstract

The main objective of the project TOIMIRAKENTEET is to develop know-how for design and implementation of intelligent and adaptive structures for machine and vehicle industry applications. The project is related to international smart materials and structures research (adaptronics, intelligent systems) and there, the application focus has been in aero and space industry products. From Finnish perspective the application focus is rather in conventional machine industry products, where the cost-effectiveness of the technical solutions is very important.

TOIMIRAKENTEET is a joint project between three research organizations, i.e., VTT, University of Oulu and Helsinki University of Technology. The project has been conducted in two phases. The first phase (2003–2004) was aimed at developing basic knowledge on appropriate technologies and implementation of multi-technical smart structures. Industrial partners were not involved in this phase. In the second phase (2005–2007), which is still going on, five industrial partners joined the project. The aim was shifted to create and implement innovative prototype solutions, utilizing smart structures technologies, for technology challenges taken from industry. The research is funded by Tekes, the Finnish Funding Agency for Technology and Innovation, the industrial partners and VTT. The total scope of the project is about 120 man-months at VTT of the overall 226 man-months.

The first project phase was divided into three workpackages: 1) **Active joint,** a workpackage to develop structural joints for controlling stiffness and damping properties, 2) **Active shell,** a workpackage to develop active composite shell structures with the capability to control the physical shape of structural members, and 3) **Active control,** a workpackage to study control systems and algorithms for controlling functional material systems.

As results of the first research phase, a national network of multidisciplinary experts on smart structures research and implementation was formed and several potential individual technologies, as well as, integrated technology concepts were developed and tested.

The second research phase consist of five workpackages: 1) **AYLE,** a workpackage on selected enabling technologies, 2) **AMASSA,** an adaptive mass damper workpackage, 3) **ASYLI,** an adaptive actuator cylinder workpackage, 4) **AKUORI,** an adaptive shell structure workpackage, and 5) **AERISTIN,** an adaptive vibration isolator workpackage.

The ongoing second research phase has put the capabilities of adaptive functional materials to test. AMASSA has studied applicability of magnetorhelogical elastomer and a novel temperature controlled epoxy material for producing adjustable stiffness components for adaptive mass damper. ASYLI has concentrated on adapting dynamic properties of a hydraulic cylinder using the properties of magnetorhelogical fluid actuator. AKUORI has supported the adaptive shell structure development work of the SULAWIND project by developing and implementing feedback control system for the shape shifting wing structure. The focus in the AERISTIN workpackage has been in studying concepts for adaptive wire rope isolator based on magnetorheological fluid and shape memory metal controlled solutions. Vibration isolators made of the novel epoxy material studied in AMASSA and similar materials are also considered.

4.5.1 Background, starting point and objectives

A smart or functional mechanical structure is capable of observing its environment, operating state, and its own internal condition and, in response, adapting its operation to achieve optimum performance in all circumstances, even in conditions unknown at the time of product design. The term "functional structure" emphasizes the active reaction capability (embedded actuators), which is a new concept from structural mechanics point of view giving great potential for innovation and novel product concepts.

In addition to the active reaction capability, functional structures typically include subsystems for sensing, decision making and communication. All such functionality should be appropriately embedded into the structure in order to form a compact assembly with excellent performance characteristics, with minimized structural mass and life cycle energy consumption. The inspiration for the development of functional structures is often sought from the nature (biomimetics).

Functional materials (smart/active materials) are one of the most important enabling technologies for smart structures. At its best, all functions required for active adaptation – sensing, actuation and control – are integrated into a single material but there are few known materials of this kind. Therefore, practical solutions are typically searched by combining functional material based actuation capabilities with embedded and networked sensor based measurements systems and compact control technique.

Developing the properties of various technologies to a level set by real world applications is naturally essential. However, the key factor to new successful innovative product concepts is the comprehensive integration know-how, with which the technology components are put together to form a reliable, well-performing, and optimized assembly. The design of intelligent functional structures calls for know-how to control the whole multi-technical design, test and implementation process and the ability to efficiently use advanced modelling, simulation and testing tools required to accomplish the task. Figure 131 illustrates the main fields of knowledge involved in implementation of smart structures.

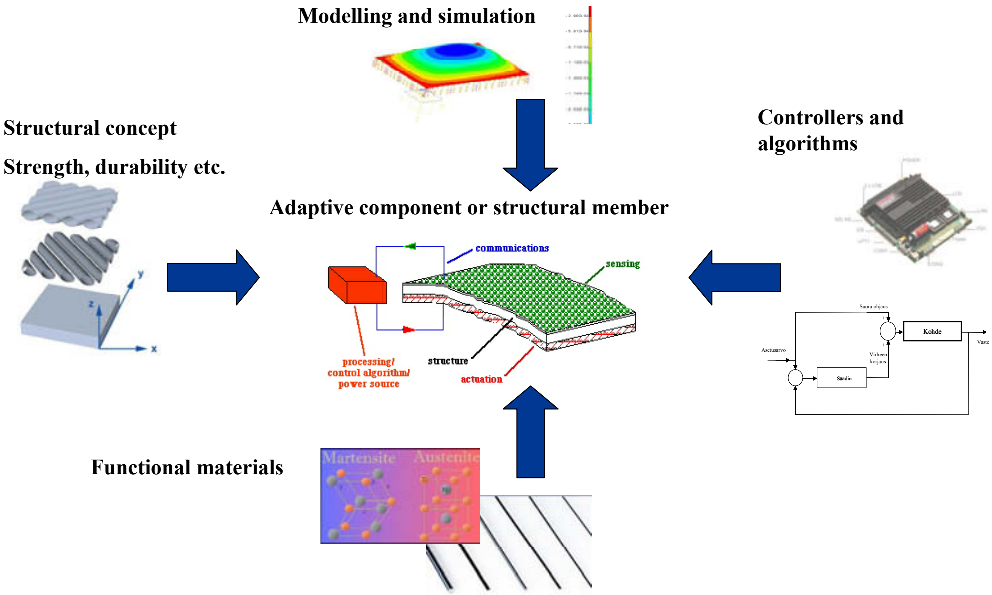

Figure 131. Smart structures – a multidisciplinary effort.

The project TOIMIRAKENTEET is related to smart materials and structures research (adaptronics, intelligent systems), which has been a hot topic in international science for about 20 years. The application drivers for this research have been aero and space industries, mainly in USA and Europe (Germany), whereas, in Japan the research have been focused on civil engineering applications like earthquake protection and vibration suppression of buildings and bridges. The high-tech solutions for these high asset-value applications, often also military in nature, has brought with several novel technologies e.g. materials, sensors, actuators, control schemes, etc. However, few practical applications for machine industry have been introduced to the market, so far. The most important applications have been noise and vibration, durability and structural shape control. The last application is mainly related to flow control; of which perhaps the most well known have been the efforts to develop deformable wings and blades for airplanes and helicopters.

In Finnish industry, the focus of R&D will certainly be in conventional machine industry products, and there, e.g., cost-effectiveness of the technical solutions is of utmost importance. Accordingly, the strategy at VTT with Finnish industry, is to adopt these technologies, their related engineering practices, etc., developed elsewhere to such high-end products or applications. Besides reducing life-cycle costs, the essential features for development in Finland are the reliability, performance, various environmental impacts. From structural point of view this could mean, e.g., simplifying or replacing complex mechanical structures or parts with innovative functional designs and/or minimizing weight and energy consumption with a novel lightweight structural solution. The vision of project is that, in the future, smart structural concepts are used, at least as components or subassemblies, in many leading edge products of machine and vehicle industry.

Objectives

The main objective of the research project TOIMIRAKENTEET is to develop know-how for design and implementation of intelligent and adaptive structures for machine and vehicle industry applications.

The underlying aim is to improve national technological competitiveness by transferring and developing implementation oriented basic knowledge at design and implementation of embedded functional materials and control technology based innovative and intelligent products.

Since the development of intelligent structures is inherently a multi-technical task requiring know-how from many different engineering fields, one important aim is to establish a virtual knowledge centre between universities and research institutes working in the field to facilitate knowledge sharing and innovation processes looking for technological breakthroughs. Contacts to top level international smart structures institutes is also one clear mission for the project.

The project TOIMIRAKENTEET strives for a technology leap in smart structures know-how in Finland. The transfer to commercial products is expected to occur mainly after 5–10 years, but also earlier spin-offs are actively searched. One aim is to promote postgraduate studies on smart structures so that at least 2–3 experts could start their thesis work during the 2 year period of the project.

4.5.2 Implementation and results

Because of the novelty of smart structures research in Finland it was decided that the project should be carried out in two phases: The purpose of the first phase to be carried out during 2003–2004 was to develop basic know-how merely among research organization Helsinki University of Technology, University of Oulu, and VTT. The purpose of the second phase (2005–2007) is to combine the developed technologies and skills into industrial prototypes in a continuation project where research organizations and industrial partners co-operate.

Workpackages of the first phase (2003–2004)

The research started with hands-on experimentation and modelling tasks of simple test cases to familiarize the group with the basics of functional materials. In the second step certain laboratory-based adaptive structural parts were created. The project was divided into three workpackages according to the identified and expected application potential for the second phase and beyond.

AJOINT, Active joint: The objective was to develop and demonstrate concepts and devices for implementing structural joints capable of actively controlling stiffness and damping properties of the joints. The focus was on the concepts of active friction joint and active stiffness controlled spring element.

This workpackage studied mainly semi-active ways to control structural impedance in joints of a modular structure. Controlling mechanical impedance is regarded as a most potential concept of smart structures. Varying mechanical impedance is applied widely in nature, e.g. in stiffness adaptation by muscular system. The approach might offer great potentials to realize cost-effective embedded structural elements to change the dynamical properties and responses of structures without inputting excessively and continuously energy and without the need of complex external control systems.

Functional materials such as commercially available piezo ceramics (PZT) and shape memory alloys (SMA), as well as, some novel materials like magnetorheological elastomers (MRE) were in major role in this study. The active operation of the structural elements under development is based on these materials.

International research efforts on various active joint concepts have been and are going on but, in general, the topic is not well covered in science.

Results

Equipment for producing chained magnetorheological elastomer (MRE) elements was developed. Several test specimens were prepared for testing the stiffness change in MRE elements under static magnetic field. Maximum increase in dynamic stiffness in compressive loading was about 60% due to applied magnetic field. The corresponding increase in static stiffness was 100% (Figure 132). MRE is considered to be promising material technology to produce adaptive stiffness components.

Secondly, two prototypes of an active friction damper, realized with high-voltage piezo actuator, were developed. The latter prototype introduced especially compact design with piezo actuator aligned with the loading road and a special link mechanism to turn the loading direction 90 degrees (Figure 133). The results showed controllable friction force in the range of 300–700 N, although desired control over force the range of 0–2 kN was not achieved. The main lesson was that flexibility of the whole loading chain should be carefully considered while designing equipment utilizing piezo and other similar kind of short stroke high output force actuators. Altogether, fast acting controllable friction damper is considered to be a potential concept for many applications calling for high force amplitudes also at low motion velocities and controllable force amplitudes ranging from zero to desired maximum value.

Literature survey on different alternatives to model frictional joints in FE-analysis was performed. The study focused on macro-scale models of friction joints. Multi-linear friction model, composed of several serially connected spring-friction elements configured in parallel, was selected as the modelling approach and was implemented in MODYSOL, a VTT developed, MATLAB based, modelling environment.

A desktop device for technological studies and demonstration of active friction joint and SMA spring element was designed and implemented. A PC-104 based control system was set up for controlling the active elements of the test device.

Researcher exchange to Stanford University was arranged. The topic for the visit was "Feasibility study on measuring structural stress using Smart Layer concept". Smart Layer is a grid of piezo based actuator/sensor elements attached on the surface or embedded inside of a mechanical component. The original use of smart layer is to identify damages inside, on the surface or in the joints of a structure. The aim was to study novel ways to exploit Smart Layer in structural loading and response measurements.

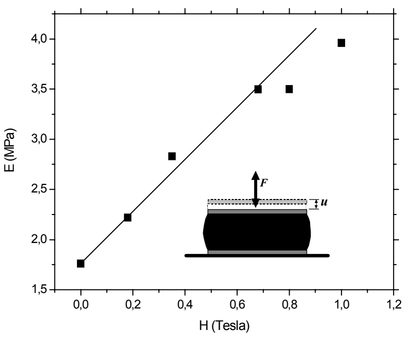

Figure 132. Modulus of elasticity for MRE material as a function of applied magnetic field in compressive loading.

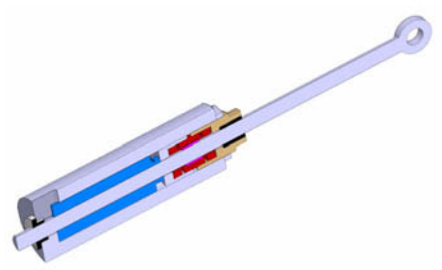

Figure 133. PZT-actuator based controllable friction damper.

ASHELL, Active shell: ***To develop and demonstrate active composite shell structures, which are capable, through smart structural design and integrated functional material systems, of reacting to internal or external stimuli with an appropriate response.***

Lightweight and effective load-bearing shell structure is common in many vehicles, machines and devices. Fibre re-enforced plastic (FRP) composite and sandwich structures were selected as starting point for the study. These types of lightweight structures are particularly interesting because their mechanical properties are relatively easy to tailor (fibre orientation, stacking of fibre layers, asymmetry etc.) according to needs. It is possible to embed functional material-based actuators and sensors – even control systems – into the structure during fabrication.

The research work was directed to implementation and demonstration of active functionality in generic structural shell elements (common in many applications). The focus was on SMA based shape control of FRP-beams and structural panels (laminated or sandwiched).

The international research of active FRP composites and embedding structural loading and damage detection measurements into composites is vivid. The potential of tailored lightweight composites combined with embedded sensing and active functionality is widely noticed.

Results

Extensive state-of-the-art reports were prepared under titles "Potentiality of functional materials in smart structures made of re-enforced plastic" and "Structural health monitoring methods in smart structures".

A Master's thesis on tailoring passive, anisotropic, composite structure, so that it increases and directs the displacements created by actuators, was prepared. Asymmetric laminate structure which has a strong coupling between bending and twisting or extension and twisting is one potential way of implementing this concept. The thesis work included FE-modelling of different design alternatives and experiments with asymmetric laminate beam which showed twisting amplitude of 3.5° under axial loading of 30 kN.

The results of controllability tests clearly indicate that SMA wire is a quite potential actuator to implement the shape control of shell structures made of reinforced plastic. Performed tests with different SMA materials and varying gauges showed good controllability as a function of applied electric current.

A demonstration structure for controlling and suppressing the deflection of a laminate beam under moving and changing loads was created. The structure is a simply supported laminate beam with an external SMA wire assembly for controlling the shape (Figure 134). The results show that this SMA assembly is very effective and highly suitable for deflection control of beams and plates. The stiffening effect of the beam was also considerable.

Because in many applications embedding the SMA wires into the laminate structure itself is preferred, also some demonstration laminates with embedded SMA's were prepared and tested. In this respect reference is made to the results of subproject SULAWIND.

The use of embedded fibre optic strain measurement for producing loading state and deformation feedback information for shape control applications was also studied (Figure 135). The studies with laminates without embedded SMA wires gave positive indication of applicability as long as the fibre embedding related challenges are properly tackled.

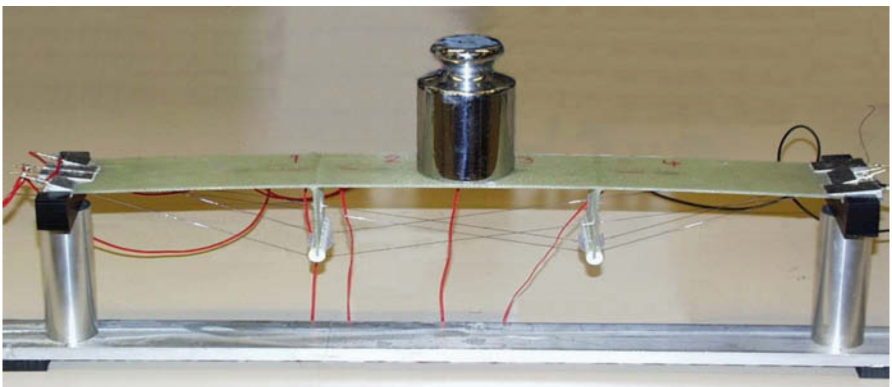

Figure 134. Deflection compensation of a laminate structure with external wire actuators.

Figure 135. Embedded Fibre Optic strain transducer (Fibre Bragg Grating) enlightened with visible laser light.

ACONTROL, Active control: ***To study and implement both general and application oriented control systems, strategies and algorithms as well as, motion amplification technology for controlling functional material systems.***

The control system including sensors, signal conditioning, power electronics, controller hardware, as well as, the control algorithms, is the brains of any intelligent system. In this context, the need is for easily programmable, compact, miniaturized and embedded, environment resistant processing cards. The computation must be real-time and capable of handling, e.g., complicated vibration and noise control algorithms of several degrees of freedom with control frequencies ranging to several kilohertz. The applications often call for in-expensive, lightweight and embedded power generation.

Acquiring know-how and experience to control certain PZT and SMA actuators was the most important task of this workpackage. Especially control of SMA wire actuators was regarded important. The topics were e.g. general controllability, heating procedures, and long-term durability issues. Systematic controllability study of SMA materials is also quite path-breaking, from international research perspective.

The researchers of this workpackage worked closely with the other two teams of application oriented workpackages, and were responsible for the control system design and implementation in general in this context.

Results

The main task of the ACONTROL workpackage was to design and implement appropriate control systems and algorithms for the demonstration devices of the application workpackages AJOINT and ASHELL. This part of the results is described in associated parts of this report. In addition to this ACONTROL workpackage prepared a literature survey on motion amplification methods for functional materials based actuators. Inherent small motion amplitude is a serious problem in many active materials like piezoceramic and magnetostrictive materials. Several prototypes of motion amplifies were also prepared. Extensive controllability tests for various SMA wire actuators were also performed.

Workpackages of the second phase (2005–2007)

The results of the first phase form the basis for continuing the technology development in the second phase. The concrete aim is to develop functional prototypes for candidate applications selected together with the industrial partners.

At the time of writing this report, the research work in the four application workpackages (AMASSA, ASYLI, AERISTIN and AKUORI) of the second phase is still ongoing at full flow. Development work in the AYLE package has been finished in summer 2006. This report describes the status of the project at the end October 2006.

AYLE, Enabling technologies: A workpackage to develop technologies beneficial for the other workpackages. The first aim is to implement the material model for SMA, identified and further developed in the first phase of the project, to develop it to an engineering design tool to be run on top of a common numerical modelling tool (e.g., Matlab, FEM). The second objective is to design and implement a prototype for an efficient, compact, and cost effective FPGA (Field Programmable Gate Array) controller suitable for smart structures applications.

Results

Based on requirements defined in the AMASSA workpackage, an FPGA (Field Programmable Gate Array) controller design has been specified and implemented. The controller consist of a processor card, an I/O card with multichannel analog-digital and digital-analog cirquitry and gates for digital I/O and digital temperature input. A preliminary version of the controller has been delivered for use as controller platform in adaptive mass damper control algorithm development.

An SMA material model (including both superelastic and actuator characteristics of the material), suggested by Prof. Sittner of Academy of Sciences of Czech Republic, has been implemented in several versions in MATLAB and ABAQUS modelling environments. The so-called iterative strain controlled model is the best performing version of all tested models. However, also this model requires too much special knowledge and interaction from the user to be considered as a practical design tool. The further development work of the SMA material model has now been shifted to another project funded by Academy of Finland (MAFESMA-project with ESF status).

AMASSA, Adaptive mass damper: The objective is to develop prototypes based on the concept of semi-active auxiliary mass damper, further based on variable stiffness and damping control studied in the first phase. Mass damper is a generic structural vibration control concept with wide application potential. Adaptability is needed to keep up the dynamic tuning of the auxiliary mass with the varying dynamic properties under control or with the fluctuating vibration excitation. Novel control schemes using material actuator based fast damping control are also studied.

Results

Comprehensive literature review on adaptive control algorithms for mass damper has been conducted. Fast control of damping force between auxiliary mass and the structure under control has been found especially interesting novel control concept, which has the potential to enhance the performance of a mass damper.

The new FPGA controller platform, delivered by the AYLE workpackage, has been set up and tested. After getting experience on the programming environment, the basic I/O routines for the controller have been programmed and the implementation of the mass damper control algorithms is underway.

A prototype of a shear spring, made of a special epoxy material with temperature controllable properties has been prepared and tested. This material, which is VTT's invention, has such characteristics that the modulus of elasticity of the polymer reduces steeply and reversibly over a narrow temperature range, which is adjustable by alloying of the polymer. At the same time with reducing modulus the loss factor of the material reaches its maximum value. With the tested material, shear stiffness of the prototype spring reduced to 65th-part of the original, over temperature range 0–60 ºC. Temperature control has also been tested as a combination of hot air blow with conventional means and cold air blow using a vortex tube. The results indicate that the temperature of the polymer is rather well controllable, if issues like heat generation due to vibration and heat transfer are properly considered.

Development work of magnetically controllable MRE-springs has been continued. Several version of the spring, made of different base polymer material, has been prepared and tested. In static compressive loading three-fold stiffness due to applied magnetic field has been reached. At the same time the dynamic stiffness change has been approximately 2–3 times the original stiffness, while using loading amplitudes of 0.125–0.5 mm and frequencies between 5–20 Hz.

Two different adaptive mass damper concepts have been designed and the implementation work is under way. In the first concept the adaptation comes with changing stiffness of the spring(s) connecting auxiliary mass of the damper to the structure under control. Varying stiffness introduces change in frequency tuning of the auxiliary mass. In this context tuning means the relation between a resonance frequency of the structure and the resonance frequency of the auxiliary mass. This tuning directly affects the vibration suppression performance of the damper. The stiffness controlled mass damper introduces temperature controlled epoxy spring for rough adjustment of the tuning frequency (20–40 Hz) and a fine tuning (a few hertz) spring made of MRE and controlled via magnetic field. The auxiliary mass (about 40 kg) is formed by the copper wired coil needed to produce the controlled magnetic field. At the time of writing the components for the springs are dimensioned and designed and final test versions are being fabricated. The detail design of the whole concept (mechanics, cooling, heating etc.) is under way.

The second concept is based on rapidly controlling damping force between auxiliary mass and the structure. A prototype mass damper consisting of conventional spring elements, mass element of the same size as in concept 1, linear motion guides, and two alternative (not at the same time) damping control devices. The first device is an evolution version of the piezo actuator controlled friction damper studied in the 1st phase of the project. Second choice is a commercially available magnetorhelogical (MR) fluid damper. In both cases it is important to achieve also, as close as possible, zero damping force, which is essential in order to achieve good vibration suppression performance with continuously changing damping.

ASYLI, Adaptive actuator cylinder: Hydraulic (and pneumatic) cylinders are common actuators in mechanical engineering, producing large actuation forces and supporting heavy machine components. These actuators are inherently flexible devices from vibration point of view, causing dynamic problems, e.g., those associated with resonance phenomena. The objective of the workpackage is to study alternative ways to control stiffness and damping properties of hydraulic cylinders to optimally adapt to changes in the dynamics of operating conditions. Primarily magnetorheological fluid (MR) based actuator concepts are studied here. Frictional damper with fast control capabilities is also of interest.

Results

The research work in ASYLI workpackage started with selection of a real world case actuator, for which adaptive dynamic properties should be developed. Long stroke hydraulic cylinder of a paper finishing machine was selected for the purpose. Here the need is to control vibration of massive beam structure supported and actuated by two such cylinders. The sizing of the actuators was suitable for research purposes and a trial machine for test was available. On the other hand this was a challenging case because the adaptation should be targeted to continuously moving actuator.

Dynamics measurement for a trial paper finishing machine was arranged in order to find out design requirements and limitations for the adaptive actuator. Dynamic FE-model of the target beam structure and the actuator arrangement was also set up. Concurrent measurement analysis and numerical calculations revealed that the dynamics of the hydraulic cylinder was different from the expected theoretical simple model.

To clarify the differences between theory and practice, a laboratory test arrangement was set up to study dynamic properties of a hydraulic cylinder as function of frequency, vibration amplitude and fluid volume. The test revealed that a hydraulic cylinder is a highly non-linear actuator in terms of vibration amplitude. The dynamic stiffness of the actuator increased rapidly with motion amplitudes under 0.2 mm supposedly due to stiffening effect of piston and rod seals. Since this is rather typical motion amplitude in vibration of machine components at frequency range of about 5–100 Hz, it is clear that this extra stiffness (compared to what is calculated based on fluid volumes) should be taken into account while designing vibration control actions. This study on dynamics of hydraulic cylinders is reported in a Master's Thesis prepared in University of Oulu.

Meagnetorheological fluid based damper device was selected as candidate solution to bring along the necessary adaptation capability to control beam vibration in the case under consideration. MR damper was selected because it is a good solution to control continuously moving cylinder and the achievable forces were estimated to be sufficient, despite the inherent flexibility of a long MR-cylinder, for controlling structural resonance related vibrations.

Based on dimensions of the original cylinder, a trial MR actuator was designed, implemented and tested. The first test was done using low-viscosity MR-fluid made by VTT. The results indicated that the energy loss in the MR-actuator could be increased five-fold by applying magnetic field to the MR-valve of the cylinder. This was calculated to be enough to reduce vibration level of the beam in case machine by 50%.

Because all necessary could not be completed during the 1st test round, the test session was repeated with several changes in the set-up including change of MR-fluid to commercially available material. This time the dynamic tests gave confusing and inconsistent results compared to the first test session. The interpretation and further analysis of the results is under way.

AKUORI, Adaptive shell structure: The adaptive wind turbine blade section, created and studied in subproject SULAWIND, is also a pilot structure for the AKUORI workpackage. The objective is to study the applicability of embedded fibre optic sensors in conjunction with FRP (Fibre Enforced Plastics) embedded SMA wires. Another objective is to implement the control system and algorithms for the active shape control of the blade section.

Results

In Helsinki University of Technology a Master's Thesis has been prepared on the applicability of fibre optic strain measurement for monitoring and feedback controlling purposes in shape control of adaptive laminate structures. The results show that embedded fibre optics is a feasible way to realise control measurement also in case of SMA actuated laminates.

A control system for shape control of the scale model wind turbine blade structure, prepared in subproject SULAWIND, has been set up and successfully tested. The control system realises feedback (strain gauges) regulation of embedded SMA laminates including heating control hardware for SMA wires and associated algorithms. The control system is programmed using LabView-program and a PC-computer. Another test session with a blade section closer to full scale blade dimensions is in progress at the moment. In addition to larger scale structure, this test includes also fibre optic strain measurement system.

AERISTIN, Adaptive vibration isolator: In real world applications, passive vibration isolation is often a compromise between vibration isolation and motion control of the system. Adaptive stiffness and damping properties of isolators would be beneficial in optimising dynamic properties for varying operation environments and loading conditions. The objective of the workpackage is to create, implement and test novel adaptive vibration isolator concepts based on functional materials.

Results

The requirements for adaptive vibration isolator were thoroughly considered in co-operation with industrial partners. Adaptation to changes in mass loading of the isolated device was chosen as an example case for the study. In physical terms this means that the stiffness of an isolator has to be adjustable. Stemming from the interest of industrial partners, solutions for adapting the properties of wire rope isolators are especially sought for.

As a result of mutual brain storming session, two identified concepts were studied further. A set-up with a wire rope isolator and a nested rubber hose filled with MR-fluid together with an attached MR-valve/hydraulic accumulator combination was made for testing. In static tests the achieved stiffness change due to MR-valve activation was three-fold. However, dynamic tests did not show as good results. At frequencies below 5 Hz the stiffening effect disappeared apparently due to inertia effects associated with the fluid flow through the MR-valve. It was decided not to continue development of this concept.

The basic idea of the second concept was adopted from the boundary condition controlled circular spring designed and tested in the SULAWIND project. This concept features wire rope isolator equipped with a SMA operated locking mechanism. The SMA wire actuator activates a clamp connection between two lateral structural members attached to opposite edges of a wire loop in a wire rope isolator. This connection changes the deformation pattern of the isolator and as a result stiffness increase can be measured. The effect was confirmed using passive connection elements. SMA operated clamping device was prepared and tested separately and positive indication of feasibility was obtained. A prototype device including all necessary parts is under preparation.

The possibilities offered by the epoxy material studied in AMASSA workpackage, will also be taken into consideration in the coming actions of AERSTIN workpackage.

4.5.3 Industrial and research networking, international position

1st research phase (2003–2004)

Research scientist Tatu Muukkonen from VTT was working at Stanford University for nine months in 2003–2004. His assignment was to study novel ways to exploit Smart Layer concept in measuring loadings of mechanical structures. He was working as a visiting scholar in Smart Structures and Composites laboratory (Department of Aeronautics and Astronautics) under the supervision on professor Fu-Kuo Chang. Professor Chang is a world famous researcher of smart materials and structures specialized on structural health monitoring and composites.

One shorter researcher exchange period to the Smart Structures and Acoustic Laboratory of University of Massachusetts/Lowell was also carried out in autumn 2004. Lauri Kantola from University of Oulu stayed for 3 months in Lowell in order to find out specific research topics of mutual interest. Prof. Christopher Niezrecki hosted the visit.

In the course of the project VTT has also established contacts to several Far East and US smart structures institutes by joining the ANCRISST consortium (Asia-Pacific Consortium of Centers on Advanced Smart Materials and Smart Structures Technologies).

2nd research phase (2005–2007)

In the beginning of the second research phase the focus of activities changed from building basic know-how to more application oriented research. The main research question was formed as follows: “What real-world problems could these technologies solve?” or “What kind of added value or new innovations could these technologies produce for industry?” The shift in the research agenda reflected also in the international research networking, which has restricted to a few visits in international conferences. On the other hand the interest of Finnish industry in smart structures related issues has grown rapidly and several companies are willing to improve their competitive edge with some new technological innovation.

4.5.4 Exploitation and industrial impacts

The results of the project are expected to be widely applicable in machine and vehicle industry products. Mobile machines, pulp and paper machinery, combustion engines, electric power engines, ships, power plants, buildings, bridges, masts etc. are a few examples of Finnish industry products, which probably can benefit from the findings of the project.

The know-how developed can be of value both for general machine building industry and for vehicle manufactures. Machine building can, e.g., gain structural stiffness and damping control elements to alter dynamic properties in order to avoid problematic vibration response states in service. With better vibration control it is possible to avoid problems in run-up/down situations and in actual service run. This could be, e.g., avoiding setting restrictions to the operation of machines (e.g., prohibited RPM-ranges) or a possibility to introduce novel methods to solve dynamic problems, which continuously make it difficult to increase production speeds etc.

One such generic vibration control concept is adaptive mass damper (AMASSA), which could be beneficial for a wide range of application as a temporary or permanent solution to handle design mistakes or some kind of unexpected changes in dynamic behaviour. These can be costly occasions while valuable assets stand idle waiting for solution to guarantee safe operation. One of the participating companies in the second research phase has started its own concurrent R&D project, one aim of which is to develop a scaleable and adaptive mass damper concept using conventional actuator technologies. The know-how gained in project TOIMIRAKENTEET has been utilized also in this development process.

Dynamic problems associated with the flexibility of hydraulic and pneumatic actuators (ASYLI) are common in mechanical engineering. Thus a simple and cost effective solution to this problem setting would certainly find many practical applications.

For vehicle and mobile machine industry the project can produce novel ways to implement semi-active dampers for vehicle motion and vibration control (axle and cabin suspensions). In semi-active operation friction dampers have several advantages over traditional fluid dampers. Adaptive vibration isolator (AERISTN) could be especially useful in vehicle applications, where varying loading and operating condition will set different requirements for the optimal operation of vibration isolation. Growing number of sensitive electronics in machinery also tends to increase the demand for advanced isolation solutions e.g. in special application seeking good combination of vibration and shock isolation properties.

The results of subprojects ASHELL and AKUORI are applicable to several flow control applications. Deforming structural members can be beneficial to several applications: Shape controlled bottom panels for fast-going motor vessels, active blades of wind power plants (vibration, durability, energy production efficiency), various kinds of turbines and bladed wheels in fans etc., and air flow control applications in general. Moreover, various impact control solutions using sandwich structures are possible for motor ships/boats as well as for other applications. Industrial fluid flow control has certainly numerous applications for this technology. E.g. applications where certain paste or fluid/solid suspension should be evenly spread through some kind of gap and the process should be precisely controlled. One imaginable object could be adaptable beds, seats and furniture in general, where the need is to be able to modify the ergonomics to fit the user's personal needs.

In addition to the above mentioned application possibilities, the project is going to produce generic advantages in the form of increased know-how on practical issues in applying functional materials (mechanical and long-term properties, application "tricks" etc.) as well as more generally applicable control methods and tools for numerical design studies of functional materials systems.

Until now several invention announcement has been turned in to VTT's evaluation process and at least two priority patent application has been deposited. Patentability of a few other ideas is under consideration at the moment.

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5. Highlighted results

5.1 Active and Communicative Package Systems

5.1.1 Impacts to industry

The project has significantly increased knowledge on designing functional inks and sensor systems combined with relevant printing methods, printed codes and printed electronically readable indicators. Also knowledge on intelligent measurements and on control systems for the transport supply chain was increased. This has served as a basis for several industrial commissions performed in parallel with the project, aiming at developing various sensor systems (Chapter 2.2) and at improving logistical supply chain management (Chapter 2.6). In addition, the knowledge and IPR generated in the project is currently being marketed to Finnish and international companies.

Todate, at least one packaging indicator product has been commercialized by Raflatac Co. The optical coding systems developed in the project are also linked to activities with Upcode Ltd. The company is commercializing a service product based on reading printed tags with a camera phone, as well as, the retrieval of product specifications or user instructions via an Internet.

5.1.2 Impacts to VTT

The increasing importance of packages as communicative media was the main motivation for the Active and communicative packaging systems project in 2002. Since then this has been seen increasingly important and potential research area within VTT, and numerous internal, jointly-funded and contract research projects has been carried our related to printed functional products. Packaging as a printing substrate has been a very important application area.

In 2005, all VTT's related research efforts were assembled in the Printed Functionality roadmap -project (Södergård et al. 2005). Printed functionality means adding new functionalities on a flexible substrate, typically paper or plastics, in addition to regular graphical properties. Such functionality can be applied on the surface of the substrate or embedded inside it, or both. Printed functionality can be codes (one-, two-dimensional, invisible, reactive, electronic) containing links to additional information, visual effects and images, multi-layer structures, electronics, optics, displays and indicators. The roadmap project concluded that Finland has a good opportunity to gain a significant role globally, especially in areas related to forest industry. However, this may happen only if VTT proactively directs resources to printed functionality. The roadmap also predicts that VTT's volume may be at least four times larger in 2015 than it was in 2005 (around 44 man years in 4 different VTT institutes). This would take VTT to a leading R&D position globally, at least in certain sectors, as analysed in the study. The global turnover is expected to grow about 300% during 10 years.

In August 2006, VTT established the Center for Printed Intelligence (CPI) to coordinate and exploit the operative efforts towards VTT's goal – Global Leading Innovation Center in Roll-to-Roll Printed Intelligence (http://www.vtt.fi/whatsnew/2006/20060905.jsp?lang=en). VTT wants this strategic initiative to contribute more effectively in the exploitation of research results for the generation of applications. By combining information technology, electronics and printing technologies, VTT is creating entirely new business opportunities. VTT has considerable competence as a developer of printed smart technologies both at the domestic and international level. VTT's new Center for Printed Intelligence seeks to break new ground in the area between the traditional ICT industry and the paper industry. An extensive review on bioactive paper was prepared in 2006 in which packaging indicators were also included (Aikio et al. 2006).

5.1.3 Summary and conclusions

In the project Printed Indicators, several printing inks containing a certain reactive substance to indicate oxygen, and suitable for ink-jet printing onto plastic materials has been produced. This kind of indicator is capable of denoting package leakage and can be used for perishable foods, sterilizable foods, or pharmaceuticals. In addition, attention was paid to the concept of freshness indicators. Humidity indicator and ethylene indicator developments have been started in the project and further developed in other projects, e.g.

SUSTAINPACK. A research environment for inkjet printing was build up during the project to enhance the ink development. VTT has patented inkjet printable indicator and sterilizable indicator, and two more patent applications on humidity indicator and coding systems will be filed still in 2006. Basic research findings related to diagnostic ink compositions and knowledge on food or package interactions and volatile analyte compounds correlating with food quality have been further utilized in three large industrial projects and in two customer-owned patent applications. Currently, two types of printable oxygen indicators are under evaluation among potential customer companies.

It has been predicted that about one billion mobile phones will be sold in the world in year 2007, and that 90% of these phones will be equipped with a digital camera. This means that most of the people will soon be using the emerging camera phone technology everyday, and this development will offer considerable prospects for the subsequent services. The technologies and the operational environment in which the new camera phone based applications have been developed in the project Optical Coding and Detecting Systems. 2D bar-code utilization in information transfer together with a piece of software enabling detection of colour-changing codes has been demonstrated. For example, a recipe to prepare a favourite food can be encoded in a 2D bar-code on a foodstuff package, to be later on read out with a properly equipped camera phone. 2D bar-codes have also been studied in the SUSTAINPACK EU project.

The series of projects Electrical Readable Indicator focused on the development of printable conductive wiring and electric thin-film indicators. The projects could demonstrate a wireless humidity sensor and the fabrication and measurement of thin-films for room-temperature oxygen sensors. Inkjet printing using nanoparticle ink and curing multiple layers led to high enough conductivity for RF-coils. The research in Electrical Thin Film Indicators was focused on studying oxygen sensitive materials that involved a change of conductivity. The studied materials were both reactive metallic thin-films and organic based thin-films, and their suitability for food packages was a prerequisite for the utilization. It was noted that thin metallic films can be applied to oxygen detection since a clear change in conductivity is observed when the film is exposed to oxygen. However, the high reactivity sets challenges to the protection procedures of the material prior to the actual use of the sensor.

The overall objective in the project Logistics – Increasing Intelligence in Supply-Chains was the development and integration of an intelligent measurement and control system for the transport supply chain. The IT architecture of intelligent monitoring equipment was created, and the architecture showed the complexity and the demanding nature of these systems. A case study dealing with temperature in a food chain showed that even this simple task is challenging in today's supply chains.

5.1.4 References

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5.2 Distributed Energy

5.2.1 Topic highlights

Considerable achievements were obtained in several projects of the Distributed Energy project. The basic idea of a distributed simulation environment has been presented and elaborated in a new context, in which building energy simulators and district heating network simulator are hydraulically and thermally linked from the power plant via the district heating network to the internal room conditions in buildings.

A new service and business concept – heat trading was developed together with tools to design, simulate and evaluate the distributed thermal energy system.

The main delivery, a brake-through achievement of the distributed energy simulation project is an alpha-prototype of a software tool capable of performing challenging task of simulating operation of the whole energy supply chain simultaneously.

New concepts were defined for the plug-and-play interconnection and management of distributed power systems. In addition to creating new software tools, considerable research effort was devoted to develop new products, including phase change materials aimed for application in thermal (and cooling) energy storages, electricity storages and in supercapacitors.

5.2.2 Summary and conclusions

Distributed energy production remains an important research topic worldwide because of economical and environmental issues and higher reliability demands for power network operation. To be able to design and manage power as well as thermal energy distribution network a close examination of economical and technical impacts of the new concepts is required. In our projects new concepts and system configurations were defined and studied, and tools and devices for the intelligent management of the distributed energy were developed.

For the thermal energy management the main achievement is development of an alpha-prototype of coupled software that is capable of mastering the distributed simultaneous simulation of the whole energy chain; this is a brake-through achievement. Models for district heating network and substation heat exchanger were developed and adapted. A system level of fuel cell model was developed and incorporated in building's energy simulation. An economical evaluation was carried out considering different heating systems operated in a group of houses connected to a district heating network and heat trade was evaluated as a new business concept and technological feasibility was found.

For the power system management the factors and existing requirement related to the interconnection of different type of generation units were defined. As a case study, a SOFC fuel cell unit interconnection was investigated, where the concept was realised by using necessary separate relay protection and functionality was divided between protection and inverter control system. For the short term electricity storing the development of supercapacitor was started by the studies of different materials and constructions.

The exploitation of knowledge created in this research work continues in the ongoing and future research projects. For example the development of the storage systems continues in the ongoing co-operation projects and the development of ENTRY-Master software tool continues in the VTT new technology theme.

The project has had several significant impacts for example a co-operation network was created connecting the VTT units, Nordic countries, EU and international co-operation levels. The project activated also numerous domestic R&D projects together with the industry. For example a national DG testing site will be built in Espoo in one of these projects. Also the international co-operation gives possibilities to start new international co-operation projects in the future.

5.3 Embedded Structural Intelligence

5.3.1 Topic highlights

From the technology development perspective given in Section 4.1.3, following topic highlights can be identified:

Know-how and tools for integration design of multi-technical systems using functional virtual prototypes.

A multidisciplinary-modeling environment has been developed and is used in power system dynamic studies of wind farms. A simulation environment incorporates hierarchic modeling of the wind farm, individual turbines (aerodynamical, mechanical and electrical behavior), intelligent subsystems and interaction with operation environment.

Different models and tools working simultaneously enable to study, which mechanical phenomena are transferred to the electrical side, the influence of network disturbances to the mechanical side, the impact of control actions and development of new control strategies, indicators that can be used for condition monitoring purposes, new technical solutions and materials in order to reduce harmful forces and events on for example drive train etc.

The mechanics of the turbine are modeled with multi-body systems code ADAMS. This complex model includes 3D-wind field and flexible parts such as blades, tower, drive-train etc. The control system of the turbine that regulates blade pitching, yawing and generator characteristics is modeled in Matlab/Simulink. The electrical components of the turbine and the network are modeled in PSCAD/EMTDC.

Along the growth of the size, the slenderness of wind turbines has increased leading to increased importance of vibration and fatigue control of blades and supporting structures. Active duration and load control algorithms have been included and demonstrated in the developed models.

Intelligence embedded in composite materials and structural joints through integration of functional materials systems.

Active composite materials: In the project the manufacturing and integration of SMA's in laminates to actively control the shape of the laminate has been in focus. Also vibration control has been tested.

A novel, advanced method to manufacture SMA composites was developed. The method is combination of mechanical sleeves and adhesive joining. The basic idea of the method is that SMA wires are connected to reinforcing fibres. With a method like this, it's possible to use larger diameter SMA wires because forces generated by wires are more evenly distributed and pullout of wires can be restricted. With the development work of adaptive wing profile, more convenient industrial scale manufacturing method has been studied. The aim of this study is to develop manufacturing method for SMA composites where no extra assembly jigs are needed. This means that adaptive composite manufacturing process would not greatly deviate from traditional composite manufacturing route in terms of used materials and manufacturing methods. Patent evaluation of developed technology is in process.

An adaptive airfoil structure representing a part of a wind turbine blade was created and tested. The structure consisted of FRP laminates with embedded SMA actuators and optical fibre sensors. Also strain gauge sensors were used. The control system was a primary controller plus a feedback secondary controller. The control system worked well enough in simple actuation, but is under more development to adapt to flow situation where the airfoil needs to act against a load caused by the wind flow.

Active structural joints: Several novel concepts to implement adaptive dynamic properties for structural joints have been introduced. These stiffness and damping control devices utilize functional active materials to produce the adaptive properties.

Magnetorheological elastomer (MRE) material and a family of novel temperature controlled epoxy material, developed by VTT, have been one of the main research focuses. Developed MRE material has shown five-fold stiffness increase due to applied magnetic field in compressive dynamic loading. The epoxy material can be alloyed to produce steep change in modulus of elasticity at desired temperature range. 65-fold reduction of shear stiffness of a spring made of this material has been measured. Several stiffness control concepts utilizing actuator property of Shape Memory Alloys (SMA) have also been develop. 3–5 fold on/off type stiffness increase has been produced with these devices. Still ongoing development work is aimed to find practical ways to exploit these material properties and concepts in adaptively controlled structural spring elements in applications like vibration isolator and adaptive mass damper. This work is done in collaboration with industrial partners.

Magnetorheological fluid (MR-fluid) actuators and piezo ceramic actuator controlled friction joints have been studied as controllable damping devices. Especially fast controllable friction joint has shown good potential for various applications, because of the possibility to produce high damping forces already at low motion amplitudes and the ability to produce good dynamic range for the force (also zero force if necessary). MR-fluid based solutions have been topic in controlling dynamics of vibration isolators and hydraulic cylinders. Balance between application requirements and possibilities offered by state-of-the-art material technology are also still sought regarding these materials and concepts.

Adaptable resonance vibration control method for rotating machinery

SULAROTOR project enabled to build a deep know how on active control systems, particularly on control algorithms. This know how is resulted a doctoral thesis and several publications.

During SULAROTOR project, the customer focus for active vibration control solutions was refined and a new development initiative was started. The new customer focus was based on technical research of the topic and market analysis regarding to the benefits of the active control solution. The research resulted to the flexible electrical machine concept that currently is being developed in a joint-funded project.

Intelligent Materials for Active Noise Reduction

The first realization of novel composite panel concept at VTT is a GFRP panel with striped core made of two different materials. The panel shows up to 10 dB better sound insulation compared to the reference (homogenous stiff core) panel.

Two types of polymer material based actuator-sensor elements have been developed together with Panphonics Oy, one for active structural control and one for active acoustic control of sound transmission loss of panel type structures.

Development of multi-channel digitally adjustable analog control system is carried out for the active systems e.g. utilising large surface polymer actuators. The developed FPAA prototype controller contains an FPAA unit board and a microcontroller. The prototype controller system has been tested in active car sound package mock-up with large surface polymer actuator-sensor pair with up to 9 dB improvement in the target frequency band with broadband acoustic excitation. Local feedback control system gives possibilities to tune and increase the sound insulation of the sound package at selected frequencies giving flexibility for the sound insulation design of car sound packages and other panel like structures.

5.3.2 Summary and conclusions

The topic area Embedded Structural Intelligence within Intelligent Products and Systems technology theme was aimed to produce know-how, verified technologies as well as integrated technological solutions for machines and vehicles industry products to improve their competitiveness. The activities have covered several aspects in facilitating intelligent and adaptive structural concepts: novel material technology, information technology solution in form of control systems as well as virtual design environments for intelligent products.

At the beginning of the technology theme in 2002, the role and level of know-how at VTT in intelligent structures related research was that of a skilful demonstrator builder. The basic knowledge on the most important individual technology fields was there but the know-how was scattered around VTT and the technology integration point of view was mainly missing. Small scale demonstrators on capabilities of functional materials had been built, active vibration control using conventional technology had been shown to work in reality, material technology and demonstrations for active noise control research had been developed etc.

At the same time the interest in new innovations and technology breakthroughs was rising in Finnish machine and vehicle industry. Material technology is an important technology field to look at when improved competitiveness is searched for. What makes materials so tempting is that developing a reliably operating and added value creating materials based solution for a product typically requires a great deal of special know-how and somewhat extensive development efforts. This makes materials based solutions difficult to copy, which helps in retaining competitive edge in the market. Adaptively controlled embedded functional materials clearly offer this kind of opportunity for innovations and novel solutions.

The technological status at VTT as well as the industry's belief in novel materials based solutions formed the basis for the selection of Embedded Structural Intelligence as one of the topic areas of the technology theme in 2002.

The research work within the topic area has clearly brought technology integration viewpoint beside the development of individual technologies. Multi-technical nature of intelligent structures concepts and the industry's demand for novel, reliable, and ready-to-go solutions necessitate close multi-disciplinary co-operation within research community. This is essential in order to be able to introduce well balanced integrated solution candidates for final commercialization process carried out by the companies. The working approach in several projects has promoted hands on collaboration between experts in different fields of engineering, sharing common application case and trying to implement a comprehensive solution.

The topic area has also highlighted the need to utilize functional virtual prototypes beside conventional physical prototype based approach in the design and development multi-technical intelligent structures. Our experience shows that well balanced numerical simulation and experimental prototyping efforts are the most efficient way to gain the necessary insight to physical phenomena involved and to find the ways to implement the intended functionality and other requirements. Trial and error based prototype development approach is often too slow and expensive alternative. On the other hand, it is neither possible nor practical to try to model every aspect of a design, not to mention the risk to fully rely on unverified models.

The co-utilization of some combination of Modern Multi Body Simulation (MBS), Finite Element Method (FE), and control system design (MATLAB/Simulink etc.) software offers a powerful tool to design multi-technical intelligent structures. The SULAWIND project has successfully demonstrated the use of this kind of modelling approach in designing structural concepts and adaptive control of wind turbines. The model covers the whole chain of dynamic physical phenomena from wind induced loads through the models of the power transmission system, mechanical structures, and control systems to the dynamic model of the power transmission grid. The uses of this kind of integrated model are numerous e.g. in mechanical strength/dynamics/durability design, design of control system and related adaptive features, design of condition monitoring instrumentation, in troubleshooting and in solving damage situations etc.

Modelling based approach was somehow utilized in all subprojects of the topic area, although the lack of appropriate numerical models for functional materials has in many cases still forced us to use experimental approach. Altogether the course of progress is evident: the utilization of functional virtual prototypes in design of intelligent structures will increase rapidly in the future.

Applying functional materials has been one major issue in the Embedded Structural Intelligence topic area. In SULAWIND and Smart Structure projects the technology to produce composite structures with embedded SMA wires as well as the technology to regulate the shape of the structure was developed. The results have been promising and the work will continue in EU-funded IP-project UPWIND (wind turbine application) and in the national Smart Structure project. The technology is inherently suitable for several flow control applications and the project team is confident that other industrial applications can be found in the near future.

The InMAR project has developed both novel passive composite structures, acoustic composite actuators, polymer material based actuator-sensor elements, and novel control approaches. All these concepts will be developed further and their capability demonstrated in applications during the rest of the InMAR project (–2008). These concepts involve new ideas for producing acoustically optimized lightweight structures, which are expected to be applicable in wide range of machine, vehicle, and civil engineering structures. The development of polymer based actuator-sensor elements is aiming to create flat actuator elements able to produce enough power to control structural vibration or acoustic field especially at lower frequencies (< 100 Hz). Novel load carrying light weight composite panels combined with panel actuator and sensor elements and together with the internationally new approach for local multi-channel feedback control based on Field Programmable Analog Array (FPAA) technology, give totally new possibilities for active increase and tuning of sound transmission loss of panel type structures, e.g. in vehicles and buildings. The project team is optimistic about achieving good results with studied actuator concepts but novel material options are also searched for. The application potential of cost-effective active control of sound is large especially in cars and other vehicles, where the objective can be, in addition to noise cancellation, active tailoring of the sound profile to the desired image of the product. Efforts to start industrial application development by utilizing so-far gathered know-how are under way as well.

Material actuators for semi-active control of stiffness and damping properties of discrete structural elements have been studied in the projects SULAWIND and Smart Structure. Shape memory metal, magnetorheological elastomer and a novel epoxy material based stiffness control elements have been designed and implemented. Another research topic has been megnetorheological fluid damping and piezo ceramic actuator based friction control elements. Five domestic industrial partners have brought their challenging applications as case structures for the Smart Structure project. Especially promising novel materials are the magnetorheological elastomers and the epoxy material, which both include VTT's own IPR. Fast friction control with appropriate actuator has also shown its potential but the stroke of current piezo actuators is about one order of magnitude too low for most applications.

Materials related activities in the topic area have produced several novel concepts, which will be further developed and applied in research and industrial R&D projects. The work has also revealed potential materials, which were not sufficiently studied in the course of the work. One such material group is the electro-active polymers, which can be potential actuator materials for several applications. On the other hand, the use of functional materials as embedded sensors to indicate loading, deformation, structural damages, wear rate etc. would certainly be an interesting research topic with a wide application scope.

The idea of the SULAROTOR project was to study active control systems and algorithms to control vibration of flexible rotor systems. In the course of the project, the focus was set particularly on rotors of electric power engines, in which the greatest potential for applications was identified. The research work is continued in a project funded by Academy of Finland, VTT and one industrial partner.

Altogether the conclusion is that many of the original objectives for the topic area "Embedded Structural Intelligence" were achieved. The research work has included genuine co-operation with prominent international experts (InMAR, SULAWIND/UPWIND, SULAROTOR). Intended active internal collaboration at VTT has also been realized in every subproject. Smart Structure project has also established active co-operation with two national universities (Helsinki University of Technology, University of Oulu) and during the second researched phase the project has focused on finding industrial partners and application areas for developed intelligent structural concepts. No such results which could be described as major breakthroughs are achieved. On the other hand, every subproject has some kind of continuing jointly funded project going on to fulfil this expectation as well. At VTT the topic area has produced one doctoral thesis and three others are in preparation (SULAWIND, SULAROTOR, and InMAR), one licentiate's thesis (SULAROTOR) and two master's thesis (SULAWIND).

6. Discussion

Intelligent Products and Systems theme programme has been an exceptional opportunity to VTT and to the particular research teams to strengthen their R&D for a longer time than has recently been commonplace in an ever accelerating and project-oriented life-style prevailed in research, too. Exploitation of research results, innovations, and fast return-of-investments were predominant research management paradigms already in 2001. The economy of a research institute, like VTT, is dependent on its success in agreeing on research consortia or even direct contracts which often means adjusting the research operations closer to R&D agendas of key industrial or commercial partners and domestic or international. However, it was also recognized in the beginning that revising seriously our scientific and technology basis is crucial for the success and growth of VTT, and for its mission to catalyze technology development activities in industry.

Certain general criteria for planning the programme and measuring its success was given: high ambition level, reaching out to international level, benefiting of the multi-technology spectrum both inside VTT and among domestic or international partners, when successful high impact to industry, enough focusing of resources and long-term goal setting. There is certainly also an upper limit how much and how long should an organization like VTT focus its resources on selected topics. Good research consortia and even research contracts may be as well very beneficial, also to the "vendor" of research results, even if measured with the same criteria as was defined to theme program projects. As pointed out several times in this voluminous report, often a combination of various types of projects was appropriate to effectively advance to the goals. Interaction with industry is essential both from substance and economy point of view but self-funding has its share, too.

The criteria for projects have been met to various extents! In the following we summarize the successes of the topic areas.

Active and communicative package system was an appealing challenge in the beginning. The project team was very competent to carry on experimental research on various chemical and other substances. It was not perhaps so difficult to discover candidate compounds, etc., suitable for the indication function as such but the hard part was the requirements for non-toxicity, applicability in industry scale inkjet printing, adhesion to plastics and paper, and other restrictions arising from the applications. One research institute has capacity to investigate a certain amount of cases and, therefore, becoming a partner in the much larger EU project was necessary; which is also a sign of international level at VTT. Similarly, it was very important to broaden the scope from visual indication to electronically signaled indication. Both global and domestic industry has also got interested in our results, as mentioned in this report.

The so called printed functionality is a significant new integrated focus at VTT. Combining the experiences and results of indicator research with the many kinds of advances in electronics manufacturing, etc., the future there looks now really striking.

The ultimate success of intelligent packages is, to a large extent judged, whether logistical or other information systems are able to benefit of the increasing intelligence of packages, even if they as such are made reliable, low-cost, etc., enough. Today, these systems do not commonly deal with individual packages, even less with their measured quality. One-dimensional bar-codes are predominant, RFID identification is slowly replacing them but a lot of standardization, information systems and business process development is still needed.

Energy sector has been and will be, to major extend, very big business – in all perspectives. Also time-spans are very long, often decades, and the same is true for distributed energy, too. In 2001, distributed electric power seemed rather distant in time and distributed heat energy even more distant. Wind energy, photo voltaic, fuel cell were already in 2001 very acute, at least in R&D. However, recent global trends have made all kinds of energy topics much more attractive, and both distributed electric and distributed heat power are much more up-to-date than even expected in 2001. Admitted though that biofuels, revised nuclear energy, oil and gas, etc., will have a major role both in industry and in research.

Modeling and simulation is a very important approach to study such new concepts. Accordingly, most of the efforts were directed to modeling work. VTT has long traditions in simulating almost any technology, and more often to an industrial or so-called real-life scale. Especially, the increased readiness to model and simulate – not just temperature and other conditions of buildings – but also entire neighbourhoods or city-blocks including power stations (very small and very large), heating grids, etc., is exceptional for a research institute and rare in general. All kinds of digitalization of civil engineering is taking giant steps now, VTT and Finland is strongly contributing to that trend, and modeling and simulation will be the key technology in this sector, too.

Modeling and simulation has become multi-technological. This was strikingly evident in the ENTRY projects, and perhaps even more predominant in the SULAWIND project. In the Intelligent Products and Systems theme program, the integrated simulator pilots were rather implemented by "experimental programming" meaning that the mathematics solving the phenomena and especially the interactions were coded in Matlab, Adams, etc. In the recently started new theme program (Complex Systems Design) we are so-to-say more professionally addressing the simulator interaction, configuration, etc., challenges by the aid of service-oriented architectures, semantic representations, etc.

All directions in the large Embedded Structural Intelligence have been successful, at least if the criteria are biased towards applied research. After a good start of the projects within the topic area, the TOIMIRAKENTEET project was ranked, and also financed, as a top technology project of the Tekes-MASINA national technology program. The industry consortium, participating first as an advisory group, continued to the second phase of the project, as a partner group with pilots taken from their R&D agendas. The joint project is still ongoing but the direction is as planned in 2001. On academic scale, the SULAROTOR is perhaps the most successful; recently it has been co-financed by the Academy of Finland that almost by rule supports only basic university research. The international dimension has been rather active, most notably the large EU InMAR project must be acknowledged here. All projects of Embedded Structural Intelligence are also good combinations of experimental and modeling & simulation work.

Finally, technology roadmapping turned out to be an effective means to steer and refocus the projects. In retrospect, the initial planning of the topic areas and the respective projects was rather informal and, in summary, based on topic maps outlines and vision descriptions. On one hand, roadmapping would have been necessary already in 2001 but, on the other hand, the project teams were very experienced, motivated, and effective in 2004 to reconsider the goals, trends, gaps, etc. The refined method to carry out the roadmapping process was also a success. It utilized maximally the experiences and opinions of the participants, and effectively directed the strategy planning to the remaining or coming years.

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Intelligent Products and Systems
Technology theme – Final report

Abstract

"Intelligent Products and Systems" has been one of the four strategic technology theme programs of VTT Technical Research Centre of Finland during 2001–2006. This theme program consisted of three topic areas with their respective research projects. The topic area "Active and Communicative Package Systems" has significantly increased knowledge on designing functional inks and sensor systems combined with relevant printing methods, printed codes and printed electronically readable indicators. Also a series of projects focused on the development of printable conductive wiring and electric thin-film indicators. The projects could demonstrate a wireless humidity sensor and the fabrication and measurement of thin-films for room-temperature oxygen sensors. In the topic area "Distributed Energy", the basic idea of a distributed simulation environment has been presented and elaborated in a new context, in which building energy simulators and district heating network simulator are hydraulically and thermally linked from the power plant via the district heating network to the internal room conditions in buildings. In addition, new concepts were defined for the plug-and-play interconnection and management of distributed electric power systems. The topic area "Embedded Structural Intelligence" was aimed to produce know-how, verified technologies as well as integrated technological solutions for machines and vehicles industry products to improve their competitiveness. The activities have covered several aspects in facilitating intelligent and adaptive structural concepts: novel material technology, information technology solution in form of control systems as well as virtual design environments for intelligent products.

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Älykkäät tuotteet ja järjestelmät
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Tiivistelmä

Älykkäät tuotteet ja järjestelmät on ollut yksi VTT:n neljästä nk. teknologiateemasta (tutkimusohjelmasta) vuosina 2001–2006. Teemaohjelma koostui kolmesta hankealueesta projekteineen. Hankealueen ”Aktiiviset ja kommunikoivat pakkausjärjestelmät” projektien ansiosta tietämys funktionaalisista musteista tai indikaattoriväreistä, vastaavista antureista, tulostustekniikoista, koodeista ja sähköisesti luettavista indikaattoreista on kasvanut merkittävästi. Muutamissa projekteissa kehitettiin myös tulostustekniikalla tuotettavia johtimia ja ohutkalvoja. Hankealueen ”Hajautettu energia” projekteissa kehitettiin alallaan ainutlaatuinen simulointiympäristö, jossa voidaan joustavasti yhdistää sekä talojen energianhallinnan simulointia että lämpöverkkojen ja lämpövoimalaitosten simulointeja. Toisissa projekteissa vastaavaa mallinnusta ja simulointia tehtiin sähköverkkojen osalta. Kehitettiin myös energiavarastoja. Kolmannessa hankealueessa ”Sulautettu rakenneäly” kehitettiin monia funktionaalisten ja adaptiivisten materiaalien ratkaisuja kone- ja kuljetusvälineteollisuudelle. Projekteissa tutkittiin uusia materiaaleja, virtuaalitekniikoita ja aiheeseen liittyviä ohjausjärjestelmiä.

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VTT PUBLICATIONS 635 Intelligent Products and Systems. Technology theme – Final report

Olli Ventä (ed.)

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