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Future Nordic Concrete Architecture

- Innovation by screening possibilities to manufacture singular concrete structures at competitive cost.
- Where is the concrete architecture heading?
- In which way should the technology be developed in order to bring the concrete architecture up front?



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Abstract: <p>The overall objective of the project is to carry on the innovation of the Nordic concrete architecture by screening the possibilities to manufacture singular concrete structures in a competitive cost frame.</p> <p>This involves focus on the usage of high-technology solutions and automation in the global concrete industry in connection to manufacturing of singular concrete structures. These areas will be analyzed through a state-of-the-art research and through tests of new technologies that makes it possible to industrialize the manufacturing of singular concrete structures.</p> <p>Furthermore, the project makes a hypothesis regarding future concrete architecture. This involves answers to the question: Where is the concrete architecture heading? And in which way should the technology be developed in order to bring the concrete architecture up front.</p>	
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Executive summary

Main objectives:

The overall objective of the project is to carry on the innovation of the Nordic concrete architecture by screening the possibilities to manufacture singular concrete structures in a competitive cost frame.

This overall objective demands fulfillment of the following sub-objectives:

- To generate an overview of the usage of high-technology solutions and automation in the global concrete industry in connection to manufacturing of singular concrete structures.
- To make a hypothesis regarding future concrete architecture. This involves answers to the question: Where is the concrete architecture heading? And in which way should the technology be developed in order to bring the concrete architecture up front.
- To test new technologies that make it possible to industrialize the manufacturing of singular concrete structures. This involves analyzing and testing new alternative and flexible formwork materials and development and testing robot technology in the manufacturing of singular concrete structures.
- To achieve consensus regarding future possibilities and challenges in the concrete architecture by arranging a Nordic workshop.

These objectives have been met the following way:

- A thorough research in the area of high technology production methods in the construction sector has been performed
- A research in Nordic concrete architecture – which resulted in a report made in connection to the project – has been performed.
- Robot technology has been used for experiments. This involves milling of formwork for concrete in casting sand.
- The possibilities of combining computer drawings and robot technology for making unique concrete structures have been demonstrated through the manufacturing of concrete sculptures integrated in specific pieces of architecture.
- A Nordic Workshop with external participants has been arranged at Danish Technological Institute.

Method/implementation:

To implement the project a mix of research and practically experiments has been used.

The State-of-the-art research in high technology production methods and the research on the future Nordic architecture have been performed using typical information databases. Add to this the usage of important networks both internally and externally.

The robot cell at Danish Technological Institute has been the basis for most of the practical experiments. Interesting results from the research part have been used to plan experiments on the robot and hereafter executed resulting in physically results. This involves the creation of digital 3D models which have been milled out on the robot using different milling tools to achieve different surface textures. The formwork material used for small scale experiments has been casting sand.

Knowledge from the casting industry has been used in order to choose the casting sand which is most suitable for milling and casting of concrete. For the large scale experiments expanded polystyrene has been used for the manufacturing of the formwork parts for the demonstrations tests.

All results from the project have been presented and discussed at the Nordic workshop arranged at Danish Technological Institute on March 17, 2010.

Concrete results and conclusions:

The research in high technology production methods in the construction sector concludes:

- In particular, the development of self-compacting concrete (SCC) have made it possible to cast complicated shaped and heavy reinforced structures. However, SCC is not straight forward and needs careful selection of the rheological properties and casting technique to avoid e.g. poor form filling and segregation. One example of a SCC application is the Ordrupgaard Museum outside Copenhagen, which won the Danish In-situ concrete price in 2006. Furthermore, developments within fibre and textile reinforce concrete will enable the production of thin shelled structures.
- Several digital fabrication processes have been identified based on the underlying computational concepts such as 2D fabrication, subtractive fabrication, additive fabrication, assembly and surface treatment.
- As alternatives to the traditional concrete shuttering (steel and plywood) materials like textiles, polystyrene foam and silicone rubber are suitable for processing using a robot.

The research in future Nordic concrete architecture concludes:

- With new possibilities to work with the plasticity of concrete it is an obvious possibility to create a working relationship between the architect and sculptor.
- In the Nordic countries the concrete architecture will be up front concerning new digitally manufacturing methods.
- The Nordic concrete architecture will continue to interpret the new possibilities with Nordic poetry and distinguished sense for both the whole and the detail.

The demonstration tests using robot technology concludes:

- There is a great potential in using casting sand as formwork material for future concrete structures due to the great advantages regarding de-moulding, easy milling, reusability, and homogeneous concrete surfaces.
- Polystyrene is an effective formwork material. It is relatively cheap and milling can be carried out a high speed due to the low density of the material.
- It is possible to produce complex shaped 3D structures in closed formworks using polystyrene formwork parts and casting with SCC. Sculptures made within the project shows this potential.
- Industrial robots are excellent tools to convert the complex ideas of shape from the sculptor into physical formwork part for concrete casting.

The Nordic workshop concludes:

- Great potential of translating the methods used in the project to other fields of construction.

- Singular concrete structures with complex shape and double curved has a high potential for the future. Architects are very interested in pushing the limits to concrete architecture and change the general perception of concrete from a low-tech construction material, which bring negative associations to peoples mind, to a construction material with strong performance both from a structural and aesthetic point of view.
- Digital 3D design tools are being used more and more. The developments in CAM technologies will help bridge the gap between architects drawings and production.

Recommendations:

- Further investigations on casting sand as formwork material.
- Implement robot industry in the concrete sector. This could e.g. be formwork producers and/or concrete manufacturers who invest in new equipment.
- There is a need to focus also on the reinforcement solution for singular concrete structures. For instance, look at the potential of shaping conventional reinforcement using robots, fibre reinforcement, and textile reinforcement.

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Introduction

The overall objective of the Nordic project 'Future Nordic Concrete Architecture' (2008-2010) is to carry on the innovation of the Nordic concrete architecture by screening the possibilities to manufacture singular concrete structures in a competitive cost frame. This involves:

- Generating an overview of the usage of high-technology solutions and automation in the global construction industry in connection to manufacturing of singular concrete structures.
- Making a hypothesis regarding future concrete architecture. This involves answers to the question: Where is the concrete architecture heading? And in which way should the technology be developed in order to bring the concrete architecture up front.
- Testing new technologies that make it possible to industrialize the manufacturing of singular concrete structures. This involves analyzing and testing new alternative and flexible formwork materials and development and testing robot technology in the manufacturing of singular concrete structures.
- Achieving consensus regarding future possibilities and challenges in the concrete architecture by arranging a Nordic workshop.

The project which has been partly funded by Nordic Innovation Center is a collaboration between the following Nordic partners:

- Danish Technological Institute (Project manager) (DK)
- Swerea Swecast AB (SE)
- Giben Scandinavia A/S (DK)
- Norwegian University of Life Sciences – UMB (NO)
- Esben Klemann (DK)

This report sums up the activities and results achieved during the project. For further details please follow the direct web-links inside the report.



Background

In the Nordic countries we have a very recognised concrete architecture tradition. Great architects like Sverre Fehn, Erik Gunnar Asplund, Alvar Aalto and Jørn Utzon has challenged the concrete in fantastic projects.

Despite this tradition and the unique fresh state properties of concrete allowing the concrete to take any given shape, the majority of the concrete architecture we know today is often dominated by repetitiveness and recognisable geometries like squares and rectangles.

The constructions sector and especially the concrete industry are outdated when it comes to manufacturing of singular concrete structures. It is still based on traditional craftsmanship which is difficult to produce, time consuming and expensive.

Through the 20th century concrete has become the most used building material in the world. The usage of concrete has led to a new architecture which exploits the isotropic properties of concrete to generate new shapes. Despite the considerable amount of concrete used in architecture, the concrete is surprisingly little visible. Often concrete is only used as the material for the load-bearing structures and afterwards hidden behind other facade-materials.

But concrete has a big unexploited potential in order to create beautiful shapes with spectacular textures on the surface. This project has explored and tested new possibility for casting concrete using automation technologies.



High technology production methods in the construction sector

Ever since concrete was first invented by the Romans it has become the most used construction material. Concrete has obvious benefits in terms of its structural behaviour but its ability to take upon any shape provides architects with a unique degree of architectural freedom compared to other building materials. However, the architects vision can only be realised to the extent the technical knowhow and economy allows it.

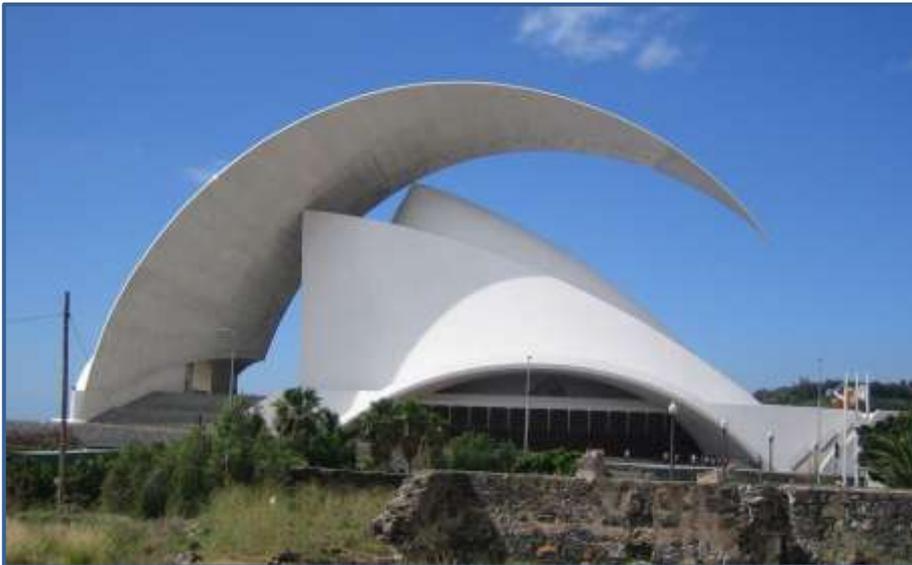


Fig. 1: Tenerife Opera House – an example of complex concrete architecture.

In many ways concrete structures consist of building blocks which are assembled to form the final shape. The blocks may be cast at the building site or at the precast element plant and they may be more or less complicated/unique.

From a concrete technology point of view, the last 10 years have shown the potential of new types of concrete. Especially Self-Compacting concrete (SCC), fibre reinforced concrete and textile reinforced concrete have opened up for new and more interesting concrete architecture. With SCC it is possible to cast very complex form work geometries which would have been very difficult or even impossible to cast using traditional vibrated concrete and fibre reinforced concrete opens up for much thinner cross sections introducing a lighter appearance to the concrete structure. However, fibre reinforced and textile reinforced concrete is mainly for use in non barring structures and cannot replace conventional steel bar reinforcement.



Fig. 2: The extension of the Ordrupgaard Museum in Copenhagen. Complex shape cast in self-compacting concrete.



From a construction point of view, advances in new construction techniques can push the limits of possible concrete architecture e.g. the Tietgenkollegiet in Copenhagen. Another example which may appear in the future is large thin shell structures. Today the use of shells is gaining more importance in architectural designs for facades, interior design and roof structures.



Fig. 3: Tietgen Collegium, Copenhagen. The circular main building has 45 hanging concrete boxes in two stories, which contain kitchens and other common facilities. The largest boxes have a free span of 8 m and weigh 250 tons. Cowi, the consultant company, solved this structural challenge by using innovative solutions and "free forward construction". It is a construction method that normally is applied for building bridges. The method has no need for scaffoldings and the result is a significant saving in time and money.

For the creation of large surface structures a viable connection technique is necessary. The connection of the elements will be established by post-tensioning. This allows for a blunt connection, that is able to transfer normal forces and moments across the connection e.g. test setup Post-Tensioned arch. In the following, the focus will be on the individual concrete building blocks and new developments especially in relation to automation, digital fabrication and handling.

Formwork manufacturing processes

Today, a lot of effort and costs go into formwork production including the load carrying formwork, recesses, and reinforcement. The formworks consist for the main part of standard modules which offer only little to the architectural quality of the structure. Complex formworks are very expensive and are mainly done in relation to prestige projects as the level of craftsmanship is very high. Especially singular or unique elements are extremely costly. That is also the reason why most of the concrete structures we see e.g. for housing are low cost constructions of low architectural quality.



Fig. 4: Complex formwork for the Ordrupgaard extension manufactured with a high level of craftsmanship.

However, digital architecture and fabrication is the future with a large potential in terms of automation and free form fabrication. The digital format has given architects a powerful tool to design concrete structures. It was only within the late 90ies that the advances in computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies started to have an impact on building design and construction practices. They opened up new opportunities by allowing production and construction of very complex forms that were until recently very difficult and expensive to design, produce and assemble using traditional construction technologies. The consequences will be profound, as the historic relationship between architecture and its means of production is increasingly being challenged by new digitally driven processes of design, fabrication and construction. Manufacturing processes include precise placement of individual parts, cutting, lifting, milling, spraying, polishing etc.

The ability to mass-produce irregular building components with the same facility as standardized parts introduced the notion of mass-customization into building design and production. Mass-customization, sometimes referred to as systematic customization, can be defined as mass production of individually customized goods and services, thus offering a tremendous increase in variety and customization without a corresponding increase in costs.

Digital fabrication refers to the computationally based processes of form production and fabrication based on a digital architectural model. Several digital fabrication processes are identified based on the underlying computational concepts such as:

- 2D Fabrication. Examples are shown in: Multi-Function-Shuttering-Robot 1/2, Multi-Function-Shuttering-Robot 2/2, Water jets, plasma-arc CNC cutting.
- Subtractive Fabrication involves removal of specified volume of material from solids using multi-axis milling.
- Additive Fabrication involves incremental forming by adding material in a layer-by-layer fashion, in a process converse of milling e.g. sprayed concrete. It is often referred to as



layered manufacturing, solid freeform fabrication, rapid prototyping, or desktop manufacturing. All additive fabrication technologies share the same principle in that the digital (solid) model is sliced into two-dimensional layers. The information of each layer is then transferred to the processing head of the manufacturing machine and the physical product is incrementally generated in a layer-by-layer fashion. Shotcreting may also be thought of as additive fabrication and fully automated robotic systems are under development.

- Assembly. After the components are digitally fabricated, their assembly on site can be augmented with digital technology. Digital three-dimensional models can be used to determine the location of each component, to move each component to its location, and finally, to fix each component in its proper place.
- Surface treatment: Different processes like polishing, sand blasting and spraying are operations which can be applied to both the formwork and the final concrete element.



Fig. 5: Digital fabrication using robot technology, laboratory of the Concrete Center at the Danish Technological Institute



Formwork materials and coatings

Precast forms are normally made of either steel or plywood. In the production of precast concrete elements, the forms are typically reused, i.e. a large number of castings are performed in the same forms which results in saving of raw materials. The number of times a Plywood form can be reused is limited to about 20 to 50 castings depending upon the complexity, maintenance and shape of the form. Standardized elements cast in steel forms are one step towards sustainable production as an almost unlimited number of castings can be made using steel forms. Standardization of precast products will save cost. Attempts by the precast industry to standardize precast cross sections are designed to save costs and increase market share by getting the maximum number of casts out of every form. The most often used alternative to the smooth appearance obtained from steel and plywood forms is by lining the formwork with timber.

A number of materials that can be used as an alternative to the traditional concrete shuttering and that are also well suited for processing using robots are listed below:

- **Textiles:** One of the new technologies in formwork technology is textile formwork – an alternative to traditional concrete shuttering that allows for more efficient and expressive structures.
- **Polystyrene foam:** Single use moulds can be created quickly using polystyrene foam and can be used for casting words, numbers or artistic elements to add interest to otherwise monotonous and stark concrete surfaces or to create unique standalone features. The main challenge is to find a good coating which can provide not only the right slip properties but also the right surface quality of the final concrete element.
- **Silicone rubber:** Multiple use moulds or form liners are created from a polystyrene pattern using silicone rubber. Large and complex patterns can be reproduced multiple times for use on precast architectural panels, and sound barriers.



Fig. 6: Textile formwork used for the casting of a concrete column.

From file to factory

Today's information technology offers an unprecedented opportunity to pull the fragmented processes of building design, product manufacturing and construction together into a highly interactive enterprise. Within the separate domains of design, construction and operations of buildings, computer tools have been applied to automating specific tasks rather than addressing the overall building process.

Three conditions exist that are likely to lead to significant restructuring of the construction industry. These are:

- the recognition that traditional contracting practices are inefficient and costly to the client,
- the growing availability of information-rich 3D parametric modeling, and
- the strong interest in integrating the issues of design and fabrication.



Thus, there is a demand for one tool that enables the communication between all links in the building process, i.e. from the first file on the architects' computer to the factory producing the end product. BuildingSMART is such a tool. The tool is developed from the philosophy that we shall always seek direct communication, i.e. direct communication between different people, or different software systems for design or machinery control. BuildingSMART is based on the open standards, IFC and IGES, which enables direct communication.

BuildingSMART was previously named as International Alliance for Interoperability, IAI and has its focus on interoperability. The IFC format was originally developed by the International Alliance for Interoperability established in 1995 by American and European AEC (Architecture Engineering and Construction) firms, along with software vendors, to promote interoperability between software in the Industry. Since 2005, the IFC specification is developed and maintained by BuildingSMART International. BuildingSMART International is actively facilitating IFC implementation and adaptation via local chapters worldwide. Graphisoft, a CAD vendor and the developers of ArchiCAD, was the first software company worldwide to allow users to save/export their files in the IFC format.

Even though BuildingSMART is a great step towards easier and more automated processes from file to factory, there are still a number of challenges to deal with before it will have a great impact on the building industry. The large numbers of formats used for different production machinery still sets a limit for the innovation. But BuildingSMART is a serious candidate to be the most preferred tool in the future process from file to factory.

Summary

Formwork manufacturing is still to a large extent based on craftsmanship and in order to keep costs low the flexibility in formwork design is very limited. New advances in automation and digital fabrication are beginning to appear in the concrete industry. One of the methods providing the greatest degree of free form manufacturing is subtractive processing i.e. where milling of the formwork material is performed. So far, only examples of milling in polystyrene have been found, which is a cheap and quick material to process. Further research will focus on coating of polystyrene to obtain good slip properties and the intended surface appearance. Combined with new advances in automated spraying technology it may be possible to find a coating material which offers a good balance between price and performance. The coming research will also focus on producing complicated elements which require closed formwork and good planning of the inlet position and the properties of Self-Compacting Concrete. Finally, research will focus more on the potential of industrial molding sand. This is a completely new material to the concrete industry and the first laboratory results have been promising and especially recycling and easy de-molding makes it a very interesting formwork material.

Further details can be found in the original report ( [D1 Automation methods in the construction sector](#)) on the following webpage: <http://www.teknologisk.dk/projekter/25112>



Future Nordic Concrete Architecture

Through the 20th century concrete has become the most used building material in the world. The usage of concrete has led to a new architecture which exploits the isotropic properties of concrete to generate new shapes. Despite the considerable amount of concrete used in architecture, the concrete is surprisingly little visible. Often concrete is only used as the material for the load-bearing structures and afterwards hidden behind other facade-materials.

But concrete has a big unexploited potential in order to create beautiful shapes with spectacular textures on the surface. This potential has been explored through a number of buildings which can be characterized as concrete architecture. In this context concrete architecture is defined as:

- Architecture where concrete is used as a dominating and visible material and/or
- Architecture where concrete is expressed through the geometry.

In the following, a number of projects characterized as Nordic concrete architecture is presented together with a description of the epochs of the history of concrete architecture to which they belong.

Nordic Concrete Architecture

In Scandinavia, conditions different from the most other places in the world prevail. The Nordic climate causes significant changing weather conditions during the 4 seasons. This results in significant fewer hours with sun. Add to this that the sun stands low in the sky – especially in the winter season. This condition has had great influence on the architecture combined with the cultural development in Scandinavia. The style of building has always been inspired of the neighbours in the south – but always with a local interpretation and the usage of local building materials.

Concrete has not played a bigger role in the Nordic architecture compared to other countries. But special about the Nordic concrete architecture is among other things the distinguished usage of concrete with a special feeling for the interaction between the detail and the whole.

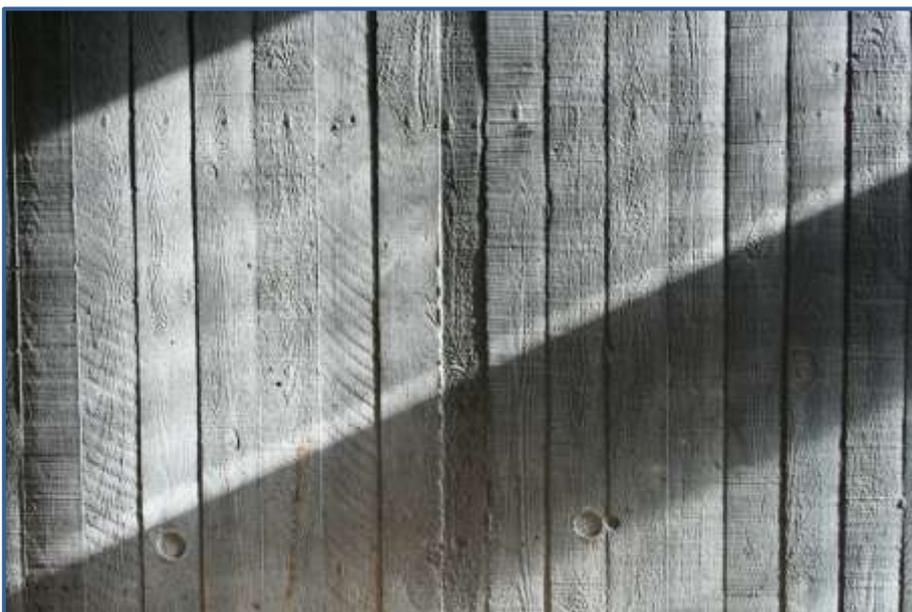


Fig. 7: Concrete wall cast against rough wooden boards.

The modern white reinforced concrete



The exhibition in Stockholm in 1930 was an important event for the Nordic architecture – and especially for the usage of concrete. It marked a shift from the classicism in the 1920's to the modernism. In the Nordic countries the modernism was called functionalism – first of all the architecture should be functional, and everything that did not serve the purpose of the building should be removed and the architecture could thereby be released from earlier styles. The characteristics of this period were the pure – often white painted surfaces. Therefore this style was also referred to as the white style.

Concrete was an integrated part of the functionalism. Earlier the concrete had not been popular among architects who claimed that concrete was missing symbolic value and a cultural history, but in this new style concrete became very interesting. Although white painted concrete was the aim, a lot of the buildings was actually built in bricks and plastered with mortar, and then white painted. But the white painted concrete surfaces were considered the most honest examples.

Beside the great Swedish architect Erik Gunnar Asplund who was leading architect on the exhibition in Stockholm, Sven Markelius – another Swedish architect stood behind a number of interesting works from the period. Among these are the Tekniska Högskolans Students House from 1930 and the concert house in Helsingborg from 1932.



Fig. 8: Sveaplans High School from 1936 in Stockholm, Sweden. An example of a building from the functionalism.

In Denmark, the architects Mogens Lassen, Vilhelm Lauritzen and Arne Jacobsen were successful in the new style. Arne Jacobsens Bellavista and Belevue Theater is masterpieces from this period – just in the spirit of the ideals of white, cubic buildings with white surfaces. And where Arne Jacobsen probably was most inspired by the German architect Walter Gropius, Mogens Lassen was most successful in translating the ideas from Le Corbusier into a Nordic version. This was evident through a number of one family houses.

In Norway it was primarily the architects Arne Korsmo, Ove Bang and Knut Knutsen who introduced the functionalism in architecture. Among the buildings is Villa Stenersen from 1939 by



Arne Korsmo and the Ekesberg Restaurant by Lars Backer from 1929, situated beautifully on a hillside with a great view over Oslo.

Over a decade Alvar Aalto was the most internationally recognized architect in Finland. Some of his works represented a Finnish version of the functionalism. Among these are the Sanatory in Paimo and the library in Viipuri. Villa Mairea was considered a Finnish counterpart to one of the international masterpieces in the modernism; Le Corbusiers Villa Savoye. Villa Mairea also marked a shift in Aaltos architecture towards a more local and organic architecture.

The brutal concrete

As a contrast to the pure white architecture a demand for a more honest architecture came after Second World War. This new architecture was characterised by emphasized structures and raw surfaces. This period was called the brutalism and concrete played a leading role. The concrete was often exposed and untreated – cast against rough wooden boards which resulted in a very rough texture in the concrete surface with a richness in the details of the surface.

In Denmark, especially the architects Friis and Moltke adopted this new usage of concrete and developed a local Danish version of the brutalism. An examples of this is a school in Ebeltoft in Denmark where almost every structure and every surface is untreated concrete. Also Hotel Lakolk on Rømø from 1966 is worth mentioning which at that time was almost chokingly brutal both outside and inside of the building.



Fig. 9: School in Ebeltoft, Denmark by the Danish architects Friis and Moltke built in 1968.

Also Gug Kirke from 1968 in Aalborg by Inger and Johannes Exner and the college from 1967 in Holbæk by the architects Gerdt Bornebusch, Max Brüel and Jørgen Selchau is brilliant examples of how concrete can give the architecture both weight and uniformity. This is especially achieved because of the ability of the concrete both to be the building material for the main structures and at the same time the aesthetic surfaces. The Viking ship museum in Roskilde by the Danish architect Erik Christian Sørensen is a very good example to demonstrate this ability of concrete. Here you can see the powerful concrete structures with rough and untreated surfaces.

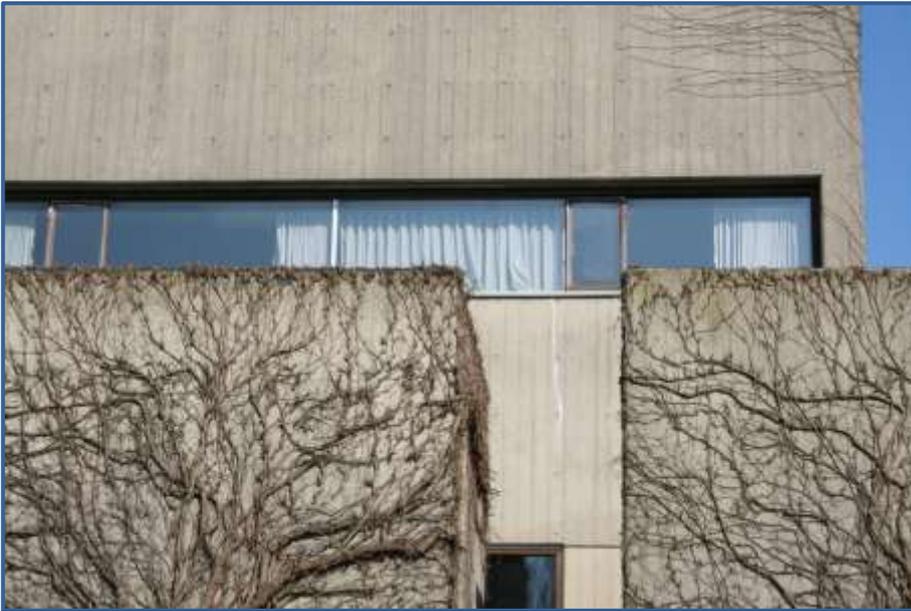


Fig. 10: High School in Holbæk, Denmark by the Danish architects Gerdth Bornebusch, Max Brüel and Jørgen Selchau – built in 1967.

In Norway, it was especially the architects Kjell Lund and Nils Slaatto who developed a Norwegian version of the brutalism. Among the representative works is St. Hallvard church with powerful structures in concrete with infill of red brickwork and the Norwegian Student society in Oslo. Also Gratangen Church by the architect Oskar Norderval where two triangular shaped concrete slabs raise to the air is a masterpiece of the period.

In Finland, the dominating architect who used the concrete rough and untreated was Aarno Ruusuvuori. Especially through several churches he used concrete as the dominating building material – and with a distinguished detailing in the facade where the vertical patterns from the wooden boards used in the formwork emphasized the horizontality of the buildings. This is also shown in Huutoniemi church from 1964 and Järvenpää church from 1967. In these examples concrete has been used as a total dominating material both inside and outside.

In Sweden the rough, untreated concrete surfaces wasn't used as often as in the rest of the Nordic countries. An exception is the library from 1967 in Norrköping by the architect Sten Samuelson.

Organized concrete elements

The industrialisation reached the Nordic countries in the late 1950's – and as a solution to the alarming need for housing, a mass production of building component was started – just like in the rest of Europe. This caused a demand for standardisation of building components which could be seen in the architecture the following years. The architecture became rational and without variation.

Concrete elements were a key to this new architecture. Almost identical concrete elements could be used for floors, walls and roof – without further treatment. Furthermore, they could be produced fast and cheap. But what seemed like a very good idea in the first place slowly changed towards massive criticism of the huge housing complexes and the concrete was pointed out to be the villain. Even though it wasn't the concrete's fault, the concrete was in a long period afterwards mainly used as a construction material covered with other building materials.



Even though the focus was on the trivial housing complexes, the period did have some very good examples of concrete architecture where concrete elements were used more interestingly.

The Norwegian architect Erling Viksjø was successful in using concrete elements as the dominating building material for several works. Among these is Bergen Town Hall from 1974. He got a patent on his so called 'nature concrete' which was a production method where gravel was placed in the mould and hereafter exposed using sandblasting. Among the most well known works is a gathering of buildings housing government offices in Oslo.

Sweden was just like the other Nordic countries dominated by the monotonous housing complexes. But one of the brilliant examples of interesting usage of concrete elements is Bergwaldhallen in Stockholm of the architects Erik Ahnborg and Sune Lindström in 1979.

In Denmark, the hospital in Herlev of Bornebusch, Selschau and Brüel was a brilliant example of powerful architecture made as an industrialised assembling building. Also the Roskilde Town Hall of the Danish architect Knud Munk is a fantastic illustration of the possibilities with concrete elements.



Fig. 11: Hospital in Herlev, Denmark by the Danish architects Gerdth Bornebusch, Max Brüel and Jørgen Selchau – built in 1976.

Utzons floating concrete structures

Jørn Utzon is probably the Danish architect who has had most influence on the development of the Danish concrete architecture. He has challenged the potential of concrete and created unique architecture, and especially his creativity with concrete elements is worth mentioning.

There are especially five of Utzons works which can be characterised as actually concrete architecture. The first one is a water tower in Svaneke in Denmark. Here, a pyramid shaped water tank is lifted up by three sloping concrete legs which make the structure thin but yet powerful.



Fig. 12: Water tower in Svanke, Denmark by the Danish architect Jørn Utzon. Built in 1952.

The next one – The Opera House in Sydney – became Utzon's main work and probably the most famous building in modern history of architecture. Even though the Sydney Opera House was built a long way from Scandinavia, some of the inspiration concerning the situation plan was gathered from the castle Kronborg in Denmark. Concerning the concrete, especially the expressive shells is a masterpiece on its own. Inside they are shaped like an organic rib-structure with untreated concrete surfaces.

If the Sydney Opera House was his International masterpiece, Bagsværd Church was his masterpiece in Denmark. Again the roof structure in concrete shows some of the possibilities to show the plasticity of the concrete. In this building the light is very important – broken down to the characteristic soft Nordic light.



Fig. 13: Bagsværd Church in Denmark by the Danish architect Jørn Utzon. Built in 1976.

In 1982, the Kuwait National Assembly was built. As in the Sydney Opera House it was mainly prefabricated concrete elements which were joint together creating the large concrete structures. Especially the monumental cover creating a big wave towards the ocean is impressive. It is stretching the possibilities with concrete.

The Paustian furniture house from 1987 is another Danish example where Utzon uses the concrete columns to create varying spaces inside the building with the inspiration from the Danish forests.

Fehns site-storytelling in concrete

The Norwegian architect Sverre Fehn is probably the most recognized architect in modern Norwegian history of architecture and concrete was often a preferred building material in his works.



The first project chosen here is a very Nordic house – but placed in Venice in Italy! It was the Nordic pavillion for the Expo 62. With the slim concrete beams in two layers the sunlight is broken down to a soft indirect light and thereby creating an almost Nordic mode on the inside.

In the Hedmarks Museum from 1969, Fehn demonstrates how concrete – a modern building material – can interact in co-existence with old stones from the Middle-age. With the Glacier Museum in Norway from 1991 he shows how an important part the site and the landscape play in his architecture. Both in shape and the choice of materials he tells a story of the rocks the glaciers has formed and left behind - and he does this with concrete.

Fehn built a number of one family houses. Among these is the Villa Busk. The house is built on a sloping rock ground and concrete was chosen to create a strong base and a building that could harmonize with the dramatic landscape.

Large scale concrete structures

Concrete has since the end of the 19th century been widely used in connection to large scale structures in Scandinavia. This has lead to a number of impressive large scale concrete structures, and the development can be seen in a number of bridge structures where concrete has been used as the dominating building material.

Among these are the Svinesund Bridge by the architects Lund and Slaatto – connecting Norway and Sweden over the Svinesund Inlet. Another bridge is the Big Belt Bridge in Denmark by the Danish architects Dissing and Weitling in 1998, which is a demonstration of how concrete structures at the same time can be both powerful and elegant. Also the Øresund bridge connecting Denmark and Sweden is impressive with the 4 almost 200 meters high concrete towers in the middle of Øresund which is the culmination on the elegant structure.



Fig. 14: The Big Belt Bridge in Denmark from 1998.

New concrete ideals

Except for a few projects the concrete is not very visible in the 1980's – a period dominated by the postmodernism. As a rebellion against the historical view in postmodernism the deconstructivism arose – characterised by a fragmented architecture. The deconstructivism never really gets popular in Nordic architecture as in other parts of Europe, probably because of a to big contrast compared to the Nordic tradition where uniformity and harmony is a beloved quality. Nevertheless at least one



significant deconstructive work was built in Denmark – Arken, a new museum for modern art by the Danish architect Søren Robert Lund – built in concrete.



Fig. 15: Arken Museum in Ishøj, Denmark by the Danish architect Søren Robert Lund. Built in 1996.

In the 1990's concrete architecture makes progress again. This was due to a number of new and young architects who could see some new possibilities with concrete – not oppressed by the history of concrete. Characteristic for the usage of concrete in the years up to today is, that the concrete is often used untreated. This results in an honest expression where the production method is visible in the concrete surface. One might say that it is a kind of a modern and distinguished version of the brutalism.

One of the new architectural firms is the Danish company Entasis. With the new head entrance for the Zoological Garden in Copenhagen they showed this honest usage of untreated concrete. In the housing complex Emaljehaven in Copenhagen they use concrete elements that are merged together – setting new standards in the construction with concrete elements.



Fig. 16: An example of new buildings in concrete. Hindemosehus in Odense, Denmark by the Danish architect Sophus Søbye built in 2006.

Also the house for the hippopotamuses in the zoological garden in Copenhagen by The Danish architectural firm Dall and Lindhardtzen is a very good example of the new ideals. A modern and distinguished version of concrete surfaces cast against rough wooden boards.

In Sweden it is the architect Gert Wingård who is experimenting with new possibilities with concrete. With the control tower in Arlanda Airport he is experimenting with different colours of



the concrete. And in the housing project Villann concrete is used untreated with smooth surfaces. Other interesting experiments were performed by the Swedish architect Johan Celsing. In the office of Riksantikvarieämbetet from 2008 he uses concrete facades cast against silicone-moulds with reliefs.

In Finland the architects Heikkinen and Komonen stands for a renewal of the Finnish concrete architecture. This is among other projects illustrated through the Emergency Service College from 2005 in Kuopio.

Nordic concrete architecture in the future

Architecture of the future faces major challenges but also a number of new possibilities. Digital 3D-modelling tools are used among architect to create new advanced shapes which are characterised by the digital architecture of the future. Still, a huge gap between what can be produced digitally and what can be produced physically exists – especially when economy is taken into account. However, this is only a matter of time – in a near future the gap will be significant smaller.

The technologies are already available in order to produce advanced shaped architecture. At the Danish Technological Institute, a robot has been installed – a tool that can be used for digital fabrication. Also through a number of research and development projects, the robot has been used for research in new digital fabrication techniques where the aim has been to develop new formwork for concrete.

From the national Danish project Unique Concrete Structures, the final result was a pavilion in concrete designed using advanced optimization tools and produced using robot technology. The structure has a very complex geometry especially in the organic rib structure.



Fig. 17: Concrete pavilion from 2010 made in connection to the research project Unique Concrete Structures. The formwork was created using the robot cell at Danish Technological Institute.

Using robot technology in the fabrication of concrete structures gives some new possibilities to produce complex geometries – but also possibilities to make new textures and reliefs to the concrete. This can be illustrated by an experiment at Danish Technological Institute where 10



different concrete elements were produced using different formwork materials and different milling strategies on the robot.



Fig. 18: Experiments in concrete using robot technology at Danish Technological Institute.

Also a sculptural concrete element designed by Esben Klemann – integrated in the architecture of the art museum on Bornholm – is a good example of the possibilities with concrete surfaces.

With technologies for digital fabrication – like robot technology – a new digital architecture will be common in the future and the development in the Nordic countries will be up front. As the tradition has showed us, this new architecture will find its own interpretation in the Nordic countries.

Concrete as an aesthetic building material will most likely have an even bigger role in future architecture than today. This floating rock is an obvious building material when the future digital architecture is built. It is a material both for the freely shaped main structures of a building and the aesthetic surfaces. Add to this the sustainability due to the long lifetime. With the possibilities of digital fabrication, the architects can lose themselves further into the details which are so characteristic for the Nordic architecture. Thus the Nordic concrete architecture will most likely continue to interpret the new possibilities with Nordic poetry and distinguished sense for both the whole and the detail.

Further details can be found in the original report ( [D2 Nordisk betonarkitektur](#)) on the following webpage: <http://www.teknologisk.dk/projekter/25112>



New and flexible formwork materials

A larger part of the concrete architecture of today demands the use of non standardized formwork. In addition the complexity of the formwork has increased over the last few years due to the development of the digital design tools used to shape the concrete. Almost all non standardized formwork used today is processed manually, and is as such very expensive to use. Many interesting projects are never realized simply due to the fact that the production of the formwork is too expensive to produce or not possible to fabricate at all.

In this project robot technology has been used in the manufacturing of new formwork materials. The robot is equipped with a milling tool which enables a processing technique where material is milled out from a block material leaving the wanted shape. Thus the research in different block materials used as new formwork materials has been in focus. The formwork materials is assessed regarding flexibility, sustainability, robustness, reusability and cost effectiveness.

Earlier experiments have shown that different kinds of foam products have been very suitable for producing formwork for concrete by milling. Especially expanded polystyrene has a big potential, mainly because of the low price. This formwork material has been used for the demonstration tests in the present project.

Flexible membrane as main formwork material for concrete surfaces

Combining a flexible membrane with a rigid form material for casting identical elements might have future potential, but experiments showed severe difficulties in controlling the geometry and de-moulding without destroying the cast element was not possible.



Fig. 19: Casting result showing variation in geometry and obstacles in deforming.

The obstacles were not to overcome within this research project, but demonstrate that the concept does not fit the scope of manufacturing singular concrete structures in a competitive cost frame.



Moulding sand as formwork material for concrete

Beside expanded polystyrene, an alternative formwork material has been chosen for further research and used for small scale experiments. It is molding sand which is used in the casting industry.

Molding sand is a completely new material to the concrete industry and there is a great potential in using moulding sand as formwork material for future concrete structures due to the great advantages regarding easy de-moulding, easy milling, reusability and homogeneous concrete surfaces.

Knowledge from the casting industry has been used in order to choose the casting sand which is most suitable for milling and casting of concrete. Thus a list of moulding sand materials and processes has been made. The chosen materials and processes chosen for assessment were:

- Clays
- Sodium silicate binders
- Alcalic resol binders
- Acid catalysed furane binders
- Vacuummethod
- Epoxy, “croning”, phenolic urethane binders etc.

On basis of the list above two types were chosen for laboratory experiments. These were alcalic phenol-resol and furan-sand. For the tests a number of samples were prepared. Moulds for concrete were milled out on the robot from basic sand-blocks. Before casting one half of each mould was covered with ‘black’ – a material used in the casting industry to seal the surface of the sand.



Fig. 20: Experiments with furan-sand where the one half of the mold was covered with ‘black’.



Fig. 21: De-molding was quite easy in the areas with the 'black' coating but it stuck to the concrete.

The experiments showed that de-moulding was very difficult. Add to this that the 'black' material stuck onto the concrete. Thus another type of sand was tested. This was a chemical bounded filter-sand which showed some more promising results.

First of all the sand was assessed as concerns how easy it was to mill it into shape with the robot. Tests with different speeds – both spindle speed on the tool and the robot speed – were performed and showed some interesting results. With both high speeds on the spindle and the robot movement the sand was milled easily and perfectly. This indicates that moulding sand compared to a number of other potential formwork materials can be processed both faster and cheaper.



Fig. 22: Milling in moulding sand can be performed with very high speeds on both spindle and robot movement.

Also the quality of the sand after milling was promising. Tests with very fine details showed that the sand could hold the shape without small pieces breaking off

De-molding has shown very different results. Tests with two different fractions of molding sand has shown that the compacting of the sand has great influence on how easy the de-molding after casting with concrete can be performed. In the first test the sand was compacted better than in the second



and the de-molding was thereby much more easy. De-moulding of the second, less compacted sand was on the other hand very difficult and tools for the de-molding process were needed.

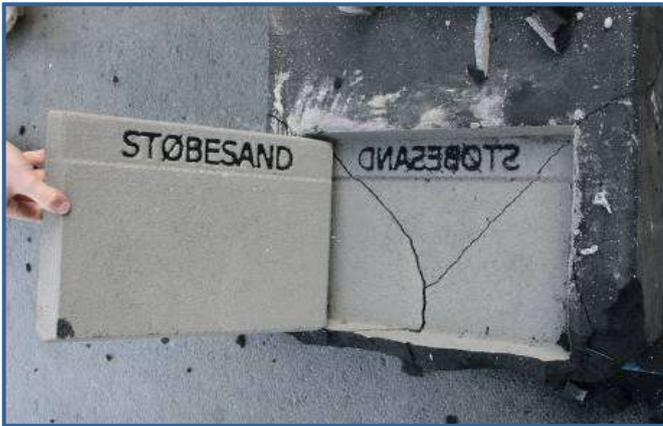


Fig. 23: On the left: Easy de-molding without the usage of heavy tools. On the right: Difficult de-molding even with the help of heavy tools

Regarding the concrete surface quality it was very acceptable. The surfaces were homogeneous and there was hardly any air bobbles on the concrete surface.

Creation of reliefs in concrete using moulding sand

A number of experiments with reliefs in moulding sand have been performed. The aim of these experiments was to utilize the possibilities with digital fabrication in order to create patterns in concrete which are not possible to produce manually.

The basis for the experiments was pictures in black and white with a high level of contrast. These pictures were imported to a 3D modeling software where each level of gray was given a specific height lifting the picture up to 3 dimensions. Then a pattern of straight lines were projected onto the picture emphasizing the shadows from the 3D picture. This final 3D model was then milled out in moulding sand on the robot creating a mould for concrete. And in these experiments the form-stability of the moulding sand was very crucial for the success.

The experiments showed that it was possible to create 3D pictures using this technique, and that the moulding sand was very suitable.





Fig. 24: Very fine details creating a 3D picture - milled in moulding sand without small pieces broken off.

Conclusions on experiments with moulding sand

Based on the tests performed, moulding sand can be concluded as a very interesting formwork material for the future. The conclusions are:

- Molding sand can be re-used. This is a great advantage compared to other known formwork materials for singular concrete elements.
- The choice of the correct molding sand is very important – add to this the need for proper compacting of the sand before use. This is especially necessary to be able to perform easy de-molding after casting with concrete.
- Due to the firmness of the molding sand it is possible to create very fine details in the concrete surface. This gives some new opportunities for designers, architect, artist etc.
- The surface of concrete cast against molding sand is very homogeneous and without air bobbles.



Demonstration tests

Through a series of demonstration tests the research project has explored some of the possibilities with new automation technologies by creating full-scale prototypes in concrete.

Staircase sculptures

A set of sculptures in concrete has been produced and exhibited in *Eventyrhaven* (Adventure garden) in Odense, Denmark. The work is by the artist Esben Klemann. It consists in adding two concrete elements to an existing staircase in the garden. One element fills up a rectangular hole in the side of the staircase. The other element continues the side of the staircase down to the ground in a twisted movement. Together, these two elements form a unique example of work, where art and architecture melts together in new compositions.

The production showed how robot technology can be used in the process of making art. First Esben Klemann came up with the idea which was transferred into digital drawings. Then the drawings were used to make tool paths for the robot, which was used in order to mill out the needed moulds in expanded polystyrene. The moulds were then filled with self-compacting concrete. The de-moulding showed that the expanded polystyrene was easy to remove when the concrete was still hot. The production of the two concrete elements was performed in the high-technology concrete laboratory at Danish Technological Institute.



Fig. 25: On the left is a computer model of the concrete elements. On the right is the production of the moulds using robot technology at Danish Technological Institute.



Fig. 26: On the left the mould is cast with concrete. On the right de-molding.



Fig. 27: The finished concrete elements.

Artistic concrete element

In connection to a special exhibition at the Bornholms Art Museum on Bornholm in Denmark a full-scale concrete element was produced.

The artistic concrete element is now exhibited direct on the existing facade of the Bornholms Art Museum. It shows how artists can bring art into the architecture in an industrialized process.

The project was made in several steps. First a small model of polystyrene was milled out by Esben Klemann in order to achieve the desired surface. Then the model was scanned into the computer using a 3D scanner. Then the surfaces was scaled and stretched using a 3D modeling program in order to fit into the building and the final shape of the concrete element. Hereafter the surface was further treated digitally to bring out the main relief of the surface. After the digital treatment, the formwork was milled out in polystyrene on the robot at Danish Technological Institute and the parts was then sent to Bornholm where PL Beton sponsored the concrete for the element. Finally the casted concrete element was placed on the facade of the Bornholms Art Museum.



Fig. 28: The artistic concrete element exhibited at the Bornholms Art Museum.



Fig. 29: Left: The robot mill out the polystyrene part for the formwork. Right: The parts brought together in the final formwork ready for the casting.





Fig. 30: Left: Computer illustration of the element. Right: The element in place in connection to the building facade.

A new production method developed for singular silicone moulds

In connection to the production of a concrete chair for an exhibition in Copenhagen, a new production method has been developed. The chair had been almost impossible to produce without the use of digital production methods. Thus, the chair is produced by milling out the chair in expanded polystyrene using the robot in the high-technology concrete laboratory on Danish Technological Institute. Then the prototype was used to cast a silicone mold which was used to cast 6 identical concrete chairs.

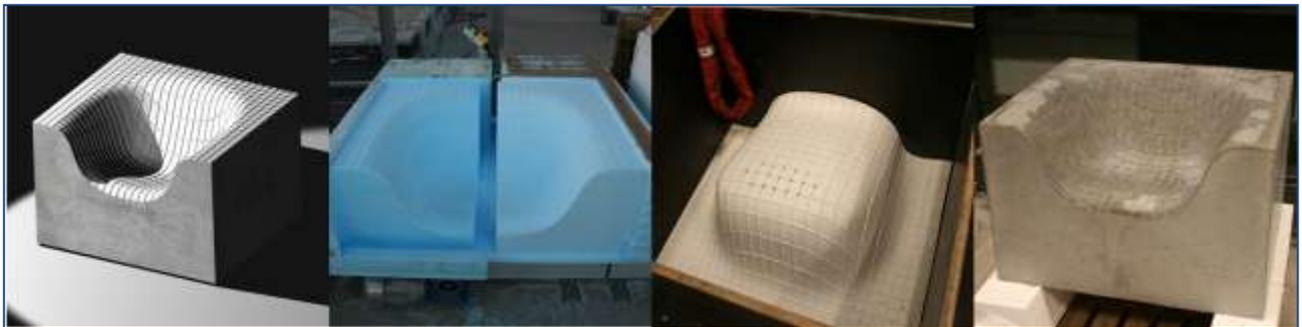


Fig. 31: From digital model to the final concrete object.



Nordic Workshop

The research project finished with a Nordic Workshop concerning automation and industrialization in the future Nordic concrete architecture. This workshop marked the finalization of the two-year research project “Future Nordic Concrete Architecture” supported financially by Nordic Innovation Centre.

Presentations on the workshop

- Architectural and structural design of concrete structures using three-dimensional topology optimization, Asbjørn Søndergaard and Per Dombernowsky, Aarhus School of Architecture
- Sculptural concrete elements in architecture, Esben Klemann
- Nordic concrete architecture – tradition and renewal, Thomas Juul Andersen, Danish Technological Institute
- Casting sand as future formwork material for concrete, Ulf Gotthardsson, SwereaSWECAST and Lars Nyholm Thrane, Danish Technological Institute
- Better digital collaboration through BuildingSMART, Eilif Hjelseth, Universitetet for miljø- og biovitenskap (UMB)
- Demonstration and exhibition in the high tech concrete laboratory, involving robot milling in casting sand and concrete elements produced using robot technology.

The presentations can be found on the following web-link: <http://www.dti.dk/inspiration/28236,2>



Conclusions

Objective 1: Generating an overview of the usage of high-technology solutions and automation in the global concrete industry in connection to manufacturing of singular concrete structures.

Manufacturing of complex concrete structures in a cost effective way require new production techniques. The work has focused on describing some of the developments and advances within:

- Concrete technology. In particular, the development of self-compacting concrete (SCC) have made it possible to cast complicated shaped and heavy reinforced structures. However, SCC is not straight forward and needs careful selection of the rheological properties and casting technique to avoid e.g. poor form filling and segregation. One example of a SCC application is the Ordrupgaard Museum outside Copenhagen, which won the Danish In-situ concrete price in 2006. Furthermore, developments within fibre and textile reinforce concrete will enable the production of thin shelled structures.
- New constructive principles. The Tietgen Collegium is an example where the so-called “free forward construction” principle was applied. This is normally applied for building bridges and resulted in significant savings in time and money. The Tietgen Collegium won the in-situ price in 2007.
- Digital architecture and fabrication. Several digital fabrication processes have been identified based on the underlying computational concepts such as 2D fabrication, subtractive fabrication, additive fabrication, assembly and surface treatment.
- Formwork materials. As alternatives to the traditional concrete shuttering (steel and plywood) materials like textiles, polystyrene foam and silicone rubber are suitable for processing using a robot.

Further details can be found in the original report ( [D1 Automation methods in the construction sector](#)) on the following webpage: <http://www.teknologisk.dk/projekter/25112>

Objective 2: Making a hypothesis regarding future concrete architecture. This involves answers to the question: Where is the concrete architecture heading? And in which way should the technology be developed in order to bring the concrete architecture up front.

A review of the Nordic concrete architecture shows that concrete as an aesthetic building material will most likely have an even bigger role in future architecture than today. This floating rock is an obvious building material when the future digital architecture is built. It is a material both for the freely shaped main structures of a building and the aesthetic surfaces. Add to this the sustainability due to the long lifetime. With the possibilities of digital fabrication, the architects can lose themselves further into the details which are so characteristic for the Nordic architecture. Thus the Nordic concrete architecture will most likely continue to interpret the new possibilities with Nordic poetry and distinguished sense for both the whole and the detail.

Further details can be found in the original report ( [D2 Nordisk betonarkitektur](#)) on the following webpage: <http://www.teknologisk.dk/projekter/25112>

Objective 3. Testing new technologies that make it possible to industrialize the manufacturing of singular concrete structures. This involves analyzing and testing new alternative and flexible



formwork materials and development and testing robot technology in the manufacturing of singular concrete structures.

Formwork manufacturing is still to a large extent based on craftsmanship and in order to keep costs low the flexibility in formwork design is very limited. The conclusions from the investigations in this project are:

- Polystyrene is an effective formwork material. It is relatively cheap and milling can be carried out at high speed due to the low density of the material. The final surface appearance and easiness of demolding depend on the choice of interface material between the polystyrene and the concrete. For smooth surfaces and easy demolding coatings like epoxy or rubber membrane should be applied. Combined with new advances in automated spraying technology it may be possible to find a coating material which offers a good balance between price and performance.
- It is possible to produce complex shaped 3D structures in closed formworks using polystyrene formwork parts and casting with SCC. The staircase sculptures for the Eventyrhaven in Odense were produced this way. The complex geometry required detailed CAD modeling and careful planning of the split lines for producing the two separate formwork parts. The formwork was milled in polystyrene. The inlet position was placed at the highest point of the formwork as gravity was the only engine to drive the flow of the SCC.
- 3D scanning is an effective tool to capture the details and geometry on the smaller scale and transform it into a 3D CAD model, which it would not have been possible to create directly in a CAD program. The CAD modeling was then used to optimize the overall design and surface appearance to fit the full scale application. This was applied to produce the artistic concrete element integrated into the structure of the Bornholms Art Museum.
- Combining a flexible membrane with a rigid form material for casting identical elements might have a future potential. However, the initial experiments showed difficulties in controlling the geometry and demoulding. The obstacles were not to overcome within this research project, but demonstrate that the concept does not fit the scope of manufacturing singular concrete structures in a competitive cost frame.
- Molding sand can be a very interesting formwork material for the future. It was found that:
 - Molding sand can be reused. This is a great advantage compared to other known formwork materials for singular concrete elements.
 - The choice of the correct molding sand is very important – add to this the need for proper compacting of the sand before use. This is especially necessary to be able to perform easy demolding after casting with concrete.
 - Due to the firmness of the molding sand it is possible to create very fine details in the concrete surface. This gives some new opportunities for designers, architect, artist etc.
 - The surface of concrete cast against molding sand is very homogeneous and without air bobbles. The surface texture is similar to the grain size applied in the molding sand.

Objective 4. Achieving consensus regarding future possibilities and challenges in the concrete architecture by arranging a Nordic workshop.

The Nordic workshop was held on the 17 March 2010 at the Danish Technological Institute. Presentations were given by members of the project as well as invited speakers Per Dombernowski and Asbjørn Søndergaard from the School of Architecture in Aarhus.



The industry was represented by architects, contractors, concrete producers, designers and craftsman. The presentations and following laboratory demonstrations give rise to good discussions about the future of concrete architecture and consensus was found on the following:

- Singular concrete structures with complex shape and double curved has a high potential for the future. Architects are very interested in pushing the limits to concrete architecture and change the general perception of concrete from a low-tech construction material, which bring negative associations to peoples mind, to a construction material with strong performance both from a structural and aesthetic point of view.
- Everyone agrees that there is a need for digital tools like BuildingSmart to close the gaps between the architects and the production chain.
- Digital 3D design tools are being used more and more. The developments in CAM technologies will help bridge the gap between architects drawings and production.
- Topology optimized design tools are interesting and is clearly relevant for some type of applications. It will improve the relation between the architectural impression and the structural performance.
- Formworks made of polystyrene have a high potential due to ease of production and material costs. However, everyone agreed that the next step for this solution is to look more into the overall economical and environmental aspects. For instance, to what extent it is possible to reuse formwork parts and the type of restrictions that may cause on the architectural degree of freedom.
- Molding sand is a promising formwork material. However, everyone agreed that it is mainly for element production and not for on-site castings due to the weight and handling of the molding sand.
- Everyone agreed that the future research now need to focus also on the reinforcement solution for singular concrete structures. For instance, look at the potential of shaping conventional reinforcement using robots, fibre reinforcement, and textile reinforcement.

Due to the contacts made during the workshop two new industrial projects have been initiated. The first one is trying to develop a new formwork system for casting the new Polar Bear residence at the Copenhagen ZOO and the second one is about using 3D scanning and prototype development of designer objects for city and landscape architecture. Furthermore, one of the participants has now become a member of the working group “synlig beton” (www.synligbeton.dk).

Business possibilities

The development of new technologies for production of singular concrete structures in a cost effective way opens up new business possibilities to the construction sector and various user groups. The following table illustrates the future expected impacts foreseen for the various groupings.

Construction Sector	Expected future impacts
Producers of formwork	<ul style="list-style-type: none"> - Enhanced ability to select and produce formwork including new materials, coatings and release agents suitable for use by automated processes and tailor-made for the specific structure. - Large cost reductions are expected from the use of lighter and recyclable materials. - Enable producers to recommend and support solutions promoting reduced on-site construction time for formwork and reinforcement installation.
Concrete producers	<ul style="list-style-type: none"> - A better understanding of client needs and ability to tailor concrete mix design, including SCC, to varying end-use applications, thereby reducing wastage; rejections; over or under estimation of quantities; delivery delays, etc., which cumulatively lead to onsite casting problems and defects.
Contractors	<ul style="list-style-type: none"> - Enhanced visualisation of the construction process based on new information and communication technology (ICT) tools for design, fabrication and simulation. - Better integration of off-site and on-site operations on a unified production and management platform. - Reduced wastage of material, and faster delivery times - An estimated 15 to 20% reduction in construction costs due to the cumulative impact of the new technologies. - Better safety and working environment at the building site due to lower weight, tailor-made formwork and due to the increased use of SCC. - Easier maintenance possibilities of unique designed details.
Architects and designers	<ul style="list-style-type: none"> - New opportunities for realising architecturally interesting projects in close cooperation with the construction sector. - ICT solutions will enable transfer of CAD drawings directly to production. - It will be possible to include complex geometric designs in construction projects without the limitations imposed by handmade formwork systems. - Specific clients' demands will be met more efficiently and effectively without extraordinary costs.
Building owners and property managers	<ul style="list-style-type: none"> - Unique concrete structures made at mass-customized prices. - The basic documentation material for construction is made more easily accessible (digital) and more easily understandable (standardized).
Automation and equipment producers including robots	<ul style="list-style-type: none"> - Increased automation of the construction process and ability to move a large number of operations off-site (e.g. prefabrication of components). - The main impact on the robotics sector is new business opportunities in the construction sector, e.g., increased demand for hardware and software fulfilling the needs for the construction sector. - In 2006 only 928 robotic installations were active in the construction industry. It is anticipated that this will increase significantly in the future.

The present project has focused on the possibility for the future Nordic architecture with focus on design, formwork material, SCC and ICT solutions to combine the work of the various actors in building process from architects to contractors. However, due to the limited time and resources it was from the very start chosen not to focus on the reinforcement, which obviously is a vital part of a load bearing structure.



However, the results of this project have been the direct course and inspiration to a new European FP7 project (www.tailorcrete.com) where the ideas described in this report are being brought into a wider European perspective. Besides continuing the work of the project, one of the major goals of TailorCrete is to focus on the reinforcement issue so that also this part of the building process can be included in the automated process. Thus, it is believed that within the near future, the technique of combining digital 3D-modelling tools and robot processing of formwork as well as of reinforcement will be put in an industrial perspective. This will enable both formwork and reinforcement producers to offer engineered solutions for geometrically complicated concrete structures. When this goal has been achieved, both concrete manufacturers and/or formwork and reinforcement producers could benefit from investing in robot technology for production of advanced shaped architecture at a rational price.



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Nordic Innovation Centre

Nordic Innovation Centre

Nordic Innovation Centre (NICe) is an institution under the Nordic Council of Ministers facilitating sustainable growth in the Nordic economies.

Our mission is to stimulate innovation, remove barriers and build relations through Nordic cooperation. We encourage innovation in all sectors, build transnational relationships, and contribute to a borderless Nordic business region.

We work with private and public stakeholders to create and coordinate initiatives which help Nordic businesses become more innovative and competitive.

Nordic Innovation Centre is located in Oslo, but has projects and partners in all the Nordic countries.

For more information: www.nordicinnovation.net