DTU Library

Proceedings of the 3rd International Workshop on Design in Civil and Environmental Engineering

Jensen, Lotte Bjerregaard; Thompson, Mary Kathryn

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

Proceedings of the 3rd International Workshop on

Design in Civil and Environmental Engineering

Lotte Bjerregaard Jensen & Mary Kathryn Thompson
Editors

Proceedings of the

3rd International Workshop on Design in Civil and Environmental Engineering

Lotte Bjerregaard Jensen
Mary Kathryn Thompson
Editors

Editors

Lotte Bjerregaard Jensen
Mary Kathryn Thompson

ISBN 978-0-9894658-3-0

3rd International Workshop on Design in Civil and Environmental Engineering

August 22nd - 23rd 2014, Kongens Lyngby, Denmark

Organized by

Technical University of Denmark

Sponsored by

COWI Fonden

Workshop Chairs

Lotte Bjerregaard Jensen	Technical University of Denmark
Henrik Almegaard	Technical University of Denmark
Toke Rammer Nielsen	Technical University of Denmark

Honorary Chair

Mary Kathryn Thompson	Technical University of Denmark

Organizing Committee

Peter Steen Mikkelsen	Technical University of Denmark
Susanne Balslev Nielsen	Technical University of Denmark
Thomas Sick Nielsen	Technical University of Denmark
Per Sieverts Nielsen	Technical University of Denmark

International Advisory Committee

Franco Bontempi	University of Rome "La Sapienza''
Renate Fruchter	Stanford University
Shang-Hsien Hsieh	National Taiwan University
Ser Tong Quek	National University of Singapore
Bjorn Sandaker	Oslo School of Architecture
Adib Kanafani	University of California, Berkeley
Tahar El-Korchi	Worcester Polytechnic Institute
Nicola Tollin	Bradford Centre for Sustainable Environments
Daniel Krause	Fraunhofer Innovation Engineering Center
Irene Paradisi	Fraunhofer Innovation Engineering Center
Dominik Matt	Fraunhofer Italia Research
Giuseppe Longhi	Master processi Costruttivi Sostenibili IUAV
Christopher A. Brown	Worcester Polytechnic Institute
Olga Larsen	Royal Academy of Fine Arts, School of Architecture

Danish Advisory Committee

Jan Karlshøj	Technical University of Denmark
Katrine Lotz	Royal Academy of Fine Arts, School of Architecture
Søren Peter Bjarlev	Technical University of Denmark
Christian Rønne	Technical University of Denmark
Anja Bache	Technical University of Denmark
Jakob Strømann-Andersen	Henning Larsen Architects
Martin Vraa Nielsen	Steensen & Varming
Henrik Elgaard Jensen	Cowi

Foreword

Civil and Environmental Engineering has a special place in the field of design methodology. Design projects in CEE are generally undertaken to provide long-term benefit to many stakeholders with different and sometimes conflicting needs. This means that design theories, tools, and techniques cannot be adopted directly from other design disciplines such as product design where different solutions can be developed for each individual or group.

CEE design projects are always influenced by their location and the associated topography, climate, etc. This means that each project is unique and must be viewed in its own right. This reduces the benefits of mass production and standardization that are so heavily emphasized in mechanical design and manufacturing.

The natural environment has dynamic, unpredictable, and sometimes chaotic properties and behavior. This is more true than ever when considering the challenge of climate change. The requirements of the human users and beneficiaries of CEE projects also vary in time. To meet these challenges, Civil and Environmental Engineering projects must be designed to be flexible so they can adjust for temporary changes in natural or human conditions. They must also be adaptable so they can evolve with technology, society, and the environment.

Design in Civil and Environmental Engineering also defines the reality in which we live, work, and play. Thus, it borders other fields such as architecture, landscape design, and urban planning - influencing them and being influenced in exchange.

Finally, the design of sustainable and climate adaptive systems and structures requires a very high level of information in all of the design phases. Addressing the challenges of tomorrow will require even more information with a better level of integration than is currently available today in either industry or education.

Because of these challenges, the 3rd International Workshop on Design in Civil and Environmental Engineering at the Technical University of Denmark focused on interdisciplinary design methods. How can we better integrate the knowledge at hand in Civil and Environmental Engineering in interdisciplinary design processes? And how can we adapt existing design processes to CEE?

The papers contained within these proceedings present methods and ideas for how to include and integrate information in the design process. They discuss topics ranging from architecture, energy, environment and indoor climate to structural engineering, transportation, water resource management, and urban planning. They also address interdisciplinary issues such as modeling and simulation, innovation, and education. In total, these papers represent a truly international group of authors with contributions from Denmark, France, Germany, Italy, Korea, Papua New Guinea, Sweden, Taiwan, the United Kingdom, and the United States.

The workshop at DTU was the third in a series of meetings aimed at exploring design as a discipline in Civil and Environmental Engineering. The first workshop was held at KAIST in South Korea in 2011. The second workshop was at WPI in Massachusetts, USA in 2013. We are very much looking forward to the fourth workshop, which will be hosted by National Taiwan University in 2015.

I would like to thank my co-chairs, the organizing committee, the international and Danish advisory committees, the industrial partners who organized the break out sessions, and COWI Fonden for their sponsorship and support of the workshop. Last but not least, I would like to thank the participants of the workshop. It is their ideas and enthusiasm that makes DCEE such a special meeting.

Lotte Bjerregaard Jensen
Department of Civil Engineering
Technical University of Denmark

November 20, 2014

Table of Contents

The City

Methods and Education

Energy

Structure

Design Education in Civil Engineering and Related Fields

Results and Recommendations

Innovation and Design Processes: Towards a Model of Social Responsibility

Giuseppe Longhi and Linda Comerlati*
longhi@iuav.it, linda.comerlati@gmail.com
IUAV University of Venice, Italy

Abstract: The design practice today is rapidly evolving due to complex and integrated driving forces that lead to a new holistic design method based on a collaborative and socially responsible approach. Due to the depletion of physical resources, we have to replace the current processes based on material consumption with new processes supplied by goods that are limitless and can be used by a large number of people without causing exhaustion. The main value of today design is then human capability to produce ideas since they are non rival and non expensive goods. The main factor of economic growth is technological progress that works at the rhythm of decoupling to increase productivity by reducing raw materials consumption. The paper proposes an organic method for urban and architectural design based on the limitlessness of human creativity and on the intangibility of scarce natural resources, implemented in a local design experience.

Keywords: Metabolic Design, Human Development, Social Responsibility, Decoupling, Disruptive Innovation.

An Organic Model of Social Responsibility

The conference topic “Design theory and methods to cross the disciplinary boundaries thank to creative and innovative solutions able to radically alter our infrastructure and built environment idea" reminds me of an important paper by Donella Meadows, “Dancing with systems” (Meadows 2008).

The question is: what are the driving forces of today’s dance design? I think they are:

- change in human resources role,
- resources depletion,
- technological innovations,
- resilience.

This system of elements suggests an interdisciplinary holistic design model, basically inspired by the theories of Robert Solow, Jane Jacobs, and Nicholas Georgescu Roengen that could be defined 'an organic model of social responsibility'.

Change in Human Resources Role

Due to the depletion of physical resources, to which the construction sector activities contribute significantly, we have to replace the current processes with new processes supplied by goods that are limitless and non rival, that can be used by a large number of people without causing exhaustion.

This principle marks the transition from a design model dominated by the supremacy of physical capital (products and goods), to a holistic model in which five driving forces interact: ideas, institutions, population, human capital (measured by education, research and development) and physical resources (measured by financial resources, artifacts, equipment and infrastructure).

The development of human resources becomes the qualifying purpose of the project, in symmetry with the model proposed by neoclassical economists since the late '60s, first with Robert Solow (Solow 1957) and later with Robert Lucas (Lucas 1988), in synergy with Jane Jacobs (Nowlan 1977), until Paul Romer (Romer 1986; 2014).

In fact, according to Solow, the main factor of economic growth is technological progress. This is mainly powered by enterprise externalities, an intuition that is completed by Lucas and Jacobs, who emphasize the role of the city (and, in particular, of its size and dynamism), because from its size depends the intensity of the externalities, in terms of human relation concentration, able to generate technological progress.

On this topic Paul Romer argues that development is a function of one unlimited available good, the ideas, which are powered by knowledge. This model introduces important changes in design thinking, because the ideas:

- are substantially different from the physical capital (land, infrastructure, capital and objects); they are non rival goods, as can be used simultaneously by a large number of people without creating congestion or depletion. So in the city it is important to encourage the growth of creative people, facilitating their importation and cultural development, stimulating the creation of new infrastructures to host new social classes, and renewing the infrastructures for the knowledge growth;
- develop new technologies, such as biotechnology, which help to demolish the specter of diminishing returns, that haunts the economic thought from

Ricardo to Keynes to the present day. On the contrary, new technologies are generative since they create increasing returns through research, to kick-start new machinery and products available at decreasing prices. In addition, in the design and construction sectors, the new frontiers of technology, based on dematerialization and biotechnology, allow the creation of artifacts without natural resources depletion, thus not affecting the carrying capacity of the Earth. As generative, new technologies inspire shared design practices;

- generate the production costs fall, translating the centrality of investment from production to research;
- are inseparable from the scale effects, and then confirm the essential role of urban concentration and, with it, the positive reading of the metropolis and globalization phenomenon;
- are based on organizational models of relationship symmetry, on collaboration and not competition.

If the project driving forces are human resources, as shown in figure 1, then the development must also take into account the role of human augmented intelligence thanks to cybernetic processes, a phenomenon that enhances the project as a cognitive construct, based on the iteration between users, their thinking and point of view about humans and built forms.

On the other hand, the processes of augmented intelligence could lead to a complete robotization of society and the city, so the wonders of a smart city could be accompanied by uncontrollable increases in unemployment rates. This is an issue that invokes the need for a strong public leadership in the project formulation and management, to avoid social catastrophes.

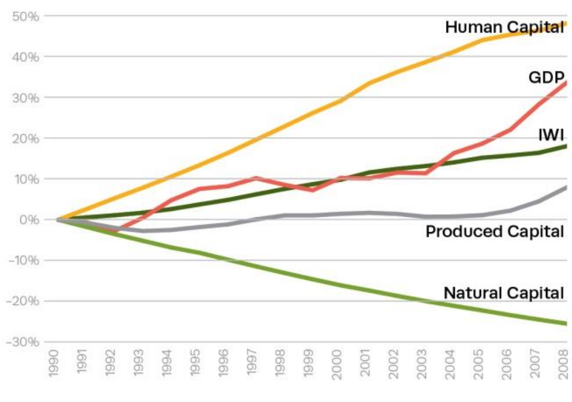


Figure 1. The Driving Forces of Development on the Basis of Inclusive Wealth Report (UNU 2012)

Resources Depletion

This topic has its driving force in the work of the Club of Rome, in addition to those of the Wuppertal Institute and of the Stockholm Environmental Institute (Rockström *et al.* 2009). These institutions have monitored the resources depletion and inspired the accountability of the international environmental conventions and EU programming defining processes. Figure 2 shows that the aim is to limit the environmental load by controlling the raw materials consumption and the substitution of semi-finished products and processes with high material consumption. The result is the reevaluation of bio-productivity thanks to the exploitation of natural resources and, as Roengen had expected, the end of bulky eso-machines design in favor of a metabolic design that replaces mechanical technologies with biological ones.

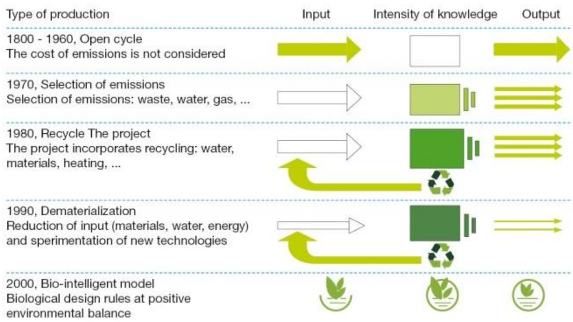


Figure 2. The Evolution of the Metabolic System of Production on the Basis of Wuppertal Institut Agenda

The exploitation of natural resources has its driving force in the Millennium Convention. The Convention is focused on the ecosystems role, the biodiversity rehabilitation, and, very important, the economic value assessment of goods and services produced by ecosystems. In this vision, the environment is no more considered in the romantic idea of garden as mitigation of the negative externalities, or as center of citizens loisir, and becomes the most important among production factors (as depleting goods), whose value has to be added to the economy traditional goods and services, as shown in figure 3.

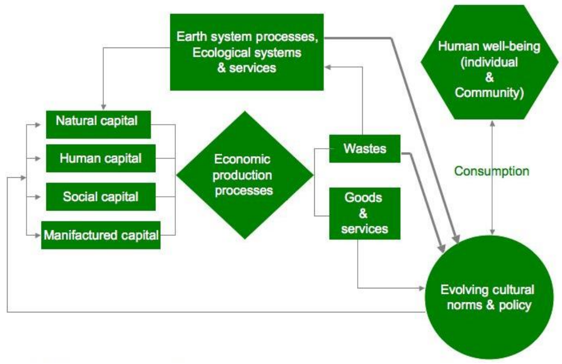


Figure 3. Partha Dasgupta and Anantha Duraiappah: Metabolic Model of Development

Thanks to the Millennium Convention, the value of the environment has to be incorporated in all development decisions, and the reevaluation of the environmental heritage (which includes the value of historic settlements) must be at the center of project operations. The Millennium Convention also marks the decline of the man's claim to guide and control the living world according to the culture of the Neolithic period, in favor of a 'revolution of living', that is the ability of humanity to take control of their own 'production', after gaining the control of their own reproduction, that is to develop in synergy with the natural resources.

Technological Innovation

Following on from the previous paragraph, technological innovation affects both urban projects, and infrastructure and buildings design, following the path defined by the Wuppertal Institute and made operational by the decoupling rules. Decoupling, as described in figure 4, is the increase in productivity by reducing raw materials consumption. Its speed forward is given by the application of the environmental standards of the international conventions through the EU budget policies (Fischer-Kowalski 2011).

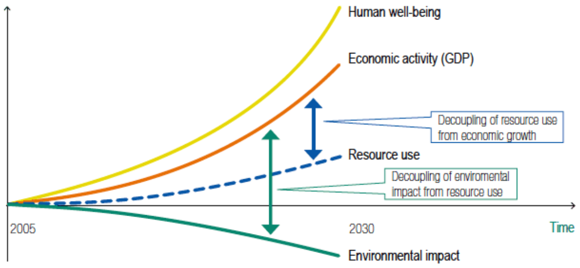


Figure 4. Stylized Representation of Resource Decoupling and Impact Decoupling

The table below shows how the design is influenced by new processes testing low material consumption, thanks to research in the field of renewable energy, to the creation of an effective agenda for dematerialisation including TLC, big data, high connectivity. The EU politics lead towards a metabolic model of development.

Table1. Metabolic Development and Decoupling: The Objectives of FP8 (ERT 2010)

Reduce the EU's raw material dependency	Reduce the EU's raw material dependency, including investing in R&D in technologies that reduce raw material needs and in new recycling techniques.
Devise programs to implement energy efficiency and climate change reduction:	
Pursue energy efficiency	New targets for energy efficiency need to progressively adapt to technological developments on the basis of a full life-cycle analysis, also taking into account resource, environmental, social and economical aspects. The use of low-carbon alternatives is encouraged.
Move towards a low-carbon economy	Encourage the continuing development of a global carbon market by taking steps towards linking the EU Emissions Trading System (ETS) with other developed country systems (notably the USA).
Progress development of the EU energy market	Follow a course of energy policy development that encourages full use of EU indigenous energy sources, setting the parameters within which the market operates rather than defining the market structure.
Foster the security of energy supply	Putting in place more infrastructure and infrastructure connections in gas and electricity networks, diversifying gas sources, routes and supply chains, including the construction of liquefied natural gas (LNG) terminals, and adopting a common EU approach to external energy relations.
Promote excellent energy infrastructure	Ensure that the necessary grid and infrastructure developments proceed in tandem with the required change in EU energy supply to meet 2020 targets and beyond, including smart electrical grids, enhanced natural gas networks to support expanded access and CO2 transport pipelines.
Promote and develop sustainable modes of transport and innovative infrastructure	Promote and develop sustainable modes of transport and innovative infrastructure designed to enable low-carbon mobility of people and goods across Europe. Integrate transport and land use planning and use EU structural funds to promote high-technology infrastructure solutions. The Energy 2050 Roadmap has been delayed. The impact of the Green Car Initiative and the Transport White Paper and the coherency of policy and funding is not clear.
Promote new ICT infrastructure:	
Develop a digital agenda	Develop a digital agenda that allows the EU to make full use of the possibilities of information and ICT to achieve the EU's policy priorities.
Reduce CO2 emissions	Reduce CO2 emissions by using all available technologies, including 'green ICT'.
Boost productivity	Boost productivity by putting in place policy frameworks fostering private investment in broadband networks, digital services and applications.
Foster societal well-being	Foster societal well-being by using state-of-the-art technologies in health, education and transport. The Commission has launched consultations on these issues, putting e-Health high on the political agenda.
Create Digital Single Market by 2015	Make all the related efforts fostering private investments.

Current innovations radically transform urban design driving forces and redefine the ecosystem of Public Administration and businesses, as the concept of value and the models of public and private organization, generating new relationships and new urban processes. This process is called 'disruptive' (see table 2, figure 5) because it produces effects not envisaged by stakeholders, who tend to see the future primarily as a linear projection of the past.

Table 2. The Main Disruptive Innovations Expected to Meet the Project World (McKinsey 2013)

Field of innovation	**Innovation**
Computer simulation of human mind	Neuronal computer
Generator	Automation of knowledge work
Dematerialization	Cloud technology Mobile Internet The internet of things
Producing in harmony with nature	Next generation genomics Protection of natural products and services
Energy from renewable sources	Renewable energy Energy storage Advanced oil and gas exploration and recovery Grid scale storage Digital power conversion Compressorless air conditioned and electrochromic windows Clean coal Biofuels and electrofuels Industrial applications Advanced robotics
Advanced robotics	Autonomous vehicles 3D printing Advanced materials
Regeneration of the city as a closed metabolic system	Neighborhood energy self-sufficiency Neighborhood food self-sufficiency Water savings (-77%) Buildings with high connectivity (100 Mb and services in the cloud) Increasing the biotic components (43% biobased materials) 0 emissions

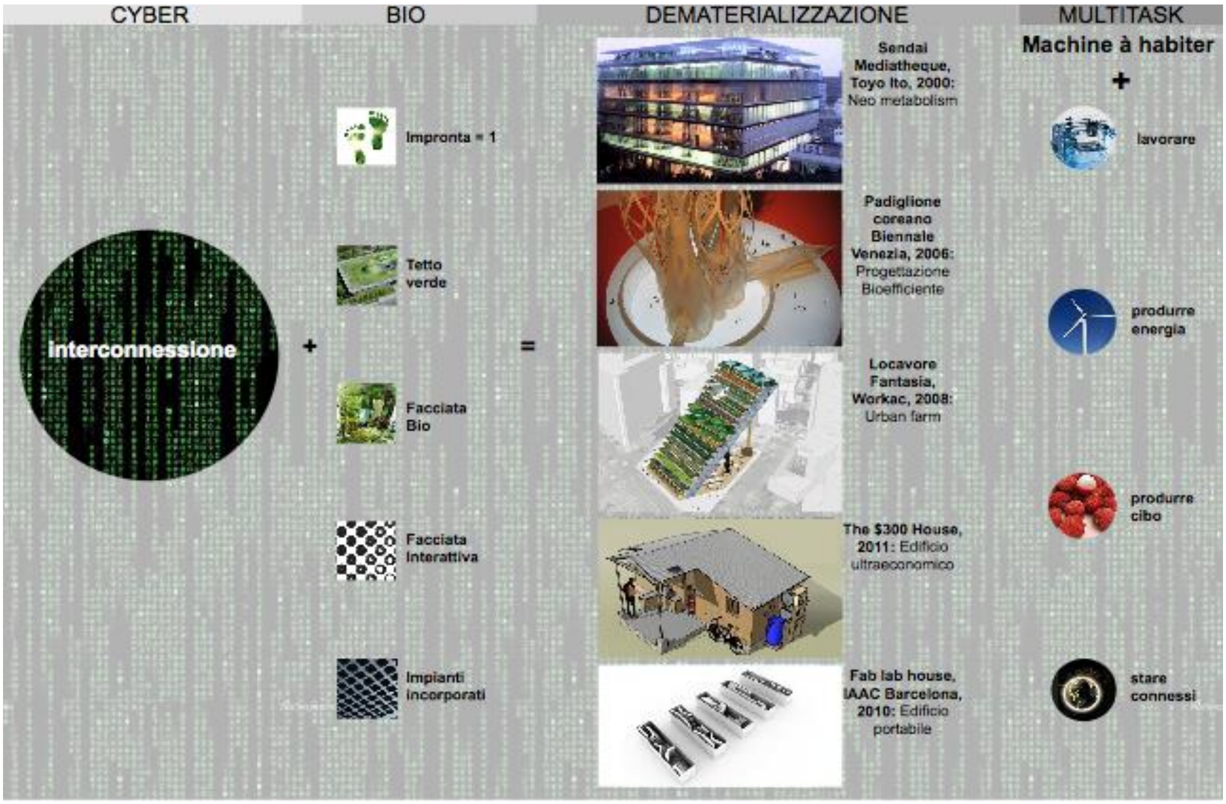


Figure 5. Main Innovations Involving Building Design

Resilience

These changes imply that the project construction is resilient, that it is able to adapt in the face of unpredictable changes in environment (e.g. climate change), technology (see disruptive technologies) and society. This draws a new holistic model of relations based on the principle that we are not simply faced with the need to renew scientific disciplines, but we must realize that we are, in fact, manipulating a system of social disciplines. As a result we need to overcome the passive project implementation, as it happens in the language of business (planning, targets, methods, procedures) on behalf of decision-making systems in which the designers' leadership is supported by technology, increasing the understanding and incorporation of foreign cultures. The result is a project structure based on the principle of inclusion and cohesion, in order to appropriately absorb the diversity, to experiment new models of social, environmental and economical organization (Ciborra 1992; 2002).

This project model is based on:

- The deep knowledge of resources, supported by the potential of the new infrastructures such as cloud computing and big data;
- Scenarios, feedback and approximation, acting to promote cohesion and inclusion and the development of human resources;
- Complex platforms, connecting local and global networks of social actors, companies, researchers, organized on the basis of the courtesy principle;
- Improvisation, to give pragmatic answers to specific situations.

This project idea replaces the certainty of thinking with a creative tinkering to generate inclusive innovation.

Towards a Model of Social Responsibility

In synthesis this paper shows the main driving forces of an organic model of social responsibility.

Table 3. The Elements of an Organic Model of Social Responsibility Design, Coherent with EU Topics in the Design Field (Fenn *et al*. 2013)

Holistic approach	It leads to multiple savings that can support each other and achieve an overall more significant impact. This approach also means that any stakeholder can be involved.
Multiple agencies/ organisations involved	It provides a wider perspective and potential for co-ordinating support to stakeholders in a holistic fashion, it creates synergies and enables the achievement of cumulative effects across a region.
Overcoming the vision of the project as a product, increasing the focus on services	Anthropocenetic design vision must reevaluate the natural resources services. The project's aim is also to increase their productivity.
Long-term vision and support	It provides longer periods for beneficiaries to access advice and support. Long-term support increases the potential to establish long-term relationships.
Collaborative approaches (including peer-to-peer learning or involvement of peer-to-peer networks)	Collaborative approaches and peer-to-peer learning can be more effective than manual or classroom based learning. The involvement of peer-to-peer networks increases credibility.
Evaluation of environmental, social and economic externalities	The evaluation of environmental, social and economic externalities increases the design generative impact.
Free data-base access	Information accessibility is a key factor for the development.
Long life cycle design	It multiplies the positive aspects for the people involved.
Multiplicity of funding sources	It increases the likelihood that the program remains active, even if one of the sources of funding will be stopped.
Exportable projects	Overcoming the projects local vision in favor of a generative philosophy, able to expand networks and increase wealth.

The organic model of responsible design is articulated in the following elements (figure 6):

- Limitlessness of human creativity, it is given by the potential of human resources increased by cybernetic technologies.
- Intangibility of natural resources: it is given by the conservation of natural resources and the optimization of metabolic processes.
- Dematerialization and connectivity: it leads to the conservation of resources and the improvement of human relations. In this way, the project material becomes, according to the definition of Nicholas Negroponte's, 'atoms and bits'.
- Resilience and inclusiveness: it concerns the governance model, that should be at territorial/metropolitan scale, in order to accommodate the new flows of culture and knowledge, and to be able to adapt to unpredictable social and environmental events.

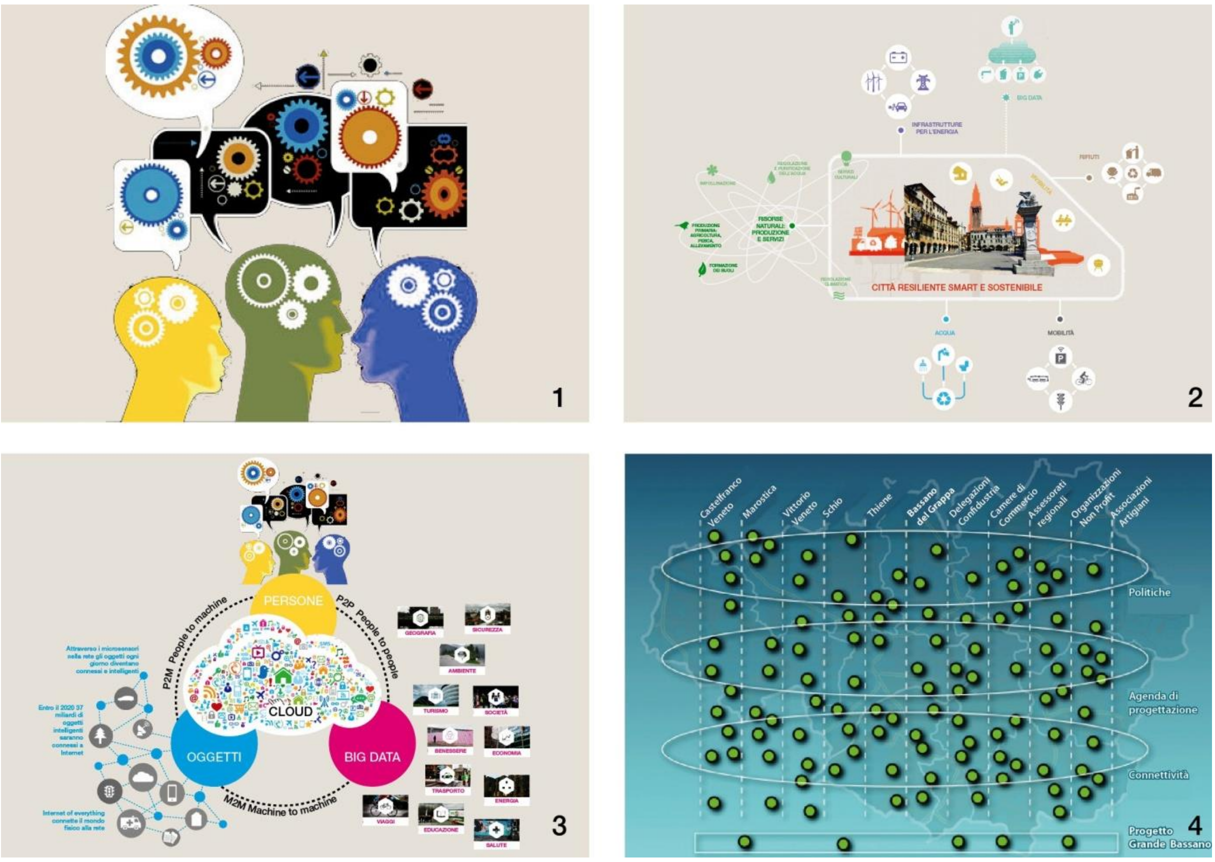


Figure 6. The Organic Model of Social Responsibility: 1_ Limitlessness of Human Creativity, 2_ Intangibility of Natural Resources, 3_Dematerialization and Connectivity,4_ Resilience and Inclusiveness

A Design Experience: Horizontal Farm, New Delhi

The Horizontal Farm (HoF) is an ideation for a urban development plan involving 150,000 inhabitants in the New Delhi megalopolis, in a semi-central area of 30,000 square meters. The project is envisioned as an integral part of the corridor Mumbai - New Delhi (Knowledge Based Infrastructure in DMIC 2014), the great experimental project for a megapolis development promoted by Indian Government with Japan financial support (100 mm. dollars) and with the technological support of 'Smarter City' program (IBM 2014). This project is based on the feedback between people, human resources reevaluation, new light technologies opportunities.

HoF is a Generator of New Capabilities

The project is inspired by Amartya Sen (Sen 2003) and Martha Nussbaum (Nussbaum 1999) thought, identifying in the population growth (in our case, mostly low-income, young and digital natives), as driving force for a new and democratic development. The capability growth on the one hand is connected with expectations of greater opportunities, and on the other has to deal with the awareness of the new values that should guide the community and the megalopolis development: cohesion, for an harmonious development in an environment marked by diversity; resilience, for an adaptation to an environment with scarce natural resources and rising unpredictable events. The project then takes as driving forces the development of human resources and the natural resources defense, in a propulsive dynamic setting, that has no precedent in the history of mankind.

The design key element is sustainability, intended as a feedback between man and nature, in an anthropocenetic vision of development (Brugmans and Strien 2014), aware of the limit of resources and able to review obsolete design practices.

The New Design Rules

These principles lead to the building of a design abacus, as shown in figures 8, 9, 10, 11, characterized by these key-words:

- 'critique waterfalls' (Chen 2012): the aim of the project is to produce 'critique waterfalls', i.e. it must go beyond the mere satisfaction of needs in one place, and be generative (Cedric Price: Fun Palace), capable of producing exportable development processes. For this reason, the HoF design solutions and organizational strategies are repeatable, and help to transform the way people live in new cities or new spaces on a global scale;
- human capabilities: the main driving force of the project is the growth of human capabilities, in

order to increase creativity, flexibility and innovation skills. Human resources organize in structures characterized by differentiation, adaptability, cross-interaction, to promote and manage innovative and flexible systems.

- metabolism: the project is based on the optimization of resources metabolism, minimizing the input of raw materials, taking advantage of the opportunities offered by the dematerialization processes and exploiting waste flows to achieve processes of productive transformation. The metabolic (Longhi 2009) system is consistent with the rules of decoupling (Fischer-Kowalski 2011) and of man and environment synergy, so that for each physical realization there has to be an equal growth of natural resources. This principle allows the project to come together with the quality parameters of the settlements proposed by international conventions on human and environmental development. The physical infrastructures become tools to produce capability, relationships, energy, food;
- biology: the technologies employed are inspired by organic models, they have a low price and a high connectivity, in order to promote highly industrious processes in an environment characterized by the lack of capital.

The project as a great tsunami

The elements that make up the agenda of the HoF project are now undergoing great and rapid changes, and their effects aren't predictable. The design model is hit by a series of tsunami (Caldwell 2012; Dua 2013; Lavery *et al*. 2013; Bower 1995):

- the abandonment of the project as a series of physical 'stable' products in favor of a system of 'meshed' flows, composed of atoms and bits,
- the transition from a system of design rules inspired by the laws of mechanics to a system inspired by the rules of biology, of self-generating processes at zero resource consumption,
- the crisis of sedentary and passive education towards online and interactive organizations,
- the crisis of the historical production cycle, characterized by a multiplicity of passages in favor of the short chain ideation-product, with low cost plants, where everyone is an entrepreneur,
- the realization of the cloud, i.e. memory stores,
- the transformation of governance rules, towards the equalization of social relationships thanks to new technologies and to the availability of more and more capable clouds,
- the transformation of public administrators in 'urban mechanics', providing tools and assistance to citizens to creatively regenerate the city.

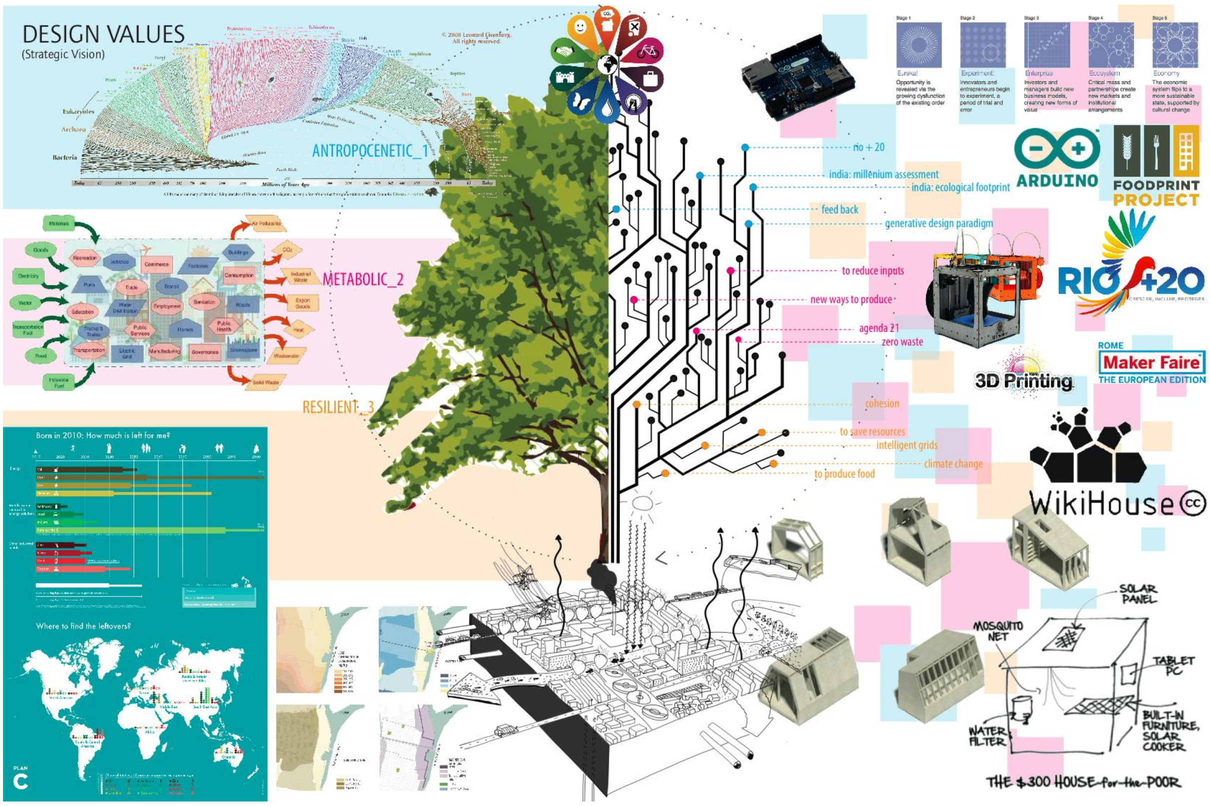


Figure 8. Hof: An Antropocenetic Design Supported By New Technologies

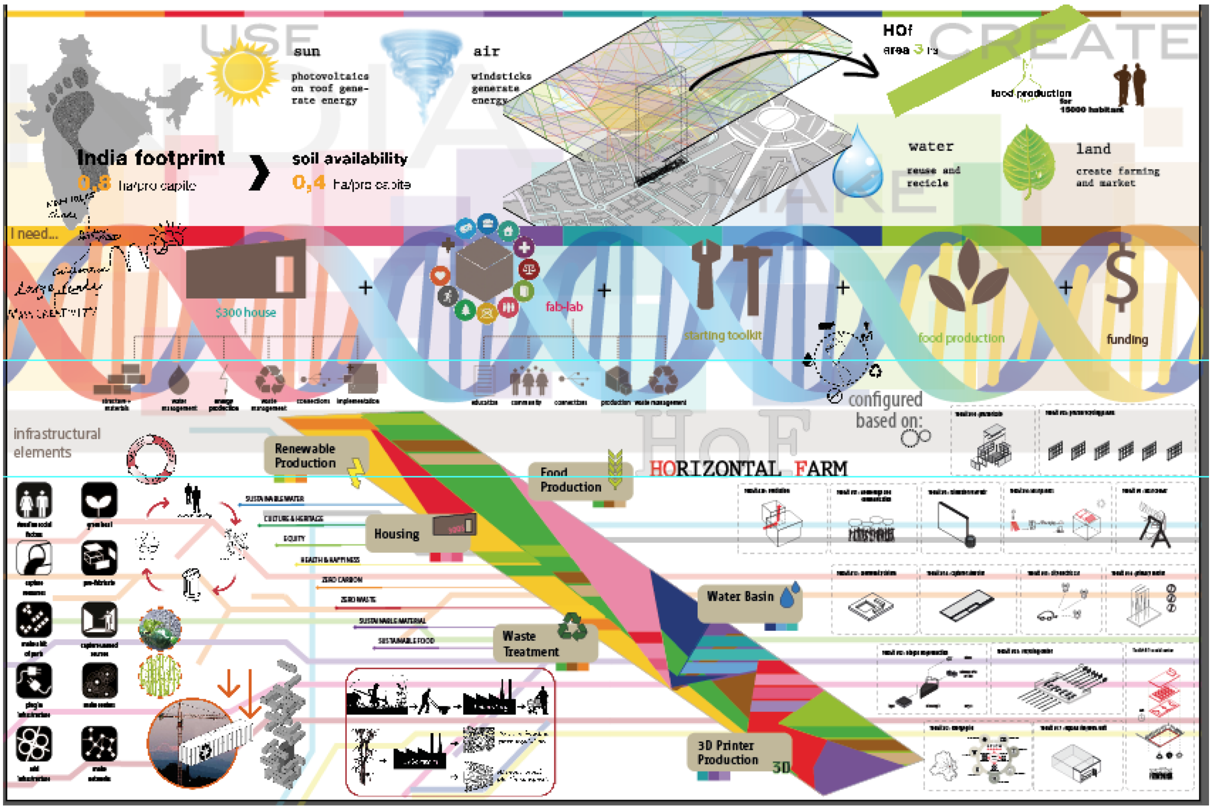


Figure 9. Hof: The Design Genoma

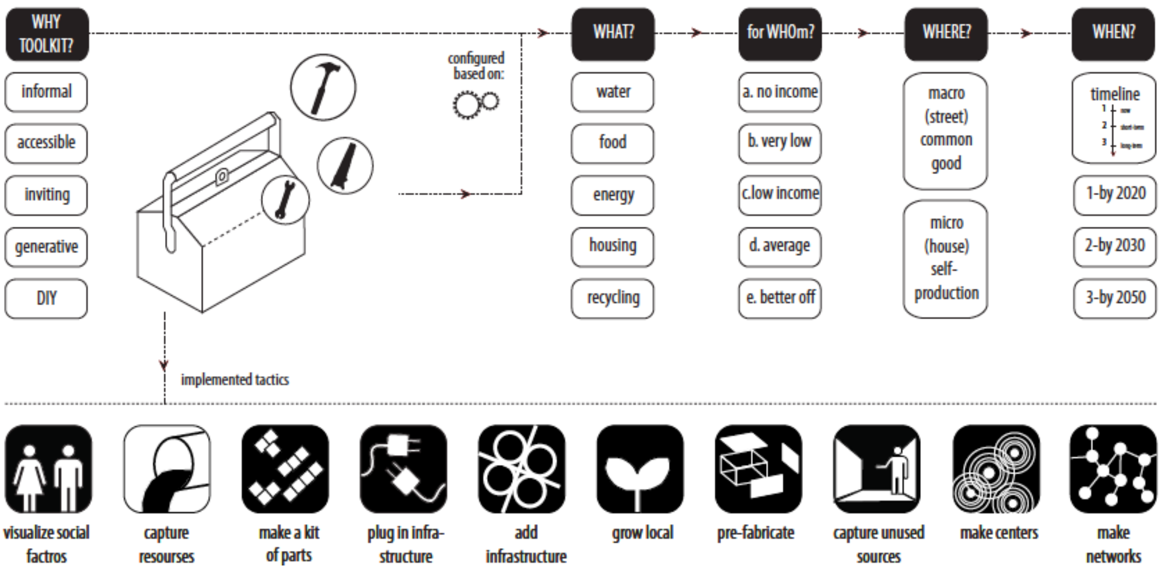


Figure 10. HoF: A Tool System Implemented by the People

Figure 11. HoF: The Urban Design is the Result of People's Creativity

Conclusions

This article re-evaluates the change of the design principles, which took place from the end of the 60s thanks to the contributions of Robert Solow and Jane Jacobs. They replaced the priority of physical capital with the priority of human capital, resulting in a pattern of 'social responsibility' in which the engine of the project, both urban and architectural, is the development of human resources against the depletion of resources, by exploiting the opportunities of new technologies, based on miniaturization, immateriality, biodiversity, reducing the consumption of natural resources. The variables of the model works in conditions of great uncertainty, thus it needs to be operationally developed according to the principles of resilience.

But the meaning of resilience is not unique. In the technical culture it means the ability of the material to resist forces of change. In the humanistic psychology it means the ability to cope in a positive manner to traumatic events, to give positive answers to difficulties. These fundamental differences in the design remind the difficult coexistence of two souls, the humanistic-creative and technological one. The first aims to re-evaluate the uniqueness and specificity of cognitive systems and to explore the future to stimulate change, the second aims at hyper rationalize the existing to maximize its effectiveness. Two differences that must be read in the social reality of the modern project. As noted by Rem Koolhaas (Koolhaas 2014), we must note that the thrust of 'fraternité, liberté, égalité' has run out and has been replaced by 'comfort, safety, eco-efficiency'.

Hence the urgency of the recovery of corporate social responsibility: the center of the project must be the search for the balance between values and techniques, the strategic task is the re-evaluation of values.

This involves reviewing the disciplinary structures, mainly by replacing the historical idea of projects as absolute (in the name of creativity of the architect or 'objective technique' of the engineer) with a new approach respectful of cognitive constructs, based on the iteration between users, their way of thinking and seeing humans and the built form. It also implies the transition from treating 'exclusively physical objects' to deal with interdependencies. It promises to be a very different way of observing and thinking, as there is the possibility of powering the design of physical spaces with the interdependence of these flows:

- biotic, i.e. those generated by natural resources and the atmosphere;
- the noosphere, i.e. knowledge, culture and technology;
- the cybersphere, that enables connectivity and augmented intelligence.

The designer has to become both a practitioner and an internist, to manage the potential of augmented intelligence, implying a radical renewal of the professional skills (Forrester 1969).

The potential of these changes in the empirical experience is applied to the project HoF - Horizontal farm in New Delhi, developed collaboratively by the students of the course 'Fundamentals of Sustainable Design at IUAV (2012/2013).

The project experiences the new design keywords, emphasizing the opportunities of new technologies and new production models, which require an initial capital significantly lower than in the past. The project thus becomes an opportunity for proposing a waterfall of creative solutions that combine the resilience with the hope of getting out of poverty thanks to the ability to use new tools and experiment new models of coexistence. The action of social responsibility that is proposed is based on investment on poor social classes, according to the lesson of Jay Forrester (Forrester 1969) in the occasion of the plan for the historic center of Boston, that is the more productive decision for urban regeneration.

References

Bower J., Christensen C. (1995) Disruptive Technologies: Catching the Wave, *Harvard Business Review*, January–February 1995.

Brugmans G., Strien J. (editors), (2014) Urban by Nature, *Catalog of Rotterdam Architecture Biennal*, IABR, Rotterdam NL.

Caldwell C., (2012) Ivory tower will be toppled by an online tsounami, *Financial Times*, August 10, 2012.

Cedric Price: Fun Palace, http://www.cca.qc.ca/en/collection/283-cedric-price-fun-palace

Chen Y. (2012) Zipf's law, hierarchical structure, and card-shuffling model for urban development, *Discrete dynamics in nature and society*, vol. 2012, art. ID 480196, Sagar, Mumbai, India.

Ciborra C. U. (1992) From thinking to tinkering: The grassroots of strategic information systems, *The Information Society*, Vol. 8, Issue 4, pp. 257-309, Taylor & Francis Group, UK.

Ciborra C. U. (2002) *The Labyrinths of Information: Challenging the Wisdom of Systems*, Oxford University Press, Oxford, UK.

Dua A., College for all, (2013) Voices on society: the art and science delivery, McKinsey, London, UK.

ERT, European Round Table of Industrialist (2010) The next EU Framework Programme for Research must reinforce the EU's innovation capacity. ERT's suggestions for FP8, ERT, Brussels.

Fenn, T., Fleet, D., Hartman, M., Garrett, L., Daly, E., Elding, C., & Udo, J. (2014) Study on economic and social benefits of environmental protection and resources efficiency related to the European Semester, DG Environment, Bruxelles.

Fischer-Kowalski, M., & Swilling, M. (2011), Decoupling natural resource use and environmental impacts from economic growth, Report of the Working Group on Decoupling to the International Resource Panel.., Swilling, M., UNEP, Nairobi.

Forrester J. W. (1969) *Urban dynamics*, MIT Press, Cambridge, MA.

Fuller B., Romer P. (2014) Urbanization as opportunity, Working paper 1, (Feb. 2014), Marron Institute, NY University.

IBM, Smarter City Program, http://www-03.ibm.com/innovation/us/thesmartercity/

Koolhaas R. (2014) Elements of Architecture, Presentation of Biennale di Architettura, Venice, Italy.

Lavery G., Pennel G., Brown S., Evans S. (2013) The next manufacturing revolution, http://www. nextmanufacturingrevolution.orgy.

Longhi G. (2009) Piano strategico sostenibile delle isole Pelagie, Il Poligrafo, Padova, Italy, 2009

Lucas R. E. Jr. (1988) On the Mechanics of Economic Development, *Journal of Monetary Economics*, vol. 22, pp. 3-42., North-Holland.

McKinsey Global Institute (2013) Disruptive technologies: advances that will transform life, business, and the global economy, McKinsey & Company.

Meadows D. (2008) *Thinking in systems*, Chelsea Green Publishing, White River Junction, Vermont.

Nowlan D. M. (1997) *Jane Jacobs Among the Economists, Ideas That Matter: The Worlds of Jane Jacobs*, The Ginger Press, pp. 111-113.

Nussbaum M. (1999) In defense of universal values, *Occasional paper series: Women and human development*, University of Notre Dame, Indiana, USA.

Rockström J. *et al.*, (2009) Planetary boundaries: exploring the safe operating space for humanity, *Ecology and Society* , vol. 14, no. 2, art. 32, The Resilience Alliance.

Romer P. M. (1986) Increasing retourns and long run growth, *The journal of political economy,* Vol. 94, Issue 5, (Oct. 1986), pp. 1002-1037, The University of Chicago Press.

Sen A. (1989) Development as Capability Expansion, in: S. Fukuda-Parr, A.K. Shiva Kumar, *Readings in Human Development*, Oxford University Press, Oxford, UK, 2003.

Solow R. M. (1957) Technical Change and the Aggregate Production Function, *Review of Economics and Statistics*, Vol. 39, No. 3 (Aug. 1957), pp. 312-320, The MIT Press.

UNU-IHDP&UNEP (2012) *Inclusive Wealth Report 2012. Measuring progress toward sustainability,* Cambridge University Press, Cambridge.

Change in Design Targets for Building Energy Towards Smart Cities

Alfred Heller[*1], Panagiota Gianniou[1], Emmanouil Katsigiannis[2], Andreas Mortensen[2] and Kyung Hun Woo[3]

alfh@byg.dtu.dk, pagian@byg.dtu.dk, s121405@student.dtu.dk, s110058@student.dtu.dk and archope@samsung.com

[1] Department of Building Energy, Technical University of Denmark, Denmark

[2] Student, Technical University of Denmark, Denmark

[3] Guest Senior Researcher from Samsung, Korea

Abstract: Designing cities from an overall energy optimization system point of view demands changes in engineering procedures, expecting that there are exposed solutions where synergy effects arise that unleash extra saving potentials. Based on the insight gained by the simulations, IT intelligence and cross-component communication are to be invented to control the components and thereby to optimize the total system performance. One main strategy in doing so is to adjust demands to the production, demand management by utilizing "flexibility" within the terminology of "smart grids". To acquire large potentials, thermal system components are studied these days upon their flexibility potentials, such as heating and cooling of whole building structures. Thereby the question arises, how much "flexibility" is there in relation to the thermal capacities of buildings that enable shifting energy demand for heating and cooling over periods of hours? While we in the past could focus on energy optimization, we now have to design our buildings to its context, offering flexibility to the surrounding energy system. No final answers are given due to the fact that this is the edge of current research in this field, while a first concept draft is presented here.

Keywords: Building Design, Flexibility, Thermal Capacity, Energy Optimization, City Design.

Introduction

In traditional energy systems, the production side was adjusted to meet the fluctuating demands by different means. The future energy system is characterized by a very large or even 100% penetration of renewable energy sources that replace the rather stabile production side with a massively fluctuating alternative. Hence both the production and the demand side of the energy system will be fluctuating. In a first attempt the electrical distribution system was strengthened to tackle the challenge of stabilizing the overall system, the "smart grid". Recently, this idea of tackling the challenge within the electrical grid only, is replaced by a more multi stringed system design that includes gas-grids, district heating and cooling as well as the buildings into the solution.

In Denmark the penetration of renewable electricity from wind farms can be up to 100% for a few days per year. It covers in some areas over half of the production, while on a national scale share is approximately 33% (Energinet.dk 2014). All this is possible due to the fact that the national net is connected to other countries nets and thereby the capacities are shared. In a future net this will not be possible due to the fact that neighbouring countries are expected to have similar climatic conditions and thereby will produce renewable energy in the same pattern as Denmark. Hence new more robust solutions are to be found. Obvious, additional potentials for stabilizing the electrical grid are large grids such as the gas grid and district heating and utilizing the energy demanding industries. Also the very large mass of the building stock could play a major role if the mass is available for storage. This is the case if the mass is available for control but is absent in case of e.g. light constructions and interior insulated buildings. Research is ongoing to reveal the utilizable capacity of buildings. In the current work, the question discussed is, how future buildings could be designed to meet the demand for flexibility by the overall energy grids and smart cities. The reader will not find the answer, but rather a proposal for a methodology that in later work will be applied for the answering of questions about available and controllable thermal mass in building and the resulting flexibility available for the smart grid. Similar issues will be the kernel of an upcoming study (IEA 2014).

The Expected Fluctuations

Given the conditions of a future el-grid with a large share of renewable energy sources for production, a balancing of the whole system is critical. The demand for electricity compared to the wind production for a few days in December 2012 for the Danish electrical grid in Jutland, Denmark, where renewable energy from wind mills can be dominating, is shown in figure 1.

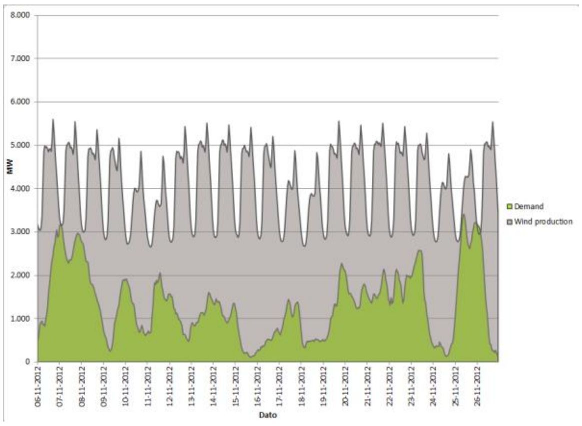


Figure 1. Demand and Wind Production for Jutland, Denmark for 2012 (Energinet.dk 2014)

A simple prediction for the corresponding curve for 2050 is shown in figure 2.

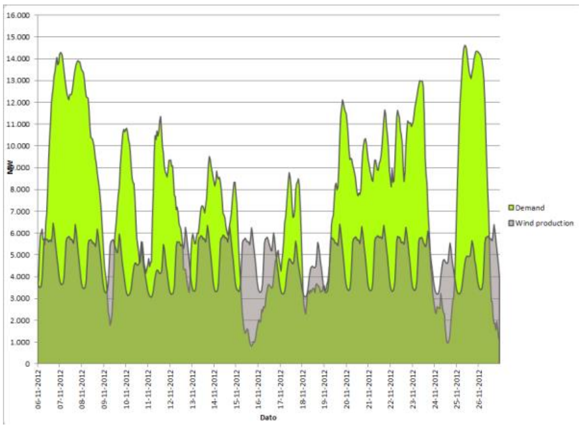


Figure 2. Demand and Wind Production for Denmark for 2050 (Energinet.dk 2014)

The above figures give an idea of the magnitude of the fluctuation and thereby the demand for balancing. The current paper reflects on whether building can be part of a stabilizing solution.

This is done by modelling the buildings within the energy grids and computing relevant scenarios. Hence the modelling of energy demand for whole cities and more precise building stocks in cities is the focus of the current work.

Limitations of Current City Level Model

Searching research literature for city energy modelling will reveal that the basic idea behind such efforts was to simulate each building individually and sum up to the aggregated level of a city or a district. This approach enables the modelling of any buildings in accordance to the knowledge available, adjusted to the given case. This makes it possible to automate the parameter specification on the basis of e.g. national building databases. Theoretically this approach is very precise; however the lack of detailed information does limit the precision of this procedure.

To move from the individual building to the city, in many cases there are applied simple sums (Reinhart *et al*. 2013; Heller 2002), where in other publications weighting factors were applied that reflect e.g. the gross area of the building or the Energy Use Intensity (EUI) (Ruchi 2011) discussed below in the current paper.

The limitation of computing each building individually is that the simulation of many buildings takes a lot of computer time. To solve this problem simplified building models are applied that are not able to capture the dynamics necessary to find flexibilities in the building masses and additional storage capacities. Therefore an alternative approach is necessary to analyse solutions to the peak shifting problem. There is a need for simplified building models that reproduce the dynamics relevant to flexibility estimations realistically.

Building Modelling for the Smart City

Before going into details with the discussion of building energy simulation models, the aim of doing so must be defined. Existing models are designed for historical and actual building technologies. For future buildings the details of design are unknown. Hence the models can be designed rather abstract, catching just the relevant characteristics of the future buildings for scenario modelling, analysis and such. This opens for the implementation of computationally efficient models. In the current paper, we will build on existing modelling methodologies and just mention what future developments could be realised.

The paper will propose a methodology to find the flexibility which buildings can offer to the surrounding energy system. More precisely, the challenge is to find how much of the thermal capacities can be utilized in the demand shifting within buildings? The methodology is basically defined by the following steps:

1. Decide on a typology for the city buildings
2. Model each type by a dynamic simulation program (e.g. Energy Plus, IDA ICE)
3. Eventually apply stochastic distribution on each type
4. Represent all buildings in the city by the types computed, and aggregate the results (e.g. flexibility) by different means discussed below.

The advantage, compared to the individual modelling, is the ability to model a large number of buildings by just computing representative types and thereby very fast computations. The drawback is the uncertainties that the method introduces. However, other stochastic uncertainties, such as building context and user behaviour, are in similar magnitude and we must accept these uncertainties and find solutions to them by stochastic means.

In the below text, the different steps are described and discussed to define a methodology that can be analysed in future work.

Step 1 – Typology

You find different terms for what we call here "typology", such as archetypes and classes, which are a classification of buildings into alike types with respect to certain criterions. The goal for finding the current typology is to classify the building stock systematically into types that represent many similar buildings in cities. Due to lack of knowledge on flexibility, which we aim at in a future work, we will here build on typologies that aimed at energy demand issues.

We did not find a comprehensive typology that is covering all buildings. The authors did often focus on a special subset of buildings such as residential buildings, offices and so on. Here is a short presentation of the findings from literature:

The European Union proposes a typology for residential building based on Eurostat data, with the three types covering 70% of the building stock in the included countries: *(a)* Single-family houses (including two-family houses and terrace houses), *(b)* Multi-family houses with more than 2 units and *(c)* High-rise buildings with more than 8 floors. In this typology, Europe is divided into three climate zones according to the degree days for heating and cooling. The methodology leads to 53 building types (Nemry *et al.* 2010).

Another approach is implemented for a few European countries in the web tool Tabula. The typology is country dependent which can be discussed to be arbitrary or methodologically significant. Within the given country the age of the building (construction traditions) and a clustering into the same types as in the previous source added a fourth type *(d)* Terraced houses, leads to a matrix of building types for each country. On top of this, there are defined three levels of maintenance/renovation, (i) the original (ii) a "usual refurbishment level" and (iii) an "advanced refurbishment level". The technical installations and the thermal installation levels are defined according to the local traditions (EU project Tabula 2014).

Buildinglessons.com is a UK web site presenting domestic, educational and other building types, all in all 22 building types. The buildings are described in IES<VE> models that describe the buildings in detail and enable standardized simulations. In case of applying other simulation software, this may be a weakness and a standardized description in one of the Building Information Models would be preferable.

The U.S. Department of Energy (DOE) has developed an online resource that defines 16 types of commercial and 5 types of residential buildings covering approximately 70% of the US building stock (DOE 2012). The DOE typology also defines "Technology descriptions" for e.g. lighting, heating and so on.

From these building types various methodologies are proposed that employ weighting factors to give a representative value for the energy demand of the building types. Within the technical report of NREL (Deru *et al.* 2011), the combination of buildings and locations is proposed for assembling the climatic and geographical effects in each building. The national data from the Commercial Buildings Energy Consumption Survey (EIA 2014), can be applied to determine the appropriate, average mix of representative buildings.

Other typologies that basically combine the mentioned methodologies can be found for non-residential buildings in Ruchi (2011) for the London area, in Matsuoka *et al.* (2013) for the Keihanshin metropolitan area in Japan, and in Fei and Augenbroe (2011) and Swan and Ugursal (2009), which proposes an archetype typology.

Step 2 – Dynamic Simulation

The above mentioned typologies are often defined with respect to energy demand on a yearly basis. The computation of these energy demands can be done in many ways spreading from simple lookup algorithms to advanced dynamic simulations and even involve Computational Fluid Dynamics (CFD) computations. In the Tabula web tool, every country applies its own methodology, tool or computer simulation program. In BuildingLessons, the simulation program IES<VE> is utilized. For UK typologies a standardized methodology is defined in the NCM activity database on www.ncm.bre.co.uk. Here there are 29 building types with a classification of 505 room types, specifications for user profiles, temperature set points, ventilation rates and much more that aim at standardizing the simulation conditions rather than to standardize the model tool.

As the aim for the mentioned simulations is the energy demand on an annual basis, for the current purpose of estimating flexibility, a building energy simulation program must be found that represents the thermal dynamics of building constructions. There seem to be traditions to apply finite difference/volume models or thermal response models (Armstrong *et al.* 2006). Due to the fact that the latter represent heat conduction by wave representations, e.g. Fourier models, the understanding of the basics is much more close to the human understanding. Hence such models can also be applied for abstract modelling of systems that are theoretically designed to have certain behaviour – e.g. you will model building constructions with slow or fast heat exchange at the surfaces (e.g. thermo-active elements). The first will have a very slow wave representation of the heat conduction, as the latter has a fast wave model applied. The drawback of this approach is that you cannot plot the temperature curves within a given construction and thereby it is difficult to see how the heat is conducted and absorbed.

Step 3 – Stochastic Distribution

The basic idea in this step is to represent the variability over buildings performance due to uncertainty in input parameters such as thermal properties of building fabric and also variation in user behaviour. The two tools SunTool (Robinson *et al.* 2007) and SimCity (Kämpf *et al.* 2009) have implemented such models, accounting for user behaviour.

There are basically two ways to implement this stochasticity, a) to use distributions on the individual parameters in the model, or b) to coat the final building results by a distribution model. The first will give the possibility to use different distribution models for many aspects to be modelled. The latter however is rather simple and fast. The idea could be to model the building types of a given topology, determine the variability and use stochastic models to catch the stochastic aspects of among other things, users' behaviour and building context (shading, heights, etc.).

Step 4– Aggregation

The aggregation is the step where one computes the impact of many buildings to a city level energy result. In literature you find very simple aggregation models for energy demands for building clusters. These models can be applied to flexibility aggregation also.
Many authors do not model the demand but rather base the energy demand on statistical data and distribute them to the buildings on basis of e.g. Energy Use Intensity (EUI) expressed per square meter floor area (Ruchi 2011; Matsuoka *et al.* 2013).

An alternative method is a simple sum of the given key performance indicator (Kämpf *et al.* 2009):

$$F = \sum_{i=1}^{n} f$$

where *F* is the flexibility for the whole city or population of buildings, *f* are the individual flexibility simulated for a given building/-type, *i* is a counter and *n* is the number of buildings/-type.

The second aggregation model adds a weight to the individual buildings which especially make sense if you apply it to building types.

$$F = \sum_{i=1}^{n} w_i f$$

where a weighting factor, w_i, is given to the individual building/-type.

As we find, the aggregations are very simple and often no stochastic variability is applied. However the two approaches can be combined and *are* combined in above mentioned work.

No model is found that represents dynamic energy consumption and an aggregation from few buildings to a large number of buildings.

Building Modelling for the Smart Energy City

What role do buildings play? It gets rather clear that the peaks are placed in the mornings and the evenings where Danish citizens are at home and do washing, cooking and such everyday tasks that demand electrical energy supply. Hence it can be argued that almost the whole peak load is related to building performances.

In more detail, the demands in buildings can be split into demand for heating, cooling, ventilation, hot water, light and electricity for appliances, whereas the first can be supplied by thermal sources directly and will not have impact on the electrical demand peak. Let us assume that we have a system that also supplies thermal services by electricity, which is the case for many buildings outside the district heating networks of Denmark. What will be the possibility for flexibility and how can we estimate it?

For this purpose the building models have to simulate the dynamic behaviour of the building, the thermal capacities of the constructions, the storage tanks and other thermal capacities within the building. Many simulation models utilized for energy demand computations will not be able to reproduce these thermal capacities due to simplifications as mentioned before.

Conclusion – A Designing Approach for the Smart Energy City

In this section the methodology proposed in this paper is summarized.

1. Find an appropriate typology for your urban area
2. Compute average energy flexibilities (the methodology is still to be defined)

3. Find appropriate stochastic models for observed variations from the average.
4. Add the overall flexibility for the whole urban area at hand.

Moreover there must be found a City Information Model that enables a description of cities in a comprehensive manner. This must be addressed in the future work.

It must be remembered that flexibility can be delivered by other technologies than building thermal masses, tank storage and the like. There are capacities in district heating and cooling networks that can be used to generate flexibility, and there are electro-thermal solutions such as heat pumps.

Acknowledgements

The current research is supported by Samsung through a visiting grant for the researcher and co-author Kyung Hun Woo.

References

Armstrong, P. R., Leeb, S. B., & Norford, L. K. (2006) Control with building mass - Part 1: Thermal respons model identification. *ASHRAE Transactions*, 112(1), CH–06–5–1.

Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., Liu, B., Halverson, M., Winiarski, D., Rosenberg, M., Yazdanian, M., Huang, J., Crawley, D. (2011) *U.S. Department of Energy commercial reference building models of the national building stock*.

Energinet.dk (2014) Wind energy production 2013 (in Danish). Retrieved June 21, 2014, from http://energinet.dk/DA/KLIMA-OG-MILJOE/ Miljoerapportering/VE-produktion/Sider/Vind.aspx

Energy Information Administration (EIA) (2014) Commercial Buildings Energy Consumption Survey (CBECS). Retrieved June 18, 2014, from http://www.eia.gov/consumption/commercial/

EU Project Tabula (2014) Tabula Webtool for European Building Typology. Retrieved June 18, 2014, from http://webtool.building-typology.eu/

Fei, Z., & Augenbroe, G. (2011) Agent-Based Modelling of Commercial Building Stocks for Policy Support. In *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, Sydney, Australia, pp. 14–16.

Heller, A. J. (2002) Heat-load modelling for large systems. *Applied Energy*, 72(1), pp. 371-387.

IEA (2014) IEA EBC Annex 67 Energy Flexible Buildings.

Kämpf, J. H., and Robinson, D. (2009) Optimisation of urban Energy Demand using an evolutionary Algorithm. In *Proceedings of the Eleventh International IBPSA Conference* (No. EPFL-CONF-148716), pp. 668-673.

Matsuoka, A., Yohei, Y., Yusuke, S., & Yoshiyuki, S. (2013) Urban scale modelling of energy demand of retail facilities. In *Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association*, Chambéry, France, pp. 1288–1295.

Nemry, F., Uihlein, A., Colodel, C. M., Wetzel, C., Braune, A., Wittstock, B.,et al. (2010) Options to reduce the environmental impacts of residential buildings in the European Union—Potential and costs. *Energy and Buildings*, 42(7), 976-984.

Reinhart, C., Dogan, T., Jakubiec, J. A., Rakha, T., & Sang, A. (2013) Umi-an urban simulation environment for building energy use, daylighting and walkability. *Proceedings of the 13th Conference of International Building Performance Simulation Association*, Chambery, France.

Robinson, D., Campbell, N., Gaiser, W., Kabel, K., Le-Mouel, A., Morel, et al. (2007) SUNtool–A new modelling paradigm for simulating and optimising urban sustainability. *Solar Energy*, 81(9), 1196-1211.

Ruchi, C. (2011) A Probabilistic Model for Assessing Energy Consumption of the Non-Domestic Building Stock. *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, Sydney, Australia, pp. 14–16.

Swan, L. G., & Ugursal, V. I. (2009) Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*, 13(8), 1819–1835.

United States Department of Energy (DOE) (2012) *Buildings Energy Data Book*. Retrieved June 18, 2014, from http://buildingsdatabook.eren.doe.gov/Glossary.aspx#Build

Climate Change Adaptation of the Built Environment – An Examination

Jonna Majgaard Krarup
Jonna.krarup@kadk.dk
Institute of Planning, Royal Academy of Fine Arts
School of Architecture, Copenhagen, Denmark

Abstract: In a Danish context, climate changes are primarily manifested in an interaction between modified wind and precipitation patterns, increasing temperature and a rising sea level. The individual factors often act together and are reinforced in interaction with already known natural and cultural phenomena. This is why the term 'environmental changes' might be more accurate than climate change. 'Environmental changes' suggests that climate changes ought to be understood as extensive environmental changes, with an impact on the built environment. Following this, it is no longer sufficient only to assess for example a building, and anthropogenic impacts on the environment, also the impact of the environment on installations, and on the human activities must be included in the analysis and assessments. Based on observations and investigations into climate change adaptation in DK and abroad the research project, Waterscape (Vandskab), focus on some of the challenges that the architectural disciplines are facing in relation to climate changes adaptation.

Keywords: Climate Change, Adaptation Methodology, Architecture.

Climate Change Processes Lead to Environmental Changes

According to UN climate panel, IPCC (2013) there is up to a 90-99% probability of greenhouse gases emitted as a by-product of human activities are causing the ongoing climate changes. The ongoing climatic changes can thus be described as the largest and most comprehensive 'design project' humanity has embarked on.

The impact of the climate change processes include the fact that the temperature is rising, the ice is melting, permafrost thaws, and the oceans become acidified. The weather becomes wilder, agriculture and forestry are affected and the ground water rises. Other effects are multiple and prolonged heat waves, wet areas will get wetter and dry areas drier. With the expected continued emissions of greenhouse gases, it is estimated that the temperature rise will be at least 0.3 degrees Celsius in the 21st century. Less optimistic estimates predict temperature increases up to 4.8 degrees Celsius. It is further estimated that the oceans will rise between 26 and 82 centimetres up to 2100 (IPPC 2013). In a Danish context, climate changes are primarily manifested in an interaction between modified wind and precipitation patterns, increasing temperature and a rising sea level (DMI 2014). The climate change process is irreversible and requires that we adapt to these new conditions, and that we try to stabilize the processes.

The individual factors in the climate change process often act together, and are reinforced in interaction with already known natural and cultural phenomena and factors. Paskal (2009) thus suggests that climate changes leads to 'environmental changes'. Paskal (2009) illustrates this by referring to damages seen on buildings, roads and energy delivery systems in permafrost areas, which now due to more frequent and longer periods of warmer weather, no longer are permanently frozen, and thus no longer provide a stable base for example buildings. Further, Paskal (2009) points out, that in addition to various damages to buildings and facilities, this also means that a standard impact assessment methodology, Assessments of Environmental Impact (EIA) is no longer sufficient - the effects of the environmental impact on a given system now also have to be evaluated.

Climatic change thus also leads to change of an analytical tool and method used by architects, and others, in planning and design processes. This points out that climate change processes can not be considered and handled in isolation and only as a climatic problem. Also, climate changes cannot be seen as a purely technical problem that can be handled with extra foundations or other technical solutions. Climate changes also affect our understanding and notion of not only the climate but of nature *per se*, and of man's interaction with nature and natural phenomena, and thus climate change also have an impact on the built environment.

- In a Danish context climate changes are primarily manifested by: rising temperatures, a rising sea level, changed precipitation and wind patterns – in short: Wilder, Warmer and Wetter. These 'markers' interact.
- The term ‘environmental changes’ describes that climate change processes can not be isolated as a climatic phenomenon, but results in extensive environmental changes, including changes in the built environment, and thus changes how the built environment is planned, designed, used and experienced.
- In addition to the more technical and economic questions raised by climate change processes, also spatial, planning, and design – in short architectural – questions are addressed.

My interest in these questions is reflected in the research project, Waterscape (Krarup 2011), supported with funding from the Danish Ministry of Culture and conducted as part of my research at the Department of Planning, School of Architecture Copenhagen. The project takes its point of departure in examples of climate change adaptation measures in Hafencity, Hamburg, Germany, and the interaction of these initiatives within the urban zone with adaptation measures taken in the rural zone, e.g. the Elb river valley. The study focuses on the interrelationship between climate change adaptation measures across zoning and administrative divisions in order to investigate and discuss whether some of these German examples and experiences may be relevant in Danish climate change adaptation planning, and thus add other complementary climate adaptation measures to those already known.

In the following, some of the discussions and results in the project will be presented here, starting with a brief description of some of the climate change adaptations that have been developed and embodied in the development of Hafencity in Hamburg, and along the Elbe in Germany. This is followed by a presentation of the study on two Danish examples Kerteminde and Reersoe. It is discussed whether there are lessons to learn from the examples in Germany, and whether they are applicable in a Danish context.

Learning From

The research project, *Waterscape*, took its point of departure with the great floods in Hamburg and along the Elbe in the spring of 2002 and 2006. During the flooding in 2006, I travelled along the Elbe from Hamburg to the Elbe source in the mountains between the Czech Republic and Poland, and experienced the extent of the flooding in-situ.

Hafencity in Hamburg is one of the most interesting examples of large-scale climate change adaptation coordinated with and incorporated in the urban development plans and strategies for Hamburg. Hafencity is situated in low-lying former harbour areas along the Elbe and the area is prone to flooding. This is why a number of mitigation and climate adaptation initiatives are taken. What is characteristic of these adaptation measures is that the flood problems in Hafencity are sought handled in a coordinated spatial, functional, and technical manner in the organization and design of this new urban district. The climate change adaptation plans and initiatives taken in Hafencity have attracted much attention in planning and architectural circles, whereas the climate adaptation measures taken in the open countryside along the Elbe are less known, despite the fact that they have an impact on Hafencity and interact with the initiatives taken and planned in Hafencity.

The climatic change processes experienced in the northern parts of Germany are in several respects comparable to those we experience in DK, e.g. a changed precipitation pattern characterized by heavy, torrential rains, changes in the wind patterns, storms and frequent strong winds from the west and northwest, and a warmer climate (NMI 2013). The normal fluctuations of the Elbe seems increasingly to be amplified by climate change, and thus increasing the risk of flooding of the low-lying areas of Hamburg.

270 km2, approximately one-third of Hamburg's total area, is located on low-lying areas around the Elbe and its tributaries Bille and Alster. Almost 180,000 people live and about 140,000 workplaces are situated in these areas. The harbour area contains storage areas for approx. 2500 companies using the 340 fixed routes connecting Hamburg with 1100 ports worldwide. At the harbour areas goods for a value of approximately 10 billion Euros (GHS 2000) are stored.

Hafencity

The plans for Hafencity outline a process of transformation running until 2020-2025. Existing industrial and harbour activities are being phased out and the area converted into a new urban district with new residential, and office buildings. Also new tourist and recreation facilities are planned together with educational and cultural institutions.

Hafencity extends over 150 hectares, making it one of the largest centrally located urban transformation areas in Europe, and will fully developed extend the area of Hamburg by approximately 40%. It is expected to built more than 6,000 new homes, and create 45,000 new jobs in the area.

Climate changes are playing a direct and decisively role in the spatial organization of the area, and in the design of the individual out-door space and buildings, and their adaptation to climate change.

New residential buildings are thus raised from the ground level. Openings in buildings are fitted with doors and shutters that can be closed at high water levels. Major roads and buildings are placed on Varfts (artificial mounds) that raises the terrain from 4.5 meters above normal water level to 7.2 m. The varfts are placed on the existing quay area, keeping a border zone of up to 20 meters free for public spaces.

This means that many of the public spaces in Hafencity are planned and designed in such a manner that they can and will be fully or partially flooded periodically. Other urban spaces such as Sandtorhafen is floating on a pontoon and thus following the water movements. Escape routes in the form of alleys and stairways are placed between the public areas in the border zone and the core, and dry, areas on the varfts.

The Elbe River Landscape

Hamburg and Hafencity is just one point, one city located in a river landscape that stretches some 1100 km. Approximately 740 km of the river flows through Germany, the remaining 370 km runs through the Czech Republic. The catchment area of the Elbe is 148 268 km2. In comparison, Denmark's total area of just over 43,000 km2, and the most water-rich river system in DK, Skjern Å, has a catchment area of 2,100 km2.

For centuries the Elb river valley has been developed into a highly specialized and increasingly mono-functional cultural landscape. The different regulatory actions can be recognized physically in the form of cultivated wet meadow areas, dikes, dams, canals, and cities and buildings located both along and in the riverbed. According to Internationale Kommission zum Schutz der Elbe (2014) the extension of the river valley has been reduced from 620 000 ha to 84 000 ha since the 12th century, which means that the buffer areas - meadows, wetlands, forest plantings, etc. - which potentially could absorb large amounts of excess water from the river system, and surface water from the adjacent land, are reduced by approximately 86%.

For long stretches the Elb river valley is thus transformed into a channel framed by dikes, and optimized to transport excess water. As a result the speed and the amounts of moving water is increased, which also increases the flood risks in Hamburg and in Hafencity. The water has little place to pause, and everybody wants to avoid and get rid of the excess water.

In this way the Elb river valley as a whole has an impact on the amount and nature of climate change adaptation taken in Hamburg and Hafencity, no matter administrative and zoning divisions. Following this, the city of Hamburg is increasingly to be seen and understood in its landscape context - in its environmental context, its Habitat (Painado Ponton 2006) – as part of a larger entity.

This suggests a more integrative and coordinated - systemic - thinking and understanding of how we see and understand cities and settlements in their landscape context, and the interdependence between, for example Hamburg and the Elbe river valley. This points towards a stronger focus on the relationship and coordination between urban planning, and landscape planning and use across competencies, legal and administrative divisions, and thus on a more holistic planning process and methodology.

Based on my observations along the Elbe the following categories of protection and adaptation measurements have crystallized:

1. Protection and adaptation at building level
    a. Mounting watertight bulkheads, doors and gates on buildings
    b. No habitation in ground floors / raised ground floors
    c. Choice of materials and design that can withstand periodic flooding
2. Protection and adaptation measures at urban space level
    a. Urban spaces as retarding basins during peak periods
    b. Spatially design that supports urban space as retarding basins
    c. Choice of materials and design that can withstand periodic flooding
    d. Floating urban spaces (pontoon on the water surface)
    e. River and water walls
    f. Urban spaces on ‘stilts’ (elevated sidewalks, squares)
    g. Urban spaces located on dikes and varfts
    h. Optimization of sewerage in terrain
3. Protection and adaptation measures on structural and spatial level (urban level)
    a. Dikes
    b. Varfts
    c. Sectioning urban areas into districts with dikes and sluices
    d. Green retarding spaces ('suction sponge' areas) in exposed areas
4. Protection and adaptation measures at landscape level
    a. Construction and/or withdrawal of dikes
    b. Construction of varfts
    c. Construction / restoration of wet meadows as retarding basins
    d. Construction / restoration of planted areas, for example forest, that can absorb large amounts of water (retarding areas)

5. Protection and adaptation measures at administrative level

1. Creation of administrative and operational modes of communication, detection and monitoring systems that transcend administrative boundaries and is adequate for tackling the problem from a holistic understanding
2. Establishment of climate adaptive measures that supports detection and monitoring systems

Ad. 4.a

Following the 2002 flood it was decided to expand the space of the Elb river bed on some stretches in Germany by withdrawal of the dikes, and thus creating a larger volume in the riverbed, and, at the same time, re-establish some of the lost wet meadow areas.

Ad. 5.a&b

A voluntary monitoring, reporting and water retarding system have been established between the German cities situated along the Elbe and its tributaries. Each town is obliged to observe, and inform each other, and to regulate the water inflow by closing or opening the inflow from the tributaries. The principle is that everyone takes their share of the excess water, and that no one 'export' more excess water than necessary to the neighbour city further down the river. A city situated by an inlet to the Elbe, will thus during peak periods have to close the water inflow to the Elbe and thereby flood its own area. This was the case in Havelberg in 2006, where it was necessary to close the inflow from the Havel to the Elbe and delay the masses of water moving down the system. This meant that larger parts of the low-lying neighbourhoods in Havelberg were flooded during my visit.

A lesson that can be drawn from the observations of climate change adaptation along the Elbe is that each initiative interacts and is part of a complex network between both natural and cultural processes and activities, between visible and invisible conditions and phenomena, between scales, and between administrative and legislative divisions. An example, the protection measures at the administrative level (cat.5) does not make sense if they are not followed up in synergy with other initiatives at other levels.

What also stands out clearly is, that the individual climate adaptation initiative in itself may be both functional and effective, but relating it to other initiatives across scales and domains qualifies each element and initiative. In order to do so it presupposes,

- The establishment of an understanding of the problem across fields of knowledge, across scales, and interests, and economic and administrative boundaries
- The development of adequate tools and methodologies, for example analysis methods for identifying relationships, impacts and interactions between, for example, natural (climatic / geological), and cultural, economic, social and spatial phenomena and relationships, and needs.

Learning For

Kerteminde and Reersoe are chosen as representative of some of the common questions concerning climate change adaptation many small Danish coastal towns and settlements are faced with due to their low location in an already low-lying Danish landscape. The two Danish examples have been studied through field studies, literature studies and through material from websites and various published municipal planning and strategy documents. The studies have focused on the extent to which official strategies and plans are influenced and motivated by climate change adaptations, and what specific adaptation measurement that might be described or taken. The studies also include spatial analyzes of the two examples.

The spatial analysis of the two examples are placed between an overall landscape character analysis (Stahlschmidt 2001), which almost does not deal with the city's location in the landscape, and, a spatial urban analysis by the SAVE method, which mainly deals with buildings, and the cultural and building structures, and only to some degree with relationship between the landscape and the city/settlement/buildings. In the following a short summery of the analysis of Kerteminde and Reersoe will be given.

Kerteminde

The municipality of Kerteminde is inhabited by approx. 24,000 people. The main city, Kerteminde, is located at the mouth of Kerteminde Fjord. The historical part, e.g. the city built before 1900 is located on a beach sediment surface at the mouth of Kerteminde Fjord. The two manor houses, Lundsgård south of Kerteminde, and Hverringe north of Kerteminde have formed barriers to the urban development along the coast, and thereby contributed to control the urban growth and push it towards the west and northwest.

Northwest of Kerteminde the landscape is a dammed and drained fjord landscape ranging from Odense to Kerteminde Bay. In this area Kerteminde Municipality has started restoring a wet meadow area, Sybergland. Between this area and Kerteminde central part is an arc-shaped little hill island, on which the modernistic part of Kerteminde is situated. Previously this area appeared as an islet with water and wetlands to almost all sides.

The industrial area is located on the flat, reclaimed land to the north and northwest of the historic center. The area turns its back to the landscape and is starting to 'float' out into the drained fjord landscape.

The streets in the historic part of Kerteminde are oriented in two directions. Langgade, Strandgade, and Strandvejen runs north south. Præstegade, Vestergade and Fiskergade runs east west, all originating from Langgade, the central spine of the city. Langgades southern end culminates in the meeting with the harbour and the bridge across the mouth of Kerteminde Fjord. To the north, the building structure in Langgade change from apartment buildings to small fishing houses situated shoulder to shoulder, and forming a fine street space that ends with a remarkable look out into the bay and Nordstranden.

Praestegade, Vestergade and Fiskergade constitute an old fishing neighbourhood. Here the houses are situated side by side and are predominantly single storey houses. Almost all the old houses have low bases at the same height. This seems to have ensured that previous floods have not reached the ground floor level. The same is true for some of the newer fishing houses around Drossingen and Havnegade on the opposite side of the harbour, where the base heights also seems fixed in a specific height as protection against flooding.

Another spatial characteristic that can be observed in the old part of Kerteminde is the long narrow gardens situated on the backs of the houses. It represent a significant spatial structure consisting of elongated pieces of land with rear buildings for fishing gear and narrow gardens. The houses in the southern part of Fiskergade have gardens ending on the water's edge. Vestergade and Praestegade have no direct access to the water, but also consist of elongated plots ending in narrow back alleys.

Urban Development Projects in Kerteminde

The most significant ongoing urban planning projects seek to repair the town's connection to the landscape context (Kerteminde Kommune 2009, 2011, 2012, 2013, 2014). The three major areas of focus in the transition between the city and the water is,

A. The outer harbour
B. Renaissance Harbour
C. The dammed meadows - Recreational lake and wetlands, Sybergland, and a private golf course

Ad A:

Based on a debate and an architectural competition, the municipality has prepared a general plan for the outer harbour area, e.g. the area east of the historic centre between Strandvejen and the marina, as well as the outer quay of the inner harbour where the Fjord and Belt Centre is situated. The plan consists of a simple zoning, each area with its own content, for example, housing or leisure, or mixed commercial activities.

The use of climate change adaptation as a planning parameter is fairly sparse: only a single sketch describes a vision about sustainability, local infiltration and green ribbons connecting the city with the waterfront.

Ad B:

The project is a result of an architectural competition and aimed to restore and reinterpret the meeting between the city and harbour. Since there is no access to the competition program, it is not possible to ascertain whether climate change adaptation were an important point in it.

Ad C:

The urban growth of Kerteminde now covers the hill island to the northwest, where the city meets the drained meadows at the foot of the slope. So far the extension of the hill island have set a limit to the city's growth. In the meadow area there are two significant landscape projects underway.

1. A restoration and recreation project, Sybergland, where the idea is to exploit the terrain-related benefits to reinterpret the fjord landscape as it was before reclamation in 1814.
2. The second project is a golf course initiated by a private consortium.

Plan Strategy 2011 for Kerteminde Municipality

The development strategy is focused on settlement, culture, education, business and commerce in Kerteminde city. In the villages, the strategy is to develop qualities based on existing resources in terms of landscape, nature, tradition, and local building tradition. Concerning the planning of the rural zone, no overarching or guiding thoughts for the rural zone, nor is a potential relationship between the landscape planning and the urban planning are outlined.

Climate Change Adaptation in Kerteminde

Over the past few years, Kerteminde has repeatedly been flooded. The recent flood was the beginning of December 2013. The historic city centre is generally situated 1.5 to 2.0 metres above sea level. In 2006, the water level rose to 1.60 metres above normal water level and large parts of the harbour and buildings with full basement, and ground floors in those houses situated directly on the ground were flooded. The floods in December 2013 were less dramatic.

Climate change adaptation measurements are sought embedded in the long-term planning of the natural and urban green areas in Kerteminde by (Kerteminde Kommune 2011) by,

- Uphold and protection of the existing green areas in cities.
- Assessing the potential for planting trees along several roads and trails.
- Thinking green areas and green urban spaces into the planning of residential areas as well as by urban renewal.
- Minimizing the extent of paved surfaces.
- Flood protection

With focus on the increasing sea level, and more frequent extreme precipitation, the following measurements are proposed to be incorporated in future municipal and local planning,

- Climate Change adaptation should be incorporated into future plans for the design of buildings and infrastructure. These are requirements to building base height, selection of materials, and design of basements, etc.
- Future reservation of land for dikes or other flood control.
- Use of the recommended minimum ground floor heights from the Danish Coastal Directorate when planning new residential areas.
- Support local (individual) initiatives concerning flood protection

Besides the above mentioned initiatives in the Plan Strategy 2011, there were mid-2013 not developed further climate adaptation strategies or plans for Kerteminde. A service has been set up at the website of the municipality, where the citizens can see the expected flood scenarios and the consequences of different water heights on the individual land.

It should be noted that a change in the national legislation in 2013 now has opened for new types of corporation between the municipalities and the water facility companies. This means that new and more inspiring plans for climate change adaptation are now being developed, and that the water companies now are allowed to invest in such projects.

It should also be noted that several of these plans are mainly focusing on storm water treatment, and not on the rising sea level, nor on the interaction or coordination between the two.

Reersoe

Reersoe is a small peninsula at Goerlev, West Zealand, covering just under 6km2, and with a 9 km long coastline, and 516 inhabitants (Den Store Danske 2014), consisting partly of permanent residents, and partly of summerhouse residents. The peninsula is located in Store Belt and separates Jammerland Bay in the north from Musholm Bay in the south. Since the municipal structural reform in 2007, Reersoe has been part of Kalundborg Municipality.

Reersoe consists of several moraine islets, which in time have become land-based and interconnected by an elevated seabed, and by drainage of the marsh areas. The former islets stand out as small hilltops on the flat terrain. The east coast is characterized by a shallow wetland. To the north the coast is characterized by a long sandy beach with a dike located between the beach and the summer house area behind. The west coast is a low cliff coast affected by material transport and erosion processes.

In the former seabed areas, Store Saltsoe, Lille Saltsoe and Tagsoe, the majority of the summerhouses are located. Reersoe old Village is located on one of Reersoe’s highest points.

The harbour area is positioned low in the terrain and at high risk of flooding. Many of the old fishermen's houses have high bases with correspondingly high ground floors, which have provided some protection against flooding. Typically, the newer houses are situated directly on the terrain.

The summerhouse area at Reersoe northern coast was developed in the 1950s and onwards. Almost all houses are from the 1960s and '70s, and located directly on the terrain and none have a high base. The area is about the same terrain level as the beach. As protection against flooding from the sea there is a dike between the area and the beach. The area is further divided by a series of open drainage channels wedged in between the plots.

Climate Adaptation Reersoe

Kalundborg Municipality participated in 2009 to 2012 in the EU project BaltCICA; a collaboration between 24 partners in eight Baltic Sea countries. The purpose of the project was to assess the impact of the climate change processes locally and test concrete solutions. The coastal areas at Tissoe and Reersoe were selected as test areas, as these hold both permanent habitation, agriculture, cultural environments and large areas of summer houses. The areas also have large natural areas with lakes, streams and marshland. Moreover Reersoe is one of the areas in Kallundborg Municipality most frequently hit by periodic flooding.

In the fall of 2009, the Technology Council and the Municipality of Kalundborg invited to a scenario workshop on climate change adaptation. The following scenarios and possible solutions were discussed:

- A basic scenario or "laissez-faire" scenario - nothing is done specifically to mitigate the effects
- A protection scenario - aimed at the utmost to try to protect all interests
- An adaptation scenario

Possible solutions included:

- The construction of sea dikes
- Establishment of large dikes on the coast and in the countryside.
- Phasing out and replacement of vulnerable settlements and constructions situated in former wet areas during this century
- Transforming exposed areas into natural areas

These formed the basis of a citizens' summit in Kalundborg March 2011, where the participants voted on the options:

- 16% were for a large sea dike
- 20% were for a large dike solution on land
- 43% were for phasing out exposed settlements
- 21% were for ongoing transformation of exposed areas into natural areas

11.2% of the total of 350 participating citizens were either from Reersoe or Slagelse.

Proposal for Climate Adaptation Plan for the Municipality of Kalundborg

Based on the mapping of risks of flooding and on citizens' summit Kalundborg Municipality prepared a climate change adaptation plan in 2013. The plan has a threefold purpose:

- The individual landowners have the opportunity to assess flood risks and act accordingly.
- The mapping allows to take into account climate change adaptation in future planning and in specific projects.
- By identifying action areas the most vulnerable areas and/or the most endangered values may be targeted.

It is generally up to the individual landowner to secure his house and property.

The plan also has a contingency significance - a flood will reduce the accessibility to the peninsula, and flooding of certain types of risk enterprises may cause major pollution problems. Ensuring greater public buildings also have a contingency significance as evacuation sites, like the municipality has an interest in ensuring their own investments (Kalundborg Kommune 2013).

Both residential, commercial, and summerhouse areas have together with the natural and agricultural areas been identified as risk areas. At a water level of +1.5 m, significant parts of the summerhouses and residential areas will be flooded. The road connection to Reersoe will be cut off and it may be critical for the emergency service to access Reersoe. Furthermore the harbour and adjacent areas will be flooded, and finally, a reflux along the drainage canal will, at a sea level of +1.4 m, flood large parts of the agricultural land to the west, i.e. Store Saltsoe og Lille Saltsoe.

The municipality prioritises the initiatives in the following order:

- Ensuring the access road - either by raising it or by marking it in such a way so that its location is visible at a flood, and the emergency service will be able to access Reersoe.
- Supporting the local Dike Group in preparing a proposal for a dike solution and assist in the dialogue with Coastal Authority.

The Dike Group consists partly of summerhouse owners and partly of residents on Reersoe. In 2009 the group developed a proposal for new and elevated dikes along the coast of Reersoe to protect the peninsula against flooding.

Discussion

In Denmark, there are no harbour cities or rivers similar to Hamburg, HafenCity and the Elbe. Nevertheless the climatic change processes experienced in the northern parts of Germany are in several respects comparable to those in DK, e.g. a changed precipitation pattern characterized by heavy, torrential rains, changes in the wind patterns, storms and frequent strong winds from the west and northwest, and a warmer climate. Comparable is also the location of settlements in the intersection between a low-lying terrain, a fluctuating water system (the sea/a river or a lake), and ‘normal’ surface and storm water treatment.

In Hamburg and Hafencity and along the Elbe the climate change adaptations are more advanced than in Denmark. Therefore, it seems interesting to consider if some of the adaptation measures and lessons learned here are applicable in a Danish context. Further, the fact that climate changes impact exceed established divisions in zoning, competencies and administration, suggests a revision of traditional ways of thinking, and methods in planning processes.

With the Local Government Reform (structural reform) in 2007 the counties (Amterne) in Denmark were abolished and their duties and knowledge on nature, environment and planning in landscape zone were transferred to the municipalities. This could be seen as an opportunity to develop and carry out a more interacting and coordinated – systemic - planning than previously possible, e.g. a planning where the landscape zone, the summerhouse zone and the urban zone, could be mutually related and coordinated to each other and to the natural basis, the geological structure, and the cultural landscape. The growing recognition that climate change processes are not just a temporary or isolated climatic problem, and that climate change affect all administrative planning zones at all levels might promote such a thinking and planning, and thus encourage a planning methodology and practice in which climate change adaptation strategies and initiatives for the benefit and development of both the landscape zone and the urban and settlement zones could be developed.

Although the competence and responsibility for the landscape planning was transferred from the counties to the municipalities by the local government reform in 2007, the county employees and their resources, e.g. their knowledge and man-hours, were not necessarily transferred to the municipalities. In several cases this has undoubtedly meant that the responsibilities and tasks relating to landscape planning were transferred to the municipalities jurisdiction, but the transfer wasn't followed either by people, their knowledge, or by time and money to carry out the assignments. Additional, the regulatory systems are still following the old administrative divisions, with imbedded potential barriers for a higher degree of integrated planning across zoning and administrative divisions.

Further, the economy in climate change adaptation is unclear – who is going to pay? Is it the individual landowner, the municipality, or the state? A discussion and definition of when climate change adaptation of the built environment is an individual responsibility, and when climate change adaptation is for the common good – on a societal level - is needed.

Also, it seems necessary to address the question on climate change adaptation measures for the common good undertaken on private ground.

Comparing the climate adaptation plans for Kerteminde and Reersoe with the climate change adaptation observed along the Elbe and in Hafencity, only few of the initiatives taken in Germany are undertaken or suggested in the plans for Kerteminde and Reersoe.

In the two Danish examples the use of high building bases in the old part of both Kerteminde and on Reersoe Harbour is observed, and in the case of Kerteminde also recommended for new buildings. Other recommendations on adaptation at building level are not observed. The installation of hatches and bulkheads (cat.1a) could be used on both existing and new buildings, whereas it does not make much sense to remove residential programmes from the ground floors (cat.1b / c), since the majority of the buildings in Kerteminde and Reersoe are one to two floors. In the construction of new buildings or new urban districts the initiative could be used, as suggested in Planstrategi 2011 for Kerteminde.

At the urban space level (cat.2) an initiative concerning optimization of sewage is observed, as well as the choice of materials (cat.2 c), which can withstand flooding as seen at the Renaissance Harbour project in Kerteminde, where granite is used for the new pavements. Water walls or spatial reconfiguration of urban space into retarding basins, as well as location of new urban space on dikes (cat.2.a/e/g) could be used.

On a structural urban level (cat.3) the construction of new dikes is promoted. In none of two Danish examples the construction of green retarding basins (cat.3 d) is discussed.

In the Plan Strategy 2011 for Kerteminde planting of trees in the urban spaces are suggested.

Kerteminde historic centre is today characterized by, 1. the absence of street trees, and, 2. of the narrow back yards, giving the area a clear and easy to read spatial character and identity, which can be undermined by planting trees in the street spaces. One might consider whether working with open water channels in the street profile, and the use of semi-permeable pavements, where it is not absolutely necessary to cover with paving stones or asphalt, could be an option instead. Many of the private gardens and driveways in Kerteminde are today unnecessarily covered with paving stones and similar water repellent materials.

The large area to the north-east in Kerteminde, is today used only for winter storage of boats, but it could possibly be redesigned in such a manner that it would not only serve as winter storage for boats, but also as a relieve area at high tide, and designed in such a manner that it could lead excess water to other relief areas - such as to the restoration area, Sybergland, north for the city. This suggests a more proactive mixing and coordinating of programs, and interest, in climate change adaptation on a general level, that seen in the two Danish examples.

Only the emergency plan for Reersoe and the Dike Group at Reersoe's wish for additional dikes involves the planning of the rural areas. Other direct initiatives to transcend and integrate administrative areas, levels and divisions (cat. 5) between urban and rural planning are not observed in the two Danish examples.

In Kerteminde, the two projects in the reclaimed meadow area northwest of the city, the golf course and the restoration of the fjord landscape, are even in conflict with each other. The golf course stretches from the village of Over Kærby on the islet west of Kerteminde, down the northwest side and ending on the flat reclaimed area (at level 0) behind the existing industrial area in Kerteminde. A golf course is a highly regulated piece of mono functional landscape design that makes great demands on drainage work - it requires static landscape conditions so to speak. The restoration project, Sybergland, is located in the same area, and bordering the golf course. The project is motivated by national targets for conversion of arable lowlands into water-rich dynamic natural areas controlled by natural processes.

There are thus two very different types of landscape projects with very different needs and demands close to each other in the area. The golf course requires a static landscape where natural processes have to be controlled as much as possible in order to meet the program requirements for a ‘permanent’ landscape.

The natural processes are to some extent met by the other project, Sybergland. But by locating the golf course in the area follows a reinforcement of the dikes and pumps located at respectively Kerteminde Bay and Odense (Orbicon 2012). Depending hereon the outcome of the restoration project, Sybergland, is likely to be a low freshwater lake depending on the climatic and hydrological fluctuations during the year under the influence of the continued regulation of the runoff by pumps and dikes. One can therefore fear that the Sybergland project will appear as a superficial landscape design, a green-washing project.

Instead, the golf course could have been located elsewhere, e.g. higher in the terrain, and the whole reclaimed low lying area given over to the restoration project, and to the natural water fluctuations by removing the dikes, and thereby ensured a potentially exciting urban landscape accessible to the public. The area could thus function both as a recreational area, and as a relief area at high tide for the benefit of the entire city.

Further, such an urban landscape could be seen as a contribution to a spatial clarification of the city's relationship to the open countryside and to the water.

At the citizens' summit in 2011 in Kalundborg Municipality 43% of the participants voted for a phasing out of vulnerable settlements. The attendants at the summit thus displayed a far more advanced understanding and acceptance of settlements as non-permanent than the authorities themselves. How many of the attendants that were summerhouse owners are not known. But the vote could be seen as in opposition to the Dike Group project that seeks to protect the exposed settlements, and maintain status quo, by constructing new dikes.

Phasing out, relocation or demolition of settlements is rarely seen in Denmark. But transformation of previously built-up areas into natural areas would in many cases undoubtedly contribute to adapt remaining settlements to climate changes. What speaks against is,

- Ownership of land and buildings is equal to the economic value
- We ascribe meaning and emotional value to a place and house
- Natural, systemic processes do not have a visible or defined place in our planning thinking and methodologies and they are rarely considered as an active participant in the planning process

On the other hand settlements may not be completely ruled out in the flood risk zones. One could for example imagine building typologies that relate actively to landscape and water fluctuation processes, e.g. building typologies that are adapted to dynamic water levels, examples already exist in the Netherlands.

A question not addressed by either Kerteminde or Kalundborg Municipality, is the question of a distinction between primary and secondary settlements, e.g. between permanent residential and recreational housing. Both municipalities state that it is the owners’ responsibility to secure their property, and thus avoid the question. But it should be possible to address the question of relocation and phasing out secondary settlements situated in low-lying terrain, if these areas could act as a relief area for permanent settlement, for a city or urban district or constructions of importance for society – for the common good.

In hindsight and under the influence of the ongoing climate change processes, the summerhouse areas on both Reersoe and by Kerteminde should have been located elsewhere or built otherwise. But this happened at a time when climate change was not on the agenda, and where we as society had an almost unlimited confidence to technological solutions to control nature and natural processes - popularly known as the technological fix. Our confidence in the capability and the raison d'etre of the technological fix is now questioned by the climatic change.

Concluding Remarks

Climate changes leads to 'environmental changes’, meaning that in addition to actual damage to buildings and infrastructure, also an architectural method such as Assessments of Environmental Impact (EIA) are affected. Besides assessing the impact of a building or some given system on the environment, also the environmental impact on a given system now has to be evaluated. Climate changes thus also affects architectural methodologies, thinking and practise.

Based on observations in Hafencity in Hamburg and along the Elbe five categories and levels of climate change adaptation in the built environment have crystallized,

1. Building level
2. Urban space level
3. Urban structural level
4. Landscape level
5. Administrative level.

One lesson that can be drawn from the observations of climate change adaptation along the Elbe is that each initiative on each level must be seen as part of a complex systemic network covering interactions between both natural and cultural processes and activities, between visible and invisible conditions and phenomena, between scales and levels, and between administrative and legislative conditions. The individual climate adaptation initiative in itself may thus be both functional and effective, but coordinating it with other initiatives across scales, and domains qualifies each element and initiative.

Based on observations from the Elbe river and Hafencity in Hamburg it is thus suggested that climate change adaptation of the built environment should be viewed in context, e.g. in relation to and in interaction with other adaptation initiatives and natural processes in the environment, across the scales, functions, interests and across administrative and legal divisions and conditions.

Following this, the need for a new understanding of the problems, which relate to the impacts of climate change processes is pointed out. It is thus proposed to understand climate change adaptation of the built environment in a larger and in a relational perspective beyond the individual initiative, the individual building, the individual urban space, and beyond the division between urban and landscape zones. This proposition is exemplified and supported by the design of the individual spaces in Hafencity in their urban and natural context, and in interaction with the whole Elbe river landscape and the adaptation initiatives taken here – Hafencity in its Habitat.

Such an understanding challenges conventional architectural and planning understanding and categorization, architectural methodology and proposal making - it points towards a reconsideration of the understanding of the relationship between the built environment and the context, e.g. the landscape and the natural processes, and human and cultural activities. And it thus points towards the development of an integrated and coordinated planning thinking, process and methodology.

Two Danish examples, Kerteminde and Reersoe, are studied and the actual and planned climate changes adaptation is discussed according to the five categories crystallized from the observations in Germany. Both in the case of Kerteminde and in Reersoe both actual and planned climate changes adaptations are rather sparse. The initiatives taken or planned are all seen individually. It can thus be concluded that, in respect to climate change adaptation of built environments exposed to both a rising sea level and flooding by storm water there is:

1. A large potential for developing a more integrated and coordinated – systemic – architectural and planning understanding of the built environment in its habitat, and of climate – nature and natural processes per se as part of, and ‘actors’, in the built environment and its planning, design and governance
2. A need to develop architectural and planning thinking and methodologies adequate and supportive for such a thinking, planning and design, and governance of the built environment

References

DMI (2014) Fremtidige Klimaforandringer I Danmark, Danmarks Klimacenter rapport 6/2014, Klima, Energi og Bygningsministeriet

GHS Gesellschaft für Hafen- und Standortentwicklung mbh, Stadt-entwicklungsbehörde der Freien und Hansestadt Hamburg (2000) Hafencity Hamburg Der Masterplan.

IPCC (2013) Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Kalundborg Kommune, Teknik og Miljø (2013) Forslag til Klimatilpasningsplan

Kalundborg Kommune, Teknik og Miljø (2013) Forslag til Klimatilpasningsplan. Bilag 1: Indsatsbeskrivelser, skema vedr. havspejlsstigning.

Kerteminde Kommune (2009) Planstrategi 2011. Kerteminde Kommune – Ramme om det gode liv,

Kerteminde Kommune (2013) Kommuneplan 2013-2025. Kerteminde Kommune. Hovedstruktur

Kerteminde Kommune (2014) Lokalplan nr. 250. Great Northern Golf

Kerteminde Kommune(2011) Planstrategi 2011

Kerteminde Kommune(2012) Forslag til lokalplan 240, Sybergland, rekreativt naturområde ved Kerteminde

Krarup, Jonna Majgaard (2011) Vandskab, KADK Denmark. (unpublished project report)

Orbicon A/S (2012) Kerteminde Kommune – Tårup inddæmmende Strand. Forslag til reguleringsprojekt, Hovedkanalen.

Painado Ponton, Javier (2006) The Meaning of

Habitat in a Changing Architectural Context, in, *De-/signing the Urban. Technogenesis and the urban image*, Patrick Healy and Gerhard Bruyns (eds.), 010 Publishers, NL.

Paskal, Cleo (2009) The Vulnerability of Energy Infrastructure to Environmental Change, Chathamhouse & Global EESE, London, UK

Stahlschmidt, Per (2001) Metoder til Landskabs-analyse. Kortlægning af stedets karakter og potentiale, Grønt Miljø, Frederiksberg, København.

The Norwegian Meteorological Institute (2013) Extreme Weather Events in Europe: preparing for climate change adaptation, NO

http://www.denstoredanske.dk/Danmarks_geografi_og_historie/Danmarks_geografi/Sjælland/Reersø (28.10.2014)

http://www.ikse-mkol.org/index.php?id=13 Internationale Kommission zum Schutz der Elbe (28.10.2014)

http://www.hafencity.com/upload/files/artikel/1409_Daten_und_Fakten_HafenCity_Hamburg.pdf (28.10.2014)

http://www.kerteminde.dk/Om-kommunen/Renæssancehavn.aspx (28.10.2014)

Design of Sustainable Use and Management of Groundwater in Morobe Province

Mirzi L. Betasolo*, Samson Gore, and Anthony Bii

mbetasolo@gmail.com, gore.samson2@gmail.com, 08300074anbi@std.unitech.ac.pg

Civil Engineering Department, The Papua New Guinea University of Technology, Papua New Guinea

Abstract: In the near future, Morobe Province of Papua New Guinea may experience a scarcity of water which is needed to meet the population and industrial needs in Lae City, the country's industrial hub and the gateway to the Highlands Provinces. This paper offers a wide review concerning studies related to groundwater resources in Morobe Province through the identification of the aquifer, wells, pumping stations and the chemical composition of the underground water. The aim of the study is to prevent the continuous depletion of groundwater resources and to sustain the aquifer usefulness in the development process in a manner that is adaptable to the prevailing economic, social, climatic, as well as hydrological conditions. This is necessary as rainfall patterns in Papua New Guinea are changing due to climatic changes and this affects the groundwater reservoir. The result shows that there is a need to keep the underground water sustainable because of the low water table that is already present in some areas of the province. The only surcharge is the rainfall that occurs in the province. Since this may be altered due to climatic changes, design and planning for sustainable use and management of groundwater such as artificial surcharge is important to prevent the depletion.

Keywords: Sustainability, Depletion, Groundwater, Aquifer, Groundwater Resources, Water Wells.

Introduction

Water is essential to human life support. It is needed in all aspects of man's life, for food, health, and economic development. It is a renewable resource, however the abundance has clouded the reality that renewable fresh water is an increasingly scarce commodity because it is depleted faster when the increase of users that draws water progresses heavily. Kumar (2003) stressed that there is essentially no more fresh water on the planet today as compared to the past 2000 years where it was less inhabited and exploited. Moreover, Brabeck-Lethmathe (2013) predicted that there will be scarcity of water for the world beyond twenty years by 50% and by 2030 water withdrawals will exceed natural renewals by 60%. Water overuse and scarcity are becoming critical issues in the new millennium at both global and regional levels. Increasing population and economic growth affect water needs for all kinds of activities and could result in a global shortfall of up to 30% in cereal production by 2025, giving us a great challenge as to how we will be able to feed the world's population in the near future. Although the groundwater is a resource that can be replaced, it is not uniform throughout the globe, making it abundant to others and scarce to some.

Groundwater is the portion of the Earth's water cycle that flows underground in soil pore spaces and in the fractures of rock formations with an unconsolidated deposit or a unit of rock that can yield a usable quantity of water, called an aquifer. Groundwater is often withdrawn to support man's activities that will support life such as use in agricultural activities, the industries in preparing their goods and households in the municipalities and cities by operating extraction wells which in the long run exhaust the resource. The long-term effect of water withdrawal may cause a gradual settling of land in the Earth's surface and also changes take place underground creating a sinking called subsidence. In some types of groundwater basins, water that is pumped to the surface is drawn from spaces between sand and gravel. In addition, layers of clay can contain large amounts of water, and water pressure in the surrounding aquifer keeps the clay particles slightly apart from each other. When the water pressure in such a basin drops due to extensive pumping, the clay particles are pushed together by the weight of the overlying sediments, which is no longer in equilibrium with the (now lower) water pressure. The lower water pressure affects the cohesion of clay particles making water getting away from the clay and the clay layers become compressed (thinner). The effect of thinner clay layers is seen as a lowering of the land surface – sometimes as much as 20 feet (6.09 m) or 30 feet (9.14 m) over several periods. The decline of land mass consequently lowers the potential of water storage naturally. Effective groundwater management utilizes the storage capabilities of groundwater basins while preventing significant subsidence from occurring. It is then, necessary to look into the condition of the area in relation to the abundance of this resource, groundwater, because water is among the most precious of natural resources that a country has, like Papua New Guinea (PNG).

For underground water to be sustainable the withdrawal of underground water from aquifers should be minimized if it is used faster than it is replenished through the natural geologic cycle. Sustainability according to Dresner (2002) as quoted from the Brundtland report "is a development that meets the needs of the present without compromising the ability of the future generation to meet man's needs". According to Ponce (2013) sustainability is "managing the resource at the local level in a way that satisfies the needs of both environment and the economy while ensuring the continued basin's health".

In the study of Bhunia *et al.* (2012) on deciphering prospective groundwater zones of Morobe Province of Papua New Guinea using GIS, they found that only 4.29 % of the Morobe Province is categorized as "very high groundwater potential zones" along the North-eastern part. There is a 15.71% "high groundwater potential zones" along the south-eastern part. 37.16% is occupied by moderate groundwater potential zone. And, 42.84% is "poor and very poor groundwater potential zone" as shown in figure 1.

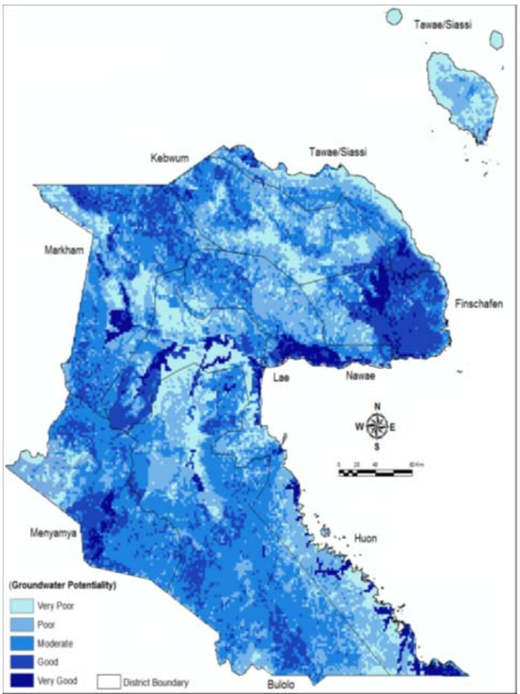


Figure 1. Groundwater Potential Zones. Adapted from Bhunia *et al.*(2012).

Morobe Province is divided into nine Districts: Bulolo, Finschafen, Huon Gulf, Kabwum, Lae, Markham, Menyamya, Nawae, and Tewai/Siassi. It stretches from the Sarawaget Range in the North along the Huon Peninsula to the east and through the Markham Valley in the center of the province. The Bulolo and Watut Valleys run north-south, with the Ekuti and Owen Stanley Ranges in the south as shown in figure 2. The Highlands Highway and a road between Lae and Wau provide reasonable road access in the province. Roads along the Huon Peninsula do not connect to Lae, making water transport more common, which becomes dangerous in the wet season. The very north of the province in Kabwum District and south of the province, around Garaina are very remote. Of all the districts of Morobe, Lae District covers the largest urban center of Papua New Guinea outside of Port Moresby and is a major commercial and industrial hub. Incomes are high from the sale of a range of goods in markets as well as many non-agricultural opportunities in Lae. Lae is a cargo port of Papua New Guinea with a population of 119,178. It is also the main land transport gateway from the coast to the Highlands region. At this urban and industrial zone, underground water in Lae is in large demand. Electricity in the province is powered by water which adds to more demand of water resources. Areas explored on locations of wells are Markham, Nawae, Huon, Bulolo and Lae because of the availability of road network. Other areas like Menyamya, Kebum, Finschafen and Tawae/Siassi were impassable so we use literature survey.

Figure 2. Morobe Province, PNG. Adapted from Morobe Province (2013)

Morobe Groundwater Characterization

From the Bhunua *et al.* (2012) GIS map on potential groundwater zones of Morobe Province of Papua New Guinea, only 4.29 % of the Morobe Province is categorized as "very high potential zones" of groundwater. Among those locations covered by this criteria are: Lae, Markham, Nawae, Huon, Finschafen (part) and Menyamya. Among those within the

15.71% as "high groundwater potential zone", along the north-eastern are Finschafen and Bulolo at the south-eastern part. To determine further development and design, a study of the groundwater capability on the ground of the identified high groundwater potentials is what this study is all about, characterizing the Morobe ground water, and discussed in this part are the geography, aquifer, wells, and pumping stations.

Geography and Location

Papua New Guinea has a climate that is tropical, dominated by three factors: 1) the equatorial low pressure and sub-tropical high pressure, 2) the influence of ocean and 3) the influence of altitude. The climate is warm with temperatures generally ranging from 20 to 30 degrees Celsius across the majority of the country, with only minor diurnal variations. Morobe Province has a land area of about 34,500 km^2 and a population of 539,404 (Morobe 2014). Situated on the northeastern coast of the PNG mainland, Morobe's coast is bordered by Madang Province to the north, and Oro Province to the southeast. Morobe Province shares its western boundaries with Eastern Highlands, Gulf and Central provinces.

The Morobe geomorphology is 71.29% covered by mountains and hills with weak or no structural control (Bhunia *et al.* 2012). This shows that the geomorphological units for Morobe are in poor recharge zones because structural plateaus, hilly terrain, and volcanic landform are poor recharge zones. Geomorphological units such as flood plains and alluvial plains are good sources of groundwater but cover only 28.71% of Morobe Province, thus a recharge is necessary for sustainability.

Its topography includes the rugged Huon Peninsula, broad Markham Valley and Wau-Bulolo uplands. Much of the northwestern coastline is rugged and drops off steeply into the sea, whereas the southeast coastline to Salamaua slopes gently. Morobe Province's offshore islands include Umboi, Siasi and Tolokiwa in the Vitiaz Strait between Morobe and West New Britain. The topography on the GIS of Bhunia *et al.* (2012) is 35.39% lying >1500 m contour line with a total of 11882.25 km^2 area. The highest elevation zone found is in the northern and southern part of the province, while the lowest elevation is in the north-central and coastal area. The steep slope was found in the north-west part of the province, and some in the south east and central part. Flat topographies are found in north-central part and some part in the northern part of the province, while most is hilly terrain having moderate to steep slopes ranging from 0^o to 89.72$^{o.}$ This shows that a high sloping region causes more runoff and less infiltration and thus has poor groundwater prospects compared to the low slope area.

The lithology was characterized as mixed or undifferentiated sedimentary rocks, limestone rocks, low grade metamorphic rocks and basic to intermediate volcanic rocks comprising about 59.47% of Morobe, with the soil class as humitropepts (moderately weathered soils having high organic carbon contents, >12 kg/m2, and low subsoil BS values) about 9172.73 km^2 and troporthents (define as mostly shallow soils that are seen in wet climates on moderate to steep slopes) about 7039.83 km^2 soils (Bhunia *et al.*, 2012). The quality of drainage network depends on lithology, an important index of the percolation rate. The drainage density of Morobe per Bhunia's *et al.* (2012) map ranges from 0.02 km to 1.18 km, having 70% drainage density of 0.49 – 0.75 km^2. The specified range is capable to recharge the groundwater water table. The variation of groundwater recharge according to Todd (1980) is controlled mainly by discharge and rainfall. To make the groundwater availability sustainable the capability for recharge must be considering the facts that the annual rainfall of Morobe is between 2000-6000 mm (Morobe 2014; Bhunia *et al.* 2012) in which 69.97% (23493.11 km^2) are within 2000- 3000 mm rainfall zone. As of last year's record of the World Weather Online (2013) the average rainfall is 9.575 per day, 287.25 per month, and 3447 per year, in which the highest of precipitation is in August, followed by April June, July, September and October helping the recharge potential in Morobe province through rainfall. Rainfall is the most vital input in the hydrological cycle as part of the water that falls on the ground is infiltrated into the soil, filling the soil moisture deficiency and part is percolated down reaching the water table known as recharge from rainfall to the aquifer.

Aquifer

There are two types of aquifers: confined and unconfined aquifer. A confined aquifer is a layer of water beneath the surface of the earth that is trapped below an impermeable upper layer. The confining layer is usually composed of clay as shown in figure 3. The figure shows and as per observation that the water level has already declined over the years and was narrated by residents nearby during one of our informal interviews. On the other hand, an unconfined aquifer (water table aquifer) is the saturated formation in which the upper surface fluctuates with addition or subtraction of water as shown in figure 4.

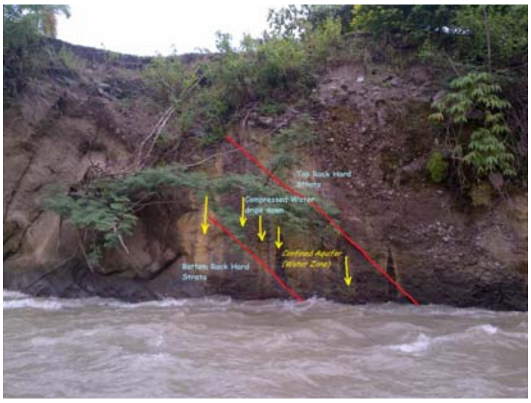


Figure 3. Cross Section of a Confined Aquifer in Erap Nawae

Figure 4. Cross Section of an Unconfined Aquifer in Erap Nawae

In the figures above it can be seen that the current water table is already far below than from years ago. Therefore, a groundwater recharge on the aquifer is necessary. To estimate the water stored in a confined aquifer, a piezometric head in the aquifer can be determined by examining wells. Flow in a porous medium is described by an equation that relates the rate of flow to the gradient of the water table and the characteristics of the aquifer known as Darcy's Law. The equation for Darcy's Law is based on the observations that the flow rate through a porous medium (such as an aquifer) is proportional to the cross-sectional area perpendicular to flow and is also proportional to the head loss per unit length in the direction of flow. Shown below:

$$Q = KA(h_L/L), \qquad (1)$$

where

Q = flow rate of liquid through the porous medium, typically in m^3/sec,

A = cross-sectional area perpendicular to flow, typically in m^2,

h = head loss over a horizontal length, in m

L = in the direction of flow (in m)

K = hydraulic conductivity, m/sec (m^3/sec/m^2)

$K = k\gamma/\mu$,

where

k = specific permeability, m^2 (a property of the porous medium only),

γ = specific weight of flowing liquid, N/m^3,

m = viscosity of flowing liquid, N-sec/m^2,

Values of specific permeability are sometimes given with the Darcy as the unit, where 1 Darcy = 1.062×10^{-11} ft^2 or 9.869233×10^{-13} m^2.

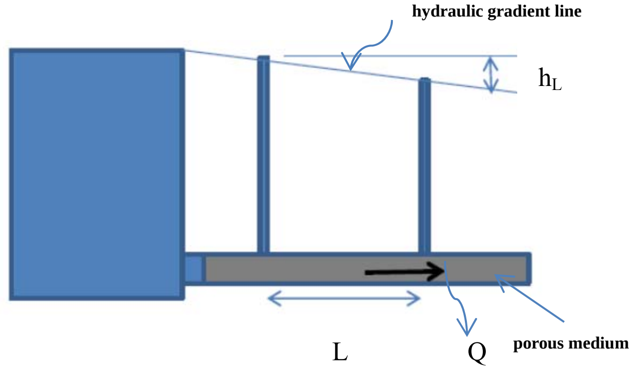


Figure 5. Darcy's Law Principle

Darcy's law demands that the head in the rock must increase with distance from the well and the piezometric surface then forms a cone of depression around the well. The extent of the cone of depression increases laterally with time with continuous pumping. At any time, there is a distance from the well beyond which there is no flow in the direction of the well. A confined aquifer has limited recharge, therefore requires analysis of water utilization and consumption. From the above figure concept, any opening near the immediate vicinity of the well the water drops very rapidly. In this case, we will discuss water well below.

Water Well

A water well is a structure either by natural state or man made created in the ground by digging, driving, boring, or drilling to access groundwater in underground aquifers (Water well 2013). Most of the wells used by villages here in Papua New Guinea are drawn by the use of buckets. In the cities, water in wells are drawn mostly using pumps. Wells can vary greatly in depth, water volume, and water quality. This study considers wells that are both drawn by hand and mechanized. Below are few of the images of the water wells inspected in the study area.

Figure 5. Open Well at Erap, Nawae

The continous flow of groundwater in the above figure is because it is located near the Busu river.

Figure 6 a. Open Well 1 at Boys town, Lae

Figure 6 b. Open Well 2 at Boys town, Lae

Figure 6 shows that well 1 in Boys town, Lae has low groundwater supply and while well 2 has high groundwater supply. This is because the population that uses the resource is less as compared to the other wells shown on figure 7. At this time, the water can still be abstracted from the well, as it is drawn only by hand which mean the drawing is less and the water level can be replenished before the next draw by human for consumption.

Figure 7. Open Well 1, 2, 3 & 4 at 40 mile, Markham

However, when water is pumped from the rock, the water pressure is lowered (i.e. water is released from elastic storage, the aquifer remains saturated). As pumping continues, the rate of local drawdown decreases and eventually stabilizes as the withdrawal is compensated for by inflow of groundwater from the surrounding area and if the pumping still continues the spreads of the water table depression goes outward which may cause the non-sustainability if it will not mitigated earlier. Below is a discussion of the current situation in the major city of Papua New Guinea.

Water Pumping

Man's needs for more water opt them to use mechanized tools such as pumps resulting to active withdrawal by pumping of groundwater changing the natural flow of water level. Our study found seven pumping stations of the Water PNG supplying Lae City's needs on water. Those seven pumping stations were just outside the fence of the Papua New Guinea University of Technology. Continuous drawdown without proper recharge will be detrimental to the health of the groundwater.

Figure 8. Pumping Station 1,2,3,4,5,6, & 7 Taraka, Lae

The above pumping stations will affect the future supply of groundwater if not mitigated earlier. The increasing population of Lae that need the vast supply of water will somehow put the supply of availability of groundwater in the future at risk if it will not be taken into consideration for recharge. Not only the availability of supply but also the condition of the ground may be affected in the near future. It is also of the same reason that the Papua New Guinea University of Technology (Unitech) ceased to pump water and supply its constituents (students and staff) to prevent this to happen and get supply of water from the services of the Water PNG.

Another attributing factor for massive drawdown of water level is attributed by figure 9 to 11 wherein each Colleges or schools are making their own pumping stations to supply water needs for their constituents. If these will continue and without the recharge plans to support continues withdrawal of groundwater, time will come for depletion of the resource, thus such study was undertaken to understand the conditions of the utilization.

Figure 9. Pumping Station Balob Teachers College a) Bore Hole b) Reservoir (2- 10,000 Liters, Supply 3000 Heads)

Figure 10. Pumping Station at Ampo Suction Pump, b)10000 Liters Reservoir

Figure 11. Pumping Station at Marthin Luther Seminary a) Suction Pump, b) 8000 Liters Reservoir

To summarize the field observations of wells, a table is presented listing the most common wells and pumping stations available on those areas, but this is not the final list as there is a difficulty for us to go the other villages of the province due to the bad road conditions. The journey will take us 2 or 3 days walking in the mountains and placing the safety of our team at risk. This constraints us to keep record of other wells. The ones we have accessed to are presented in table 1.

Chemistry of Water From Wells

Water pollution is inevitable; therefore we include determining the quality of water from the wells found in the area thru water test. Pollution of groundwater according to Nwankwoala *et al.* (2013) is an impairment of water quality by chemicals, heat or bacteria to degree that does not necessarily create hazards to the general public but will affect adversely for domestic, farm, municipal or industrial use. The water within the area studied was tested at the laboratory for chemical characteristics and the result is shown in table 2.

Table 1. Summary of Wells Observed in Morobe

Location	**Type of well**
Nadzab, Markham	3 wells
Erap, Nawae	2 open wells
40 mile, Markham	5 wells
41 mile, Markham	1 artesian well
Balob Teachers College, Lae	2 bore wells
Independence Drive Taraka, Lae	Bore well (7 pumping stations)
Bumbu (Kamkumu), Lae	2 open wells
Lae proper	2 wells
Ampo, Lae	1 bore well
Martin Luther Seminary, Lae	1 bore well

Table 2. Chemical Characteristics of Water From Observed Wells

Samples	**BOD (5 day)**	**Calcium(mg/) WHO, <7.5)**	**Hardness(mg) as CaCO3 (WHO, < 500)**	**Magnesium (mg/L) (WHO, < 0.1)**	**Turbidity (N.T.U)**
40 mile sample 1	4.2	20	190	57	3.6
40 mile sample 2	4.4	106	286	37	0.40
Erap sample 1	4.1	26	418	4.6	6.6
Erap sample 2	6.6	24	83	4.5	0.47
Boys town sample 1	3.8	72	79	19	26
Boys town sample 1	4.1	78	282	21	0.25

Based on the result above, the data are above that required of World Health Organization (WHO). Human health is dependent on the wholesome and reliable supply of water. It is noted that half of the people living in developing countries are suffering from water-related diseases caused directly disease-carrying organisms such as mosquitoes that breed in water and other parasites that may infect human beings living in the area. Most widespread disease occurring in Papua New Guinea is malaria. The results also show high concentration of calcium. Water with a high concentration of calcium according to Offodile (2002) is a hard water. This is the result of contamination of water from laundry and other domestic and industrial purposes. Generally, high calcium and magnesium make the groundwater "hard" or "very hard". Hardness is very undesirable due to the potential incrustation build-up in pipelines and household appliances. This needs to be taken into consideration practically when considering the construction of a water supply system. A higher magnesium concentration according to Todd (1980) has a laxative effect.

Groundwater Sustainability Design

Below is the discussion on the groundwater sustainability design based on the data collected and presented in the previous pages. The presentation of the design is based on the concept of sustainable use and management of groundwater in Morobe. Currently we are continuing in the collection of data on storm water volume in a separate research project conducted both by our colleague and students. The use of underground model software's for calculations and images of its flow are used in a separate research project that is still on going. So our discussion in the design concept is based on the five elements of sustainable water resources of which some are already implemented. These are:

1. Alternatives to Surface storage (e.g. water harvesting)
2. Wastewater reclamation and reuse
3. Water Conservation
4. Demand management
5. Protection of water resources.

1. Alternative to Surface Storage

For recharging depleted groundwater aquifers, a water collection initiative is run in the university as well as other parts of the city through programs on roof-top water harvesting structures that will help to restore the depleting quantity and quality of ground water as shown in figure 12. This is implemented in most of the residential areas of staff's accommodation of the Papua New Guinea University of Technology or Unitech.

Figure 12. Water Harvesting in Unitech

2. Wastewater Reclamation and Reuse

The main purpose of artificial aquifer recharge technology is to store excess water for later use, while improving water quality (decreasing the salinity level) by recharging the aquifer with quality water. There are several artificial recharge techniques among those are infiltration basins and canals, septic-tank-effluent disposal wells, water traps, diversion of excess flows from flood into the surcharge tanks, cutwaters, and surface runoff drainage wells.

Infiltration Basins and Canals. This technology is planned to be used in the Markham River basin of Lae. This is the longest river of about 180 km and with the Busu River, which is categorized as the fastest flow river and is also the 7^{th} fastest flowing river in the world (Morobe, 2014), where artificial recharge experiments is proposed.

Septic Tanks and Effluent Disposal Wells. Another source of artificial groundwater recharge is effluents from septic tanks, using soakaways. Currently, the University is constructing a sewage system in which the effluent is planned to return to the groundwater. The soakaways used for this purpose are very similar to suckwells in design and construction methodology, with the exception that they are always covered. This is also conducted in a separate project and is undertaken in conjunction with the Project Office of the University.

Water Traps. Water traps are used to increase infiltration in streambeds. The traps are dams made of earth at different height, usually 1m to 3m, which are constructed using local materials. Water traps are arranged perpendicular to river banks 1 kilometer stretch at an interval of 70m to 100m designed to operate during rainfalls. Their storage capacities fluctuate between 250 and 400 m^3. They have an estimated life span of 20 to 25 years, given proper maintenance. This design is taken into consideration.

Diversion of excess flow from flood into surcharge tanks. This is also another source of artificial groundwater recharge. Lae is experiencing flooding that causes its road sealed with sand and gravel to deteriorate faster making more potholes prevalent and making the city as a pothole city, as shown on the photo below, figure 13 and 14.

Figure 13. Flooding in the City (Source: MKonzang)

Figure 14. Potholes in the City (Cource MKonzang)

3. Water Conservation

Recharge

Groundwater is naturally recharged upstream and discharged downstream. Recharge areas are close to mountain peaks, where precipitation is likely to be higher than in the adjacent lowlands. Shallow groundwater discharges directly into the valleys and other low lying zones while deep groundwater discharges directly into the ocean, rainfall infiltration (main component), return flow (e.g. irrigation), leakage from fresh water distributing systems, river and wadi flows (Runoff), artificial recharge (e.g. Injection wells), leakage from wastewater collection systems (e.g. discharge points) (Ponce 2013; Muath 2013).

Aquifer

Aquifers according to Muath (2013) can be sustained by the following:

1. Perennial Safe (Sustainable) Yield: The amount of abstractions that can be safely abstracted without long or short term adverse conditions occurring.
2. Maximum Perennial Yield: The maximum yield available annually subject to all available recharge resources being utilized at optimum level by allowing specific drop in storage on the calculation that this will be recovered during specific year circle of recharge.
3. Stressed Sustainable Yield*:* The amount of water that can be extracted > Perennial safe yield over a long planning period (e.g. 25 years) on the condition that the over pumped water can be recovered over a future period in which the basin can be managed wisely.

The yield for unconfined aquifers is calculated by the formulas:

$$Q = \frac{\pi K\,(h_w)}{\ln\,(r_w)} \tag{4}$$

where: Q, is the discharge in m^3/day
K, is the permeability of the soil m/day
h_w , is the depth of water in observed well
r_w , is the distance to the observed well

$$Q = \frac{\pi K B\ (h_w)}{\ln\ (r_w)} \tag{5}$$

where: Q, is the discharge in m^3/day
K, is the permeability of the soil m/day
h_w , is the depth of water in observed well
r_w , is the distance to the observed well
B, is the thickness of aquifer

The volume of recharge over the aquifer is calculated as:

$$Rv = \sum_{i=1}^{n} (R_d)_i \times A_i \tag{6}$$

where : Rv, is the recharge volume in m^3/yr
R_d, is the recharge depth in m/yr
A ,is the area in m^3
i, is the cell
N, is the number of cell

The equation above calculates the recharge volume to replace the volume abstracted or discharges from wells and pumping stations which can be made possible either by artificial surcharge.

Using this equation we are now observing the fluctuation of the volume of the aquifer and calculating the possible recharge volume using modeling software that the University is still in the process of acquiring. We are currently using free downloadable demo software and so the results cannot be presented at this time.

Rainfall

On rainfall recharge, below are the equations used in the design.

Rainfall-Recharge Equations

$$R = 0.6\ (P - 285) \qquad P > 700\text{ mm}$$
$$R = 0.46\ (P - 159) \qquad 700\text{ mm} > P > 456\text{ mm} \tag{7}$$
$$R = 0.3\ (P) \qquad 456\text{ mm} > P$$

Where: R is the recharge from rainfall in mm/yr
P is the annual rainfall in mm /yr

Rainfall data for Lae as provided to us by Mr. Nimiago of the Forest Research Institute, using Nylex rain gauge 1000 type, calculated an annual rainfall that ranges from 4000 – 5800 annually since year 2007 – 2012. This also conforms to that conducted by Bhunia. He further stated that the months of October to March are the low rainfall months while April to September are the months with a lot of rainfall, and the wettest period is between June and September. Currently, the only natural surcharge affecting the groundwater is the rainfall. Other parameters affecting this are also presented in the geography part as discussed that may affect the slow process of recharge than that of its withdrawal or use. Therefore, a demand management is presented below.

4. Demand Management Pumpage

Focusing our attention on the effects of withdrawing ground water due to a huge demand, a management system should be established to properly make the water resources available for the next generation. Therefore, whenever pumpage of water is increased according to Alley (2013) it must be supplied by more water entering the ground-water system (increased recharge), opt for less water leaving the system (decreased discharge), and removal of stored water in the system, or some combination of these three. This statement can be written in terms of rates (or volumes over a specified period of time) as:

$$\text{Pumpage} = \text{Increased recharge} + \text{Water removed} \tag{8}$$

The withdrawal can be prevented or minimized not by using the resource but by ensuring that there is a capability to replenish the water taken due to withdrawal. Therefore the process of incorporating this in the building code of Papua New Guinea is being proposed so that a zoning provision or be incorporated in the issuance of building permits to assure that no reduction of groundwater level on any construction site or industrial activities without a recharge mechanism to help raise up the level of groundwater to safe level. Also planned along this is to map out in detail the available supply of water level on ground.

5. Protection of Water Resources

In this regard to protect the water resources, educating the population is the best way. This can be accomplished by incorporating this concept in the education system of the country, providing awareness via media and other means to provide campaign awareness to protect the water resource.

Conclusions and Recommendations

The present groundwater is already showing depletion. This will continue if not mitigated based on observations of different wells and pumping stations around the study area, Morobe Province. In as much that direct precipitation is the main source of recharge where annual rainfall for the province is as high as 3000 – 4000 mm annually, which makes the Lae City, the urban city of Morobe Province, to be known as rainy Lae. However, because of the changes in climate, hence, it is recommended to conduct precise estimation of ground water resource and recharge potentials as it is a prerequisite for planning and development. Also recommended to determine the actual discharges of the wells identified in the study and provide a groundwater map level using groundwater software models or simulation software's. FEFLOW simulation software model is recommended as it provides a flexible environment to represent different kinds of groundwater flow systems in 2D horizontal or cross sectional projection as well as 3D representation, confined, partially confined or unconfined conditions, boundary conditions including multi-layer wells, physical constraint to boundary conditions and constraint, definition of selected parameters (e.g., groundwater recharge) by applying user-defined equation, and possibility to couple groundwater flow simulation.

Acknowledgements

Acknowledgement is given to the Department of Civil Engineering for providing the research team with funding for the water tests and the mobilization in collecting information on the groundwater characteristics around Morobe Province. We are also indebted to Mr. Patrick Nimiago, of the Ecosystem Management Section of the Natural Forest Management Program for the rainfall data provided to us. Our sincere gratitude goes to the Water PNG for their support.

References

Alley, William, Reilly E. Thomas, O. Lehn Franke. (2013) *Sustainability of Ground- Water Resources.* Denver Colorado, 2009. Retrieved July 13, 2013 from: http://pubs.usgs.gov/circ/circ1186/pdf/circ1186.pdf

Bhunia, Gouri Sankar, Sailesh Samantah, Babita Pal. (2012) Deciphering prospective ground water zones of Morobe Province , Papua New Guinea. *International Journal of Engineering Research and Applications (IJERA),* Vol 2, Issue 3, May-Jun 2012, pp.764

Bouwer, Herman (2002) Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal 10:121 142*. Doi:10.1007/s10040-001-0182-4

Brabeck-Letmathe, Peter (2013) Water Scarcity and Food Security: The Role of virtual water trade. Retrieved July 29, 2013 from: www.communityplan.blogspot.com.

Dresner, Simon (2002) *The Principles of Sustainability*. 2nd Edition. Earthscan Publishing. USA.

Groundwater. (n.b) Retrieved July 13, 2013 from: https://en.wikipedia.org/wiki/Groundwater.

Kumar, CP. (2003) Fresh Water Resource: A Perspective. *International Year of Fresh Water*.

Lae (2013) Retrieved June 24, 2013 from: http://en.wikipedia.org/wiki/Lae.

Lae Weather (2014) Retrieved July 1, 2014 from www.worldweatheronline.com/lae-weather-averages/Morobe/PG.aspx

Morobe Province (2013) Retrieved June 5, 2013 from: www.morobe_province.pdf

Muath Abu Sadah (2013) Assessment of Sustainable Yield of Aquifer. Retrieved July 29, 2013 from: http://www.hwe.org.ps/Projects/Training/Groundwater%20Wells/presentations/Assessment%20of%20Sustainable%20Yields%20of%20aquifers%20%28SESSION%206%29.pdf

Nwankwoala H.O, and C.J. Udom (2013) Hydrogeochemical evaluation of groundwater in parts of Eastern Niger Delta, Nigeria. *Journal of Academic and Applied Studies. Vol. 1(2)*July 2011, pp.33-58. Retrieved June 24 2013 from: www.academians.org

Offodile, ME. (2002) Mecom Eng. Services Ltd, Jos Nigeria, pp. 239 -345.

Ponce, Victor M. (2013) Groundwater Utilization and Sustainability. Retrieved July 29, 2013 from: http://groundwater.sdsu.edu/

Subsidence (2013) Retrieved July 29, 2013 from: http://www.water.ca.gov/groundwater/well_info_and_other/land_subsidence.cfm.

Todd, DL. (1980) *Groundwater Hydrology*, John Wiley and Sons, New York, pp. 267 -315

Water well (2013) Retrieved July 29, 2013 from: en.wikipedia.org/wiki/Water_well

World Weather Online (2013) Lae Montly Climate Average, Papua New Guinea. Retrieved July 29, 2013 from: www.worldweatheronline.com/Lae-weather-averages/Morobe/PG.aspx

A Comparative Study of Contextual Urban Design Approaches in the UK and DK

Jonas Højriis[*1], Ivan Tengbjerg Herrmann[2], Per Sieverts Nielsen[2], Paul Bulkeley[3]

hojriis87@gmail.com, ithe@dtu.dk, pernn@dtu.dk, paul@snugarchitects.co.uk

[1] Technical University of Denmark, Department of Civil Engineering, Denmark

[2] Technical University of Denmark, Department of Management Engineering, Denmark

[3] The University of Southampton, Engineering and the Environment, UK

Abstract: During the last century urban planning has changed dramatically, due in part to vehicular development, a modernist design culture, rapid urbanisation and new computer technologies. This planning strategy has resulted in newly-implemented areas that look incredible from a helicopter, but the human scale has, as a consequence, often been completely shattered. The existing context has predominantly not been preserved, or adequately considered; the shape of buildings has been the most significant focus in the planning process. A more contextual approach to both comprehensive development and cellular renewal will be introduced as a different way of accommodating more contextual urban renewal. In this paper, four different case studies in two different cities, Winchester in the United Kingdom and Copenhagen in Denmark, are examined in regard to their urban planning and their use of the two above-mentioned approaches. A number of different Key Performance Indicators (KPIs) have been selected, analysed and evaluated in a spider web, to clarify where in the process the planning could have been better or improved with regard to future similar planning processes and urban developments. The two cities, Winchester and Copenhagen, and the four case studies, selected in the beginning of this paper, turned out to be more dissimilar than anticipated. This was due to cultural traditions and different construction methods in the two countries. In spite of this, clear improvements in the process of using comprehensive development and cellular renewal have been identified. Both case studies approached by cellular renewal turned out to be the most contextual urban design, where the focus on social- and physical contextualism was introduced early in the process. With that said comprehensive can still be considered and approached using contextualism.

Keywords: Cellular Renewal, Comprehensive Development, Urbanisation, Key Performance Indicators.

Introduction

When there is an urban development, new buildings are placed within historical established areas. This creates a desire for buildings with a high standard of design to fit in with the already established city area, the established context (Golding 2001). The increased inflow to the cities has awoken a fresh focus on urban growth (Statistik 2011; BBC 2014; Castberg 2013) and in particular how to accommodate urban population growth and improved life quality by increased living space. This implies that councils are forced to consider and develop strategies in order to meet the need for new buildings. Within these strategies it is necessary to consider the allocation of land parcels and new places around the city (Walton *et al. 2000*).

Background

City councils all over the world are forced to consider urban development, regardless of size and culture. It is essential to have a clear strategy to follow (DETR 2000). Contextual urban design must balance a concern for both the physical and social aspects, as the former urbanist Jane Jacobs said, "*New ideas really do require old buildings*" (Jacobs 1961). Jane Jacobs was focused on making recreational areas without making them boring for the citizens. Jan Gehl (2010) mentioned in the book "Cities for people", that cities have to be designed for people on "the human scale". According to the two urbanists it is necessary not only to involve the public in the overall development concept, but also to place them as a main priority in the townscape, and due to this fact, cities have to be planned and developed for the people.

Different Urban Development Approaches

Jan Gehl (2010) supports Newman (1996) who believes that the modern city is a product of the industrial city, where it is rather complex to grant all desires and requests because of the many different approaches to plan and incorporate new city areas (Newman 1996). To address this complexity, this paper is aiming to define relevant approaches and the impact of their implementation on contextual urban design.

Two different methods are introduced to approach urban design developments: comprehensive development and cellular renewal. How comprehensive development and cellular renewal can be approached is described in table 1 and illustrated in figure 1, where the differences in the two approaches are underpinned. Comprehensive development is characterised by the wholesale planning, design and delivery of large scale, often isolated pieces of a city whilst cellular renewal is often focused on smaller pieces and involves the replacement of an existing cell through a combination of retention, refurbishment, and replacement. Cellular renewal can be comprehensively planned. The result in cellular renewal is the rejuvenation and densification of an existing piece of the city whilst comprehensive development creates an extension or new piece of city.

Table 1. The Main Functions by Using the Approach

Approach	Main functions
Comprehensive development	Larger scale construction, limited constrain, often located on the periphery of existing cities
Cellular renewal	Smaller scale construction, often highly constrained, existing cells and densification

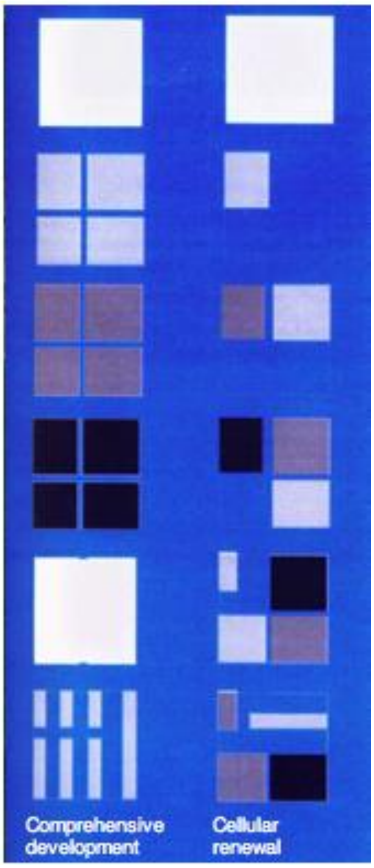


Figure 1. Gradual Renewal Program

An understanding of change management, for industrial use will be introduced to emphasise the requirement of basic knowledge in changing areas on behalf of the public. It is difficult to make any approaches work/fit without introducing theories about change management and without an understanding of the needs of cities to adopt constant change in the demographic development (Cummings & Worley 2014).

Public engagement is introduced to fulfil the citizens' desires, expectations and requirements. When considering the mechanisms and relationship between the council and the public, it is essential to foster a supportive relation, especially with the contextual design in mind (Agger & Hofmann 2008).

Cellular Renewal

Cellular renewal is known by a number of different terms: partial development, urban regeneration, etc. In this paper it will be referred to as cellular renewal. Cellular renewal covers different aspects: urban planning, urban renewal, cellular development and area densification (García 2004). One has to consider how to replace and, renew and regenerate the already integrated parts of cities (Landry 2005; Carden 2014; Lange 2014). Cellular renewal seeks to deliver urban renewal on several sites across the whole city. Cellular renewal involves the redevelopment and densification of multiple sites within the existing city and may be planned comprehensively or through the creation of ad hoc implementation of available building sites, what is known as windfall (Landry 2005; García 2004).

Cellular renewal has a tendency to fit within a contextual approach, due to the fact that cellular renewal sites are already located in existing city areas. Under normal circumstances the public, specifically nearby communities, will be involved and their opinions will be taken into consideration in shaping the final development (Agger & Hoffmann 2008).

Comprehensive Development

Comprehensive development is an urban renewal with the primary focus to deliver city growth through the wholesale development of a virgin periphery of an existing urban area, green- or brownfield. It seeks to deliver city growth on the fewest number of sites (Carden 2014).

Comprehensive development is widely considered to be easier to deliver and implement regarding urban growth. Comprehensive development presents some challenges to build in context, due to the fact that the sites often are located in the periphery of cities and are perceived as a 'blank canvas'. This also entails that there are no neighbours or if so, they are on the edge of the site (Golding 2001). In these kinds of cases a contextual analysis, regarding existing suburban areas, should be carried out around the city and should influence the masterplan.

Brownfield Development

Brownfield development can be approached by both cellular renewal and comprehensive development. If a brownfield development is approach by cellular renewal, it will often involve retention of existing buildings and new constructions. If comprehensive development is used to approach brownfield developments, all existing constructions will be demolished, except a few key buildings, and the area will be built with new constructions.

Public Engagement

Public engagement has always been an issue when it comes to urban planning, because of public uncertainty, mistrust and resistance to change. There are differences in the way of including the public/citizens' regarding comprehensive development and cellular renewal. Public engagement has been improved during the last decade, but there is still space for improvement.

Theory of Scope Selection

To generate and clarify the scope of this paper and the choice of the right focus in the analysis of the identified Key Performance Indicators (KPIs), some underlying considerations will be introduced to maintain a retrospective approach.

Underlying Considerations Regarding Urban Development

A decision model, as shown in figure 2, is created from the function below:

f(A,B,C)=E(U)

where:

A is resources available for the analyst
B is scope of the investigation
C is capability of the analyst
E(U) is the expected uncertainty of the statement (Herrmann *et al.* 2014), B is further defined in Herrmann *et al*. (2014).

In figure 2 the y-axis gives the different KPIs used in the (given) study and the x-axis illustrate a time-line with the event horizon at present time. The four different paths shown "in the future" define:

1. The desired path outcome of the completed construction, where all the KPIs are at a maximum level (green).
2. A process/path where the final construction is true to the design phase/planned outcome, without any changes (blue).
3. An example of an actual outcome/path (pink).
4. A process/path where final construction is not true to the design phase, because of change(s) (red).

In figure 2, there is a "books and reference" block to indicate how the different KPIs for this study have been defined (by literature study) for what good urban design is. The case studies are integrated as well and are illustrated in the centre of figure 2; their individual timelines are different from each other, depending on the project start.

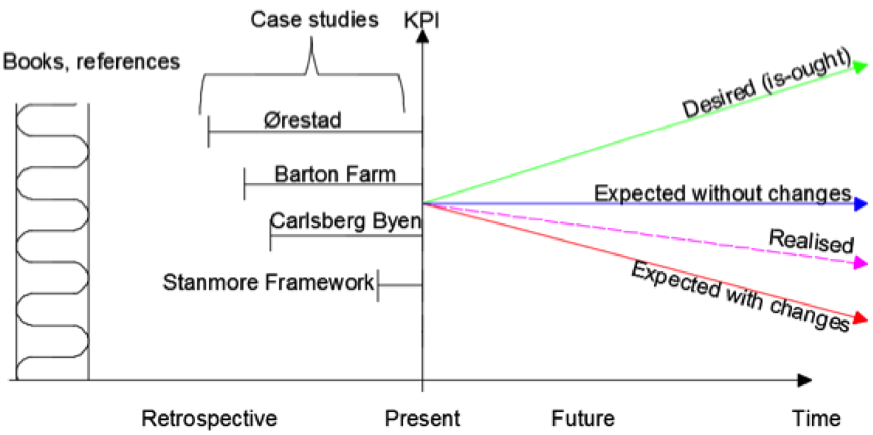


Figure 2. Decision Model

The desired outcome that is shown in figure 2 is related to the "is-ought" problem, which was addressed by David Hume, a Scottish philosopher, in 1888. The distinction between the four different paths, defined in figure 2 is important for the discussion and understanding of the results of this study. As an example of the is-ought problem, it is the authors who have defined the applied KPI's in this study that is the authors have defined the KPI's that ought to be used (although backed by plenty of distinctive urban design literature). Hence, the research method that has been applied in this study is to investigate past events, evaluate the outcomes of these events and then rank the different urban design approaches. However, some of the evaluated outcomes are to some extend expected outcomes. Since most of the cases in this study are in an early stage, the selected KPI's are based on values defined by professional urban designers rather than the final users of the new urban areas. This can cause some risks of bias (assuming that it is the citizens that should evaluate the performance of the new urban area), it can be too theoretical, and non-user functional. Therefore, one has to be vigilant of these problems.

Case Studies

Barton Farm, Winchester (Comprehensive Development)

Barton Farm is a comprehensive development of a virgin green field used for agriculture for decades. Barton Farm will be an integrated part of the city and the nearby neighbouring communities (Thompson 2012). John Thompson & Partners (JTP) has developed the design code for Barton Farm, which includes its investigation of the area and the contextual analysis.

Stanmore Planning Framework, Winchester (Cellular Renewal)

The Stanmore Planning Framework is an urban renewal of Winchester (UK) approached by cellular renewal. The area of Stanmore was constructed in the post-war period as a comprehensive development. Stanmore is beginning to decay and there is a need for a general renovation and revival of the area (Broadway Malyan 2013). The framework covers a lot of different sites in one overall plan; in brief it is a comprehensive masterplan, which is provided by Broadway Malyan (2013).

Ørestad, Copenhagen (Comprehensive Development)

Ørestad is a new integrated part of Copenhagen (DK) which is constructed as a comprehensive development, with an overall none-contextual design. The Finnish drawing office APRT and the Danish architect company KHR Arkitekter presented together a final masterplan in 1997, and the first office building was completed in 2001. The first phases were completed to accommodate city growth with a lot of prestigious buildings, which provides a very modern and interesting architectural expression (Faber 2010).

Carlsberg Byen, Copenhagen (Cellular Renewal)

Carlsberg Byen is a brownfield development. The building site is very similar to a cellular renewal with a comprehensive masterplan, located in Valby (DK). Several of the existing buildings will be preserved to maintain the originality and integrity of the area. The Danish architects Entasis created Carlsberg Byen the masterplan, which was launched in 2007, but suffered from the financial crisis (2007-2010), which has meant that the development is still ongoing.

Definition of the KPIs

A set of KPIs has been identified to measure, examine and compare each case study's level of contextualism. The KPIs are listed below, where they are divided into two main categories, *social contextualism* and *physical contextualism*. When the KPIs have been analysed, a pattern of the pros and cons in each case study will appear, thus giving an opportunity for discussion and conclusion. The KPIs are selected to achieve social- and physical contextualism.

Social Contextualism

There is no general or correct answer to how much, when or how public engagement should be performed in respect to urban development (Agger & Hoffmann 2008). This paper focuses on either established area densification or virgin area development. A certain level of public engagement will be considered necessary to gain information and support from the involved/interested community stakeholders in the area. Arnstein's metaphor about an involvement ladder, see table 2 (Agger & Hoffmann 2008) will be introduced to illustrate the different levels of public engagement.

Each step on the ladder describes the different levels of involvement and influence. This paper will focus on the extent to which the public are involved and the dialogue between the council; comprising of the politician, developer, design team and civil service, and the public; comprising of the citizen, interested stakeholders in the community and local experts with professional knowledge. The social contextualism is subdivided into several sub-KPIs, to achieve a comparable base.

Table 2. Arnsteins Ladder on Tabular Form Rewritten by Niels Helberg (Agger & Hoffmann 2008)

Step	Method	Description
5	**Self-determination**	Delegating e.g. local councils
4	**Co-determination**	Participation e.g. joint working
3	**Dialogue**	Debate such as public meetings or via internet / e mail
2	**Information**	Household-distributed leaflets, information on websites, etc.
1	**No involvement**	None

When was the Engagement Introduced

To achieve a well-integrated urban development there has to be some engagement with the community. The earlier in the process this is done, the better because it encourages a democratic process (Agger & Hoffmann 2008). But this still must be done with a consideration of the right level of involvement to avoid the public taking over the leadership of the development and thereby become totally self-determined (table 2).

Engagement of Local Community

Engaging with the local community through workshops/exhibition is a relevant way to maintain a relationship and to inform the community during the development (Burd 2010). This can also introduce new initiatives, stages and progress solutions in an illustrative and engaging way, because it provides an opportunity for the developer to meet the community and get central local knowledge (Agger & Hoffmann 2008).

Evidence of Engaging with Specialists

Local specialists might be in possession of invaluable professional and historical knowledge. If a stable relationship can be maintained with such people it can be very beneficial for the process (Kitchin 2010).

Evidence of Public Presentations

Evidence of public presentation in the proposal is done to ensure that the final product has been introduced to the community and to maintain the democratic process with the public and encourage early adoption (Agger & Hoffmann 2008).

Physical Contextualism

The physical contextualism is interesting to investigate, because it is in this process that urban planners make connections between the physical context and proposed development. The physical constraints and opportunities and prevailing character of an area form an objective basis for design decision-making. There is a complex interrelationship between the social and physical dimensions of a place. While social contextualism has to be considered, it is the physical that the urban planner ultimately has control over.

Density of the Buildings

The density and scale of buildings should relate well to the density of buildings in the surrounding areas (Golding 2001).

Pattern of Streets/Urban Blocks

This is the prevailing layout and form of the physical infrastructure of the city and relates to historic patterns of construction, movement and land ownership.

Pedestrian and Vehicular Connections to Surrounding Areas

A development should be well connected to its immediate surroundings. Permeability will encourage physical and subsequently social connections between new and old pieces of a city. These connections are to be considered, even in small scheme developments. Cellular renewal sites will, from the starting-point, have existing points of access that have to be considered (Walton *et al*. 2000).

Historical Layout and References/Exiting Landscape Features Integrated

When new areas are constructed in cities, it will normally interfere with the existing city and thereby the historical layout (Golding 2001). This is particularly true when developments take place in a historically sensitive context. Is there evidence of these features in new designs?

Topography and Landform Influencing Layout

When urban developments are constructed, the current/actual topography and landform has to be investigated to ensure continuity in the area and a natural fit. Contextual development shows signs of having been moulded by its topography (Walton *et al*. 2000).

Results

The KPI will be evaluated using a simple rating system, which will ensure a consistent review and interpretation of the case studies. The rating systems is divided into five steps from low to high where low is considered very little or none and high is very deliberate (table 3). The idea is that the rating in this way is consistent through the evaluation process (table 4, figures 3, figure 4 and table 4).

Table 3. Rating System for the KPIs

Low	1
Below average	2
Average	3
Above average	4
High	5

The consistent evaluation of the case studies is necessary, due to the fact that these different studies have to be comparable.

The following will focus on a comparison of the outcome of conducted spider webs. The spider webs are used as visualisation of the differences in the case studies and outline the different approaches of urban planning strategies seen in the different case studies.

Five KPIs from the two groups, social contextualism and physical contextualism, have been selected as the most central KPIs. One has to remember that all the KPIs creates a picture of how contextual a development can be. Table 4 is established to give an overview of the rated KPIs.

Social Contextualism

The two KPIs for social contextualism (when engagement was introduced and the engagement of the local community) are chosen because of their two significant impacts on the design process. They enable the planners to have a direct impression of what the public considers to be necessary in any given development and they give an indication of what would give the best outcome. According to Gehl (2010), the human scale is the most important factor, and is therefore needed to achieve a decent and liveable place. The ratings of the different KPIs regarding social contextualism, including the two chosen KPIs are visualised in figure 3.

When was the Engagement Introduced

According to Agger & Hoffmann (2008) public engagement is a necessary part of the building process. This statement is supported by Howard & Gaborit (2007). The idea is to receive the public's attitudes and opinions as early as possible.

There is a significant difference between the approaches of comprehensive development and cellular renewal. Cellular renewal, which includes two of the case studies (the Stanmore Planning Framework and Carlsberg Byen) is rated higher than comprehensive developments, which include Barton Farm and Ørestad. The differences between the case studies are as expected. Cellular renewal is per definition interacting with existing areas and often in existing cells and is thereby significant to interact and engage with the local community and the citizen. This interaction gives cellular renewal an advantage, because the council has to engage in an early stage to inform the citizen about the initiatives in the area. Comprehensive development is often located in peripheral regions, which are likely to generate less public objections, because the sites do not interfere with existing parts of the cities. This difference is clearly demonstrated in the subjective assessment of the case studies, when considering the case of Carlsberg Byen.

Carlsberg Byen is developed on brownfield ground, but it is not interacting in the same way as a traditional cellular renewal, because it is from the starting point located in an area with no existing liveable residents. In spite of this, urban planners are still striving towards the brownfield area as traditional cellular renewal (Entasis 2007).

Table 4. Summarised KPIs

Case study	*Selected KPIs (max 25)*	*All KPI (max 45)*	*Social KPIs (max 20)*	*Physical KPIs (max 25)*
Barton Farm	*12*	*24*	*8*	*16*
Stanmore Planning Framework	*22*	*35*	*15*	*20*
Ørestad	*6*	*15*	*8*	*7*
Carlsberg Byen	*18*	*34*	*14*	*20*

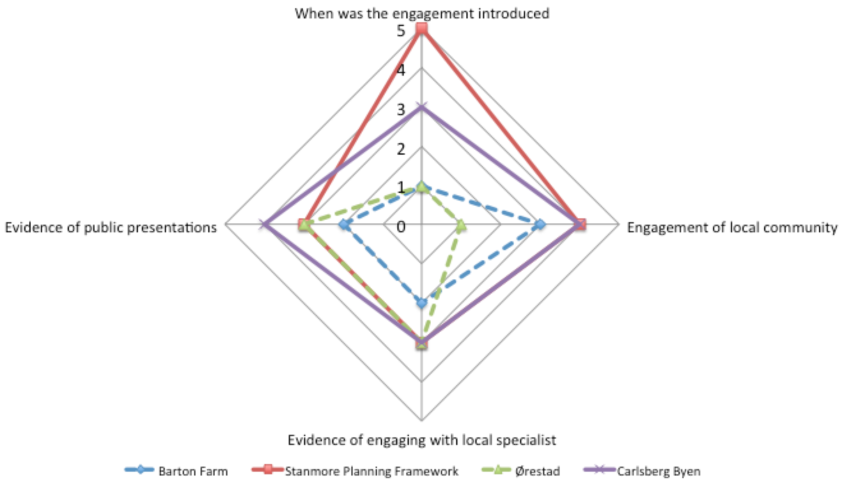


Figure 3. Social Contextualism (The dotted lines represent comprehensive development and solid lines represent cellular renewal.)

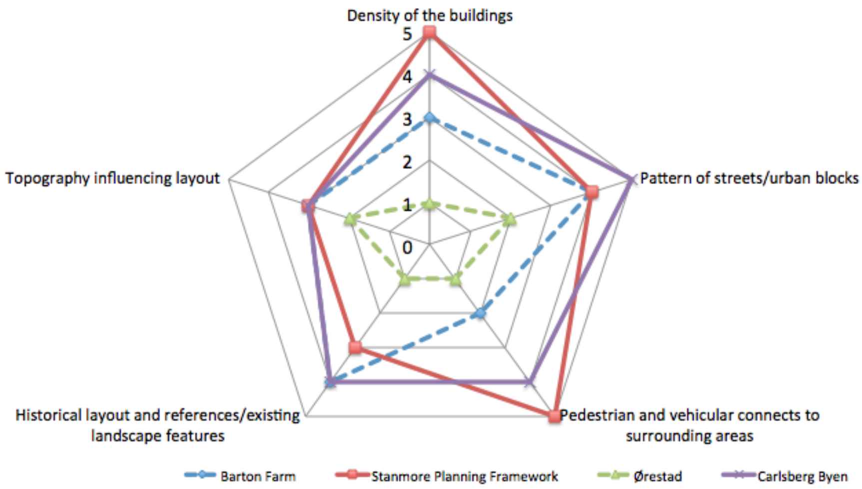


Figure 4. Physical Contextualism
(The dotted lines is comprehensive development and solid lines is cellular renewal.)

Engagement of the Local Community

The engagement of the local community considers how, and on what level, the community has been engaged in design workshops during the building phases. Design workshops are an appropriate opportunity to engage actively with the public (Momirski & Andrews 1997). The Stanmore Planning Framework, Barton Farm and Carlsberg Byen are all rated fairly high, because of the focus in the design- and planning process. This collaborative engagement by using workshops, gives the planners an understanding and an opportunity to notify and involve the impacted communities/citizens (Thompson 2012). The public engagement in Ørestad was on a very low standard regarding. This was due to the fact that Ørestad was the first larger urban expansion in Copenhagen in decades (Boserup 2014). Because of this, the process became more policy-oriented rather than public-oriented. This is the reason that Ørestad has achieved the lowest rating: public engagement has been given low priority and this is reflected throughout this process.

Physical Contextualism

Three out of five KPIs (density of the buildings, pedestrian and vehicular connections to the surrounding areas, and topography and landform influencing the layout) and have been selected to consider the level of contextualism and ability to respond and understand to the surroundings (Golding 2001). The ratings of the different KPIs regarding physical contextualism, including the three chosen KPIs, are visualised in figure 4.

Density of the Buildings

The density has to be appropriate to the surrounding areas, to correspond to the existing context whilst balancing the need for densification and a requirement for more efficient use of land. There is a fundamental variation in the urban planning systems of the UK compared to DK; the

UK is more traditional and strict in their approach to planning within the same density. A capital requires more visionary architectural expression; establishing new and attractive places, while retaining historic areas. In comparison, the provincial cities are arguably more traditional in their interpretation of architecture (Hein 2000).

Barton Farm is planned to be a new contextual suburb in Winchester. The site was developed on the basis of exhaustive research of the existing suburbs in Winchester. This process has given the urban planners an extensive knowledge of the structure and values of Winchester, but might also give an old-fashioned interpretation of the opportunities (Carden 2014). Barton Farm is rated with a medium ranking, because of its response to the current density in the city's other suburbs. The density of Barton Farm could also have been achieved by either developing a large number of houses to increasing the density and simply by using less land to accommodate the current number of houses. The density and scale in Ørestad was not a topic that was considered during the design process because Ørestad was seen as a new part of the city where the focus was to create modern and extravagant buildings (Boserup 2014). The focus was elsewhere which, as the low rating indicates, is regarded as poor practice from an approach of contextual perspective and corresponded with the surroundings areas.

Carlsberg Byen has chosen to accommodate the current density, and maintain a lot of the existing, and in some cases, preserved buildings (Entasis 2007). This way of approaching the contextual design corresponds well with the understanding of designing in context, where the buildings are in scale.

The Stanmore Planning Framework corresponds well to the current scale of existing buildings and has chosen to create only 2 storey building to keep the scale.

Pedestrian and Vehicular Connections to Surrounding Areas

Pedestrian and vehicular connections create/provide the area with the primary connection with the surrounding areas. Carlsberg Byen has been focusing a lot on the urban space, where the street pattern of connections has a central place (Entasis 2007). Due to the status as a former industrial field, the area is supplied with several connections to primary routes. This gives advantages before the construction phase begins.

One of the main problems with the connections in Ørestad is that the site is formed like a necktie; this creates long distances for pedestrians and with few primary connections to the existing areas. This is mitigated by the introduction of the local metro station, but the area has failed in connections and permeability to its neighbour areas.

The Stanmore Planning Framework is an example of cellular renewal that has been comprehensively planned, but new infrastructure has been a main focus from the start. Pedestrians and vehicles have been considered and a new entrance and exit will be implemented to accommodate the necessary transportation into and out of the area (Broadway Malyan 2013).

Barton Farm is located close to the roman road, Andover Road, which in the future will be converted to a pedestrian and bicycle path. This main access road to the city will be brought through the site and will serve the site during the different phases of development. Apart from this, the connection to the surroundings are limited and this lack of permeability might create issues with connections in the future.

Topography and Landform Influencing Layout

According to Golding (2001) an avant-garde high-rise construction can lead to dissatisfaction in the area due to the change in topography. This change can lead to a lack in continuity and recognisability to the people who are intended to live in the area, which according to Gehl (2010) is critical to create an urban development where people would like to live. The DETR (2000) supports both the view of Golding (2001) and Gehl (2011; 2010) and mentions further, the significance of including, graining, climatic and ecological, etc., information which can have a beneficial and strengthening impact on the outcome of the development (Walton *et al*. 2000). This way of considering the surroundings gives an opportunity to create building profiles that rises of the ground/surroundings (Walton *et al.* 2000).

In all of the case studies the topography has been considered in the layout, but it has not been given any significant influence/part in the planning process from the urban planners. For example, Carlsberg Byen has tried to create the area as a whole by placing trees between the streets and corners (Entasis 9). The two case studies from the UK, has similar considerations of using the topography. Ørestad is rated lower compared to the other case studies, which is caused by different considerations regarding the architecture and appurtenant topography in Ørestad. One of these differences is the missing strategy for developing the subdivide fields. As a result, the spaces between the buildings have not been implemented and this has caused issues regarding especially the recreational spaces and also the topography (Faber 2010).

The Sum of the KPIs

To complete the assessment and to give a thorough understanding of the most important KPIs, 5 KPIs out of 9 have been selected to create a simple outline. It cannot be assumed that a case study with a low summarised KPI-rating would not function as intended. The outcome of the KPIs is on a tabular form in table 4. Both the Stanmore Planning Framework and Carlsberg Byen have turned out to be well functioning, in respect to the investigated KPIs. These two case studies have in an early phase focused public engagement to respond in an appropriate way to the physical context and have been consistent with the public engagement throughout the whole design process. This has resulted in a high rating of the approaches,

The rating of Ørestad is rated relatively low. This was expected because Ørestad has not been built in context, but with the intention of creating and accommodating the need for city growth in Copenhagen.

On this basis, the analysis of Ørestad's approach to a contextual design has been, to some degree, unreasonable, but this is one of the differences in culture and urban planning style between Winchester and Copenhagen. In addition, the lack of public engagement has also influenced its low rating. All things considered, Ørestad has failed on most KPIs.

In the case of Barton Farm, the physical contextualism has been on a respectable level, but the absence of early public engagement has meant that the rating is lower than what had been initially expected, due to the wanted level of contextualism from the City of Winchester. If Barton Farm were rated on behalf of the last years work the outcome would definitely be different.

Discussion

Ørestad has failed on social and physical contextualism, which in this case has been the source of significant criticism after the construction of the first phase, because people simply were not integrated in the process. Regarding the physical context Ørestad scores the lowest possible rating in 3 out of 5 KPIs. An example is the "Pedestrian and vehicular connects to surrounding areas" KPI where the connections to its surrounding areas are very limited. Despite this, the vehicular infrastructure is well integrated into the city centre and highway, but in this case it is the nearby context that is being rated.

Comprehensive development has turned out to be less contextual on all KPIs compared to cellular renewal. One of the reasons could be that the chosen case studies, Barton Farm and Ørestad, were launched in the early nineties and the cellular renewal case studies, the Stanmore Planning Framework and Carlsberg Byen, were launched within the last ten years.

This research suggests that the public engagement has improved over the last ten years, which has caused an improvement of the social contextualism in the developments in this period. If this improvement had been implemented before the planning of Barton Farm it might have been rated similar to the cellular renewal developments and thereby been more comparable and more contextual.

Conclusion

The Stanmore Planning Framework has turned out to be the case study with the highest score overall and the highest score regarding the selected KPIs. Both the Stanmore Planning Framework and Carlsberg Byen have the highest overall scores. This suggests that cellular renewal is more likely to generate both social contextualism and physical contextualism. This is not to say that if a development is approached as comprehensive development it cannot be contextual. It does however suggest that it will be less likely. It is of note that both the Stanmore Planning Framework and Carlsberg Byen are pieces of urban design that have been carried out more recently, which suggests an growing emphasis on contextualism in urban planning.

References

Hoffmann, B. (2008) *Borgerne på banen*. Velfærdsministeriet.

BBC (2014) People move to the city. http://www.bbc.co.uk/learningzone/clips/urbanisation-why-do-people-move-to-the-city/511.html [accessed 29 Oct. 13]

Boserup, R. (2014) Interview about urban design. (Personal communication, 10.2.14, 15:30)

Broadway Malyan (2013) Stanmore Planning Framework – Final report, Broadway Malyan

Burd, L. (2010) Developing technological initiatives for youth participation and local community engagement. *New directions for youth development*, 2010 (128), pp. 95-104.

Carden, M., (2014) Interview about urban design. (Personal communication, 11.1.14, 11:30)

Hertz, K., Castberg, A., & Christensen, J. (2014) Super-light concrete decks for building floor slabs. *Structural Concrete*.

Cummings, T., & Worley, C. (2014) *Organization development and change*. Cengage Learning.

DETR: the Regions, Commission for Architecture, & the Built Environment (2000) *By design: urban design in the planning system: towards better practice*. Thomas Telford.

Entasis (2007) Lokalplan 432 Carlsberg II, Københavns Kommune

Faber (2010) Arkitekt: Derfor er det gået galt i Ørestaden http://politiken.dk/kultur/ECE977681/arkitekt-derfor-er-det-gaaet-galt-i-oerestaden/ [accessed 13 Dec. 13]

García, B. (2004) Urban regeneration, arts programming and major events: Glasgow 1990, Sydney 2000 and Barcelona 2004. *International journal of cultural policy*, *10* (1), pp. 103-118.

Gehl, J. (2011) *Life between buildings: using public space*. Island Press.

Gehl, J. (2010) *Cities for people*. Island Press.

Golding, F. (2001) *Building in context*, Westerham Press Ltd.

Hein, C. (2000) Choosing a site for the capital of Europe. *GeoJournal*, 51(1-2), pp.83-9.

Herrmann, I. T., Hauschild, M. Z., Sohn, M. D., & McKone, T. E. (2014) Confronting Uncertainty in Life Cycle Assessment Used for Decision Support. *Journal of Industrial Ecology*.

Howard, T. L., & Gaborit, N. (2007) Using virtual environment technology to improve public participation in urban planning process. *Journal of Urban Planning and Development*, 133(4), 233-241.

Jacobs, J. (1961) *The death and life of great American cities*. Random House LLC.

Kitchin, D. (2010) *An Introduction to Organisational Behaviour for Managers and Engineers*. Routledge.

Landry, C. (2005) Urban acupuncture. *Planning Theory & Practice*, *6*(1), 117-118.

Lange, J. (2014) Interview about urban design. (Personal communication, 11.4.14, 11:00)

Momirski, L. and Andrews, R. (1997) *Urban design workshops: A planning tool*, Urban Planning Institute of the Republic of Slovenia No 30:31

Statistik, (2011) Flere unge fravælger provinsen, http://www.dst.dk/da/Statistik/bagtal/2011/2011-07-011-unge-forlader-provinsen.aspx [accessed 29 Oct. 13]

Thompson (2012) *Design Code*, Winchester Council

Davies, L. (2000) *Urban design compendium.* London: English Partnerships.

A Functional Thinking Approach to the Design of Future Transportation Systems: Taxis as a Proxy for Personal Rapid Transit in South Korea

Mary Kathryn Thompson*[1] and Hyun Hye Bae[2]
mkath@mek.dtu.dk, hb2455@columbia.edu
[1] Department of Mechanical Engineering, Technical University of Denmark, Denmark
[2] Graduate School of Architecture, Planning, and Preservation, Columbia University, USA

Abstract: For over 50 years, personal rapid transit (PRT) has been viewed as one of the most promising ways to provide sustainable, economical, and convenient transportation while reducing reliance on personal automobiles. However, despite concerted efforts around the world, the promise of PRT has yet to be realized. This work demonstrates that different physical means, such as the Korean taxi system, can be used to perform the same highest-level functional requirement, satisfy the same constraints, and provide many of the benefits that are expected of a city-scale personal rapid transit system. Thus, Korean taxis can be used as an alternative embodiment of personal rapid transit and can serve as a test bed to support PRT-related design, research, and development. The paper then explores the transportation patterns and characteristics of cities in South Korea and the United States in order to determine the conditions necessary to create and maintain a PRT-like taxi system and to demonstrate the differences between 'normal' and PRT-like taxi systems. Finally, the future of personal rapid transit as a functional and physical transportation paradigm is discussed.

Keywords: Personal Rapid Transit, Taxis, Functional Thinking, Korea, United States.

Introduction

For over 50 years, personal rapid transit (PRT) has been viewed as one of the most promising ways to provide sustainable, economical, and convenient transportation while reducing reliance on personal automobiles. However, despite concerted efforts around the world, the promise of PRT has yet to be realized.

This work suggests that the adoption of personal rapid transit has been limited, in part, by a fixation on the physical attributes of PRT systems such as exclusive guideways and autonomous operation, and demonstrates that the basic functions of an ideal PRT system can be performed and many of the same benefits can be achieved using different physical means such as taxis. By taking a functional approach, taxi systems that exhibit PRT-like behavior can be used as PRT alternatives for existing cities and as test beds to support PRT-related research and development. This could provide important insights into PRT user behavior, allowing designers to formulate better requirements and validate design concepts before a substantial investment is made in their technological implementation.

In the first part of this paper, we describe the history and challenges of personal rapid transit. We define the highest-level functional requirement and constraints of personal rapid transit. Then, we present the results from a series of observations of taxis and their users in a medium-sized city in South Korea. This information is used to compare the functions, characteristics, and benefits of Korean taxis and an ideal PRT system. Next, we examine the taxi usage patterns and characteristics of cities in South Korea to determine the conditions necessary to create and maintain such a system. The taxi system in the United States is briefly introduced to demonstrate how taxi usage patterns and characteristics are different in cities without PRT-like taxis. Finally, we discuss the benefits and limitations of taxis as a proxy for personal rapid transit and the implications of this work for the development of future transportation paradigms.

Personal Rapid Transit Systems

Personal rapid transit systems are defined by 5 characteristics (Delle Site and Filippi 2005):

- Small vehicles "for exclusive use by an individual or a party, i.e. a small group – typically 1 to 6 passengers - travelling together by choice"
- Vehicles that are fully automated (no human drivers)
- Vehicles that operate on a reserved guideway (parallel to existing transportation infrastructure)
- On demand service (no fixed schedules)
- Direct station-to-station service (no need to transfer or stop at intermediate stations)

Theoretically, these characteristics result in shorter waiting times, shorter transit times, and shorter walking distances to the station than traditional public transit options; comfort, convenience, privacy and security that is comparable to a personal automobile; lower traffic congestion, energy usage, and air and noise pollution by replacing fossil fuel based personal automobiles with shared electric vehicles; and improved mobility and reduced disenfranchisement of citizens who do not have access to a car because of age, health, income, or other factors (Parent 1997; Dunning and Ford 2003; Anderson 2006; Carnegie and Hoffman 2007; Lohmann and Guala 2009).

A Brief History of Personal Rapid Transit

The concept of personal rapid transit emerged around 1953, when “Donn Fichter and Ed Haltom, working with no knowledge of each other, invented … a system of small, fully automated vehicles that carry people nonstop between off-line stations on a network of exclusive guideways”. The idea was re-invented (or re-discovered) at least a “half dozen” times during the 1960s (Anderson 2000).

There were a number of projects to develop PRT systems in late 1960s and early 1970s including Aramis in France, Cabtrack in England, Cabintaxi / Cabinlift in Germany, CVS in Japan, Kruass Maffei in Germany (Carnegie and Hoffman 2007), and the Morgantown PRT in the US. However, only three were ever put into operation: the Morgantown PRT, the CVS PRT, and the Cabinlift.

The Morgantown PRT system was commissioned in 1970 to link the three Morgantown campuses of West Virginia University. The system consists of “8.7 miles of guideway serving five passenger stations and two maintenance facilities.” It has a fleet 71 electric vehicles, each capable of carrying 21 passengers (Raney and Young 2005). The system began limited operation in 1972 (Carnegie and Hoffman 2007). It was briefly closed for expansion in 1979 and has been operating at its current capacity since (Raney and Young 2005).

The CVS PRT was a demonstration system that “carried 800,000 passengers during a 7 month exhibition” in a suburb of Tokyo in 1972 (Andréasson 2001). Each vehicle could accommodate up to 4 passengers and ran between 2 stations along a 4.8km long track (Anon. 2014a).

Finally, a spin-off of the Cabintaxi program, the Cabinlift, was build at the Schwalmstadt-Ziegenhain hospital in Germany (Carnegie and Hoffman 2007). This system could move up to 12 passengers (or a smaller number of gurneys) 578 meters between 2 stations. This system was used between 1975 and 2010 (Anon. 2014b).

During the 1980s and 1990s, three projects made it to the prototype stage. A test track for the PRT 2000 system was built in Marlborough, Massachusetts as part of the Raytheon project for Rosemont, Illinois. The system, which had one offline station and 3 vehicles, was operational by 1995 (Anderson 2006). A test track and 22 vehicles for Austrans, an Australian hybrid personal rapid transit (off-peak) / group rapid transit (GRT) (peak travel) concept, was completed outside of Sydney in 2000 (Andréasson 2001). And, a test track for the Vectus PRT system with one station was operational in Uppsula, Sweden in 2007 (Gustafsson 2009). A second Vectus demonstration system was built in Suncheon Bay, South Korea and was operational in 2013 (TDI 2014).

The company 2getthere has been developing technology that can be used for personal rapid transit, group rapid transit, and freight rapid transit since the 1990s. They developed the FROG Park Shuttle, a GRT driverless mini-bus. Four Park Shuttles have been operating in a long term parking area at Schiphol airport near Amsterdam since December 1997. An addition three Park Shuttles have been “operating over a distance of 1.3 kilometers between a metro station” and Rotterdam’s Rivium Business Park since Februrary 1999. Both systems use a fenced-off 3-meter wide asphalt surface with embedded transponders (Andréasson 2001). 2getthere also developed Abu Dhabi’s Masdar PRT system. The Masdar system has been operating since 2010 with 2 passenger stations, 3 freight stations, and 1 station for maintenance (De Graaf 2011).

Finally, from 2001 to 2004, the European Union sponsored the Evaluation and Demonstration of Innovative City Transport (EDICT) project to evaluate PRT as a potential urban transport solution in Cardiff, Wales; Huddinge, Sweden; Eindhoven, Netherlands; and Ciampino, Italy (Carnegie and Hoffman 2007). A 1 km long test track for the ULTra PRT system was constructed in Cardiff in 2001. This laid the groundwork for London Heathrow Airport’s ULTra PRT system, which has been operating since 2011 with “21 vehicles, a total of 3.8 kilometers of one-way guideway, and three stations” (Ultra Global 2014).

In total, “about 40 known PRT concepts existed as of 2007”. Of those, “19 were being actively developed (i.e., not dormant, with some testing completed)” (Cottrell and Mikosza 2008). However, only five concepts (the Morgantown PRT, the Cabinlift, the Park Shuttle, the Masdar PRT, and the Heathrow PRT) have ever seen long-term use. Of those, only two (the Masdar PRT and the Healthrow PRT) carry few enough passengers to be classified as personal rapid transit instead of group rapid transit systems. And none of the systems ever built are of sufficient scale (i.e. have enough stations) to fully test the concept or realize the benefits of PRT.

Challenges to Operationalizing PRT Systems

A number of factors have slowed the adoption of PRT. Most cities do not have the space to accommodate new infrastructure for PRT guideways. Even if a system can be built, the guideways and stations can have a substantial and potentially negative impact on the visual landscape (Cottrell 2005).

The need for a separate guideway substantially increases the cost to build a PRT system. For example, the PRT study for San Diego estimated a cost of $18 million USD per kilometer, while the Wellington Public Transport Spine Study estimated the capital expenditure of the PRT system at $7.5 million to $16.8 million dollars per kilometer (Cottrell 2005). Guideway construction cost was cited as one of the reasons why the PRT 2000 project for Rosemont, Illinois was cancelled (Carnegie and Hoffman 2007).

There has been a long-standing concern that "PRT technology has not yet advanced to a state of commercial readiness" (Carnegie and Hoffman 2007). The systems discussed above have "successfully demonstrated several aspects of PRT with a small number of vehicles operating on a closed circuit" but say nothing about the "reliability, availability, dependability, and safety of a large number of PRT vehicles operating over a large network" (Cottrell 2005).

There is also still no validation for the social acceptance, expected operating income, and operating costs for full-scale PRT systems (Carnegie and Hoffman 2007). This is illustrated by the fact that "low fare-box recovery estimates" were another reason for cancelling the Rosemont PRT 2000 project (Carnegie and Hoffman 2007).

Finally, the "theoretical benefits of PRT," including improvements to the personal transit experience, the environment, and society as a whole, have yet to be demonstrated (Carnegie and Hoffman 2007).

A Functional Approach to Personal Rapid Transit

The challenges above combined with the financial and political risks associated with building a new PRT system mean that investors usually want "to see a [full scale] PRT system running somewhere else before a purchase will be seriously considered" (Anderson 2000). This leaves the public without a convenient replacement for personal automobiles and leaves companies and researchers in a position where they must prove the benefits of PRT without a city-scale system to study. To address both sets of needs, we can simulate a PRT system by finding or building a system that "can be organized to exhibit nearly identical behavior" (Simon 1969). In other words, we need to find or build a system that performs the functions of a PRT system, and thus provides (most of) the same benefits, using physical means that are less costly and more readily available. This is consistent with the principles in Suh's (1990, 2001) Axiomatic Design Theory and with engineering design thinking in general.

Based on the characteristics and expected benefits of PRT systems described above, PRT systems can be said to have one highest-level functional requirement (FR):

FR1 = Provide non-stop on-demand station-to-station transportation to individuals and small groups choosing to travel together using public vehicles and infrastructure.

In order to perform this function and still provide most of the anticipated benefits of PRT systems, several constraints must be added:

C1 = The system must have many stations (pick up / drop off locations)
C2 = The walking distance to a station must be short
C3 = The waiting time for a vehicle must be limited
C4 = The travel time (and therefore the congestion within the system) must be limited
C5 = The price to use the system must be reasonable
C6 = The cost to build and operate the system must be reasonable

Automated vehicles running on a captive guideway can perform the highest-level FR and may be able to satisfy all of these constraints. We hypothesized that a well-run system of taxis with substantial ridership could too.

Methods

In order to test this hypothesis, 440 taxis and their users were observed at 11 common destinations around the Korean city of Daejeon during the summer and autumn of 2009 (figure 1). The locations included a large apartment complex, two shopping malls, a shopping district (market), two train stations, City Hall, a hospital, a hotel, a park, and a movie theater (table 1). All of the observations were performed in areas where high accessibility to public transportation would be expected or needed. Several were chosen based on PRT station locations discussed in the literature (Andréasson 2001; Carnegie and Hoffman 2007; Tegnér *et al.* 2007). The redundant locations were added to determine whether an available subway connection would affect taxi (PRT) usage.

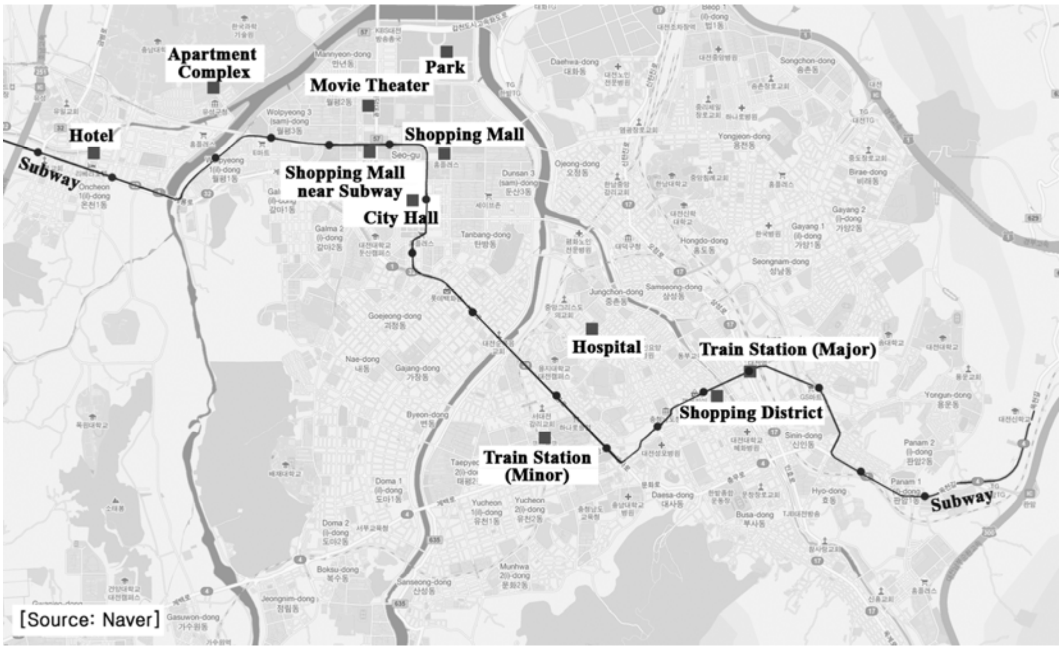


Figure 1. Taxi Observation Locations in Daejeon

Table 1. Details of Taxi Observation Sites and their Accessibilities to the Subway and Parking

Description	Name	Off Peak	Peak	Subway Accessibility	Parking Availability
Shopping Mall	Dunsan Homeplus	Tue - Thu 10am - 1pm	Sat 2pm - 11pm	-	+
Shopping Mall near Subway	Dunsan E-mart	Tue - Thu 10am - 12pm	Sat 2pm - 11pm	+	+
Train Station near Subway	Daejeon Station	Tue - Thu 2pm - 5pm	Fri 6pm - 10pm	+	
Train Station	SeoDaejeon Station	Tue - Thu 2pm - 5pm	Fri 6pm - 10pm	-	
Movie Theater	Dunsan CGV	Tue - Thu 10am - 2pm	Sat 4pm - 10pm	-	
Hotel	Yuseong Hotel	Mon - Thu 10pm - 4am	Sat - Sun 11am - 3pm		+
Hospital	Daejeon Sun Hospital	Tue - Thu 2pm - 5pm	Mon 9am - 12pm	-	+
City Hall	Daejeon City Hall	Tue - Thu 9am - 4pm	Mon 9am - 4pm	+	
Shopping District	Eun-Hang Dong	Tue - Thu 9am - 3pm	Sat 3pm - 9pm	+	-
Apartment Complex	Hanbit Apartments	Sun 7am - 9am	Mon - Thu 7am - 9am	-	+
Park	Daejeon Grand Park	Mon - Thu 10am - 2pm	Sat - Sun 11am - 3pm	-	+

Video recordings of each destination and the roads adjacent to it were taken during two time periods (peak and off-peak) for twenty minutes each during good weather. Multiple cameras were used for locations with multiple entrances. The recordings were examined to determine:

- The number of taxis arriving at, departing from, and passing by each site
- The number of other vehicles arriving at, departing from, and passing by each site
- The number of visitors arriving at and departing from each site by taxi
- The number of visitors arriving at and departing from each site without a personal vehicle
- The initial, final, and total number of taxis at taxi stands near each site
- The waiting time of each taxi for a passenger and of each passenger for a taxi
- The number of passengers in each taxi arriving at or departing from each site.

No distinction was made between roaming taxis and call taxis at any location or between available or occupied taxis passing each site. The data sets for the shopping district and the main train station are incomplete because of the difficulty in determining the origin of pedestrians approaching or leaving the site.

Results

The detailed results of the Daejeon taxi observations and the derived data from those observations are listed in tables A1 through A3 at the end of the paper. Selected results concerning the distribution, supply, demand, and usage patterns of taxis in Daejeon are discussed below.

Distribution of Taxis in Daejeon

During the period of observation, taxis in Daejeon constituted 14.56% of local traffic, with an average of 101 taxis (or 5 taxis per minute) observed passing each site. The percentage of taxis in passing traffic was relatively stable between peak and off-peak periods. The greatest difference in passing taxi percentages was observed at the hotel (9.47 to 20.21%) where demand is primarily determined by event schedules. The smallest difference in passing taxi percentages was observed at the park (8.26 to 8.61%) where there is little or no demand. The average difference was 4.35%.

Demand for Taxi Transportation to and from Popular Locations

Taxis are predominantly used in Daejeon to connect to other forms of transportation and for recreation. The highest numbers of arriving taxis and passengers were observed at main train station and the shopping district, while the highest percentages of arriving taxis and passengers were observed at the minor train station and the movie theatre. Similarly, the highest numbers of departing taxis and taxi passengers were observed at the main train station, while the highest percentages of departing taxis and taxi passengers were observed at the train stations and the movie theatre.

Taxi usage appears to increase in areas where congestion is heavy and parking is expensive and/or scarce. By far, the largest percent of passing taxis were observed in the shopping district (30.27% during peak hours, 28.64% total) where traffic is high and parking availability is poor. The locations with the largest numbers and percentages of arriving and departing taxis and passengers (both train stations, the shopping district, and the movie theatre) all have limited pay parking.

Overall, the number and percentage of arriving taxis (5.85 or 12.10%) and passengers (7.27 or 5.63%) are substantially lower than the number and percentage of departing taxis (19 or 16.09%) and passengers (14.14 or 19.35%). The most notable exception was City Hall, where taxis constitute 18.52% of arriving traffic but only 10.53% of departing traffic.

We believe the discrepancy between arriving and departing passengers occurs because passengers are too tired or have too many packages to carry to walk or take public transit on their return trip. We assume that there are more arriving visitors at City Hall because visitors use taxis to ensure an on-time arrival for business meetings. However, the high arrival rates at City Hall may be coincidental since relatively few passengers (7 arriving and 3 departing) were observed.

Subway access did not appear to play a major role in taxi availability or usage.

Waiting Time

During this study, only 7 out of 418 observed passengers waited for a total of 5 taxis. The average recorded waiting time of a passenger for a taxi was 2 minutes at City Hall and 36 seconds at the apartment complex. Passengers did not wait at any of the other locations.

The longest average waiting times of taxis for passengers were observed at the shopping district (36:41) and the hospital (30:00) both during off peak hours. The shortest average waiting times of taxis for passengers were observed at City Hall (0:00), the apartment complex (1:40), and the hotel (1:39) all during peak hours. The overall average waiting time of a taxi for a passenger was 10:49.

Taxi Stand Inventory in Daejeon

The inventory of taxi stands in Daejeon seems to be based on their maximum instantaneous demand rather than their time averaged demand. The largest queue was located at the main train station (40 taxis with roughly 200% turn over in each 20 minute period), followed by the minor train station (15 taxis with roughly 100% turn over in each 20 minute period), the shopping district (9 - 15 taxis) and the movie theatre near the express bus terminal (9 - 14 taxis). With the exception of the shopping district, each of these locations is subject to impulse loading when trains, buses, and/or movies disgorge large numbers of people over a short period of time. Thus, a larger taxi inventory is required to ensure a zero wait time for customers. During their peak periods, both the movie theatre and the shopping mall near the subway had similar numbers of departing taxi passengers (26 vs. 21) but substantially different taxi queue sizes (9 - 14 vs. 4 - 6 taxis) because the taxi demand of shoppers is more continuous than the bus / movie theatre patrons.

Taxi supply and demand is well matched in Daejeon. Only the hospital (+6) and the movie theatre (-5) showed a surplus or deficit of more than 3 taxis in their taxi stands during the 20-minute observation period. Interviews with Daejeon taxi drivers revealed that they kept personal records of taxi user behavior in Daejeon and had different taxi stand preferences for different times of day and days of the week. Thus, the taxi drivers automatically and efficiently reallocate themselves to meet the demand in a remarkable example of group intelligence.

Number of Passengers Per Taxi

The average number of passengers per taxi was 1.31 with 75% of taxis carrying a single passenger, 19% carrying two passengers, and 6% carrying three passengers. No taxis were observed with four passengers, although a fourth passenger is permitted in the front seat. The movie theatre, the shopping district, and both shopping malls had highest percentages of multi-passenger taxis (7 to 10%) and the highest passenger to taxi ratios (1.32 to 1.83) for the combined peak and off peak periods. This is to be expected since these are often group-based or family-based activities. The smallest ratios of passengers to taxi were found at the hotel (1.0), the minor train station (1.05), the apartment complex (1.05), and City Hall (1.11).

Comparison of PRT and Korean Taxis

In this section we use the results from the taxi observations and additional information from the literature to compare the Korean taxi system to an ideal PRT system.

Short Walking Distance to Stations

Lohmann and Guala (2009) state that an ideal PRT system should ensure that the maximum walking distance from any point in the city “to the nearest PRT stop is no greater than 150 meters.” This requires 14.2 stations per square kilometer. Dunning and Ford (2003) state that the walking distance should be “around 500 meters or less.” This requires 1.27 stations per square kilometer.

In Daejeon, there are 157 government taxi stands. Of those, 147 are located in the central part of the city. The city occupies an area of 539.97 km^2 and the city center is approximately one quarter of the total area (Daejeon Metropolitan City 2012). Therefore, there are approximately 1.08 taxi stands per square kilometer in the city center. This calculation includes the areas covered by parks, forest, and rivers. Thus, a taxi stand should usually be located within 500m.

In addition to the government taxi stands, there are an unknown but large number of taxi stands that are hosted by schools, universities, companies, and other organizations. Taxi drivers also regularly establish defacto taxi stands in areas with reliable patronage and room to park. As a result, many of the taxi stands in Daejeon also meet the 150m criterion.

Short Passenger Waiting Time

In “a well functioning system, PRT vehicles” are expected to wait for passengers (Dunning and Ford 2003). Lowson (2001) says that the ULTra PRT design target is to provide 90% of immediate services within a minute. Anderson (1988) suggests that in off-peak periods, there should be no wait at all and that “about 98% of the rush-period wait times” should be less than three minutes with an average wait of less than one minute. It was shown above that taxis at popular locations in Daejeon are able to meet and exceed these design targets. The taxis observed provided immediate service (no wait) to over 98% of their passengers during both peak and off-peak times at popular destinations. All passengers observed received service within 2 minutes.

Non-Stop Station-to-Station Service

By definition, PRT systems provide non-stop, station-to-station service (Delle Site and Filippi 2005). By law, Korean taxis must also provide non-stop service between their pick up and drop off locations.

Privacy and Choice of Companions

As noted above PRT vehicles are intended to be “for exclusive use by an individual or a … small group - typically 1 to 6 passengers - travelling together by choice” (Delle Site and Filippi 2005). Most Korean taxis are sedans and can accommodate up to 4 passengers. A small number of Korean taxis are minivans and can accommodate 5 or more passengers. Full sized vans are usually only available as livery or call taxis. Choice of traveling companions is guaranteed in Korean taxis by the Passenger Transport Service Act, Chapter I, Article 26 (Korean Ministry of Government Legislation 2012).

Round-the-Clock Service

PRT systems are expected to “run 24 hours a day and seven days a week” (Dunning and Ford 2003) Korean taxis are also available 24 hours a day and seven days a week. However, their relative availability is not the same. Because the vehicle supply is constant in a PRT system, there should be better availability and decreased waiting times for a vehicle during off peak times when demand is low (Lohmann and Guala 2009). In contrast, taxis in

Korea match supply to demand. As a result, they have less availability and increased waiting times during off peak periods. The difference is primarily due to the need for human taxi operators.

Dynamic Distribution of Vehicles in the Network

PRT systems are expected to have "demand-responsive, fully-developed vehicle prepositioning capability" that can place "empty vehicles that are ready for use in locations where demand is expected to materialize" (Dunning and Ford 2003). The observations of taxis in Daejeon demonstrated that Korean taxi drivers also distribute themselves throughout the city automatically, dynamically, and extremely effectively.

Dynamic Rerouting

PRT systems are also supposed to avoid network congestion, thereby decreasing travel time, by dynamically rerouting vehicles (Lohmann and Guala 2009). The same is true for taxis. Korean taxi drivers automatically adjust their routes to compensate for traffic in order to maximize their daily revenue. However, Korean taxis offer one additional service: Korean taxi drivers provide advice to travelers and sometimes refuse passengers who would be better served by an alternate mode of transportation. For example, it is common for taxi drivers in Seoul to suggest that a potential passenger take the subway for a long trip across the city during rush hour. Thus, Korean taxis not only reroute themselves throughout the taxi system, they also reroute travelers throughout the transportation network.

Shared Vehicles and Infrastructure

Finally, Lohmann and Guala (2009) state that in an ideal PRT system, one vehicle should be able to perform the task of 30 to 40 private cars. Korean taxis do as well. Lee and Kim (2001) reported that taxis in Gwangju made an average of 57 trips per day in 2000. Hwang and Yoon (2006) reported that taxis in Daegu made between 33 and 39 trips per day in 2005. In interviews with the authors, Daejeon taxi drivers reported an average of 40 trips per day in 2009.

Implications

This comparison shows that the Korean taxi system performs the same highest-level functional requirement, satisfies the same constraints, and provides many of the benefits that are expected of a city-scale personal rapid transit system. This implies that the Korean taxi system can be used as a test bed to support PRT-related design, research, and development. It also implies that PRT-like taxi systems can be developed in other countries and contexts to address the challenges associated with operationalizing PRT. For example, a PRT-like taxi system could be used to verify local demand and predict user behavior before building a PRT system. It could also serve as a short to medium term alternative while PRT technology and infrastructure are being developed or as a long-term replacement for PRT in areas where separate guideway infrastructure is infeasible.

Usage Patterns of PRT-Like Taxis in Korea

In this section, we examine the transportation patterns in South Korea to better understand how a city-scale system that provides PRT-like services is and could be used.

Choice of Transportation Mode in Korea

In 2008, taxis were used in 5 to 11% of all trips, and 7 - 26% of all motorized trips, made in major Korean cities (table 2). In comparison, personal automobiles were used in 20 to 36% of all trips, local buses were used in 17 to 25% of all trips, the subway was used in up to 29% of all trips (where available), and walking was chosen between 17 and 37% of the time (KMLTM 2009). The usage rates show that taxis are a small but important part of the overall transportation network in Korea. The variations in usage between Korean cities in table 2 shows that transportation mode of choice is strongly dependent on the options available.

Length of Passenger Travel in Korea

The average length of a taxi trip in a medium-sized Korean city is between 3.5km (2.17 miles) and 4km (2.48 miles) (Lee and Kim 2001; Hwang and Yoon 2006). This shows that Korean taxis are generally used for short trips that cannot be made quickly or easily on foot.

Common Destinations in Korea

It was shown above that taxis in Daejeon are predominantly used to connect to other forms of transportation, for transportation to and from recreational activities, to eliminate the need to park, and to ensure an on-time arrival to important meetings. This is consistent with other reports from the literature. The Korea Transport Institute (2004) reported that passengers in Seoul (the capital) and Suwon, (one of the cities in the capital area) used taxis most for recreation, social visits and tourism (36.8%), followed by business trips (21.0%) (KOTI 2004). Similarly, Song and Song (2000) found that the primary use of taxis was for business (50.4%).

Table 2. Transportation Mode of Choice for all Trips in Korea by Region in 2008 (KMLTM 2009)

	Private Car	Public Bus	Subway	Taxi	Bicycling	Walking	Other
Seoul	19.9	23.5	28.5	5.6	1.2	17.4	3.9
Busan	27.7	25.1	8.2	10.8	0.4	24.6	3.2
Daegu	33.4	16.8	5.2	7.7	2.1	33.1	1.7
Incheon	32.1	22.2	8.8	6.4	1	22.6	6.9
Gwangju	32.4	18.1	1	8.4	1.4	37.3	1.4
Daejeon	36.1	17.9	1.5	8.4	1.5	33.4	1.2
Ulsan	36.2	20.6	0.1	9.3	1.3	29.3	3.2

Table 3. Transportation Mode of Choice (%) for Commute to Work / School in Korea by Region in 2005. Private buses are run by schools and corporations for the benefit of their students and employees, while express buses are exclusively for intercity travel (Statistics Korea 2005).

	Private Car	Public Bus	Private Bus	Express Bus	Subway	Train	Taxi	Bicycle	Walking	Other
Total	33.3	17.7	5.2	0.7	7.5	0.1	0.5	1.2	30.3	3.6
Seoul	22.2	18.6	2.3	0.6	24.1	0.1	0.4	0.9	29.3	1.3
Busan	30.0	28.4	4.9	0.4	6.6	0.1	0.6	0.5	26.3	2.2
Daegu	38.6	21.6	4.4	0.3	2.7	0.2	0.5	1.5	27.5	2.7
Incheon	35.7	21.1	4.5	0.9	8.4	0.0	0.5	0.8	25.9	2.1
Gwangju	38.6	24.3	5.3	0.4	0.5	0.0	0.5	1.0	27.4	2.0
Daejeon	43.7	19.9	4.1	0.5	0.0	0.4	0.6	1.0	27.9	1.9
Ulsan	37.7	18.2	8.5	0.4	0.0	0.0	0.8	1.9	27.3	5.1

However, taxi usage in Korea depends on the time of day. During interviews with the authors, taxi drivers in Daejeon said that between midnight and 2am passengers are generally coming from downtown and want to go home. From 4am to 8am passengers generally want to go from home to work. From 8:30am to noon passengers want to go from home to shopping areas. From 4pm to 7pm travelers usually go home. And, from 7pm to 9pm travel is mostly to the downtown areas. This implies that taxis are also used at night to avoid drinking and driving.

Taxis in Korea are rarely used for daily commutes to work or school. Jung and Kim (2000) found that only 1.8% of commuters in Busan (Korea’s second largest city) chose to use taxis for their entire daily commute, while the Korean Statistical Information Service (Statistics Korea 2005) indicates that taxis were only used for 0.5% of commutes to work or school in 2005 (table 3).

The Korea Transport Institute reports that Koreans generally choose taxis because they provide the fastest transit time (47.5%) and the most comfort and convenience (31.5%) for a given situation (KOTI 2004). This is consistent with the observations above.

User Profile

Korean taxi usage is relatively consistent among socio-economic groups with the most usage by those with average annual incomes. Song and Song (2000) found that 82.4% of taxi use was by those with annual incomes between 6 and 42 million won per year (table 4). For reference, the average salary in 2000 was 15,766,920 won (KMOEL 2000). While this tells us nothing about the percentage of taxi users within each socioeconomic group, it is likely that individuals with the lowest annual incomes prefer to less the less expensive bus system, while those with the highest annual incomes prefer chauffeured black cars.

Song and Song (2000) found that the highest taxi use in Gyeonggi-Do (the Seoul metropolitan area excluding Seoul) was by 20 to 30 year olds. In interviews with the authors, Daejeon taxi drivers also reported that approximately 80% of their fares are between 20 and 30 years old, with fewer than 5% younger than 20 or older than 40.

In interviews with the authors, taxi drivers in Daejeon reported that most of their passengers are female (80%). However, gender ratios change over the course of the day with more female passengers during the day and more male passengers at night. This is consistent with the day and nighttime destinations reported by taxi drivers.

Table 4. Korean Taxi Usage by Socioeconomic Group in 2000 (Song and Song 2000)

Annual Income (million won)	Taxi Users (%)
6,000,000 or less	5.7
6,000,000 - 18,000,000	31.5
18,000,000 - 30,000,000	30.1
30,000,000 - 42,000,000	20.8
42,000,000 - 54,000,000	7.1
54,000,000 - 66,000,000	2.9
66,000,000 or more	1.9

Conclusions About PRT-Like Taxi Usage

From this discussion, we conclude that passengers in a PRT-like taxi system are average people who weigh the costs and benefits of using mass transit, of using personalized transit, and of operating and parking a private automobile for each situation. They do not use taxis as a daily or default mode of transportation. Given the age and gender of passengers, PRT-like taxis might also be used to supplement families with a single car or to delay the purchase of an automobile until later in life.

Conditions Necessary to Support PRT and Its Proxies

In this section, we explore the operating environment of Korean taxis in order to determine the conditions necessary to create and support a PRT-like taxi system.

Extensive, High Quality Public Transportation

Korea offers an extensive network of high quality public and private local and long distance mass transit options. The high rates of public transportation use shown in tables 2 and 3, the high rates of taxi usage observed at the train stations in Daejeon, and the short average distance of a taxi trip indicate that PRT-like taxis are used to supplement and connect to the public transportation network rather than to bypass it. On this basis, we propose that an extensive and high quality public transportation network is a pre-requisite to support a personal rapid transit system or its taxi equivalent.

High Quality of Service

The quality of service from Korean taxis is also very high. Taxis are well maintained and are generally considered to be a safe mode of travel. Taxi drivers are proud of their profession and are respected by passengers. And, taxi drivers are usually honest, choosing the quickest and shortest routes to maximize their number of trips per day. Thus, there is little in the taxi experience in Korea to discourage use.

High Population and Housing Density

Next, we believe that high population density in general and high housing density in particular are important to developing a personal rapid transit system. In 2010, approximately half of the Korean population (46.1%) lived in Korea's 7 largest cities. An additional quarter of the population lives in the suburbs of Seoul, giving the Seoul metropolitan area 49% of Korea's population (Statistics Korea 2010a).

Only 27.9% of Koreans live in a single family detached dwelling. Most (58.3%) live in apartments (Statistics Korea 2010a). Korean apartments are usually located in collections of high-rise buildings, some of which host 5,000 families or more. In 2005, 69% of all apartment buildings in Korea and 78% of the apartment buildings in Daejeon were at least 15 stories tall (KMLTM 2007). Korean apartment complexes generally have their own primary (and sometimes middle and high) school and a department store / shopping mall which contains a grocery store. In less dense areas, high-rise apartment complexes are usually surrounded by a village of low-rise (3 to 5 story) buildings that contain shops, restaurants, smaller apartments for rent, and the occasional single-family house. As a result, most basic necessities are available within walking distance of home. This eliminates the need for a personal automobile and supports the use of public transit in daily life. This type of urban planning also means that a taxi stand or PRT station is or can be located near home for most of the population.

Large Numbers of Vehicles in Service

The number of vehicles in service is an important factor to ensure that taxis or PRT vehicles wait for passengers. Over the 5 year period from 2003 to 2007, Daejeon had approximately 8,800 taxis and a population just under 1.5 million, for an average ratio of 167 people per taxi (Daejeon Metropolitan City Statistics 2009). From this, we conclude that large numbers of taxis are needed to foster a PRT-like taxi system.

Reasonable Price and Operating Costs

PRTs and taxis must also be affordable to use and to operate. As of 2013, taxi fares in Korea were 2800 or 3000 won for the first 2 km (depending on the city) plus 100 won for every 140 to 150 meters or every 30 to 40 seconds. A 20% surcharge is also applied for late night trips and trips outside of the operating district (Visit Korea 2014). This policy encourages passengers to take short trips. It also encourages taxi drivers to maximize their number of trips per day rather than the length of each trip.

Although there is no information in the literature about average taxi fares in Korea, taxi drivers in Daejeon reported an average fare of 4000 won (~$4 or $0.625/mile) in interviews with the authors. This is much lower than the average cost in the US ($2.25 per mile) (Litman 2010) but is approximately the same if the costs are normalized by the average incomes for each country. Thus, taxis are still relatively expensive to use in Korea. This implies that taxis and PRT systems do not have to be inexpensive to have high utilization.

The revenue that a taxi driver can earn in a day must be enough to cover all expenses (car, fuel, insurance, etc.) as well as his or her cost of living. In Korea, this is achieved, in part, by zero-cost licensing. In interviews with the authors, representatives from the Seoul Private Taxi Association and individual taxi drivers stated that there is no cost for a taxi medallion in Korea. (There is a small processing fee.) Medallions can be held indefinitely but they cannot be sold. Retiring drivers must return their medallions to the city to be reassigned. This vastly changes the economics of taxi ownership and operation and may be one of the keys to running an economical PRT-like taxi system.

Low Automobile Ownership is Not Required

Given a total population of 48.5 million people in 16.4 million households and a total automobile ownership of 12.8 million cars in 2010 (Statistics Korea 2010b; KMLTM 2010), we estimate that up to 26.4% of Koreans or up to 78% of Korean households have at least one car. This is consistent with Song and Song's (2000) report that only 18.2% of households in Gyeonggi-Do, the providence in which Seoul is located, did not have a personal automobile in 2000. Since most Koreans have access to a personal automobile, we conclude that low personal automobile ownership is not a requirement for high PRT or taxi usage.

Comparison of Taxis in the US

Finally, we present a brief overview of taxis in the United States in order to demonstrate how a 'normal' taxi system differs from a PRT-like taxi system.

Taxi Usage in the US

Taxis are a niche market in the US. In 2001, taxis were used in 0.1% of trips for work and work related travel, 0.1% of trips for shopping and services, 0.1% of trips for social and recreational purposes, and 0.1% of trips for travel to school and church. Overall, taxis were used in less than 1% of all trips made by all socio-economic groups. In comparison, automobiles were used in 86.4% of all trips for all purposes (Pucher and Renne 2003).

Unlike Korea where taxis are used by all but the most and least wealthy, taxi usage in the US is "bimodal, with the highest usage among the poor and the affluent." Individuals with household incomes less than $20,000 per year generally rely on public transit when it is available, and thus use taxis more during off-peak hours (when they constitute 18.4% of taxi users) rather than during peak hours (when they make up only 8.8% of taxi users). Wealthy individuals who make more than $100,000 per year are unaffected by public transit schedules and make up 35 to 38% of taxi users during both peak and off-peak periods (Pucher and Renne 2003).

Taxi usage in the US is also affected by automobile ownership. In 2001, households without a car used taxis 1.0% of the time, while those with only one car used taxis 0.2% of the time and households with 2 or more automobiles used taxis 0.1% of the time (Pucher and Renne 2003). This indicates that automobiles are a necessity in the US and that taxis are used as short-haul automobile replacements.

Taxi drivers in Boston, MA reported that most passengers are professionals, students, and tourists and that the majority of their trips are made on Fridays and Saturdays. Like Korea, common destinations include the airport, hotels, shopping districts, places with poor parking (like Fenway Park) and "home". However, unlike Korea, very few passengers in Boston taxis to connect to the subway or other forms of public transportation; more want door-to-door service. In interviews with the authors, taxi drivers in Austin, TX, where there are limited public transit options, reported that almost all taxi trips in the city were made to and from the airport. For longer trips, visitors generally rented cars or were given rides by friends, family or colleagues.

The average length of a US taxi trip in 2001 ranged from 4.1 miles (for households with incomes less than $20,000) to 7.5 miles (for households with incomes between $40,000 and $74,999) with an average of 5.6 miles per trip for all socio-economic groups (Pucher and Renne

2003). This is more than twice the length of an average taxi trip in Korea.

The low overall rates of taxi usage and the higher average length of trip can be attributed partially to the nature of American cities. In 2000, over half of the US population lived in suburban areas (Hanlon et al. 2010) with 60.3% of the population living in single family detached dwellings and only 17.3% in apartment buildings with 5 or more units (US Census Bureau, 2005). This decentralization increases the cost and decreases the efficiency of mass transit and has led to a massive increase in personal automobile ownership. By 2001, over 90% of US households had at least one car (Pucher and Renne 2003).

The need for, access to, and love of personal automobiles in the US means that there is little demand for taxi services. A 2007 study of taxis in the Coachella Valley near Palm Springs, CA showed that the average number of trips per day per taxi ranged from 1.2 to 15, with only 5 out of 21 taxi companies reporting an average number of trips per day above 6 (Mundy 2007).

New York City: A Special Case

The only place in the United States that comes close to having a PRT-like taxi system is New York City. Taxis in New York transport 11% of all “taxi, bus, subway, car service, or black car passengers in New York City, and 25% of those traveling within Manhattan” (Schaller 2006). These are similar to the usage rates reported in Korea. To satisfy this demand, taxis in New York average 12.29 to 28.10 trips per shift (Farber 2008). The average taxi fare in New York City is “$9.61 for a 2.8 mile trip, or $11.44 when surcharges and tips are included” (Schaller 2006). This is a shorter average trip and a higher average cost per mile than in other parts of the US. New York taxi usage rates, trip length, and trips per shift are closer to those observed in Korea.

The conditions in New York City are also closer to those observed in Korea. In New York, only 9.8% of residents live in single-family detached homes and only 7% live in single-family attached homes. The majority of the population lives in apartment buildings with 5 or more units (60%) with approximately half of those residents (or 30.7% of the NYC population) in large 50+ unit complexes (US Census Bureau 2010). However, there are some major differences. New York is a region of low automobile ownership. For example, in 2000 only 44.3% of households in NYC had an automobile available to them (US Census Bureau 2000). Also, New York has a much lower taxi density than Korea. Given an estimated population of 8,214,426 (US Census Bureau 2006) and a total of 12,779 taxicabs (Schaller 2006), New York City had approximately 1 taxi for every 642 residents in 2006. This is only 26% of the per capita taxi rate in Daejeon.

Discussion

Limitations of Taxis as Proxies for PRT

The functional similarities between the Korean taxi system and an ideal PRT system make the Korean taxi system an ideal way to study the impact of variables such as station density, vehicle availability, travel cost, travel time, and system congestion on user preferences and behavior. However, the physical differences between PRTs and taxis, especially in terms of exclusive guideways versus shared roadways and autonomous operation versus human operation, can have a major impact on the infrastructure costs, operating costs, and safety of the two systems. Studying a PRT-like taxi system will provide little or no information about these factors. Also, PRT-like taxis have a different impact on automobile traffic congestion than a true PRT system would. And, studying taxis with internal combustion engines provides little information about the environmental impact of switching to electric PRTs.

Limitations of PRT Compared to Taxis

On the other hand, taxis have some advantages over PRTs. Taxis provide better service by picking up and dropping off passengers closer to their starting and final destinations. Because taxis use the existing roadway, the taxi system is more flexible and thus better able to respond to changes in technology, city infrastructure, and population. And, taxis create more long-term jobs than an automated PRT system would.

Perhaps more importantly, this work has shown that a taxi system that offers the same level of service (station density, waiting time, trips per day, etc.) as a PRT system will still only be used in 5 to 11% of all trips or 7 to 26% of all motorized trips. This leads us to question whether the cost of the exclusive guideway infrastructure and the station density necessary to address the last mile problem will ever be justifiable. If not, perhaps the very definition of personal rapid transit will have to evolve to place more emphasis on the functionality and less emphasis on the physical attributes of these systems. Such a change could make room for app-based ride sharing programs, public bicycle rental systems, driverless automobiles, and other paradigms that provide different physical means to perform the same functions and obtain the expected benefits of personal rapid transit.

Limitations of this Study

Transportation planning and transportation mode of choice depend strongly on context. This paper showed that urban planning is an important factor in creating and maintaining a PRT-like taxi system. However, urban planning is affected by local factors such as culture, climate, and the age and history of the city. Taxi driver and taxi passenger behavior are also heavily influenced by culture, climate, and the nature of the city. Thus, PRT-like taxis may work better in one context while traditional PRTs may work better in another. Similarly, the conditions necessary to make a physical solution work in one context may not be same in another. This underlines the importance of functional thinking in the design of transportation systems. Clearly and accurately defining the functional requirements and constraints at the beginning of a project can greatly increase the probability of identifying and ultimately selecting the best physical means to achieve them for a given situation.

Implications for the Future

Finally, transportation planning and transportation mode of choice are not static. Instead, they evolve with the economy, society, technology, and public policy. For example, widespread mobile internet access has made networking ride share program such as Uber a reality. Driverless vehicles are also being tested and eventually will be commercially available. New technology may address the existing shortcomings of taxis and personal rapid transit, allowing one or both of these options to reach their full potential. However, changes in technology and society may also lead to demands for new functionality and services that cannot be met by existing transportation paradigms. This could cause taxis and personal rapid transit to become relics of the past. Uncertainty, especially over long periods of time, is one of the major challenges of design in civil and environmental engineering. Designing for uncertainty at the urban scale (both in space and time) is one of the topics that we hope the DCEE community will address in the years to come.

Summary and Conclusions

This work has used a functional thinking approach to explore the past, present, and future of personal rapid transit. It has demonstrated that taxis in Korea perform the same highest-level functional requirement and provide many of the benefits that are expected of a city-scale personal rapid transit system. Thus, Korean taxis can be used as an alternative embodiment of personal rapid transit and can serve as a test bed to support PRT-related design, research, and development.

It was shown that taxis in Korea are predominantly used to connect to other forms of transportation, for transportation to and from business and recreational activities, and to eliminate the need to own, operate, and/or park an automobile. Taxi trips are short and expensive relative to other modes of transportation. Passengers are average people who weigh the costs and benefits of using a taxi for each situation, rather than using taxis as a daily or default mode of transportation.

It was proposed that five conditions are necessary to create and support a PRT or PRT-like taxi system:

- Extensive, high quality public transportation
- High quality of (taxi / PRT) service
- High population and housing density
- Large numbers of (taxi / PRT) vehicles in service (1 taxi for every 150 to 200 residents)
- Reasonable price and operating costs

Finally, it was shown that regions like the US that do not share these characteristics also do not have PRT-like taxi systems.

It is hoped that the functional thinking approach used in this paper will help us to better understanding existing transportation paradigms like personal rapid transit, to support the development of new transportation paradigms in all physical forms, to match the best functional and physical solution to each context, and to plan for the unknown but inevitable changes that will affect the demands on our transportation systems in the future.

Acknowledgements

The authors would like to thank Mr. Charles Seo, Ms. Sehee Kim, Mr. Yurim Park, and Ms. Yunhee Jung for their help in collecting and processing the data presented in this paper. They would also like to thank Mr. D. H. Kim and all of the other taxi drivers who were interviewed for this work. This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) and was funded by the Ministry of Education, Science and Technology (2010-N01100273). Their financial support is greatly appreciated.

References

Anonymous (2014) Description of the Japanese Computer-controlled Vehicle System (CVS), http://faculty.washington.edu/jbs/itrans/cvs1.htm (Accessed August 1, 2014).

Anonymous (2014) Cabinlift, http://faculty.washington.edu/jbs/itrans/cablift.htm (Accessed August 1, 2014).

Anderson, J. E. (1988) The TAXI 2000 personal rapid transit system, *Journal of Advanced Transportation*, 22(1), 1-15.

Anderson, J. E. (2000) A review of the state of the art of personal rapid transit, *Journal of Advanced Transportation*, 34(1), 3-29.

Anderson, J. E. (2006) The future of high-capacity personal rapid transit, PRT International, LLC, Minneapolis, MN.

Andréasson, I. (2001) Innovative Transit Systems: Survey of Current Developments, The Swedish Agency for Innovation Systems Report VR 2001:3.

Carnegie, J. A. and Hoffman, P. S. (2007) *Viability of personal rapid transit in New Jersey*, Report No. NJ-2007-001.

Cottrell, S. (2005) Critical Review of the Personal Rapid Transit Literature, *Proceedings of the 10th International Conference on Automated People Movers*, Orlando, Florida, pp. 1-14.

Cottrell, W. D. and Mikosza, O. (2008) New-Generation Personal Rapid Transit Technologies: Overview and Comparison, *Transportation Research Record: Journal of the Transportation Research Board*, 2042 (1), pp. 101-108.

Daejeon Metropolitan City (2012) *Taxi Stand Locations*, Transportation and Parking Division.

Daejeon Metropolitan City Statistics (2009) Passengers per Transportation Mode, Daejeon Metropolitan City Website. http://www.daejeon.go.kr/dj2009/statistics/db/01/db.01.001.action (Accessed Jul. 28, 2009).

De Graaf, M. (2011) PRT Vehicle Architecture and Control in Masdar City, *Proceedings of the 13th Int. Conference on Automated People Movers and Transit Systems*, pp 339-348.

Delle Site, P. and Filippi, F., D. (2005) Design of operations of personal rapid transit systems, *Proceedings of the 10th meeting of the EURO working group on transportation*, Poznan, Poland.

Dunning, B. and Ford, I. (2003) Personal automated transportation: status and potential of personal rapid transit, Main Report. Advanced Transit Association.

Farber, H.S. (2008) Reference-Dependent Preferences and Labor Supply: the Case of New York City Taxi Drivers, *Am. Econ. Rev*., 98(3), 1069-1082.

Gustafsson, J. (2009) Vectus - Intelligent Transport, *Proceedings of the IEEE*, 97 (11), November, 2009.

Hanlon, B., Short, J.R., and Vicino, T.J. (2010). *Cities and Suburbs: New Metropolitan Realities in the US*, Routledge, New York.

Hwang, K.H. and Yoon, D.S. (2006) A Comparative Analysis of Operation of Corporation-owned and Owner-driver Taxies using Tachometer Output Data, *Journal of Korean Society of Transportation*, 24(6), 45-54.

Jung, H.Y., and Kim, J.J. (2000) Mode Choice Behavior Analysis of Commuter Feeder Passengers to Subway System, *J. of Korean Soc. of Transp.*, 18(5), 69-82.

Korean Ministry of Employment and Labor (KMOEL) (2000) Salary and Working Environment by Work-type, Education, Age, Gender (2000~2008), Korean Statistical Information Service, http://kosis.kr/gen_etl/start.jsp?orgId=118&tblId=DT_PAYM002&conn_path=I2&path=**중앙행정기관-고용노동부-고용형태별근로실태조사((구)임금구조기본통계조사포함)-직종분류별 통계**(1993 **년 이후**) (Accessed Jun. 29, 2011. Requires plug-in to view).

Korean Ministry of Land, Transport and Maritime Affairs (KMLTM) Housing Land Office (2007) Apartment Floors by Region, Korean Statistical Information Service, http://kosis.kr/gen_etl/start.jsp?orgId=116&tblId=DT_MLTM_722&conn_path=I2&path=**건설·주택·토지-주택-아파트주거환경통계 -지역별 층수 현황** (Accessed Jun. 28, 2011. Requires plug-in to view).

Korean Ministry of Land, Transport and Maritime Affairs (KMLTM) (2009) *Research on Transportation Distribution and Transportation Performance Analysis.* 2008 National Transportation Demand Research and DB Construction 388-9-15., Gyeonggi.

Korean Ministry of Land, Transport and Maritime Affairs (KMLTM) (KMLTM), Transportation Policy Office. (2010) Registered Automobiles, Korean Statistical Information Service, http://kosis.kr/gen_etl/start.jsp?orgId=116&tblId=DT_MLTM_2040&conn_path=I2&path= **교통·정보통신-교통-자동차현황-자동차등록현황보고-이륜차신고현황_시도별** (Accessed Jun. 29, 2011. Requires plug-in to view).

Korean Ministry of Government Legislation (2012) Passenger Transport Service Act.

Korea Transport Institute (KOTI) (2004) *Taxi Fare Policy Improvement Methods*, Korea Transp Inst, Policy Res. 04-05., Gyeonggi.

Lee, J.W. and Kim, H.J. (2001) The Analysis of Operation Condition of Corporation Taxicab Using the Tachometer Output Data, *KSCE Journal of Civil Engineering*, 21(6D), 785-797.

Litman, T. (2010) *Evaluating Public Transit Benefits and Costs: Best Practices Guidebook*, Victoria Transport Policy Institute, Victoria, BC, Canada. www.vtpi.org/tranben.pdf (Accessed Jul. 12, 2011).

Lohmann, R. and Guala, L. (2009) Introducing PRT to the sustainable city, *Proceedings of the ASCE 12th International Conference on Automated People Movers*.

Lowson, M. (2001) The ULTra PRT System, *Proceedings of the ASCE 8th International Conference on Automated Automated People Movers*, San Francisco, CA.

Mundy, R.A. (2007) *Coachella Valley Taxi Study*, Tennessee Transportation & Logistics Foundation, St. Louis. http://www.sunline.org/pub/pdfs/Coachella_Valley_Taxi_Study.pdf (Accessed Jul. 12, 2011).

Parent, M. (1997) Automated public vehicles: A first step towards the automated highway, *4th World Congress on Intelligent Transport Systems*.

Pucher, J., and Renne, J.R. (2003) Socioeconomics of Urban Travel: Evidence from the 2001, *NHTS. Transp. Q.*, 57(3), 49-77.

Raney, S. and Young, S. (2005) Morgantown People Mover - Updated Description, *Proceedings of the Transportation Research Board Annual Meeting*, Washington, D.C.

Schaller, B. (2006) *The New York City Taxicab Fact Book*, Schaller Consulting, Brooklyn, NY. http://www.schallerconsult.com/taxi/taxifb.pdf (Accesed Jul. 12, 2011).

Simon, H. A. (1969) *The Sciences of the Artificial*, Cambridge, MA, MIT Press.

Song J.R. and Song H.J. (2000) *Research on Methods to Improve Gyunggi-do Taxi Service*, Gyueonggi Res. Inst. 388.41321, Gyeonggi.

Statistics Korea, Total Population Research Division (2005) Gender/Age/Commuter to Work/School (12 years and older) by Region (10% Sample), Korean Statistical Information Service. http://kosis.kr/gen_etl/start.jsp?orgId=101&tblId=DT_1T0515&conn_path=I2&path=인구·가구-인구총조사-인구부문-총조사인구(2005)-통근·통학(10 % 표 본)-성/연령/통근·통학유형별인구(12 세이상)-시군구 (Accessed Jun. 29, 2011. Requires plug-in to view).

Statistics Korea (2010a) Preliminary Results of the 2010 Population and Housing Census, Statistics Korea. http://kostat.go.kr/portal/english/news/1/1/index.board?bmode=download&bSeq=&aSeq=245048&ord=1 (Accessed Jul. 12, 2011).

Statistics Korea, Total Population Research Division (2010b) Census General, Korean Statistical Information Service. http://kosis.kr/gen_etl/start.jsp?orgId=101&tblId=DT_1IN1002&conn_path=I2&path=인구·가구 - 인구총조사 - 인구부문 - 총조사인구(2010) - 전수부문 – 인구 (Accessed Jun. 27, 2011).

Suh, N. P. (1990) *The Principles of Design*, New York: Oxford University Press.

Suh, N. P. (2001) *Axiomatic Design: Advances and Applications*, New York: Oxford University Press.

Tegnér, G., Hunhammar, M., Andréasson, I., Nowacki, J.-E., Dahlström, K., (2007) PRT in Sweden: From Feasibility Studies to Public Awareness, *Proceedings of the 11th International Conference on Automated People Movers*, Vienna.

Transport Design International (TDI) (2014) Personal Rapid Transit, http://www.tdi.uk.com/EN/vectus-prt/ (Accessed August 1, 2014)

Ultra Global (2014) http://www.ultraglobalprt.com (Accessed August 1, 2014).

US Census Bureau. (2000) New York City, New York, Profile of Selected Housing Characteristics, Census 2000 Summary File (SF 3). U.S. Census Bereau American Fact Finder. http://factfinder.census.gov/servlet/QTTable?_bm=y&-qr_name=DEC_2000_SF3_U_DP4&-geo_id=16000US3651000&-ds_name=DEC_2000_SF3_U&-_lang=en&-redoLog=false&-_sse=on (Accessed Jul. 12, 2011).

US Census Bureau. (2005). Historical Census of Housing Tables: Units in Structure. U.S. Census Bureau. http://www.census.gov/hhes/www/housing/census/historic/units.html (Accessed Jun. 15, 2011).

US Census Bureau. (2006) New York City, New York, State and County Quick Facts, U.S. Census Bureau. http://quickfacts.census.gov/qfd/states/36/3651000.html (Accessed Jul. 12, 2011).

US Census Bureau. (2010). New York City, New York, Selected Housing Characteristics, 2005 – 2009 American Community Survey 5-Year Estimates. U.S. Census Bureau. http://factfinder.census.gov/servlet/ADPTable?_bm=y&-qr_name=ACS_2009_5YR_G00_DP5YR4&-geo_id=16000US3651000&-ds_name=ACS_2009_5YR_G00_&-_lang=en&-redoLog=false&-_sse=on (Accessed Jul. 12, 2011).

Visit Korea (2014) Taxis http://asiaenglish.visitkorea.or.kr/ena/TR/TR_EN_5_2.jsp (Accessed August 1, 2014).

Table A1. Detailed Taxi Observation Results by Location (Part 1)

		CGV Dunsan **Movie Theater**		Yuseong **Hotel**		Sun **Hospital**		Daejeon **City Hall**		Eunhang-Dong **Shopping District**		Daejeon **Train Station near Subway**	
		Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak
Passing by the Site	Number of vehicles excluding taxis	1346	1377	154	153	331	323	350	258	348	569	725	688
	Number of taxis	111	141	39	16	65	72	59	58	121	247	181	130
	Total number of vehicles	1457	1518	193	169	396	395	409	316	469	816	906	818
	% of taxis to total vehicles	7.62	9.29	20.21	9.47	16.41	18.23	14.43	18.35	25.80	30.27	19.98	15.89
Arriving at the Site	Number of visitors without personal car	29	65	32	96	91	142	27	28			159	748
	Number of visitors arriving in taxis	3	13	1	0	2	7	5	2	10	36	5	44
	% of taxi passengers to total visitors without a personal car	10.34	20.00	3.13	0.00	2.20	4.93	18.52	7.14			3.14	5.88
	Number of cars	5	21	37	67	35	36	12	17				
	Number of taxis	3	9	1	0	2	5	4	2	7	27	4	40
	Total number of vehicles	8	30	38	67	37	41	16	19				
	% of taxis to total vehicles arriving at site	37.50	30.00	2.63	0.00	5.41	12.20	25.00	10.53				
	Initial number of taxis at taxi stands	14	9	3	2	7	10	0	0	9	15	40	40
	Final number of taxis at taxi stands	9	12	4	0	13	9	0	0	9	15	40	40
	Number of taxis entering taxi stands during 20 min period	2	21	2	1	7	8	2	1	5	30	85	78
Departing from the Site	Number of visitors departing without a personal car	15	62	39	27	95	69	19	34			265	745
	Number of visitors departing in taxis	7	26	1	3	2	11	2	1	7	49	107	106
	% of taxi passengers to total visitors without a personal car	46.67	41.94	2.56	11.11	2.11	15.94	10.53	2.94			40.38	14.23
	Number of cars	3	10	58	45	42	45	16	22				
	Number of taxis	7	18	1	3	1	9	2	1	5	30	85	78
	Total number of vehicles	10	28	59	48	43	54	18	23				
	% of taxis to total departing vehicles	70.00	64.29	1.69	6.25	2.33	16.67	11.11	4.35				
	Average waiting time of passengers for taxis	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:02:00	0:00:00	0:00:00	0:00:00	0:00:00
	Average waiting time of taxis for passengers	0:24:29	0:05:34	0:22:52	0:01:39	0:30:00	0:14:49	0:03:55	0:00:00	0:31:40	0:05:51	0:09:32	0:10:19
	Average number of taxis waiting for passengers	13.09	10.91	3.91	0.64	8.27	8.55	0.40	0.00	9.00	15.00	40.00	40.00
Arriving & Departing	Total number of visitors without car	44	127	71	123	186	211	46	62			424	1493
	Total number of visitors arriving and departing in taxis	10	39	2	3	4	18	7	3	17	85	112	150
	% of taxi passengers to total visitors without a personal car	22.73	30.71	2.82	2.44	2.15	8.53	15.22	4.84			26.42	10.05
	Number of cars	8	31	95	112	77	81	28	39				
	Number of taxis	10	27	2	3	3	14	6	3	12	57	89	118
	Total number of vehicles	18	58	97	115	80	95	34	42				
	% of taxis to total vehicles	55.56	46.55	2.06	2.61	3.75	14.74	17.65	7.14				
	Average number of passengers per taxi	1.00	1.44	1.00	1.00	1.33	1.29	1.17	1.00	1.42	1.49	1.26	1.27

Table A2. Detailed Taxi Observation Results by Location (Part 2)

		SeoDaejeon **Train Station**		Homeplus **Shopping Mall**		E-mart **Shopping Mall near Subway**		Hanbit **Apartment Complex**		Daejeon Grand **Park**				
		Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Min	Max	Avg
Passing by the Site	Number of vehicles excluding taxis	413	571	390	786	1188	1275	234	433	844	1199			634
	Number of taxis	126	105	49	68	145	251	21	18	76	113			101
	Total number of vehicles	539	676	439	854	1333	1526	255	451	920	1312			735
	% of taxis to total vehicles	23.38	15.53	11.16	7.96	10.88	16.45	8.24	3.99	8.26	8.61	3.99	30.27	14.56
Arriving at the Site	Number of visitors without personal car	180	193	25	85	68	129	20	17	2	9			107.25
	Number of visitors arriving in taxis	8	7	2	1	6	7	0	1	0	0			7.27
	% of taxi passengers to total visitors without a personal car	4.44	3.63	8.00	1.18	8.82	5.43	0.00	5.88	0.00	0.00	0.00	20.00	5.63
	Number of cars	10	11	43	42	77	135	60	74	3	21			39.22
	Number of taxis	8	6	2	1	3	4	0	1	0	0			5.86
	Total number of vehicles	18	17	45	43	80	139	60	75	3	21			42.06
	% of taxis to total vehicles arriving at site	44.44	35.29	4.44	2.33	3.75	2.88	0.00	1.33	0.00	0.00	0.00	44.44	12.10
	Initial number of taxis at taxi stands	15	15	5	6	5	6	5	2	0	0			9.45
	Final number of taxis at taxi stands	15	15	3	5	4	6	6	0	0	0			9.32
	Number of taxis entering taxi stands during 20 min period	14	10	3	6	4	12	8	9	0	0			14
Departing from the Site	Number of visitors departing without a personal car	116	118	47	75	43	169	27	75	2	11			102.65
	Number of visitors departing in taxis	15	10	8	12	10	21	7	13	0	0			19.00
	% of taxi passengers to total visitors without a personal car	12.93	8.47	17.02	16.00	23.26	12.43	25.93	17.33	0.00	0.00	0.00	46.67	16.09
	Number of cars	8	6	53	82	34	128	147	339	0	21			58.83
	Number of taxis	14	10	5	7	5	12	7	11	0	0			14.14
	Total number of vehicles	22	16	58	89	39	140	154	350	0	21			65.11
	% of taxis to total departing vehicles	63.64	62.50	8.62	7.87	12.82	8.57	4.55	3.14	0.00	0.00	0.00	70.00	19.35
	Average waiting time of passengers for taxis	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:32	0:00:00	0:00:00	0:00:00	0:02:00	0:00:01
	Average waiting time of taxis for passengers	0:20:00	0:28:58	0:10:06	0:08:41	0:07:39	0:11:57	0:08:58	0:01:40	0:00:00	0:00:00	0:00:00	0:31:40	0:10:49
	Average number of taxis waiting for passengers	15.00	15.00	3.27	4.00	4.10	6.00	4.91	1.27	0.00	0.00	0.00	40.00	9.24
Arriving & Departing	Total number of visitors without car	296	311	72	160	111	298	47	92	4	20			209.90
	Total number of visitors arriving and departing in taxis	23	17	10	13	16	28	7	14	0	0			26.27
	% of taxi passengers to total visitors without a personal car	7.77	5.47	13.89	8.13	14.41	9.40	14.89	15.22	0.00	0.00	0.00	30.71	10.75
	Number of cars	18	17	96	124	111	263	207	413	3	42			98.06
	Number of taxis	22	16	7	8	8	16	7	12	0	0			20.00
	Total number of vehicles	40	33	103	132	119	279	214	425	3	42			107.17
	% of taxis to total vehicles	55.00	48.48	6.80	6.06	6.72	5.73	3.27	2.82	0.00	0.00	0.00	55.56	15.83
	Average number of passengers per taxi	1.05	1.06	1.43	1.63	2.00	1.75	1.00	1.17			1.00	2.00	1.31

Table A3. Number of Passengers Per Taxi by Location

		CGV Dunsan		Yuseong		Sun		Daejeon		Eunhang-Dong		Daejeon		SeoDaejeon		Homplus		E-mart		Hanbit		Daejeon Grand	
		Movie Theater		**Hotel**		**Hospital**		**City Hall**		**Shopping District**		**Train Station near Subway**		**Train Station**		**Shopping Mall**		**Shopping Mall near Subway**		**Apartment Complex**		**Park**	
		Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak
Arriving	1 passenger car	3	6	1	0	2	4	3	2	4	21	3	36	8	5	2	1	0	1	0	1	0	0
	2 passenger car	0	2	0	0	0	0	1	0	3	3	1	4	0	1	0	0	3	3	0	0	0	0
	3 passenger car	0	1	0	0	0	1	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
	4 passenger car	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Arriving Passengers		3	13	1	0	2	7	5	2	10	36	5	44	8	7	2	1	6	7	0	1	0	0
Total Arriving Taxis		3	9	1	0	2	5	4	2	7	27	4	40	8	6	2	1	3	4	0	1	0	0
Departing	1 passenger car	7	13	1	3	0	7	2	1	3	17	66	54	13	10	3	3	2	5	7	9	0	0
	2 passenger car	0	2	0	0	1	2	0	0	2	7	16	20	1	0	1	3	1	5	0	2	0	0
	3 passenger car	0	3	0	0	0	0	0	0	0	6	3	4	0	0	1	1	2	2	0	0	0	0
	4 passenger car	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Departing Passengers		7	26	1	3	2	11	2	1	7	49	107	106	15	10	8	12	10	21	7	13	0	0
Total Departing Taxis		7	18	1	3	1	9	2	1	5	30	85	78	14	10	5	7	5	12	7	11	0	0
Arriving & Departing	1 passenger car	10	19	2	3	2	11	5	3	7	38	69	90	21	15	5	4	2	6	7	10	0	0
	2 passenger car	0	4	0	0	1	2	1	0	5	10	17	24	1	1	1	3	4	8	0	2	0	0
	3 passenger car	0	4	0	0	0	1	0	0	0	9	3	4	0	0	1	1	2	2	0	0	0	0
	4 passenger car	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Passengers		10	39	2	3	4	18	7	3	17	85	112	150	23	17	10	13	16	28	7	14	0	0
Total Taxis		10	27	2	3	3	14	6	3	12	57	89	118	22	16	7	8	8	16	7	12	0	0
Average		1.00	1.44	1.00	1.00	1.33	1.29	1.17	1.00	1.42	1.49	1.26	1.27	1.05	1.06	1.43	1.63	2.00	1.75	1.00	1.17	0.00	0.00

Developing an Engineering Course for Fostering Future-Oriented Interdisciplinary Team Design Skills

Mei-Di Chen[*1], Shih-Yao Lai[2], Mei-Mei Song[3], and Shang-Hsien Hsieh[1]

mindychen@ntu.edu.tw, laisy@ntu.edu.tw, song@mail.tku.edu.tw, shhsieh@ntu.edu.tw

[1] Department of Civil Engineering, National Taiwan University, Taipei, Taiwan

[2] Graduate Institute of Building and Planning, National Taiwan University, Taipei, Taiwan

[3] Graduate Institute of Futures Studies, Tamkang University, New Taipei City, Taiwan

Abstract: The rapid advancement of technology and changes in society in recent decades have made future engineering challenges harder to predict than ever. On the other hand, some elements crucial to cultivating problem-solving abilities targeting future issues can be readily identified: teamwork, innovation across multiple disciplines, future-oriented thinking, and creativity. Therefore, it is necessary to help civil engineering students develop these abilities. This paper reports an ongoing effort in the Department of Civil Engineering at National Taiwan University (NTU) on developing a course that intends to foster future-oriented team design power among students with a variety of expertise. Professors and experts from the fields of civil engineering, architecture, mechanical engineering, futures studies, and education are invited to co-teach and help develop the course contents. A student-centered, project-based approach is employed for students to learn in teams, with a team project theme of how to make the NTU campus more sustainable through Building Information Modeling-enabled design.

Keywords: Interdisciplinary Course Development, Futures Thinking, Engineering Education.

Introduction

The rapid advancement of technology and changes in society in recent decades have made it crucial for university education to enhance future-oriented thinking in order to help students adapt to a complex and diverse world. Future-oriented thinking is especially vital to engineering students and specialists because their designs must meet the demands of society in the future. However, the educational system in Taiwan mainly uses lectures as a teaching method in an instructor-centered and passive learning way, a method that does not emphasize training to imagine the future world. We contend that we must let students reflect on social issues and blind spots through long-term thinking towards the future and empower them to create alternative futures for themselves and for society. That is, the objective of future-oriented thinking in education is not merely to assist students to “future-proof” but also to help them actively construct their preferred futures (Facer 2011).

Engineering is a highly collaborative process (Bucciarelli 1996). Today’s complex engineering systems require the collaborative effort of engineers and non-engineers across multiple fields (Sheppard *et al.* 2008). It is necessary for teachers to create a learning environment for students to team up with different professional fields and to learn to communicate actively and positively with each other. To respond to these challenges, the Department of Civil Engineering of the National Taiwan University has recently made some curricular changes, creating a series of design project-based courses by integrating original and new programs. Cornerstone courses, aimed at fresh students before they start to learn professional civil knowledge, include imagination training and hands on practice. Optional keystone courses combining theory with pragmatic operations are offered to sophomore students. Examples of such courses include the design and construction of functional prototypes that exploit principles of structural and fluid mechanics. Finally, junior and senior students can take optional capstone courses, focusing on developing solutions to realistic engineering design problems (Capart *et al.* 2013).

The engineering course for fostering future-oriented interdisciplinary team design ability is designed to be a capstone course. This course is included in the undergraduate curriculum for university students, but graduate students also can take the course through a registration process, and even industry insiders can participate in specific modules of interest to them by sitting-in on this class. This research will be executed for three years. Teaching materials and teaching plans will be cultivated and amended back and forth through three instruction times, and the course effectiveness will be evaluated and refined by questionnaire and interview results from teachers and students. It is hoped that this course will be used as an example in the development of general teaching and learning principles, and that the resultant teaching and learning model could be applied to every department to tie previous and subsequent courses together into a series of interdisciplinary curricula.

Course Goals

One issue necessary to conquer and resolve in this course for the society of the future is the proposal of innovative design learning. Professors with different expertise are gathered and are invited to teach and help develop the course content. Students are divided into several groups by distinct departments or specialties and practice on a real case to learn and design creatively.

Three targets were designed in the teaching plans for this course:

Interdisciplinarity

Interdisciplinarity is a key feature of the design of this course. Teachers play the role of manager to arrange the course content. Since these lecturers are all from different departments, they must comprehend the relationship among their occupational domains before the course begins, and design a learning environment based on the learning situation of their targeted students. Furthermore, in order to help students to understand different fields, a range of necessary interdisciplinary skills is included. Thus, students can utilize their specialized skills well through cooperation with team members.

Collaboration

The ability to work and function as a team is a valuable skill for students to possess. They are distributed into heterogeneous group to achieve learning goals and finish learning missions together. They learn to trust, communicate, and interact with team members.

Virtuality

We bring imagination into real life by using virtual technology. By employing parameterized simulation functions with computer software in teaching, we can create realistic, future-appropriate scenarios. It is possible for students to simulate a wide range of circumstances in this virtual reality. Furthermore, they are able to modify future scenarios in the virtual space by comparing differences from the simulation results. Enabled by this visualization system, students are trained to have the ability to think independently, which will help them to make the right judgments and cultivate the ability to solve problems.

Students are encouraged to cultivate five core capabilities in this course using future-oriented thinking methods.

Interdisciplinary Communication

Communication among all the professors and students from areas of diverse expertise is the keystone of the current course. Lecturers are asked to help to develop course content for those who are unfamiliar with it. Furthermore, students are required to collaborate with their peers through this course. Both the lecturers and students could hence become familiar with each other and improve their communication skills.

Teamwork

Teamwork is one of the fundamental values of futurology. Future society should be framed by people working together, thus the ability to link and interact with each other will be very important. Therefore, we emphasize the value of teamwork and communication in the course design.

Imagination

Imagination is like a blueprint for the future. By exploiting a diverse array of futurology methods, the course assists students to sketch the future. Hence, they will not just stop at the imagination stage, and their capability to actually change the world will grow.

Observation

Students can find a specific role in society for themselves via several activities and hands-on practices, which focus on surveying the past, present, and future to observe society.

Reflection

Future thinking is a process of reflection. Differing from neutrality, future thinking enables people to implement certain values or test hypotheses of human beings from the past and present by extending the time scale and widening the point of view. Therefore, we can reshape the image of the future to fit contemporary visions.

Course Design and Implementation

The Technology and Application of BIM (Building Information Modeling) course was developed to enhance students' basic BIM knowledge and the skills applied in BIM for engineering issues for sophomore and graduate students at the Department of Civil Engineering of National Taiwan University since 2011. Furthermore, the BIM Implementation Practice course covering the practical design and analysis of a real, new building case was run at National Taiwan University campus in spring 2013.

BIM is a rapidly developing new technique in the architecture, civil, and construction fields. Key success factors of BIM implementation for engineering projects are interdisciplinarity, collaboration, and virtuality.

BIM uses a digital model to build, manage, and apply virtual construction for better control and integration before the actual execution of engineering projects. Regardless of what types of engineering works are examined, different staff and departments are required to cooperate across dissimilar engineering stages. The owner, designer, construction department, administrator, and supplier join the projects together and invest their efforts in distinct stages. Thus, communication and co-ordination are indispensable, an aspect that matches the teaching philosophy of this course.

In view of the above, we redesigned the BIM Implementation Practice course in spring 2014 to foster students' futures competencies, with "a sustainable NTU campus in 2030" as the center of all course activities. The course is integral in reinforcing every student's professional specialty and pushing ahead with team cooperation. The course took the NTU CSIE building as a case for innovation and design with BIM simulation and analysis methods, along with emphasizing energy conservation and water saving to improve existing buildings on campus and the environment in order to carry out the vision of sustainable campus in future.

This class was held for a total of 18 weeks on Monday nights and Wednesday afternoons in this semester, and one of the classes will be divided into two associated workshops on two designated weekends (table 1).

Table 1. The Content of the BIM Implementation Practice Course

Instructional strategies and methods	Percentage
Lecture	19%
Student Team Learning	12%
Workshop	12%
In-class Discussion	7%
Guest Speakers	19%
Final project	31%

Lecture

The contents of lectures were focused on interdisciplinarity. Since the course was held by the Department of Civil Engineering, it was expected that the backgrounds of attendants will generally be limited to the College of Engineering. Besides, considering that interdisciplinary communication is necessary for the working scenarios of civil engineers, the contents were designed specifically for those in the Architecture Department, Civil Engineering Department, and Mechanical Engineering Department. The content consisted of Building Information Model (BIM) technology, which is rapidly gaining popularity in the field of civil engineering, participatory design in architecture and urban planning, energy-saving performance measurement and verification methods for air conditioning. Before the execution of the course, all the teachers and teaching assistants were trained in future-oriented thinking by means of a workshop. We aimed to help students to comprehend the technical terms among different fields, and encourage communication and cooperation between team members.

Student Team Learning

After every lecture, students received certain related literature to study and discuss with the group. After discussing the literature, they collected other literature comprising different themes to report to the teacher and other group members.

Workshop

Students were asked to participate in a two-day workshop for future-oriented thinking. The theme of this workshop was the campus of the National Taiwan University in 2030. Using six pillars in futures thinking (i.e. mapping, anticipating, timing, deepening, creating alternatives, and transforming futures) to make trainees engage in future-oriented thinking, they discussed and envisioned university life in the future as engineering technology becomes more advanced, simultaneously reflecting changes in university education. They were also empowered to create futures based on their imagination, and apply the basic tools of futures thinking by means of hands-on practice (figure 1).

Figure 1. Presentation and Discussion at the Futures Thinking Workshop

In-class Discussion

We revised a futures triangle method and CLA (Causal Layered Analysis) in a workshop that made students practice these methods by teams. The futures triangle method employs an interaction using the pull of the future, push of the present, and weight of history to build a plausible future. CLA has four layers to resolve and deepen futures. The first layer is litany, the official unquestioned view of reality. The second level is the social causation level, the systemic perspective. The data of the litany is explained and questioned at the second level. The third level is the discourse/worldview. The deeper, unconsciously held ideological worldviews and discursive assumptions are unpacked at this level. The fourth level is the myth/metaphor, the unconscious emotive dimensions of the issue (figure 2). The challenge is to conduct research that moves up and down these layers of analysis and thus is inclusive of different forms of knowledge.

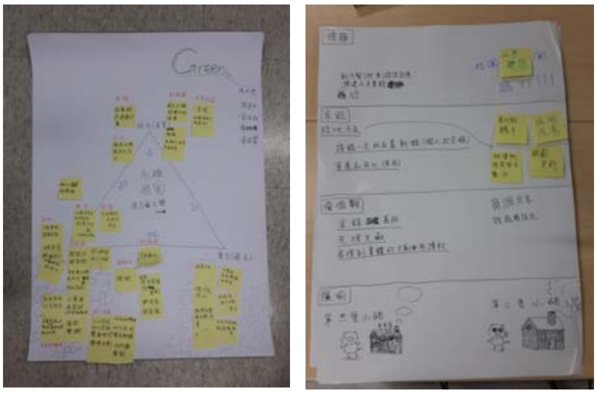


Figure 2. Futures Triangle Method and CLA for the NTU Campus

Guest Speaker

During the final project, we invited experts to share their experiences of energy conservation and water saving a total of seven times. After visiting an energy saving guidance group and campus planning group in NTU, students became able to comprehend the campus building principles of comprehensive planning, land development, and architectural programming with regard to policies and the current situation (figure 3). Depending on the sustainability issue in question, we had speeches from industry experts and architects with EEWH (Ecology, Energy Saving, Water Reduction, and Health) and LEED (Leadership in Energy and Environmental Design) practical experience, and researchers engaged in related energy and water research. Students could then apply relevant technologies and trends to develop imaginative designs in the final project.

Figure 3. Visiting an Energy Saving Guidance Group and Campus Planning Group in NTU

Final Project

For the final project, the requirements were as follows:

1. Imagination of the Future: Using the method of future-oriented thinking, students should discuss and picture their vision for the possible future sustainable campus, and clarify the demands for energy and water resources for the sustainable campus. In addition, students should also complete the following tasks:
   - Use the futures triangle to picture the possible future of the sustainable campus.
   - Use Casual Layered Analysis to pinpoint possible trends and issues for the future, and think deductively what future innovative architecture would be like.
   - Make proposals for achievable main policies and milestones accordingly.
2. Assessment and renovation project: Defining the unavoidable issues for the 2030 sustainable campus project using the case above. Energy and water saving issues should be included but other possible topics should not be excluded. A renovation project should be proposed accordingly. Besides, an assessment of the current situation is also needed. The items assessed should include the condition of the construction site, the existing building, the users, and their activities around the area. Green Building assessments such as LEED or EEWH should also be referred to for energy and water saving considerations at the time. Finally, a renovation project should be proposed according to the assessment above. The proposal should include the current situation, issues to be addressed, and possible solutions for improvement.
3. Design proposal: Using the same case to propose solid renovation ideas for energy and water saving, BIM technology should be used to simulate and analyze efficiency after the renovation.

Closure

All the lessons of the first year have been conducted. There were ten students in the first class. There was only one senior undergraduate student in the class, and the remainders were graduate students, including two doctoral students. In terms of their disciplines, one student was an architecture major and the others were civil engineering majors. Among those students from the Civil Engineering Department, one was from the Structural Engineering Division, one was from the Construction Engineering, and Management Division, and the rest were from the Computer-Aided Engineering Division. Because the course is offered by the Civil Engineering Department, it is difficult to attract students from other departments, and the course promotion was obviously insufficient. Furthermore, the name of the course, “BIM Implementation Practice,” gives the impression that it only focuses on a specific technology (i.e., BIM) and fails to demonstrate the important aim of interdisciplinary cooperation. These are considered the reasons why the course did not attract more students from other departments.

In order to improve the heterogeneous cooperation of the students in the groups, we used the results of the Kolb's Learning Style survey to understand which learning methods the students applied most in their learning. Accordingly, we can divide the students into groups according to different departments, specialties, and learning styles. As for the training for future thinking, we used a two-day workshop and arranged teaching activities that allowed groups to discuss the issues involved in the project. We interviewed the students mid-term and at the end of the term to answer the following questions: Are the course arrangements useful for students to develop the five core abilities? What should be the chronological order of the five abilities? How can students get inspired through these training activities? We also had discussions with the teachers to figure out some issues: How can interdisciplinary results of learning methods be evaluated from the entire design of the curriculum? What level of interdisciplinary understanding should the students achieve in order to cooperate with people in other fields? How can teachers help students to develop their abilities in cross-boundary thinking and resolve problems through improving the curriculum?

In order to increase heterogeneity of the future course, the three professors are to offer a new course following the model of this one in the second year of this research. They will continue to co-teach the course but, in order to attract a variety of clusters of students, will offer a course in their individual departments (civil engineering, architecture, and futures studies). Teaching activities from the three courses are to be carried out together at the same time and in the same place. In addition, a new course title friendlier to students outside civil engineering will be utilized. Hopefully, in this way, we will attract a wider variety of students, even those from the fields of psychology, humanities, etc. to enrich the learning experiences of the students. In addition, we will reorganize and enhance the teaching elements developed in the first year and classify further the interrelationships among the five core abilities through teaching. Furthermore, we hope to establish the general principles of teaching and learning so that the other teachers can easily adopt these principles in their teaching and in the development of similar courses.

Acknowledgements

The authors would like to thank the Ministry of Science and Technology, Executive Yuan, Taiwan for their financial support under the Project No. NSC 102-2511-S-002 -011 -MY3.

References

Bucciarelli, L. L. (1996) *Designing Engineers*. Cambridge: MIT Press.

Capart, H., Hsieh, S. H., and Leu, L. J. (2013) Cornerstone, Keystone and Capstone Design Project courses for Civil Engineering Students. *Proceedings of the Second International Workshop on Design in Civil and Environmental Engineering*, Worcester, USA.

Facer, K. (2011) *Learning futures: Education, technology and social change*. New York: Routledge.

Sheppard, S. D., Macatangay, K., Colby, A., and Sullivan, W. M. (2008) *Educating Engineers: Designing for the Future of the Field*. San Francisco: Jossey-Bass.

Parametric Design and Analysis Framework with Integrated Dynamic Models

Kristoffer Negendahl
krnj@byg.dtu.dk
Department of Civil Engineering, Technical University of Denmark, Denmark

Abstract: In the wake of uncompromising requirements on building performance and the current emphasis on sustainability, including building energy and indoor environment, designing buildings involves elements of expertise of multiple disciplines. However, building performance analyses, including those of building energy and indoor environment, are generally confined to late in the design process. Consequence based design is a framework intended for the early design stage. It involves interdisciplinary expertise that secures validity and quality assurance with a simulationist while sustaining autonomous control with the building designer. Consequence based design is defined by the specific use of integrated dynamic modeling, which includes the parametric capabilities of a scripting tool and building simulation features of a building performance simulation tool. The framework can lead to enhanced awareness of building performance in the early stages of building design, thus improving energy performance and many other quantifiable performance objectives.

Keywords: Integrated Dynamic Model, Consequence Based Design, Parametric Tool, Building Performance Simulation, Integrated Design.

Introduction

Nearly 80% of the design decisions that impact energy consumption are made during the first 20% of the design process (Theßeling *et al.* 2008). Regardless of the numerous attempts to structure the design process, and in so doing improve performance of buildings, no tangible multi-disciplinary structure is found in the design approaches in Danish building design practices today. One reason is the diverse and segregated cultural differences between those who design and those who calculate (Bleil de Souza 2012). Another reason is the absence of tools that meet the performance analysis needs of both architects and engineers in early design (Toth *et al.* 2011).

Many engineering consultancies offer architects building energy consulting expertise in the early stages of building design, but very few projects are fashioned within a true integrated design process[1]. This means only few projects today are designed by design teams consisting of experts in many disciplinary fields of the AEC industry.

Energy analysis (and other performance analyses and assistance) are for this reason either handled by the architects themselves or not considered at all. Engineers usually assist the architect with the aid of building performance simulation (BPS) tools in later stages, which often results in easy-fix solutions which are far from ideal in terms of performance, cost-efficiency and the overall holistic and human centered solutions.

Background

The analysis procedure when operating BPS tools requires a user with suitable knowledge of the tools and understanding of building physics as well as insight in regulatory building energy requirements. Of this reason BPS tools are often handled by experts (often associated with a simulationist or engineering analyst (de Souza 2009)). Nevertheless different software developers (e.g. IES (Integrated Environmental Solutions 2013), Autodesk (Autodesk 2013c)) have over the past few years produced simplified versions of their BPS products to accommodate building designers, thus making the process of energy simulation an accessible task for non-simulationists. The simpler tools have proved very powerful in improving energy performance from the earliest design stages which is demonstrated in previous studies e.g. Bambardekar & Poerschke (2009) and Doelling & Nasrollahi (2012). However non-simulation-experts may have difficulties establishing the required quality assurances (Hensen 2004) when handling the BPS environments, meaning non-simulationist often do not have the required competences to use and analyze BPS. The inclusion of a specialist in the early design stage is paramount to achieve a valid ground for informed design.

[1] Integrated design as defined by IEA task 23 (Löhnert *et al*. 2003)

The geometric modeling procedure when using BPS tools has been reduced dramatically due to better interoperability between BPS tools and design tools (often classified as CAD software). The technical foundation for model level collaboration has for this reason improved significantly. Yet many problems still exist when seeking to either unify or couple design tools and BPS tools (Negendahl 2013). One solution in coupling the design tool and the BPS tools is by introducing a middleware. A scripting tool can act both as middleware while it can enhance modeling prospects by integrating parametric variables into the model. In the past few years scripting tools have become more common amongst engineers and architects. Even though scripting tools (e.g. Grasshopper (Robert McNeel & Associates 2013a), GenerativeComponents (Bentley 2013), Dynamo (Autodesk 2013a) and Design Script (Autodesk 2014)) are used very differently by architects and engineers, the ecosystem of parametric tools and scripting environments are gradually changing the way architects and engineers cooperate. Toth *et al.* (2011) were the first to suggest the combined use of scripting tools and BPS tools in a collaborative environment. With the aid of a plug-in structure to link a design tool e.g. Rhino (Robert McNeel & Associates 2013b) or Revit (Autodesk 2013c) with a BPS tool it is possible for the building designer to maintain control of the geometric properties of a model and the BPS in the same unified modeling environment. Yet again the quality assurances mentioned by Hensen (2004) are still missing when using these parametric building performance simulation models.

Three major challenges in using BPS in building design are identified:

1) Building designers are rarely experts in building performance evaluations.
2) Expert knowledge in building performance is rarely part of the early design stages.
3) Integrated design methods in the early design stages are a rare phenomenon.

Introducing Consequence Based Design

Consequence Based Design is an interdisciplinary dynamic framework for improving building performance [2] in the early design stage. The framework can support any type of analytical performance metric and is able to provide consequence feedback of design changes to a building designer in any stage of the design process. This article focuses on the use of consequence based design as a framework to improve building energy and indoor environment in the early design stage.

Consequence based design provides visual building performance simulation feedback in the building designer's native design tool (CAD) while maintaining the validity and accountability provided by a simulationist. The framework is defined by the use of three categories of tools operated by three categories of operators, together creating and employing an integrated dynamic model: 1) Design tool 2) VPL (visual programming language / scripting tool) and 3) BPS environment (Negendahl 2013).

Each of these tools is operated by a specialist, hence introducing a new role distribution challenging the classic separation of the architect and the engineer. This new role distribution is based on personal expertise rather than disciplinary background, focusing on three subjects 1) building (model) design 2) building model parameterization 3) building model analysis as shown in figure 1.

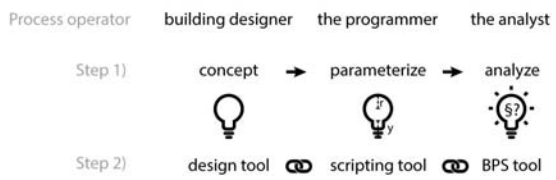


Figure 1. Consequence Based Design Framework. Step 1 – Creating and Defining an Integrated Dynamic Model. Step 2 – Operating the Integrated Dynamic Model.

The design process is defined by two steps: step 1 is defined by the creation and definition of an integrated dynamic model and step 2 is the operation of the integrated dynamic model. Step 1 is about forming the scope of the design while step 2 is about the exploration of the design.

Integration and Collaboration in the Early Design Stages

Integrated dynamic models can be operated by anyone (see figure 2), which is why such model can accommodate the building designer alone as characterized by the simplified standalone BPS tools such as Vasari (Autodesk 2013d) and Ecotect (Autodesk 2013b). The real difference from these standalone tools is the option to operate the integrated dynamic model in a collaborative and highly custom environment, of the simple reason that the tools defining an integrated dynamic model remain separated. Additionally, the ability for the user to customize the design environment to fit the special needs of the particular operators, is an exclusive characteristic of the integrated dynamic model (Negendahl 2013).

[2] Building performance is in this article refereeing to calculable, measurable performances such as energy consumption, temperature, cost, etc.

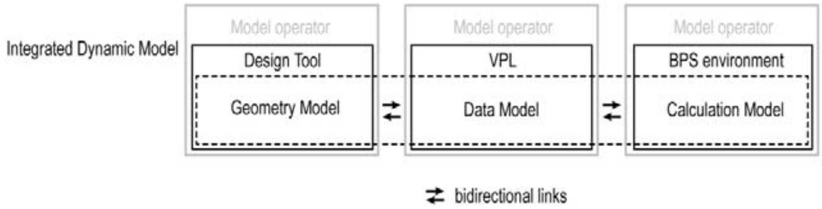


Figure 2. Integrated Dynamic Model: A Combination of: 1) Design Tool 2) VPL (Visual Programming Language – Scripting Tool) and 3) BPS Environment

The process of creating and using an integrated dynamic model is somewhat similar to the integrated design process as described by Löhnert *et al.* (2003) and utilized by e.g. Petersen (2011). The method detaches itself from the traditional integrated design process by being able to support changing criteria and multiple parallel concepts, using advanced parametrical operations and is defined by the integration of runtime linked BPS tools. When the model is created the method allows the building designer to work intuitively and uninterrupted with building performance feedbacks. The framework embraces the supremacy of "computer intellect" in terms of calculation, data analysis, and information retrieval while acknowledging the superiority of human intelligence when it comes to strategy of designing high performance buildings. The integrated dynamic model is introducing a whole new level of disciplinary independence that may open up for new creative solutions and more focus on the analytical part of design exploration.

In contrast to other goal seeking methods based on integrated design processes, the framework of consequence based design supports the experimenting nature of architecture in the early design stages and is highly adaptable in terms of BPS tools, consequence feedbacks as well as performance representation forms. The framework describes a data driven approach rather than a criteria driven approach, meaning the method is applicable outside the realms of structured design teams and role definitions often required in integrated design.

The framework of consequence based design is developed to improve the support of performance expertise in the early design stage by acknowledging the simple train of thought; conflicts between people in the early design stages lead to poor interdisciplinary collaboration, poor collaboration results in poorly designed buildings. When conflicts arises around the matter of who is in control and who is the decision maker when determining and crafting buildings, a design team is ineffective, since the conflicts may very well rise between the parties in the design team.

If a team of experts is to design high performance buildings in a collaborative environment, such an environment must be very attentive to cultural, ideological and basic human differences. Consequence based design is dealing with this delicate matter by utilizing the model as a medium to distribute knowledge.

The idea is to define custom integrated dynamic models aimed for the building designer, thus maintaining the building designer as the lead operator role in the early design stage. The model is created with the intent of experimentation. And as a fundamental part of an integrated dynamic model is the presence of parametric objects and variables. The consequence feedback from the linked BPS tool(s) is translated into direct visual input within the design tool, thus providing valid results in an integrated environment.

The consequence based design framework seeks to address the lack of operator expertise by defining a division of operator-to-tool solution, thus shifting the avertable interaction between people to an interaction through models. Bear in mind that when the model is created, the BPS tool is linked to the design tool through a scripting tool. This combination of tools gives the simulationist the option to define the necessary input requirements of a building performance simulation. Thus, in this framework embedded expertise (Kilian 2006) arises. Following embedded expertise, the building designer is less dependent on operator-to-operator interaction. This expands the autonomy of the designer, which many architects' request (Banke 2013; Hermund 2012). It is likely that an adequate amount of embedded expertise, when provided by a combination of a geometric model and results from a calculation model will deliver sufficient knowledge to make up for the lack of knowledge held by the practitioner. However, embedded expertise when provided from a computer simulation does not necessarily ensure sufficient analytical experience of the practitioner (Negendahl 2013). For this reason, the framework of consequence based design is sustaining the analytical responsibility with the simulationist. The role of the simulationist is to become all the things the simulation tool cannot be. By using integrated dynamic models the simulationist is able to automate rules of input variables, requirements of systems and even decision sequences, thus making the job of the simulationist less focused on performance simulations and more on performance analysis.

The Dynamics of the Design Process

Shaviv *et al*. (1992) described an ideal transition from heuristic knowledge into the use of various procedural precise calculation models (see the upper part of figure 3). The argument is that some BPS models are more suitable than others in supporting the building designer in the various decompositions of the design stages. This means that to better support the designer, the BPS tool has to follow the information level throughout the dynamics of the design process. While various standalone BPS tools can effectively be used to calculate the impact of design changes throughout the early design process, the very fact that multiple models have to be built in multiple environments may be a problem for the designer. Also the requirement of multiple tools further reduces performance quality assurances as mentioned by Hensen (2004). An integrated dynamic model support BPS tools at any scale and any information level, and the framework of consequence based design follows the idea of using procedural precise BPS tools throughout the design process. Figure 3 shows the use of various types of integrated dynamic models, where the linked BPS tools are replaced as the design decisions becomes more stable and more data has been collected. The figure also depicts the shifting control level of the integrated dynamic model. Every time a new type of analysis is required, the model must accommodate new input, new variables and parametric definitions. The model control peak points of the programmer are defined by the new implementation of parametric relationships and changes in the code. The model control spikes with the analyst are representing the necessary implementation of requirements to perform meaningful simulations with of the changing model. To make sure the new model works as intended, the building designer, the programmer and the analyst must collaborate. In figure 3, the peak points of collaboration at the model level can be seen when the three operators level of model control overlap. Ideally, collaboration between the programmer and analyst is initiated before a new model is taken into use by the building designer. In this way, many BPS tool specific requirements can be integrated before the model requirements and terms of experimentation from the building designer is implemented, leaving more time to implement the building designer's specific requests of the model. The collaboration between the programmer and the building designer is required to provide sufficient variability in the parametric definitions. Since the analytic knowledge (embedded expertise) of performance is distributed through and by the model, the contact between the building designer and the analyst is fully confined to the model. However, collaboration in the human interaction domain will always be beneficial for the process.

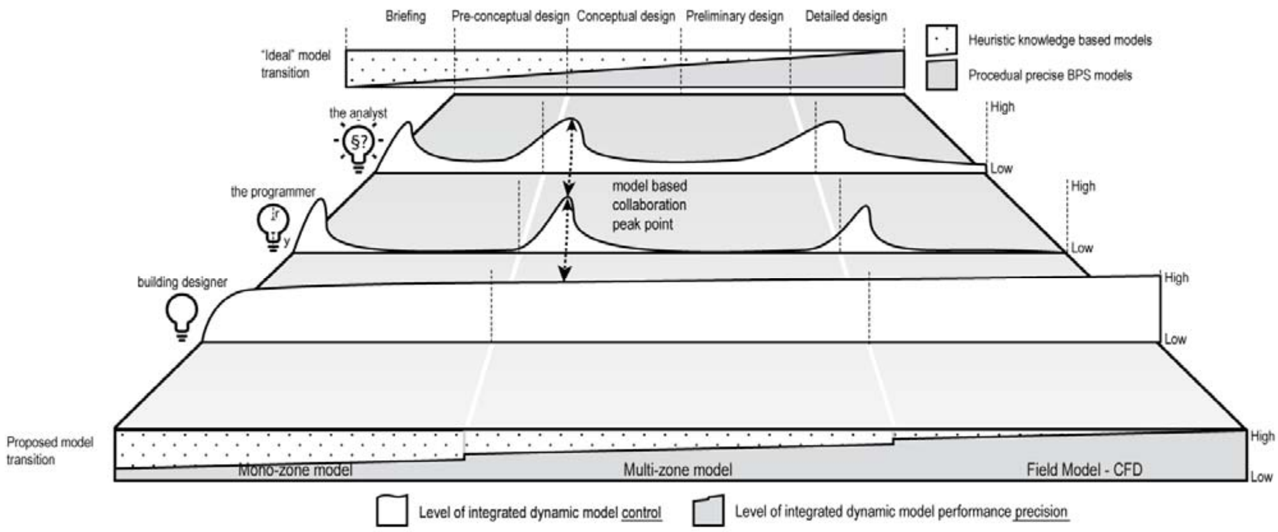


Figure 3. Consequence Based Design Framework. Integrated dynamic models are used throughout the design process and benefit from procedural precise calculation models, as described by Shaviv *et al.* (1992), here illustrated with three different types of runtime linked BPS tools. When transiting from one BPS tool to another, model control collaboration between the operators is required. These can be seen as model based collaboration points.

Compared to the integrated design methodology, the consequence based design framework only requires few peak points of collaborational interaction between the operators. The process of integrated design is often associated with parallel operators and team decision making in continuous iteration loops. The consequence based design framework does not require continuous human interaction. Once the integrated dynamic model is created, the programmer will only assist in using and modifying the model and the analyst will only monitor and provide feedback of the issues the model itself cannot handle, while the building designer has the actual model control. As seen in figure 3, the building designer remains in control of the model throughout the entire process. Even if fairly advanced simulation tools such as CFD are used, the building designer will never notice the difference in analysis complexity. The analyst remains in charge of providing valid input variables as well as managing important performance results back to the design tool. As Kaley *et al.* (via Shaviv *et al.* 1992) advocated with their procedural precise models, it is suggested to use simple mono-zone models in the earliest stages, transit into multi-zone-models and in the end, when assumptions are unnecessary, field models can be initiated.

The true value of using the consequence based design framework over the integrated design framework is the acknowledgement that building performance consists of more than a result from a BPS tool. The consequence based design handles unquantifiable parameters and objectives which are equally important as of those that are measurable and calculated. Consequence based design is about being aware of the consequences of design choices, since performance feedback is only one of many consequences the building designer should react upon. By integrating the performance feedback into the design tool, the designer has both the visual feedback of the geometry and the performance in the same place, thus aligning performance with composition, layout, aesthetics, social impact and many other unquantifiable characters of a building.

Discussion

Daniel *et al.* (2011) observed that if parametric modelling is to become central to the design process, then it will be necessary to deal with complexity and particularly in a collaborative environment. With the introduction of the operator, the programmer is removing the accountability of a coding-skilled building designer. However, a skilled building designer may very well take the role as the programmer, thus advancing the parametric possibilities of the framework even further.

The real challenge in using the integrated dynamic models in integrated environments is how criteria and goal specification are understood by the design team. The way the team collectively handles the few collaboration points throughout design process (as seen in figure 3) is crucial to how well the integrated dynamic model is integrated into the design.

Undefined, inaccurately followed and misinterpreted performance requirements can in the worst case lead to a poorly performing building design. For this reason, when building performance is an important aspect of the building design, clear performance objectives are required. Following that statement, every requirement must be acknowledged by all operators of the model.

Bachman (2004) described his concern of the role as a building designer compromised by integration; if building designers still wish to control their design as a whole instead of purely becoming professional specifiers, the integration of requirements must be handled with care. Integration can be a dangerously all-inclusive term. Once the idea of integration is announced, any conversation on how to attain it can easily become unduly elaborate and all-encompassing. The problem is one of scope. Integration is about bringing all of the building components together in a sympathetic way and emphasizing the synergy of the parts without compromising the integrity of the pieces (Bachman 2004).

In this respect, the idea of consequence based design is simply emphasizing the consequences of design choices in terms of particular performance metrics. The integration is not about people, nor about requirements, but about knowledge and information. Performance feedback from an integrated dynamic model is itself a valuable piece of information that the building designer can chose to act upon. While the desire of the building designer in conforming to certain (performance) requirements is not explicitly necessary, the framework of consequence based design is defined by visualizing (or by other means provide) the performance consequences from the designer’s own choices. In this way, the building designer needs to behave towards the responsibilities following choices he or she makes.

Such behavior can lead to many interesting directions. The first reaction of the building designer may be experimentation of design solutions based on his or her intuition of performance. The intuition is then challenged by the hard data of the performance feedback. This process can change the perception and intuition of non-simulationists to require better understanding of the buildings they design. In this way consequence based design is a very un-intrusive framework to support performance based design, however it will never guarantee better building performance. Only the building designer's reactions to the consequences of their design choices can lead to better performing buildings.

Another use of the framework is the building designer acting as a problem solver. The problem solver will seek to minimize energy consumption, improve indoor environment, or whatever the scope is in terms of the provided performance feedback. In such cases, the quality of the integrated dynamic model is the only limiting factor to what extent the building performance can be optimized.

Consequence based design is defined by the explicit use of integrated dynamic models. This means that the BPS tool can cover any simulation tool, which may be runtime coupled with a scripting tool thus introducing multidisciplinary collaboration and true awareness of subjects which require expert knowledge, e.g. structural performance, life cycle cost, environmental and social impact. In any of these cases, a coordinated goal specification between the analyst and the building designer can lead to high performance buildings. This is, of course, optional, but the framework supports a much more objective focused design method if the team wishes so. With clear objectives, advanced automation features such as multi criteria optimization, shape grammar and agent based assistants can be incorporated into the integrated dynamic model without great difficulties (Negendahl 2013). The middleware, the scripting tool, is the sole reason for an easy model transition with these options. However, in such situations, the term “optimization” has to be redefined to accommodate the enhancement of both the quantifiable and the quality defined objectives which is yet to be resolved.

Conclusion

In the pursuit of improving building performance, the way experts from the various disciplines in the AEC industry are collaborating is redefined by the framework of consequence based design. While building designers rarely are experts in building performance evaluations, the parametric framework of consequence based design puts the building designer in charge of one or more BPS tools. Only through an integrated dynamic model is the validity and required expert knowledge present without continuous attendance of a simulationist. This gives the building designer a new level of freedom and autonomy to experiment with the building design, while relying on valid performance feedback. The framework gives the simulationist more time to analyze results and support the building designer in ways a BPS tool cannot, meaning the quality and depth of the building performance analysis can be greatly improved. Tedious tasks of reminding the building designer to adjust window-wall-ratios and using sufficient insulation are no longer necessary. However, with the actual presence of a simulationist acting as an expert analyst, knowledge in building performance has become a central part of the early design stages.

While consequence based design detaches itself from many procedural ideas in the integrated design process, the framework of consequence based design is capable of delivering the same end goals as described in IEA task 23 (Löhnert *et al.* 2003). However, consequence based design is not explicitly distinct by improving energy performance and indoor environment, since any simulated performance metric by a can be used. Treating quality defined and quantifiable objectives as equal is what makes consequence based design a framework superior in the integration of disciplinary expertise in the early design stage.

References

Autodesk (2013a) Dynamo. Retrieved from http://wikihelp.autodesk.com/Vasari/enu/Community/Work_in_Progress/Dynamo_for_Vasari

Autodesk (2013b) Ecotect. Autodesk. Retrieved from http://usa.autodesk.com/ecotect-analysis/

Autodesk (2013c) Revit. Autodesk. Retrieved from http://www.autodesk.dk/revit

Autodesk (2013d) Vasari. Autodesk.

Autodesk (2014) Design Script. Retrieved from http://designscript.ning.com/

Bachman, L. (2004) *Integrated buildings: the systems basis of architecture*. John Wiley & Sons, Inc., Hoboken, New Jersey.

Bambardekar, S., & Poerschke, U. (2009) The architect as performer of energy simulation in the early design stage. In *Proceedings of the 11 th International IBPSA Conference.* Glasgow, Scotland, pp. 1306–1313.

Banke, T. (2013) *Parametri i praksis - Generativ performance i arkitektur*. Det Kongelige Danske Kunstakademis Skoler for Arkitektur, Design og Konservering.

Bentley (2013) GenerativeComponents. Bentley. Retrieved from http://www.bentley.com/GetGC

Bleil de Souza, C. (2012) Contrasting paradigms of design thinking: The building thermal simulation tool user vs. the building designer. *Automation in Construction*, 22, 112–122.

Daniel, D., Jane, B., & Mark, B. (2011) Untangling Parametric Schemata: Enhancing Collaboration through Modular Programming. *CAAD Futures 2011*.

De Souza, C. B. (2009) A critical and theoretical analysis of current proposals for integrating building thermal simulation tools into the building design process. *Journal of Building Performance Simulation*, *2*(4), 283–297.

Doelling, M., & Nasrollahi, F. (2012) Building Performance Modeling in Non-Simplified Architectural Design. *Proceedings of the 30th CAAD Curricullum 1*, 97–106.

Hensen, J. L. M. (2004) Towards more effective use of building performance simulation in design. *Proceedings of 7th International Conference on Design & Decision Support Systems In Architure and Urban Planing*, 2–5.

Hermund, A. (2012) *Anvendt 3D modellering og parametrisk formgivning*. *Design*. Det Kongelige Danske Kunstakademis Skoler for Arkitektur, Design og Konservering.

Integrated Environmental Solutions (2013) IESVE. Integrated Environmental Solutions. Retrieved from http://www.iesve.com/

Kilian, A. (2006) *Design Exploration through Bidirectional Modeling of Constraints*. Massachusetts Institute of Technology.

Löhnert, G., Dalkowski, A., & Sutter, W. (2003) Integrated Design Process Task 23 Subtask B Design Process Guidelines.

Negendahl, K. (2013) Building Performance Simulation in the early design stage: An introduction to Integrated Dynamic Models. Submitted to *Automation in Construction*.

Petersen, S. (2011) *Simulation-based support for integrated design of new low-energy office buildings*. Technical University of Denmark.

Robert McNeel & Associates (2013a) Grasshopper3d. Robert McNeel & Associates. Retrieved from http://www.grasshopper3d.com

Robert McNeel & Associates (2013b) Rhino. Robert McNeel & Associates. Retrieved from http://www.rhino3d.com

Shaviv, E., Kalay, Y. E., & Peleg, U. J. (1992) An integrated knowledge-based and procedural system for the design of energy conscious buildings. *Automation in Construction*, 1, 123–141.

Theßeling, F., Schlüter, A., & Leibundgut, H. (2008) Energy and Exergy Performance as Parameters in Architectural Design Sketching -a Case Study. In *eCAADe 26*, pp. 477–482.

Toth, B., Salim, F., Burry, J., Frazer, J., Drogemuller, R., & Burry, M. (2011) Energy-Oriented Design Tools for Collaboration in the Cloud. *International Journal of Architectural Computing*, 09 (04), 339–360.

Designing With Knowledge Through Trans-Disciplinary Experiments

Ellen Kathrine Hansen* and Michael Mullins

ekh@create.aau.dk, mullins@create.aau.dk

Department of Architecture, Design and Media Technology, Aalborg University, Copenhagen, Denmark

Abstract: Taking its point of departure in a series of architectural experiments realized in the period from 2001-2011, this paper approaches the problem area of the development and application of new knowledge through design in a trans-disciplinary environment. This praxis grounded in innovation and design theory demonstrates that research from different traditions can be integrated in the design process using distinct criteria. It is thus possible, in the same process, to work with hypotheses that are tested in parallel on the basis of technical/scientific, social science and art/humanities traditions. It is also demonstrated how a procedural model derived from the trans-disciplinary experiments can be applied to the curriculum of a cross-disciplinary graduate university programme.

Keywords: Trans-disciplinary Design, Innovative Design Process, Design Research, Knowledge Based Design, Architectural Experiments.

Introduction

Designing is a process with many dimensions, where values from diverse fields of aesthetic, technical, theoretical and experienced knowledge must be synthesized in a creative practice. This process aims to create and combine products into buildings that meet the needs of both current and future generations, ideally without using more than it gives back to the environment.

The development of technological knowledge is generally founded on quantitative, measurable values and methods established through linear, evidence-based procedures. In contrast, design of space and atmosphere is primarily a qualitative, creative process that is guided by experience, intuition and open iterative approaches that are difficult or impossible to measure quantitatively. In the practice of architecture, these knowledge domains, cultures and practices are difficult to combine, and commonly lead to misunderstandings between the disciplines. The development of knowledge in technology and design therefore often takes place in isolated environments.

These issues are a central problem in a perspective, where building design is increasingly complex, where collaborations across disciplines and cultures are fundamental to reach national and international strategic targets, where new trans-disciplinary educations are being encouraged, where artistic educations are to be more research-based, and where science has to be related to design and innovation. Furthermore, there is a need to focus on user related aspects of design and holistic qualitative values, that is, in situations where scientific and technical knowledge are mixed with cultural awareness. These contemporary demands create the need to clarify how the domains can share their knowledge in trans-disciplinary processes. These difficulties raise some fundamental questions.

How it is possible to work across professional boundaries and in particular how to combine design and science?

This set of questions has been raised in the three architectural experiments realized by the first author in the period from 2001-2011. The experiments included projects and prototypes encompassing the environments of research, education, industry, technology and practice in the context of designing technical as well as qualitative environmental solutions. These experiments have been used as empirical material in the Ph.D. thesis by the first author "Architectural Experiments – designing with knowledge on light, a multidimensional design element" (Hansen 2013).

The thesis addresses the question of how the tacit knowledge inherent in different discipline domains can be integrated in the design process, how innovation is enhanced thereby and how knowledge gained in the project is made explicit. In a previously published paper (Hansen 2014) the authors developed the theoretical framework around the reflections on practice and employed the procedural model to demonstrate how research traditions can be integrated with explicit design criteria in trans-disciplinary experiments. Developing these themes further, this present paper will give an account of the research background and demonstrate how the procedural model can be employed in a pedagogical application for a graduate program of higher education which synthesises engineering and design.

Design through Practice and Research

"The deliberations of daily life concern in largest measure questions of what to make or to do. Every art and profession is faced with constantly recurring problems of this sort" (Dewey 1925).

The development of knowledge and explanatory theoretical principles, logic and practice in architecture and design are more often than not induced from experience and observed phenomena in the context of the built environment. Principles and tacit knowledge are logically inferred from observations of human patterns and reflections on the results of previous projects. This inductive process generally prevails among architects and designers over deductive experiments applied and tested in a context-free environment, as practised in scientific, clinical and engineering experiments where little or no empirical evidence for a theoretical standpoint may exist. Where these latter methods have been attempted in architecture, such as in evidence-based design methodology, they are often embedded in a knowledge base that lacks an explanatory theory which adequately predicts why some design solutions work and others do not (Stankos & Schwarz 2007). This may be explained by the context-free single-variable nature of deductive hypothesis tests. The practice of architecture demands the resolution of a complex web of problems in arriving at contextually determined design decisions.

The development of a pragmatic theory derived from these conditions has been expressed as the "declarative proposition that such and such an act is the one best calculated to produce the desired issue under the factual conditions ascertained" (Dewey 1925). More particularly, developing theoretical propositions for multi-disciplinary practice implies incorporating proficiencies and judgments acquired through experience, observations and reflection, with the best available external evidence from systematic research; in other words, the combination of the art and science of architecture.

Methods

The Three Experiments

"Any deliberate action undertaken with an end in mind is, in this sense, an experiment…the move is confirmed when it produces what is intended for it and is negated when it does not" (Schön 1987).

Three experiments, incorporating technical knowledge from a diversity of fields amongst engineering provide the empirical material from which a procedural model for interdisciplinary action is developed (figures 1 through 7). These will be briefly described and their principles defined in terms of theoretical models that underlie their procedures.

Experiment 1 (EX1) developed architectural parameters for future PEC cells (Photo Electrochemical solar Cells). Four workshops were held at the Aarhus School of Architecture and the School of Architecture in Copenhagen in close cooperation with PEC Group's Danish Technological Institute. Knowledge of the angular selective PEC solar cells, known as Grätzel Cells, and indoor air quality were integrated into creative exercises to develop future energy generation and climate responsive transparent facade.

Experiment 2 (EX2) developed strategies for valuing existing transparent solar cell components through a three-week workshop with 60 master students at the Aarhus School of Architecture in a series of 1:1 experiments. The components were studied in compositions with light using light-filtering solar cells as multi-functional components to contribute to indoor climate, quality of lighting and at the same time used to produce electricity.

Experiment 3 (EX3) was an experiment to design a smart-home of architectural quality: an energy producing single-family house with good daylight conditions, indoor air quality and high aesthetic value. Working closely with the construction industry (VELFAC and VELUX) and consultants (AART Architects and Esbensen Engineering) qualitative and quantitative criteria were defined, developed and tested across the various disciplines involved in the project.

Figure 1. Three Experiments: Solar Cell Technology; Transparent Solar Cell Components; Energy Producing Smart Home (Hansen 2013)

The three experiments represent scales and stages in the development of the interdisciplinary enquiry, spanning the development of future solar technology, the definition of architectural potential in commercial solar components to the design of an assembly of building components and technologies incorporated into a dwelling. A systematic account defined four main principles used to describe and compare the experiments:

- Vision: A shared vision for the project, which is based on the definition of three criteria.
- Criteria: Three criteria, which represent knowledge in different disciplines, functions and cultures. This knowledge is developed through exercises, models and concepts and compiled in a matrix.
- Construction: The criteria are synthesized through the design and construction of models and mock-ups.
- Evaluation: Designs are evaluated in terms of the applied criteria. (Hansen 2014)

Common to all three experiments is that in each case criteria were formulated which related to specific areas of knowledge. In EX1 these comprised 'technology' (solar cells), 'function' (indoor climate) and 'aesthetics' (transparency). In EX2 the criteria were 'regulating', 'communicating', and 'producing'. In EX3 the criteria were 'energy', 'indoor climate' and 'aesthetics'. In all cases, the criteria suggest solution-oriented approaches commonly employed in different professional domains, with the intention to integrate these qualitative and quantitative aspects of knowledge into creative and innovative designs.

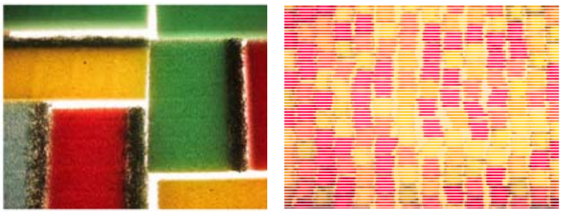


Figure 2. Exercises in EX1 exploring solar cell technology, transparency and light in space. Light is absorbed, transmitted or reflected in transparent solar cells. (Hansen 2013)

Figure 3. Exercises in EX2 exploring how light can create new communicating qualities in transparent solar cell components. (Hansen 2013)

Figure 4. Exercises in EX3, for an energy producing smart home, the cross disciplinary group defined personas and models, digital sketches and luminance animations. (Hansen 2013)

Figure 5. Constructions in EX 1, ice-cube bags and ornamentation imitating red colour pigment in PEC solar cell technology. Illustrates how solar cell technology can affect daylight in the façades and interiors. (Hansen 2013)

Figure 6. Construction exploring the potential of transparent solar cell panels, EX2. (Hansen 2013)

Figure 7. The construction of Energy-producing smart home, EX3. (Hansen 2013)

By comparing the three processes of the experiments, three models for integration and synthesis of knowledge were produced (Hansen, 2013).

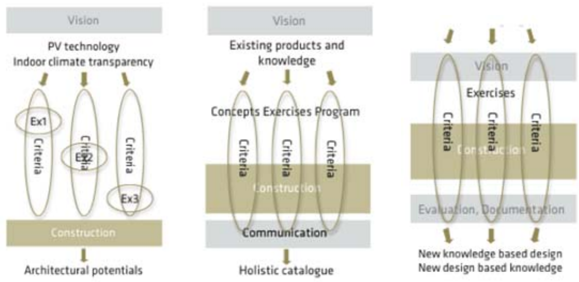


Figure 8. Three models, representing EX1, EX2 and EX3. (Hansen 2014)

The three process models illustrated in figure 8 show how the three criteria are incorporated in different ways. EX1 used the three criteria only in the early design phase, translating knowledge from discipline domains to design elements. Thus, knowledge of 'solar technology', 'indoor air quality' and 'transparency' was incorporated into the creative process of designing a solar cell integrated as an element of a transparent facade that evokes new architectural potentials, translating knowledge from various disciplines and integrating it into the design of future solar cell technology.

In EX2 the criteria were maintained throughout the process. The exercises in the early design phase were concentrated into a single criterion as the purpose of the experiment was to evoke architectural potentials of components already available on the market. The focus was thus on defining qualitative values and integrating these with quantitative values defined by other parties in the project. Participants collaborated across disciplines, but did not design together; in consequence knowledge is not transformed but only translated in the form of a matrix.

EX3 defined a vision within each of the three criteria. The vision was experienced as a source of motivation and commitment from the different parties. Communication across the three criteria had a large degree of influence on the design process, making it possible to evaluate ideas on energy and climate perspectives at all levels of the process. Specialists are part of a team where specific domain knowledge comes into play. This can be characterized as "hybrid design" in which technical, scientific and artistic disciplines linked together in a new way, defined by Meeth (1978) as “trans-disciplinary”, where knowledge is acquired from respective team members in pursuit of a common vision.

The three experiments illustrate a difference in that knowledge in EX1 is tacit, in EX2 it is both tacit and explicit and in EX3 it is largely explicit. This difference is determined by how the criteria are maintained and whether evaluation criteria, hypotheses or research questions can be evaluated.

In EX1 knowledge is communicated through the design, the construction can be seen and discussed, and images are created which demonstrate that the transparent solar cells can influence form and space. With reference to Schön (1987) description of three types of experiments, EX1 can be described as “explorative”; EX2 as “move–testing” where all three criteria representing the discipline domains were applied throughout and disseminated in the form of a matrix; and EX3 as “hypothesis-testing”. In both EX1 and EX2 evaluation takes place in the form of discussions on the basis of presentation and observations of the designed models. However, no research question, hypothesis or a program can be evaluated. In consequence, most of the knowledge developed remains tacit, is difficult to transfer and cannot be generalized.

EX3 can be described in terms of Schön’s definitions as “hypothesis testing”, where knowledge was disseminated and evaluated within the three criteria and the building was actually constructed for use as a dwelling. However, the hypotheses generated are not limited, as Schön (1978) describes them, in terms of science but derive from several research traditions and can thus be evaluated through a variety of qualitative and quantitative methods. The model of Experiment 3 is therefore strongest in its combination of creative and knowledge generating logic and will in the following section be related to the theory of innovative processes and design research in order to test and improve the process of creating explicit knowledge in design.

Innovation and Design Research

Innovation theories developed by authors such as Carlile (2004) emphasize the importance of the people who are the generative source of new knowledge. This human factor is emphasized by applying verbal descriptors to the four steps of the model: ‘transfer’ (here applied to the transfer of knowledge from several disciplines), ‘translate’ (here translated as knowledge through exercises) and ‘transform’ (here transformed as knowledge through construction). Another essential element of innovation theory is the notion of iteration, illustrated in the model by an arrow to indicate the transport of explicit knowledge back to the domains behind the process.

Koskinen *et al.* (2011) illustrate how traditions with different methodological approaches encompassed by design research can be represented by "the lab, the field and the showroom." These three methods are related respectively to technical-scientific, social-scientific and artistic-humanistic research traditions. Koskinen’s purpose is to illustrate how the design practice must understand and accept the differences between these traditions and how they can be combined in the course of a broader research perspective. By relating Koskinen’s methods to the criteria described in the model of EX3, support is provided for the potential of a simultaneous interdisciplinary design process in which different criteria can be evaluated by different research methods.

The observations of the three architectural experiments indicate that there is a potential to improve design methods by making knowledge more explicit. In order to achieve this, it is necessary to reflect on how elements of the scientific tradition, such as the research question, hypothesis testing and analysis can be integrated in the model. Bang *et al.* (2012) discuss this issue and present the concept of the "entrance level". This can be described as the initial stage of design where there is space for conjecture, ideas and assumptions based on past experience, and where the opportunity for creation of new combinations of existing knowledge is greatest. The entrance level concept is used by the model, through work with introductory exercises that develop an overall and shared vision between the disciplines. While research questions and hypotheses as such were not described in the three experiments, the vision described in the model can beneficially be defined as an ‘entrance level’.

Pallasmaa quotes Immanuel Kant as saying: “In knowledge imagination serves the understanding whereas in art understanding serves the imagination” (Pallasmaa 2011). To resolve these very different ways of approaching design problems, the initial research question can rather be defined as "an imaginative research question", that is it begins with the question: “What if we imagine that ...?” This supports the intent of the initial exercises to develop the criteria of the model and can be used to clarify tacit assumptions within each discipline’s criterion. It is then possible to formulate hypotheses or predictive statements within each of the various criteria, all of which are derived from a common vision. These statements can subsequently be tested independently by methods of the different research domains and the findings gained can be expressed as explicit and transferable knowledge.

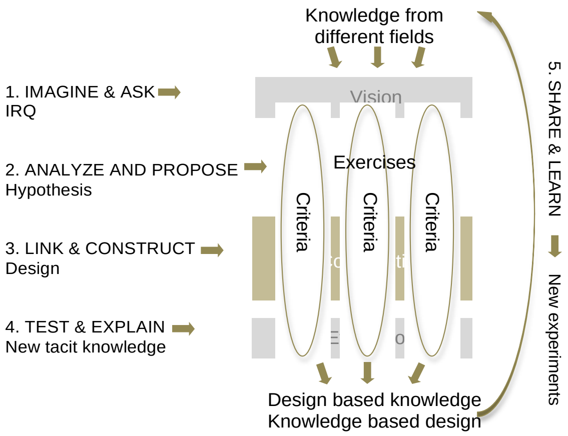


Figure 9. Model for the Trans-Disciplinary Experiment (Hansen 2014)

Analyses

The procedural model for the trans-disciplinary experiment (figure 9) summarizes the observations made from empirical data gained from three separate experiments of an interdisciplinary nature. Building on theories of innovation and design, the model attempts to resolve the question first formulated of how knowledge of different disciplines can be thoroughly integrated in the design process, create innovative solutions and generate new explicit knowledge.

The model comprises five steps where different criteria or discipline-related goals are transferred, translated, transformed, tested and shared as researched-based knowledge. The respective steps and approaches associated with the different discipline domains are defined as exemplified here in the context of team-based projects for lighting design in the built environment.

- Step 1 IMAGINE AND ASK (‘transfer’)
  Knowledge from different disciplines can be included in the early design phase, “the entrance level", where a common vision meaningful to all parties is created. This step cuts across knowledge boundaries and its output is ‘the imaginative research question’, which expresses a common commitment to create value through the experiment.
- Step 2 EXPLORE AND PROPOSE (‘translate’)
  The unfolding of the research question is defined by criteria that represent knowledge in the domains of the participating teams. The output is a formulation of an explicit statement or hypothesis within each criterion particular to a discipline domain, and which attempts to pose a solution or answer to the ‘imaginative research question’.
- Step 3 LINK AND CONSTRUCT (‘transform’)
  The three criteria are resolved into preliminary design solutions, each representing the input from discipline domains. The criteria are explored and translated in a common language of models, sketches, photographs, diagrams, concepts and matrices.
- Step 4 TEST AND EXPLAIN (‘evaluate’)
  Preliminary designs are tested in terms of the statements or hypotheses within each of the criteria which generated it, through methods specific to the diverse research traditions. The results of the hypotheses tests are combined and assessed in terms of how criteria individually and collectively answer the "imaginative research question”.
- Step 5 SHARE AND LEARN (‘communicate’)
  Knowledge is shared and iterated with the intention of obtaining a holistic solution to the issues at hand. Explicit knowledge is spread into the specialized networks behind the project partners, and communicated externally to users, practitioners and academics. (Hansen 2014)

Pedagogical Application

The models drawn from empirical material gathered by the experiments and theoretical explorations described in this paper provide a framework for a new pedagogical curriculum for lighting design (figure 10). The graduate program is designed to fulfil a documented need in society for trans-disciplinary lighting designers (*Behov for lysuddannelse i Danmark* 2012). The training comprises a full-time interdisciplinary, research-based program that combines natural and artificial lighting knowledge within the subjects of media technology, engineering and architecture. In addition to aesthetic values, the aim is to produce graduates with academic, technical as well as process-related skills in virtual and physical light. The students are given an understanding of the interaction between light, its context of the built environment, light technologies, digital media, human factors and design methods. The educational program is structured such that the students develop their skills in synthesizing knowledge from the program's three disciplines through immersion in team-based problem solving within the context of real-world project experiments, and which have tangible results.

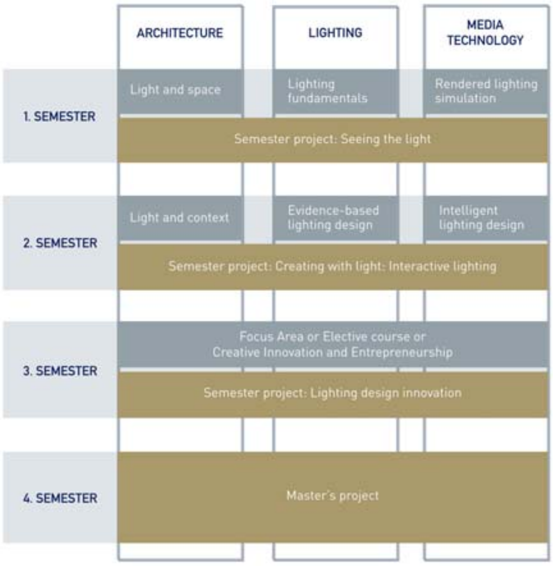


Figure 10. The curriculum of the MSc in Lighting Design, synthesising the three academic disciplines, light, architecture and media technology in the problem based project work. (Hansen 2014)

These intentions give rise to diversity among the backgrounds of students as well as among academic researchers, teachers and representatives from the lighting industry associated with the program. Undergraduates who have been accepted for admission to the graduate program come from previous studies such as architecture, industrial design, architectural engineering, natural science, electronic engineering and civil engineering, among others. This situation of widely disparate knowledge domains can be termed multi-level learning competencies, where for some students design knowledge may be strong and technical skills weak and vice-versa. The challenge for educators is to integrate divergent threads from these knowledge spaces into a coherent whole – the lighting designer.

This tri-disciplinary approach is layered with the three criteria developed by the model through architectural experimentation. The curriculum is then built around three 'academic pillars'. Knowledge within each subject is taught through various courses by the professional disciplines themselves, while this knowledge is synthesised in the process of semester projects based on "Problem based learning": idea generation, problem analysis, problem solving, design, and implementing solutions.

Idea generation relates to Step 1 in the Model, "Imagine and ask" and definition of the IRQ. The Problem analysis relates to Step 2, the translation "Explore and propose" of hypotheses through analysis exercises. Problem solving relates to Step 3, transformation, "Link and construct"; Implementation relates to Step 4 of "test and explain". An essential point in innovation is to return this new knowledge to the different discipline areas. This is what occurs in Step 5, where the knowledge is shared among the disciplines and thereby can feed into new experiments. This step can create a new understanding of how the knowledge achieved through the courses is transformed by the students in the experiment and generates new explicit knowledge. The model demonstrates how this new knowledge can feed back, in this case, into the three academic "pillars" at the university, architecture, light and media technology.

Learning needs and multi-level entry competencies may thereby co-exist within one curriculum and focus on the transformation of knowledge across boundaries in an innovative design process.

Problem-based, project-oriented learning is thus combined with the trans-disciplinary process represented by the procedural model for the trans-disciplinary experiment.

Conclusion

The paper discusses the need for an integration of scientific, technical and creative approaches in trans-disciplinary design and presents empirical experiments, theory, methods and applications toward fulfilling this need.

A procedural model developed on this foundation shows how distinct qualitative and quantitative criteria in different disciplinary traditions can be integrated successfully, despite disparate technical/scientific, social scientific and art/humanities backgrounds. The model may be applied as a pedagogical application in the context of multi-level learning competencies as when designing at engineering educations.

References

Bang, A. L., Krogh, P., Ludvigsen, M., & Markussen, T. (2012) The role of hypothesis in constructive design research. *The Art of Research IV.*

Behov for lysuddannelse i Danmark. (2012) Copenhagen: Dansk lys innovationsnetværk, Dansk Center for Lys.

Carlile, P. R. (2004) Transferring, translating, and transforming: An integrative framework for managing knowledge across boundaries. *Organization Science*, 15(5), 555-568.

Dewey, J. (1925) Logic: The theory of inquiry (1938). *The Later Works, 1953*, 1-549.

Hansen, E. K. (2013) *ARKITEKTOISKE EKSPERIMENTER design med viden om lys, et multidimenstionalt design element.* (Ph.D. thesis, Aalborg University).

Hansen, E. K., Mullins, M. (2014) Lighting Design: Toward a synthesis of sience, media technology and architecture, eCAADe 2014 *Fusion*, Volume 2, 613-620. Northumbria University, Newcastle.

Koskinen, I., Zimmerman, J., Binder, T., Redstrom, J., & Wensveen, S. (2011) *Design research through practice: From the lab, field, and showroom.* Elsevier.

Meeth, L. R. (1978) Interdisciplinary studies: A matter of definition. *Change: The Magazine of Higher Learning*, 10(7), 10-10.

Pallasmaa, J. (2011) *The embodied image: Imagination and imagery in architecture.* John Wiley & Sons.

Schön, D. A. (1987) *Educating the reflective practitioner.* Jossey-Bass San Francisco.

Stankos, M., & Schwarz, B. (2007) Evidence-based design in healthcare: A theoretical dilemma. *Interdisciplinary Design and Research E-Journal*, 1(1).

Method for Integrating Simulation-Based Support in the Building Design Process

Steffen Petersen*, Jacob Bryder, Kristian Levinsen, Jon Strunge
stp@eng.au.dk, j.bryder@gmail.com, kristian.levinsen1@gmail.com, jonstrunge@gmail.com
Department of Engineering, Aarhus University, Denmark

Abstract: This paper presents a proposal for a method to incorporate simulation-based support in the early stages of building design. The aim is to develop a method that can be applied without any drastic interference or modification of prevailing architectural design processes. The simulation-based support consists of results from fast and reliable indoor climate, daylight and energy performance prediction of a design proposal. The performance prediction is embedded in a software platform which is already widely used in the architectural sketching phase. Besides the immediate performance prediction, the method will also provide design advice to improve indoor climate, daylight and energy performance. The paper also presents the outcome from interviews of representatives from five reputable Danish architecture companies. The aim of the interviews was 1) to investigate the state-of-the-art in the use of building simulation tools and collaboration between architects and engineers in the early design stage, and 2) whether the proposed method is desirable for architects. The outcome from the interviews is used to target the further development of the method.

Keywords: Design Method, Building Simulation, Parametric Design, Indoor Climate, Low-energy Buildings.

Introduction

Building designers should strive to design buildings that fulfil user expectations with regard to the quality of the indoor climate and environment. Furthermore, designers must also make designs that contribute to a sustainable development. In the European Union, this especially means that compliance with an increasing regulatory pressure (EPBD 2010) on the building industry to produce low-energy buildings becomes decisive for design decisions in the building design process.

The fact that early design decisions have greater impact than later decisions is widely accepted and even considered ‘self-explanatory’ (Struck and Hensen 2007). Designers therefore need to know how potential design decisions would affect the quality of the indoor climate and environment as well as energy performance before making any actual design decisions in the early design stages. This requires the management of a large amount of information on the detailed properties of design options and the simulation of their performance. Computer-based building simulation tools are ideal for this and, consequently, there is an increasing interest in the use of building simulation tools to generate decision support in the early design phases. Early research on this like Robinson (1996) argues that easy-to-use tools with comprehensible interfaces are of crucial importance if simulation tools are to be adopted in the design process. This is supported by de Wilde *et al.* (2001) who also argue for the development of procedures in the building design process in which the use of building simulation tools can be embedded. Current research aimed at enhancing the use of building simulation tools in the early stages of building design agrees with these findings. New and existing tools with facilitating interfaces and support for analysis of performance data are often presented in combination with proposals for procedures and methodologies to integrate their use in the building design process, e.g. Soebarto and Williamson (2001), Morbitzer (2003), de Wilde (2004), Ochoa and Capeluto (2009), Petersen and Svendsen (2010), to cite but a few. However, there is no firm knowledge on whether any of these approaches are actually adopted by designers or design teams in real building design projects. The notion is that it is rare. A reason might be that current proposals for procedures and methodologies are only assumptions of, or they interprets wrong, what architects actually need (de Souza 2011). This is why we in this paper are reporting on an interview-based qualitative study where representatives from five reputable architecture companies in Denmark were asked to give their opinion on a proposed method to incorporate simulation-based design support in the building design process. The aim is to investigate implications that may hinder a more widespread use of performance simulation in the early stages of the building design process. This knowledge is valuable to target the development of methods and tools useful to architects.

Method

Building Simulation Tools for the Early Design Phase

In this section, recent studies regarding the use of building simulation tools in the early design phase is reviewed to identify what architects consider to be important traits for building simulation tools if they are to be used in the early design phase. The purpose is to form a basic argumentation for dispositions in our proposal for a method to incorporate a tool for simulation-based support in the building design process.

de Souza (2011) finds that when design proposals are investigated, architects want information about how their moves affect the overall thermal performance, and thus expect simulation inputs and output to be coherent with this. The meaning of performance results should somehow to be connected with the form. Time graphs and temperature tables are meaningless for architects to use, and should instead be linked as consequences of the building manipulation.

Attia (2011) finds that informative support and instant feedback is important. This informative support should include geometry rather than just constructions and systems. The information and suggestions should be based on performance evaluation of the previous iteration to develop and improve a design concept.

Lehrer and Vasudev (2010) find that architects are interested in using simulations for generating general performance data which is visualised in a way which provide a quick overview to inform the design.

Attia (2010) finds that architects believe that the most important trait for a simulation tool is intelligence, i.e. the opportunity to inform the decision making rather than being just evaluative. Other criteria were (in prioritised order) usability, interoperability and accuracy. Architects furthermore valued (in prioritised order) the ability to compare multiple alternatives, graphical output, exploration of alternatives, easy change of input parameters, user friendly HVAC templates and error checking to ensure models are correct.

Petersen (2011) used a building simulation tool specially developed to inform design decisions in the early design phase in three different building design projects. The experience was that there were differences in the extent to which the design support was allowed to influence the design. This was mainly due to different attitude towards the idea of multidisciplinary collaboration in the early stages of design and whether considerations regarding indoor climate and energy use were considered relevant at this stage.

Koch and Hauberg (2011a, 2011b) investigate the practical use of integrated design process models in two different design competition projects. All teams used energy calculation tools to inform decisions. They found that there was a lack of tools and procedures to support interaction between architects and engineers evidenced by statements from participants, predominantly architects, who felt that the use of calculation tools was constraining the interactive process.

According to Banke (2013) the most desired value when using simulation tools is the support of design development and secondly to improve communication with specialists. The most crucial parameters of functionality was speed and to get visual output. To achieve speed in the architectural design process, not only simulation speed but also the operability and flexibility of simulation software influence the time consumed in getting useable outputs.

From the literature it can be learned that architects are interested in using building simulation tools in the early design phase but only if they are conformed to fit their design process. Experiments where the design process has been altered to accommodate the functionality of building simulation tools are rare but the same conclusion applies: building simulation tools that does not “interfere” with the design process needs to be developed if they are to be useful to architects in the early design stage.

Proposal for Method

Based on the literature review, it might seem contradictory to propose a certain method. However, we believe that a methodical context is needed to be able to discuss cross-disciplinary collaboration and the development of useful design support generated by building simulation tools. The main idea of the method is to generate reliable indoor climate, daylight and energy predictions directly in the software platform already used by architects in the sketching phase. Besides the immediate performance prediction, the method should also generate design advice, i.e. suggest means that will improve the indoor climate, daylight and energy performance.

A workflow of the proposed method is shown in figure 1. The method consists of two parallel tracks: an “architect” and an “engineer” track. Different consecutive tasks are executed within these tracks. First, the architect proposes a design in the 3D drawing program Rhino (2014). Next, the geometry is set up as a parametric model in the Grasshopper programming environment (2014). The engineer may help linking the model to the simulation tool and set up simulation parameters. Details on the simulation tool are described in Petersen and Lauridsen (2014).

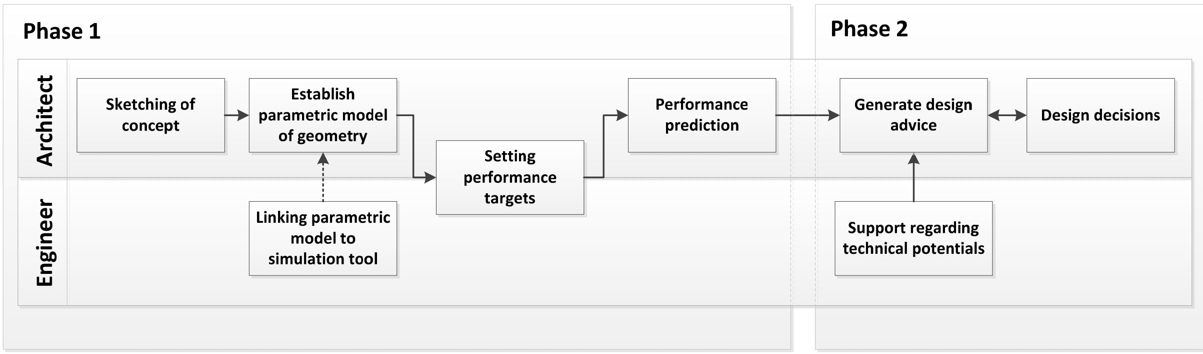


Figure 1. Workflow of the Suggested Method

Performance targets regarding indoor climate, energy and daylight level are then defined; perhaps in a joint workshop. The architect can then make a performance prediction and evaluate the outcome in relation to the performance targets. This is where the typical evaluative use of building simulation tools stops and enigmatically leaves the task of remedying oversteppings of performance targets to the architect. As an alternative, we suggest that the architect continues to phase 2 of the method. Here, the architect decides on a number of design variables (e.g. window size, and orientation) and their boundary conditions (e.g. window height between 1 m and 2.1 m, orientation between 0° and 35°). The simulation tool then automatically generates design advice. The design advice could be the output from a sensitivity analysis of variables or output from an optimization algorithm, e.g. as proposed by Petersen and Lauridsen (2014). An iterative process of design decisions and performance predictions then starts and later ends when a satisfactory design is obtained. In this process, the engineer may support regarding technical aspects of the solution space.

Interviews

Representatives from five reputable Danish architecture companies were interviewed to assess whether design practitioners finds the proposed method compatible to their design process. This is important because the core idea behind the proposed method is to have a platform where use of building simulation tools would have an actual chance of being implemented in the early design phase. The interviews were performed in a semi-structured manner where a number of predefined questions concerning design process and building simulation tools was used to initiate discussions. The data from this type of interviews are qualitative and it allows discussions that might bring up data that would not have been obtained through a more rigorous approach. The interviews started out by asking questions aimed at getting data on their usual process when it comes to collaboration with engineers and considerations about performance. Subsequently, questions regarding the use of performance simulation tools in the early design phase were asked. Finally, the proposed method was presented together with different proposals on how to illustrate the design advice generated in the method (see section “Proposal for method”), and the interviewees were asked to express their immediate opinion.

Results

This section summarises the prevailing answers and main tendencies from the interviews. The authors are in possession of audio files and transcripts of all interviews in their full length.

Collaboration with Engineers and Considerations About Performance

What is the degree of collaboration between architects and engineers in the early design stage?

In competition projects, the architects often take care of the whole project alone. Performance issues, if considered, are treated based on past experience and some rules of thumb. This is, according to the interviewees, because these projects are much more about the design itself, and not so much about the engineering performance indicators (indoor climate, energy performance, etc.). In commissioned projects, where the economy is fixed, the engineers are much more integrated in the process. However, engineers are still primarily contributing with guidance based on experience and rules of thumb.

Have you ever practiced a formal Integrated Design Process?

The interviewees were aware about the existence of the concept of integrated design process (IDP) but they had no or little theoretical knowledge about IDP. They associated IDP with some sort of process where engineering calculations and analysis is used to assess design proposals in the early design phase. The major concern about their notion of IDP was that it may compromise aesthetics and the architecture in general, e.g. if (measurable) performance criteria and architectural (non-measurable) criteria are equal. However, some perceived elements of IDP to be an advantage as the inclusion of the engineers in early design decisions may make it easier to collaborate with the engineers in the detailed design stage: the engineers can vouch for the design and, consequently, fewer corrections have to be made. Another argument for early inclusion of engineering calculations was that it also becomes easier to make arguments for the design directed at the building contractor. IDP is currently not a part of the Danish architectural culture. The interest and willingness to learn more about IDP was present but there is no time available to overcome its steep learning curve. One suggested that IDP could be taught as a part of the basic training programme in architectural studies.

Describe barriers and experiences associated with collaboration with engineers in the early design phase.

A main barrier for cooperation in the early design stage is economy. Handling engineering performance aspects in this phase increases the workload which is not compensated in fees. Another barrier is that some are worried that the early inclusion of engineers in the process is limiting their architectural freedom. The experience is also that the engineer's desire for preciseness and measurability is slowing down the dynamics of the early design phase where changes are made rapidly. There is a general perception that the engineer only wants to make one calculation on the final design rather than making numerous calculations as design advices.

Are architects considering performance issues like daylight levels, indoor climate, energy consumption and HVAC sizing in the early design phase?

Daylight issues are often considered and are mostly taken care of by the architects themselves. A few are also doing some overall building energy analysis. Indoor climate (thermal and air quality) is not considered. However, some points out that there is a risk in letting the architects do the analysis as they are likely to downgrade the issues in favour of the architectural aspects. Technical aspects such as HVAC systems are not considered.

Are architects interested in increasing the focus on these issues in the early design phase?

All are aware that the industry is moving towards a more performance based design culture and the willingness to focus more on the energy and indoor climate issues is present. However, engineers are considered to be too slow when it comes to performance simulations which make the architects highly interested in doing the performance simulations themselves to speed up the overall design process. The main disadvantage of making simulations without the presence of the engineer is that the architects are not trained in setting up models and interpreting results from simulations which can lead to serious mistakes. Another crucial concern in the increased focus on energy and indoor climate is that the architects feel that the softer architectural values are lost in the discussions on the energy and indoor climate performance.

Indoor climate is related to rooms. Are architects willing to design on room level in the early design phase?

The design process starts by considering the overall building geometry. Room level analysis is done at a later stage when the overall building form is established. In general, the architects are not interested in getting information on room level when they are in the creation of the overall building geometry in the early design phase: it is considered irrelevant. Defining model in existing tools is time consuming and requires too detailed information about the design which is not present at this early stage.

The Use of Performance Simulation Tools in the Early Phase

Which building simulation tools are used in the early design phase?

The primary interest is daylight, and especially two programs for the daylight simulations are mentioned: Velux Daylight Visualizer (VELUX 2014) and the DIVA plugin to the Rhino platform (DIVAforRhino 2014). When it comes to tools for evaluating energy consumption of different of different building designs, one company mentions Ecotect (2014), Vasari (2014) and Green Building Studio (2014). The mentioned tools are used by the architect without interaction with the engineer. Some express a concern that the architect lack of proper skills to use the simulation programs correctly.

Are currently available performance simulation tools fit for the design process workflow?

The short answer is no. Several problems are mentioned: poor interfaces, poor interaction between designer and program, output difficult to comprehend, too slow, import/export of data, incapability to handle complex construction geometry, extra time consumption and data loss when moving geometry between different programs.

How should performance simulation results be presented?

The majority of the interviewees expressed that they would like very graphical presentations of performance data instead of showing a lot of numbers, which should only be secondary. This would help architects to decipher data but also make data presentable to clients. One finds that even simple graphs are only for engineers, and that design consequences should be related to building geometry.

Thermal indoor climate seems to be hardest performance issue for architects to comprehend. One interviewee elaborates that he would not know how to act if a thermal diagram showed excessive overheating. Another thinks that standardized indoor climate classes are minded more at engineers. Despite this resignedly attitude, thermal performance is considered a relevant design issue.

Immediate Opinions on the Proposed Method and Proposals on How to Illustrate the Design Advice

The Proposed Method

The feedback regarding the method mainly concerned the simulation tool enabling the generation of performance evaluation and design advice. The most important functional trait was considered to be the relatively fast calculation time (approx. 30 seconds per performance prediction). This was mentioned by many as crucial when it comes to the potential of having building simulation tools properly implemented in the design process. Some do actually even find it to be almost too slow and would like if simulations could be real time even if it means loss of accuracy. Others do care about accuracy and stress the importance of a validated simulation engine.

One of the interviewees was somewhat skeptical towards the chosen platform because it is not a tool used by his company. However, the majority were positive as many of them use this platform already.

A major concern was that the tool operates on room level. The majority feel that this is way too specific and detailed for the early phase and more in the engineer’s field of expertise. However, there are a few that do not consider this a problem but as a new and useful option.

Sensitivity Analysis as Design Guidance

The idea of making sensitivity analysis to inform the design process was in general very positively received. Some of the companies are already doing this primarily with regards to daylight performance. One company also compares energy consumption via Ecotect (2014) or Vasari (2014). Sensitivity analysis is considered a powerful method for processing design proposals. Another stated that he likes the sensitivity analysis because it can help coupling answers to the questions of "what is the performance?" with an explanation of "why is the performance like this?" and "which parameters do I need to work on?".

Optimization as Design Advice

The idea of automatically optimizing a design for the best performance was by some considered an interesting option but primarily for inspiration or guidance. One expressed skepticism concerning that you cannot count on the software to be creative and that there needs to be room for innovation. Another explained that it is important not to dictate a solution but to guide the architects in a good direction and explain the context and why a given solution might be good. A suggestion was that optimization can be used later in the process to optimize e.g. window sizes or orientation. Almost all preferred the sensitivity analysis approach over the optimization approach.

Suggestions for Improvements and Added Functionality

Many suggested that there should be separate simulation tool user interfaces for architects and engineers to ensure that the architect is not confronted with too much (or any) technical information. The architect interface should be quite simple e.g. with drop down selections whereas the engineering interface is completely open and fully adjustable.

One suggested that some sort of check box system could enable designers to easily select which parameters from the sensitivity analysis to include in your next design iteration. Another suggestion was to evaluate data according to the demand for documentation in the Danish DGNB certification system (DGNB 2014). One suggested implementing some sort of function that helps to store knowledge learned in individual projects so it can be transferred and used in the next project. Other suggestions were to have the ability to evaluate solutions with natural ventilation, evaluation of wind pressure on façades, and some sort of area management where you can clearly see the number of square meters for all surface areas.

Discussion

Based on the interview, it seems that architects in general works alone in the early design stage. The architects may ask the engineers to provide some rules of thumb regarding engineering performance issues like daylight level, thermal indoor climate and energy use prior to initiating their mono-disciplinary design process. It is difficult to identify the exact reason why this is, but statements indicating that engineers are “too slow”, “not willing to participate” and “limiting design freedom” are prevailing. A barrier seems to be the engineer’s desire to calculate and measure before taking any decisions. This is often a slow process especially compared to the process of architects which seem to move faster forward because they mainly prefer to operate with design criteria that they consider to be “non-measureable” and therefore can judge by immediate intuition.

It was striking that the indoor climate was not mentioned as a design issue in the early design stage. The understanding was that this can be fixed in the detailed design phase. The lack of interest in indoor climate is a barrier for integrating thermal building simulations in the early design stage as a major functionality of building simulation is to evaluate indoor climate and, consequently, energy performance. Another barrier is that some of the interviewee states that engineering performance always comes in secondly if there is a conflict between architectural and engineering performance issues. If this is the case, then why even bother with building simulation if their information ultimately always will be overruled?

The interviews indicated a certain collaboration crisis between architects and engineers. This crisis was underlined when we presented the tool used in the method: now it seemed that the architects want the knowledge and ability of the engineer packed into a piece of software. This reaction was not surprising taking into account their statements regarding lack of proactivity among some engineers and the lack of suitable tools. However, we are of the view that the use of building simulation tools – simple or advanced – requires specialist knowledge coming from years of training. The design process therefore have to include a certain degree of interpersonal cooperation between experts in architecture (architects) and experts in building simulation (engineers) if building performance simulation is to be integrated as a useful tool in the design process. The collaboration crisis therefore has to be solved. The method proposed in this paper is an attempt to create a platform to vitalise the collaboration between architects and engineers. The method and its tool hopefully enable and motivate engineers to become a more active participant in the dynamic process of early stages of building design while intensifying an interest among architects to integrate considerations regarding engineering performance issues in design decisions made in the early design phase.

Conclusion

This paper reports on a qualitative study based on interviews of representatives from five reputable architecture companies in Denmark. The aim was to investigate implications that may hinder a more widespread use of building performance simulation in the early stages of the building design process. The following main implications are identified:

- Engineering performance issues regarding indoor climate is basically considered irrelevant in relation to form-giving in early design phases.
- A concern that (measurable) engineering performance issues may overrule (non-measurable) architectural design issues.
- Mindset and workflow mismatch between architects and engineers.
- Insufficient and inappropriate simulation tools.
- Limited economy allocated to the early design phase (e.g. in competitions) is a barrier to close collaboration between architects and engineers.

A conceptual idea for a method to generate simulation-based indoor climate, daylight and energy predictions and design advice using a rapid, yet precise, simulation tool was presented and discussed. The immediate feedback from the interviewees mainly aimed at the functional traits of the tool. The rapid simulation time and the fact that simulations could be performed within one of the preferred sketching platforms were considered to be a very important step towards the implementation of building simulations in the early design stage. During discussions it was suggested that future development of the tool should include a simple user interface with few settings but with an opportunity to access detailed settings, and careful consideration about how to present simulation output for intuitive interpretation.

The suggested method for collaboration was given little attention in the discussions. But statements in other parts of the interviews showed that the interviewees had a genuine desire for closer collaboration with engineers in the early design stage. There is a hope that the development of various BIM systems and strategies will generate platforms for communicating design issues in an interdisciplinary collaborative design process. Furthermore, collaborative processes like the integrated design process was suggested to be a discipline taught during the basic training at architectural and engineering schools/ universities.

Acknowledgements

We would like to express our gratitude to the representatives from the architectural companies for their hospitality and willingness to be interviewed.

References

Attia, S. (2010) *Building Performance Simulation Tools: Selection Criteria and User Survey,* Technical report, Université catholique de Louvain, Louvain La Neuve, Belgium.

Attia, S. (2011) *State of the Art of Existing Early Design Simulation Tools for Net Zero Energy Buildings: A Comparison of Ten Tools*, Technical report, Université catholique de Louvain, Louvain La Neuve, Belgium.

Banke, T. (2013) *Parametri i praksis - Generativ performance i arkitektur*, Ph.D. thesis (in Danish), Copenhagen, Denmark, Designskolens Printcenter.

de Souza, C. B. (2011) Contrasting paradigms of design thinking: The building thermal simulation tool user vs. the building designer. *Automation in Construction*, Vol. 22, pp. 112–122

de Wilde, P., Van Der Voorden, M., Brouwer, G., Augenbroe, G., Kaan H. (2001) The Need for Computational Support in Energy-Efficient Design Projects in the Netherlands, *Proceedings of the 7th International Building Performance Simulation Association (IBPSA) Conference*, Rio de Janeiro, Brazil, pp. 513–520.

de Wilde, P. (2004) *Computational support for the selection of energy saving building components*, Ph.D. Thesis, Delft, The Netherlands, Delft University Press.

DGNB (2014), Green Building Counsil Denmark, Denmark, http://www.dk-gbc.dk/

DIVAforRhino (2014) Solemma, US, http://diva4rhino.com/

Ecotect (2014) Autodesk, US, http://www.usa.autodesk.com/ecotect-analysis/

EPBD – Directive 2010/31/EU of the European Parliament and of the Council of 19 December 2010 on the energy consumption of buildings (recast).

Grasshopper (2014) Scott Davidson, US http://www.grasshopper3d.com/

Green building studio (2014) Autodesk, US, https://www.gbs.autodesk.com/GBS/

Koch, C. and Haubjerg, E. L. (2011a) Designing clean, *6th Nordic Conference on Construction Economics and Organisation–Shaping the Construction/Society Nexus Volume 2: Transforming Practices,* Copenhagen, Denmark, pp. 329–340

Koch, C. and Haubjerg, E. L. (2011b) Performing the transistion – integrated design process in climate change mitigation, *Proceedings of the 27th Annual ARCOM Conference,* Bristol, UK, pp. 1155-1164.

Lehrer, D. and Vasudev, J. (2010) Visualizing Information to Improve Building Performance: A Study of Expert Users, *ACEEE Summer Study on Energy Efficiency in Buildings*, pp. 141–515.

Morbitzer, C. (2003) *Towards the Integration of Simulation into the Building Design Process*, Ph.D. thesis, University of Strathclyde, Glasgow, Scotland.

Ochoa, C. E. and Capeluto, I.G. (2009) Advice tool for early design stages of intelligent facades based on energy and visual comfort approach. *Energy and Buildings*, Vol. 41, pp. 480–488.

Petersen, S. and Svendsen, S. (2010) Method and simulation program informed decisions in the early stages of building design. *Energy and Buildings*, Vol. 42, pp. 1113-1119.

Petersen, S. (2011) *Simulation-based support for integrated design of new low-energy office buildings*, Ph.D. thesis, Kgs. Lyngy, Denmark, DTU-Tryk.

Rhinoseros (2014) Robert McNeel & Associates, US, http://www.rhino3d.com/

Robinson, D. (1996) Energy model usage in building design: A qualitative assessment. *Building Services Engineering Research and Technology* vol. 17, pp. 89–95.

Soebarto, V.I. and Williamson, T.J. (2001) Multi-criteria assessment of building performance: theory and implementation. *Building and Environment*, Vol. 36, pp. 681–690.

Struck, C. and Hensen, J. (2007) On supporting design decisions in conceptual design addressing specification uncertainties using performance simulation, *Proceedings of the 10th International Building Performance Simulation Association (IBPSA) Conference*, Beijing, China, pp. 1434–1439.

Vasari (2014) Autodesk, US, http://www.autodeskvasari.com/

VELUX (2014) VELUX Daylight Visualizer, Horsholm, Denmark, http://viz.velux.com/

The Potential of the Technical University of Denmark in the Light of Sustainable Livable Cities

Lotte Bjerregaard Jensen[*1], Per Sieverts Nielsen[2], Susanne Balslev Nielsen[2], Thomas Alexander Sick Nielsen[3], and Peter Steen Mikkelsen[4]
lbj@byg.dtu.dk, pernn@dtu.dk, sbni@dtu.dk, thnie@transport.dtu.dk, psmi@env.dtu.dk
[1] DTU Civil Engineering, [2] DTU Management Engineering, [3] DTU Transport, [4] DTU Environment
Technical University of Denmark

Abstract: The Technical University of Denmark (DTU) has a long tradition for research and education in urban planning and sustainable urban development. An increasing societal focus on sustainability and urbanization in society supports this continuous focus on sustainable urban planning in technical educations. The focus on sustainable urban development includes understanding the role of civil engineering, water engineering, sustainable mobility and energy, and communities in developing future desirable solutions. However, beyond the challenges faced in each of the specific technical fields, there is a growing demand for integrated solutions. A proposal has been developed in the last couple of years to further develop DTU's education in urban development and livable cities with an emphasis on integration and interdependencies in urban engineering. This paper describes core professional design niches which by themselves have an impact on urban development, including water in cities, climate adaptation, mobility planning, building, energy, and community designs. A number of challenges in developing an integrated approach in the technical education are discussed in the paper. The increasing focus on sustainability but also on global urbanization, compact cities, and smart cities supports new thinking in urban planning and design in technical education. The paper suggests a new initiative to further develop the sustainable urban planning research and education at DTU.

Keywords: Sustainability, Livable Cities, Research, Design Education in Civil Engineering, Design Method.

Introduction

Societal challenges of the present are to a large extend contained within the field of urban design. The challenges are numerous and involve climate change and CO_2 reduction issues, which again are linked to health and social stability problem areas. There is a demand to manage this complexity in a systematic design process where very high levels of information concerning all levels are infused from the earliest of design phases.

The mission and strategy of DTU was to answer to this call for a higher information level in urban design processes, from politicians and others with responsibility of design of future urban developments (Technical University of Denmark 2013). An interdisciplinary task force of faculty from different departments was placed in charge of the work. This paper presents the mapping of the different technical scientific fora with relevancy in the urban scale. Important questions concerning interdisciplinary organization were investigated and the committee presented a first attempt on concluding on the specific yet generic question (Nielsen *et al.* 2012).

Task Force Results

Explorative and Consensus Seeking Meetings

Headed by an engineer with a management background and a facilitator, with a communication background, representatives from the main departments participated in a series of meetings initiated by the Deans of DTU. The head of the committee has been employed at DTU for a long period of time and has a background in urban planning (Hoffmann *et al.* 2004), and based on this knowledge she suggested representatives from DTU Environment, DTU Management Engineering, DTU Transport, and DTU Civil Engineering. To some extent this selection involves an undesirable narrowing of the disciplines involved, however a small core group was required in order to facilitate communication and the process. The meetings had a workshop character because the group made a clear decision from the beginning that the end result should have qualities of being operative and realistic ideas for the near future at DTU. The university had previously worked with mapping and outlining other interdisciplinary subject areas such as 'sustainability'. Technical scientific knowledge relevant for informing design processes on an urban scale is a much more narrow perspective. For example, it was relatively clear to observe how much existing relevant research existed within DTU's existing structures.

In order to help define a space of solution the first meeting focused on a SWOT analysis (Strengths, Weaknesses; Opportunities and Threats). The SWOT should define the framework both viewed from within DTU and in a broader context of Society. See figure 1.

Internal view of DTU: strengths	Internal View: weaknesses
▪ DTU: Depth in Technical Scientific competences ▪ DTU Have design competences ▪ DTU: High ranked, research based University ▪	▪ Lack in priority given to coordination and integration of relevant specializations. ▪ No common understanding of and vision for the subject field. ▪ Low level of interdisciplinary culture and skills in the field. ▪ Low levels of holistic understanding in the urban field.
External view of DTU -Opportunities	**External View of DTU -Threats**
▪ A demand in society – exlicit from politicians for innovation, integrated solutions to many new challenges, new standards. ▪ A professionalization is in progress on the municipal level. ▪ Great potention for innvoation, governal support and export.	▪ If Urban planning and design praxis is not based on a high level of knowledge, society risk making the wrong decisions (the post-factual society). ▪ Other academic institutions have strong brands in urban issues. ▪ Large scale international initiatives is currently redefining research and praxis of urban planning and design.

Figure 1. SWOT

The SWOT outlined that DTU's focus on technical scientific knowledge in urban scale issues could reserve a major role for the university because it is an exclusive role in the Danish context. At DTU there exists profound technical scientific knowledge within core urban issue areas. The other major Danish university stakeholders place their focus on social sciences or work within the Arts (design and architecture). However the profound technical scientific knowledge at DTU exists in its own right and the question of informing ongoing design processes with this knowledge has no or low priority. Failing to activate the knowledge present at DTU would pose a risk to society because investments in infrastructure, climate change issues, and new urban developments would not be based on the available knowledge, but only on knowledge at hand for the designers.

The Mapping of Existing DTU Research and Knowledge Areas with Urban Scale Relevancy

At DTU research environments in the departments are independent. In a number of these research environments, aspects of the research have a relevancy in the urban scale. The holistic design of cities as such is not explicitly a research area of any of the departments. Large amounts of knowledge that can be utilized in a design process are available. But some of the knowledge compounds of relevancy are actually just sidekicks to a central research area. In order to begin a more structured integration of this knowledge, a mapping of existing urban scale knowledge at DTU was made by the committee.

DTU Environment - Water and Waste Management

The Department of DTU Environment is experiencing a steep growth in interest concerning their research areas: water and waste management. Climate change, resulting in intensified rainfall and a raising sea level, places this department in the fore of what DTU can offer to future urban design processes.

Much water management research has focused on technical innovation with a range of new solutions developed to achieve a 'more sustainable and integrated urban water management cycle'. However Danish municipalities and utility companies are struggling to bring such solutions into practice. 'Green infrastructure', for example, requires the consideration of a larger range of aspects related to the urban context than the traditional urban water system optimization (Fratini *et al.* 2012).

Integrated urban water models should focus more on addressing the interplay between social/economical and biophysical/technical issues, while its encompassing software should become more user-friendly. Possible future directions include exploring uncertainties and broader participatory modelling. (Bech *et al.* 2014).

To achieve a successful and sustainable adaptation to climate change we need to transform the way we think about change.

DTU Transport

Transport is an important topic for cities across the world as accessibility and mobility are closely linked to urban development, competitiveness and wellbeing and therefore highly wanted. But other aspects of transport are also nuisances: congestion, risk, and reduced quality of life especially in urban areas where densities increase accessibility as well exposures to negative effects (Kristensen *et al*. 2014). Managing transport is therefore critical, but difficult as behavioral choices and responses plays a large role.

DTU's department of transport covers transport from the perspective of transport systems analysis, transport planning, transport optimization, and transport policy. Transport planning is conventionally supported by transport modelling as the main input to assessing and developing the transport system. Transport models developed by the department include spatially detailed in- and outputs partially supporting assessment of effects of future urban development patterns. However, more work is required to develop and exploit this capability in integrated urban and transport planning.

The emphasis in urban transport planning is becoming increasingly interdisciplinary with reference to multiple objectives such as congestion, environment and public health, as well as increasing intermingling of conventional transport planning (networks and fares) with urban design and management – including area renewal and actual 'leverage planning'. Examples include the current emphasis on cycling promotion (Nielsen *et al.* 2013), green transport plans, and high profile public transport infrastructure projects such as light rail and metro lines in Greater Copenhagen. In this widening agenda, the capacity for integration of transport with urban management, urban design, environmental planning – as well as IT and communication requires further emphasis.

DTU Civil Engineering

The design and construction of the buildings and infrastructure that make up the city as such is the topic of civil engineering. However, classic civil engineering is challenged in the present because traditional structures and systems are expected to be part of a larger whole. For instance the operation of buildings is traditionally the area of HVAC engineers. When legislation favors buildings that produce energy, the traditional operational system of a building becomes an integrated part of the energy grid. Another example of the new complexity is how research demonstrates that urban layout determines the later energy consumption of the buildings (Strømann-Andersen 2012).

In order to design low-energy buildings, the building industry has developed very good software that quickly and accurately can simulate daylight, sunlight and the effects on indoor-climate/energy-balance of a building. These tool are slowly been transferred to urban design in order to calculate the energy production potential of a structure and the local climate of an urban space in a planned development.

Taking inspiration from the building industry, urban planners and designers could study the development of highly informed design processes behind zero-energy buildings. In a developing process between engineers/architects and software developers, an array of simulation tools with good interfaces to 3D modelling software has been developed. These tools condense technical scientific knowledge and make it easier to integrate this knowledge in design processes in order to achieve documented levels of sustainability.

For example, computational fluid dynamics was used decades ago as a simulation tool for calculating flow in tubes, etc. but is now so fast and accurate that it can inform an ongoing design process about the flow of wind in a planned urban development.

DTU Management Engineering

DTU Management Engineering contributes actively to the development of decision-making tools, process optimization and an innovative, competitive and sustainable use of technology thereby addressing some of society's grand challenges including sustainable cities. The research especially focuses on the areas of energy and climate, production, cities, health, and food. The department is organized with its own administration and consists of five research divisions: Management Science, Quantitative Sustainability Assessment, Technology and Innovation Management, Systems Analysis and Production and Service Management - and two centers: UNEP Risø Centre and DTU Business.

Seeing real-life decision-making as deliberate choices between identified solutions on an identified problem, engineers often have the role of designing and evaluating the expected costs and benefits of these alternative solutions and to ensure decisions can be made on an informed basis. In the ideal world, all information is available, however the reflective practitioner has to operate and execute decisions in situations with inadequate knowledge. The tendency in management research founding is to set up interdisciplinary teams which can provide decisions makers with both qualitative and quantitative justified decisions. For municipalities, which have sustainable development as their core business (Galamba and Nielsen 2010), there are challenges with inherent dilemmas of increasing complexity and where simplifications includes both ethical and specialist insight (Hoffmann *et al.* 2004).

Mapping of DTU Courses Relevant for the Urban Scale

Research is not the only potential contributor to new urban design processes. Education also plays an important role in pushing the development towards a holistic and design-process-oriented approach. Educational programs can be a tool to make the desired development take place. However the realistic scenario would be to make a patchwork of existing courses and connect them into being a new context for DTU's urban focus.

The task force group made a mapping of university courses that could be stepping stones in the process of outlining applicable technical scientific knowledge to future urban design processes. A few of the courses were actual urban planning courses, but the majority was courses where a small part of the course program contained subjects of importance for an urban scale.

An overview of the courses is given in Appendix 1. Each course has a 5 digit identity code. Those without a course number (XXXXX) are suggested courses, which are currently not in the official course catalogue. The courses are changing and the current version of the DTU courses database is available at www.dtu.dk.

The courses were divided into four categories. The first category consists of courses about technical scientific subjects where a small part has relevance for an urban scale: e.g. courses on building energy, daylight, computational fluid dynamics, wind, lighting, district heating, large scale structural design, soil engineering etc.

The second category consists of courses about urban management with content relevant for a design process: environmental management, integrated water resource management, transport economy, transportation models, risk assessment methods, Planning Theory, introduction to planning, knowledge based entrepreneurship, technology, economics, management and organization , strategy and planning methods, management of change, product development/ conceptualization, environmental economics, and innovation management.

The third category consists of courses with a major part that is relevant for urban design: water supply, sewage systems, waste management and traffic planning.

The fourth category involves design projects and courses on interdisciplinary design methods.

Based on this mapping the committee outlined a new 2 year MSc. Program made from existing courses supplemented by interdisciplinary design projects.

Mapping of Existing Interdisciplinary Cultures within DTU

Research in design methods that can integrate technical scientific knowledge in design processes is taking place in different research environments at DTU but an explicit focus on Urban Planning and Design is not a research area. Interdisciplinary design methods are dealt with on the same level. This ability to assist society in making the informed decisions demands the development of an interdisciplinary approach within the university. It also requires that the high ranked research environments should invest time in making their knowledge accessible to non-engineers in order to make this knowledge operational in a design process.

DTU Management Engineering & Interdisciplinarity

DTU Management Engineering has the role of providing generic research and education that transcends the knowledge ‘silos’ of DTU across the departments. “Cities” is one of the focal areas within the department and can be characterized by three different main approaches with roots in different research groups’ tradition: system analysis at local and societal level; products and service systems (e.g. Quantitative Sustainability Assessment); and the stakeholder perspectives e.g. of a facility owner (PSM). Courses are offered as part of the education on Design and Innovation; the education on Planning, Innovation and Management; and as generic courses which feed into all of DTU’s educations.

DTU Civil Engineering & Interdisciplinarity

UN statistics demonstrated a decade ago that 40% of the energy consumption used in society was for operating buildings. In order to reduce this, highly informed design processes were developed. ‘Integrated Design’ and ‘Integrated Energy Design’ are design methods developed in close collaboration with engineers, software developers and architects. The basic point made is that the major part of a buildings’ energy consumption is determined in the early design decisions (often made by architects). An effort was made to develop software that could simulate indoor climate and energy consumption in the early design phases and was easy to use by a multidisciplinary design team. The lessons from this period were brought into the field of BIM (building information modelling). BIM was a decade ago mainly about having a 3D digital model of a building or infrastructure project that would enable a more efficient detailing and construction phase. Learning from Integrated Energy Design, simple 3D models are now produced in the early design phases and imported and exported in different simulations software, thus gradually informing the design more and more until the final 3D model is used for construction. 3D models and simulation software with good interfaces to the 3D modelling ‘drawing’ programs enable a much closer interdisciplinary work process.

DTU Environment & Interdisciplinarity

The Department of Environmental Engineering ceased to teach any drawing or 3D modelling skills to students and faculty a decade ago. This constitutes an important obstacle in integrating the technical scientific knowledge of the department in the urban design process. Concerning simulations tools, several GIS based tools exist. However they can only depict existing situations and have no interface with common CAD software. In a simulation tool like Mikeflood, new designs can be investigated but all new systems must be designed within the software and no drawings can be exported or imported. Mikeflood is time consuming and thus risks being bypassed in the design process.

DTU Transport & Interdisciplinarity

DTU Transport has a strong position in transport modelling, transport planning, and policy – all topics which are obviously linked to urban planning and multiple other policy areas. Importantly, however, the department has gravitated towards national or large scale issues as well as towards project appraisal. Developing projects/proposals is more weakly positioned in the curriculum and this may make it more difficult to engage in interdisciplinary design. Additionally transport systems issues are often approached at a scale somewhat above a 'usual' design scale (zones) which may also be an obstacle for interdisciplinarity. But as new urban brown field developments like 'Nordhavnen' involve travel behavior objectives, and transport outcomes are affected by urban form, interdisciplinarity should be developed. Simulation tools like Vissim provide a link to the design scale (interface to CAD) and can simulate the flow of cars, bicycles and people as part of a traffic impact assessment. However, they require supplementary evidence/tools depending upon which outcomes are in focus (CO_2, congestion, public health, etc.). Important issues may involve bridging between spatial scales as well as between cultures. Transport planning may be said to be less visual and less confident in its ability to determine the outcome of a specific project compared to e.g. urban design in general.

DTU Educational Programs & Interdisciplinarity

Concerning education, DTU Architectural Engineering and DTU Design & Innovation are study lines focused on the interdisciplinary integration of engineering knowledge in the design processes. DTU Design and Innovation has a bias towards social sciences and small scale products where DTU Architectural Engineering tends towards architectural design and the built environment.

DTU External Partners & Interdisciplinarity

In general, there are strong links between specific DTU departments and external partners concerning interdisciplinarity. Collaboration with industry is common at the course level and is a prerequsist in most, larger research applications where it is common to involve several DTU institutes and external partners.

Apart from the ad hoc environment of specific research projects, the integration of technical scientific knowledge from many different departments into the design processes is the core interest at several "close to practice" initiatives e.g. DTU IPU; Scion DTU; Climatekick, DANVA; ATV to mention a few major players. At DTU Environment there are close links to the Landscape Design Department of the University of Copenhagen.

At DTU Architectural Engineering there are permanent collaborations with the Royal Academy of Fine Arts, School of Architecture and Design concerning research and mutual courses.

Outline of Institutional Features to Enhance the Development Further – The Synthesis

DTU has platforms in IPU, DTU Management Engineering, Design and Innovation, and Architectural Engineering for interdisciplinary design processes. However the interdisciplinarity is not systematically organized and as employees at DTU we experience both visions of integration but also physical, organizational, administrative and economic barriers for further interdisciplinary collaboration.

There seems to be a deficit in the integration between knowledge silos within DTU's departments. DTU departments have separately developed interdisciplinary collaborations with external partners within the urban design field. However this is not coordinated and exposed internally at DTU.

A release of the DTU potential would demand that DTU would be willing to place more interest in design processes, because this is where project decisions are made. DTU is a technical university where focus has always been the actual making of 'things', which should make it possible to bridge the internal 'knowledge silos' and bridge from research out to the ongoing urban design processes. However, the kind of development needed in order to meet the expectations from politicians and society, would demand a huge effort and focus at a strategic level on interdisciplinary urban design process.

Discussion

The initial driving force for the work was the SWOT analysis. It showed the potential of combining different technical scientific disciplines in an interdisciplinary design process together with architects. The potential risk of society making poor investments if the designs are not based on high levels of knowledge also stood out. However the design of cities is so all-encompassing a subject that university leaders and others are challenged by how to set the boundaries and thus settle the funding. In this way 'urban design' is linked to the term 'sustainability' in the sense that it is too large and all-inclusive. However the same was said a decade ago about sustainable buildings and by limiting the focus to indoor climate and energy consumption a major step was taken. In the same sense, a higher information level in the design processes behind urban development could also be achieved by focusing on the tools and methods at hand in narrow areas, and combining those.

DTU is doing exactly as described above by establishing a Water Technology Center hosted by

DTU Environment (starting this year) and a Climate Center next year. They represent looser networks around a dominating single discipline that is not specifically urban design focused. Interdisciplinary design and highly informed modern design methods can develop from this. They have, as a foundation, the same integration between departments.

As with buildings, it is in the early design decisions that will have the largest effect on a city's later performance. The classic dilemma is that researchers are identity challenged, when they are asked to simplify their knowledge into something so fast moving that it can inform an ongoing multidisciplinary design process in the early phases of the process.

Conclusions

The conclusion of the group was to recommend a Centre that should do 3 things:

- Maintain and host a high level of research in interdisciplinary design processes
- Coordinate DTU knowledge and research with relevance at the urban level, and host large interdisciplinary urban scale research projects
- and last but not least, coordinate and host a M.Sc. program in Livable Cities, where the combination of deep technical scientific knowledge and the application of this in design projects should be the topic.

The committee presented the idea for a center of livable cities in December 2013. Unfortunately, DTU could not accommodate the suggestion at that time.

The mapping shows that DTU has a large amount of research and education relevant for urban design. However the efforts are not coordinated and the research is not exposed and communicated to the other departments and the outside world as important to urban design process. Other characteristics include the fact that several of the 'silos' at DTU lack design skills and tools and that while interdisciplinary fora exist at DTU, the work is not focused on urban design.

While a Centre has not been realized as suggested, other initiatives are indicating that DTU is developing to meet the societal challenges also in urban planning, but still from a mono-disciplinary approach.

References

Bach, PM, Rauch, W, Mikkelsen, PS, McCarthy, DT & Deletic, A (2014), A critical review of integrated urban water modelling – Urban drainage and beyond, *Environmental Modelling & Software*, vol 54, pp. 88-107., 10.1016/j.envsoft.2013.12.018.

Fratini, C, Elle, M, Jensen, MB & Mikkelsen, PS (2012) A conceptual framework for addressing complexity and unfolding transition dynamics when developing sustainable adaptation strategies in urban water management. *Water Science and Technology*, vol 66, no. 11, pp. 2393-2401.

Hoffmann, B, Elle, M, Nielsen, SB, Jensen, JO & Hoffmann, B (2004) The Seven Challenges of Sustainable Cities. *COST C8 final conference on Sustainable Urban Infrastructure: approches - solutions - methods*. Temi Editrice, Trento, Italy, pp. 379-387.

Kristensen, NB, Nielsen, TAS, Gudmundsson, H, Meza, MJF, Haustein, S, Møller, M, Christensen, L, Knudsen, MA, Pons Rotger, GA, Grunfelder, J, Mulalic, I, Pilegaard, N, Madsen, E, Abate, MA & Kveiborg, O (2014) Drivers and limits for transport: Report 9. Technical University of Denmark, Transport.

Nielsen, SB & Galamba, KR (2010) When Sustainable Development is Core Business. *Proceedings of the 9th EuroFM Research Symposium*.

Nielsen, TAS, Skov-Petersen, H & Agervig Carstensen, T (2013) Urban planning practices for bikeable cities - the case of Copenhagen. *Urban Research & Practice*, vol 6, no. 1, pp. 110-115., 10.1080/17535069.2013.765108.

Nielsen; S.B.; Jensen, L.M.; Mikkelsen, P.S. and Nielsen, P.S. (2012) Forslag til overordnet plan for byplanlægning på DTU. (Internal DTU document).

Strømann-Andersen, JB, Bjerregaard Jensen, L, Svendsen, S & Kongebro, S (2012) Integrated Energy Design in Master Planning. Ph.D. thesis, Technical University of Denmark, Kgs. Lyngby.

Technical University of Denmark (2013) Strategy 2014-2019. Web access http://www.dtu.dk/english/About/facts-and-figues/Strategy.

Appendix 1

Vision	Engineering Smart Sustainable Livable Cities Conceive, Design, Implement, Operate (CDIO)					
Themes	Transportation and mobility	Building design	Water management	Space and GIS	Facilities management	Climate adaptation
Courses: single theme	13106 GIS and road traffic planning for MSc students 13133 Introduction to transport models 13150 Transport economics 13232 Transport safety 13233 Decision support and risk analysis 13236 Sustainable transport assessment 13428 Urban planning and transport planning 13450 Intelligent transport systems (ITS) - modelling and analysis 13531 Transport logistics and optimisation	11115 Building energy and technical services- integrated design 11116: Sustainable buildings 11127 - Sustainable heating and cooling of buildings 11142 Daylight and lighting 11374 Seismic and wind engineering 11994 Engineering in urban design 11997 Sustainability and life cycle assessment 11420 - Engineering in mountains - soil, rock and nature 11375 - Bridge structures 11129 - Sustainable district heating 11222 - Indoor climate 11465 - Advanced geotechnical engineering	12233 Water pollution 12236 Environmental and human health risk assessment of chemicals 12333 Water resource management 12335 Ground water resources 12500 Energy resources 12242 Environmental management and ethics	30090 Design of digital systems, 30510 GPS, GIS and setting out 30532 - Introduction to digital mapping and GIS	42259 Facilities management XXXXX Sustainability in FM XXXX Real estate strategies XXXX Maintenance and operation of buildings and infrastructures	42262 Climate models, observations of the past and the present and climate changes projections including sea level rise 30730 - Space weather forecast and effects
Courses: urban planning	42279 Interdisciplinary urban planning course of Danish universities (LFB) 42280 Smart, connected and livable cities 42273 Urban planning and sustainable urban development 13235 Planning theory					
Other relevant courses	42246 Project management 42XXX Innovation management 42631 Environmental economics 42628 Product development/ conceptualization 42543 Management of change 42532 Strategy and planning methods 42490 Technology, economics, management and organisation (TEMO) 42435 Knowledge based entrepreneurship 42401 Introduction to planning 42084 Work system design 46200 Planning and development of wind farms 41083 Technology platforms and architectures 41272 Risk and decision-making 42171 System safety and reliability engineering					

Problems in Problem Analysis

Henrik Almegaard
hal@byg.dtu.dk
DTU Civil Engineering, Technical University of Denmark, Denmark

Abstract: The majority of literature on engineering design methods is focused on the processes of fulfilling the design goals as efficiently as possible. This paper will focus on - and discuss - the processes of determining the design goals: the specifications. The purpose is to draw attention to the inherent problems, dilemmas and possibilities in these processes bearing in mind that that the most important decisions in a design project are taken in the beginning of the project.

Keywords: Engineering Design, Problem Solving, Problem Analysis, Efficiency.

Background

The author is teaching engineering design at the department of civil engineering at the Technical University of Denmark (DTU). The course was developed for the B.Sc. program in architectural engineering that started in 2012. The methods taught are based on the methods that were developed at DTU Mechanics in the 1970s, on experience from practice and on literature, first and foremost (Billington 1983 and 1996) and (Vincenty 1990).

Engineering Design

Engineers design things (structures, machines, network and processes) (Billington 1996) that have a function. And they aim for making the function reliable, efficient and economical. The way engineers do this is not very different from skilled craftsmen; they take different parts and put them together to form these “things” or more correct constructions. The origin of the word construction is the latin *construct-* 'heaped together, built', from the verb *construere*, from *con-* 'together' + *struere* 'pile, build'

One difference from craftsmen is that engineers do this on a scientific basis. This does not mean that engineering is just applied science, but that engineering is based on - and formed by - a vast body of engineering knowledge, that has been established using scientific principles (Jevons 1976).

Another difference is that in general engineers do not take the actual physical parts and bring them together. They plan what parts to bring together and how to bring them together. And they do this by taking different parts of the engineering knowledge and bring that together, to form either new knowledge or new versions of existing knowledge. (To make things a little more complicated, engineers may very well make physical constructions: models, prototypes etc. during the design process in order to obtain this knowledge.)

In this way the engineer constructs on two different levels. They make constructions on the practical level and although they don’t do it physically they have their focus on the practical level, but doing so they also make constructions on a knowledge level.

In general engineering design involves problem solving processes which span between the two extremes: tame problems and wicked problems.

Tame problems are in short defined as problems where input determines output. This means that a tame problem can be solved by following a logical - often mathematical - procedure. The procedure is based on assumptions that have to be fulfilled; otherwise the result will be unreliable. We may say that solving tame problems just create new versions of existing knowledge, because in principle such a procedure just process information. But this process may produce new knowledge from which decisions can be taken.

Wicked problems were identified by Rittel and Webber (1973). In short they are indeterminate, ill structured and open ended. This means that it is part of the problem to give it structure and organise the processes. Also it means that the result can’t be predicted. And often most of the premises for the actual solution have to be established during the process.

Wicked problems are much more complicated to handle than procedures, and as engineers are aiming for efficiency there is a constant desire for pushing design processes towards procedures. Also this paper is an example of this.

Design Projects as Design Objects

Design problems are wicked problems. This is self-evident; if no indeterminacy, everything is determined in advance, and then no design is needed. And since design problems are ill structured, also the design project in itself is a design object. The process has to be designed - or redesigned - for every new project.

The whole reason for dealing with engineering design processes is that we want the whole process to be intelligent and not just governed by iterations based on trial and error. As found in many optimization problems iteration may just lead to a local optimum. So just as any other engineering design we want also the design process to be reliable, efficient and economical.

To design the processes in engineering design projects we use design methods. This is a variety of structured processes, intellectual concepts and ways of thinking that are based on design experience, design theories, project management methods and knowledge picked up from other scientific fields like philosophy and psychology. These methods are used to organise the intellectual processes in the project.

Unless you happen to be in a specific organisation with specific design objects, it makes no sense to focus on specific design processes. From a scientific point of view it makes sense instead to study general concepts end elements in the design process. From these the designer will be able to develop her own detailed processes.

Example: How to perform interviews in the early phase of the design project when needs are to be identified? A good answer would be: Ask open-ended questions. Use sentences starting with: who, what, where, when, why, how. But this answer is nothing but the general guideline for any conversation, where you want to know the person that you are talking to.

Two important design methods / intellectual concepts are the general problem solving method and the hierarchical tree structure of problems and solutions. Both concepts were described in Stahl and Tjalve (1977).

The General Problem Solving Method

The general problem solving method consists of four steps: 1) Analyse problem, 2) Seek solutions, 3) Examine and modify, 4) Evaluate and choose (figure 1). A fifth step: Implement, can be added, but in a design process the next step would most often be to go to a more detailed level of design, solving new problems on this level.

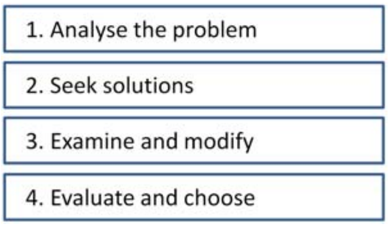


Figure 1. General Problem Solving

In this paper focus will be on the problem analysis, but it is important to notice that the most important reason for going through this process is the desire to uncover the whole space of solutions in order to find the best solutions.

The Tree Structure of Problems and Solutions

The tree structure of problems and solutions show a system structure with different levels and design elements or solutions (figure 2).

Considering a problem on one level we will normally have several solutions to solve that problem. Each of these solutions implies a number of design problems at a lower level. Each of these problems has several solutions and so on. If for some reason no acceptable solution can be found on a certain problem, this map shows that we can go one level up – or two levels up – and choose another branch of solutions.

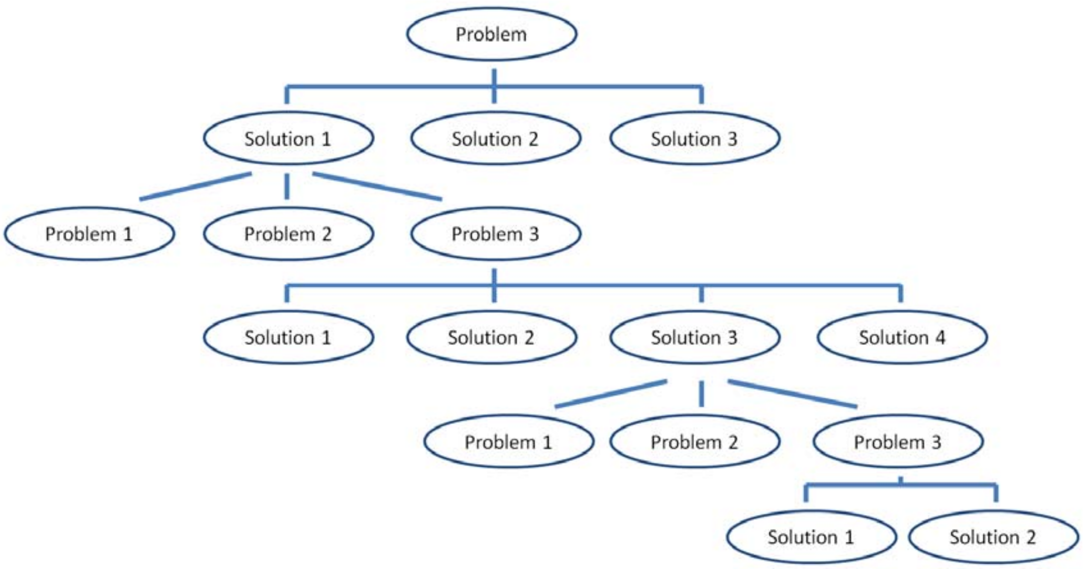


Figure 2. Tree Structure of Problems and Solutions

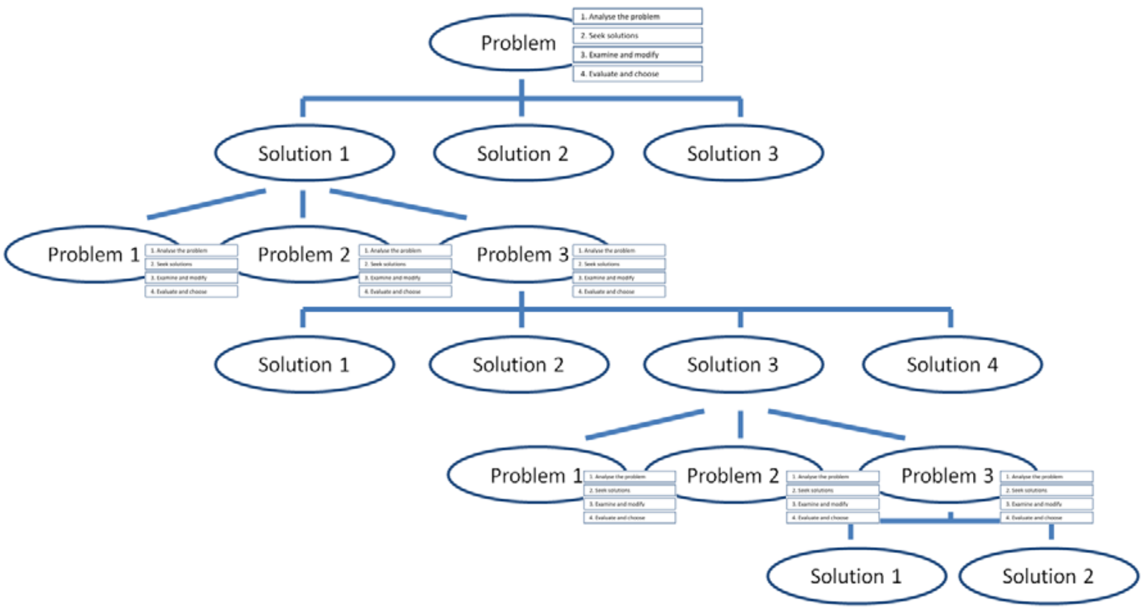


Figure 3. The Problem Analysis Method is Applied for Each Problem Considered

In the design process these two intellectual concepts are combined so that for each problem, beginning at the top, the general problem solving method is applied.

The first step in the general problem solving is the problem analysis. The extent of the problem analysis depends on the type of problem and on how precise the problem is described beforehand. But it is obvious that the problem analysis is decisive for the quality and efficiency of the solution.

First Problem in the Problem Analysis

The problem analysis consists of:

1. Collection of information
2. Analysis of needs
3. Problem formulation
4. Specifications (functional requirements)

The second task in the problem analysis is the analysis of needs. This task can be divided into three subtasks:

a) Analysis and identification of users and stakeholders
b) Analysis of activities
c) Formulation of needs

The analysis and identification of users and stakeholders is basically an analysis of where to seek information. It consists of answering the following questions:

- Which users and stakeholders will be affected of – or could have interest in – how this problem is solved?
- Who are the most important?
  - Who has most influence?
  - Who has – directly or indirectly – the most interesting information's on this problem?

Stakeholders may include construction, repair and cleaning personnel.

Information on activities can be obtained in a number of ways. In the literature on product design interviews, questionnaires and focus groups are dominant (Ulrich and Eppinger 2008; Otto and Wood 2001). But if we want to have the opportunity to identify needs that people are not aware of, and hence to invent new functions/products, we must focus on the user and stakeholder activities. Then we must analyse the activities and derive needs from these. This is exactly what is done by a new type of consultant firms. They are using anthropologists and sociologists to make observations and interpretations of costumer - or future costumer - activities and to report these (Bernsen 2014).

The analysis of activities consists of at least one of the following tasks:

- Interviews, questionnaires or focus groups meetings
- Observation of activities
- Imagination of activities (perhaps by an expert)
  - From experience
  - From an articulated vision or ideal

Interviews, questionnaires, focus groups meetings and observations are useful only if the situation and circumstances are somehow similar to the solution from which the considered problem arises. If the solution is new we cannot use observations and then we must use imagination. This is discussed in next section.

When the information is collected the last subtask is to formulate the needs. This includes:

- Analysis and interpretation of the information
- Formulation of needs
- Prioritising of needs

How to Control the Quality?

Now let the scientific scheme of the experiment be applied to this process. This scheme consists of three parts taking place one after each other:

- Observation
- Hypothesis (on how different entities are connected and influence each other)
- Experiment / Test of hypothesis

In this case the "hypothesis" is the list of needs. In a design project it is hard, time consuming and costly, to make experiments and test needs. This is especially the case in the beginning of the project. It will for example often require a number of prototypes, but prototypes will not be ready until much later in the project.

In civil and architectural engineering often just a single object is designed and in that case a complete test is impossible until the structure is built. And even then often only time can show if the needs was well chosen. This means that the testing has to be done in other ways.

Off course interviews, questionnaires, focus group meetings can be made once more, but now with focus on the clarification of some specific questions. And later in the project testing on prototypes will become an option. But in the beginning of the project when the consequences of mistakes are most critical the quality has to be ensured in other ways.

The inherent dilemma is that the choice of observations to report or questions to ask, the interpretations of the reported activities or answers as well as the formulation of needs, is based on the viewpoints and intensions of the observer and the interpreter. This means that the formulation of needs is completely dependent on the focus and mindset of the persons involved whether they are aware of this or not. The voice of the costumer may just be the echo of our own voices.

This leaves us with two general methods for quality control of specifications: critical thinking and reviews.

Critical Thinking

Critical thinking consists in essence of considering the following questions:

- Are the observations (premises) that are chosen as basis for the formulated needs (conclusions) representative and logically coherent?
- Are the conclusions logically derived from the premises or could other conclusions be drawn just as well?

Critical thinking can actually be used on each part of the problem analysis process, but also on the whole problem analysis process. Critical thinking is in fact a structured method that can be used in every part of the design process.

Review

A review could in this context consist of considering the following questions:

- Do the designs that seem to be the most promising at this stage reflect the original understanding of the problem, or has the process drifted so that we now have created solutions to a nonexistent problem – or to a problem of less importance?
- Do the solutions found and the process leading to these indicate that the original problem was not completely understood / somehow misunderstood, so that the specifications - or some of them - have to be reconsidered?
- Do the large number of technical problems that we have to solve at this stage of the process indicate that we have not fully understood the concepts and solutions that we have chosen at earlier stages?

Second Problem in the Problem Analysis

In order to describe the second problem we first have to examine the consequences of the independence axiom for the problem analysis. The independence axiom was formulated by Suh (1990). It means that ideally each functional requirement is fulfilled by just one single design element. If two design elements fulfil the same two requirements they become interdependent and we don't want this because interdependence makes the actual design more complicated and vulnerable than it would be if the requirements were fulfilled independently. (Actually it is caused by anticipation a solution on a lower level than the actual level). If one design element fulfils two requirements we call it integration. If we need two design elements to fulfil one requirement then either we can do without one of the elements or the functional requirement is in reality demanding two functions, and then has to be reformulated into two requirements.

For the process of determining requirements, the independence axiom has the effect that:

- We may very well have several observations leading to just one need, but a single observation cannot lead to several needs.
- We can have one need leading to one functional requirement, but we cannot have two or more needs leading to just one requirement, because the needs should be the basic elements from which requirements are derived.
- In the same way we cannot have a single need leading to two requirements. Because if so we would anticipate a solution on how this need is met.

Considering the tree structure of problems and solutions (figure 2) and translating design element to design solution, it is seen that the tree structure fulfils the independence axiom.

Furthermore it is seen that needs and requirements have to fit the level of the actual considered problem. This means that the solutions on the levels above have to be determined before the needs and requirements at the considered level can be specified.

It also means that you cannot set up a requirement if you by doing so, assume a specific solution on a lower level. In that case you would violate what Suh (1990) calls solution neutrality.

Example: If a need for hot water has been identified, we cannot conclude that we have two functional requirements: 1) Water 2) A heating device. Because by doing so we would presuppose a two step solution and then ignore all possible one step solutions, like for example water from a hot spring.

The problem is that by anticipating a solution, other solutions are automatically eliminated. And since the best solutions could be among these, we reduce the efficiency of the process and the possibility of success.

In practice this means that we cannot specify anything but very general needs in the beginning of a project without anticipating specific solutions to fulfil the considered needs. Only when the particular solutions are defined we can obtain more specific needs.

Example: If a need for fast transportation of human beings between cities is identified, it makes no sense to specify more detailed needs or functional requirements until a mean is specified. Possible means could be: walking, horse riding, train, bus, car, bicycle, airplane, etc. A more detailed need could be a need to sit down when the transportation is taking place.

Since it is not practical to make observations, interviews etc. at each level of problem solving, the information's collected during the project must be seen as a reservoir of knowledge from which needs and requirements can be extracted.

Often most of the information on the user activities and needs is collected in the beginning of the project. This means that the concept of this information as a reservoir makes the demands for this collection process; it has to provide a fund of information for identifying and formulation of needs at all levels in the whole design process.

Third Problem in the Problem Analysis

If the considered type of solution already exists we can make observations. But if we invent a new solution fulfilling the identified need, we cannot use observations to generate the specific needs and requirements, but have to use our imagination, experience and general knowledge of human behaviour.

This indirectly defines three types of engineering design projects:

1. Improvement of an existing solution
2. Invention of a new solution to an existing problem
3. A new solution to a new problem

Improvement of existing solution may involve invention of a new solution to a problem on a lower level. This solution may just be new in this context, but known in other contexts. In that case observation from these may provide useful information.

Invention of a new solution to an existing problem may be based on new observations or new interpretations of activities, but also on new technical ideas or possibilities.

A new solution to a new problem may very well be based on a vision. Ideally it is a vision for a better life. Since a vision often describes a new set of activities it may be a good basis for formulation of needs.

Conclusion

In practice it is hard, time consuming and costly, to make experiments to test if the specifications comply with the stakeholders needs. In civil and architectural engineering it is often impossible. This leaves us with two methods for quality control of specifications: critical thinking and reviews. The hierarchical structure of the complete solution implies that needs and requirements cannot be specified on the level of the actual considered problem until the solutions on the levels above have been determined. The information collected during the project must therefore be seen as a reservoir of knowledge from which needs and requirements can be extracted for each specific problem. Finally, if we invent a new solution that fulfills the identified general needs, we cannot use observations to generate the specific needs and requirements, but have to use our imagination, experience and general knowledge of human behaviour.

References

Bernsen, M. (2014) På feltstudie i privatlivet. *Weekendavisen #10*, 7.marts 2014. (in Danish).

Billington, D. P. (1983) *The Tower and the Bridge.* Princeton University Press, New Jersey.

Billington, D. P. (1996) *The Innovaters – The Engineering Pioneers Who Made America Modern.* John Wiley & Sons, Inc. New York.

Jevons, F. R. (1976) Interaction of Science and Technology Today. *Technology and Culture.* Vol. 17, No. 4, pp. 729-742.

Otto K. N. and Wood K. L. (2001) *Product Design – Techniques in Reverse Engineering and New Product Development.* Prentice Hall, New Jersey.

Rittel, H. W. J. and Webber M. M. (1973) Dilemmas in a General Theory of Planning. *Policy Sciences* **4**: 155–169.

Stahl, H. and Tjalve, E. (1977) Konstruktions-teknisk problemløsning, AMT, DTH. (In Danish)

Suh, N. P. (1990) *The Principles of Design*, Oxford University Press.

Ulrich K. T. and Eppinger S. D. (2008) *Product Design and Development.* McGraw-Hill. New York.

Vincenti, W. G. (1990) *What engineers know and how they know it*. The John Hopkins University Press. Baltimore.

Methodologies of Sustainable Planning for Operational and Service-Optimized Building Design

A-Rum Krause-Cha[*1,2], Dominik Matt[1,2] and Daniel Krause[2]

Arum.Krausecha@natec.unibz.it, dominik.matt@unibz.it, Daniel.Krause@fraunhofer.it

[1] Faculty of Science and Technology, Free University of Bolzano, Italy

[2] Innovation Engineering Center, Fraunhofer Italia Research s.c.a.r.l., Bolzano, Italy

Abstract: Consideration of the whole life cycle is necessary to obtain sustainability for buildings. Within the life cycle, there are different phases: concept, design, construction, operational and recycling. Among these phases, the operational phase is the longest and most expensive one. Therefore a building cannot be sustainable if the operational phase is not sustainable and optimized. The operational phase can only be optimized if operation-oriented decisions are taken during the design and construction phase. In practice, decisions during the design and construction phase are taken without knowing the real consequences on the operational phase. Some of these decisions are wrong and make future building operation, such as operational Facility Management (FM), difficult or even impossible. These wrong decisions can be seen as design failures (e.g. uncleanable facades, long service provider routes, etc.), even if there are no errors in construction or design. Therefore many methodologies have been recently developed to create a FM-oriented approach to design and construction. This paper introduces these methodologies and discusses whether they are suitable to achieve design optimization and to reduce design failures in the operational phase.

Keywords: Facility Management, Building Design, Building Design Methodology, Optimization of Operational Phase, Green Building, Operational Phase.

Introduction

The sustainability of a building can only be reached, if all phases of the life cycle of a building are considered. This starts with the concept phase and goes on with the design phase (including the authorization phase), the construction phase, the operational phase (including the implemention phase) and ends with the demolition/ recycling phase (figure 1). But often, the operational phase is not considered during the design of a building and within the operational phase, facilities management (FM) plays a big role.

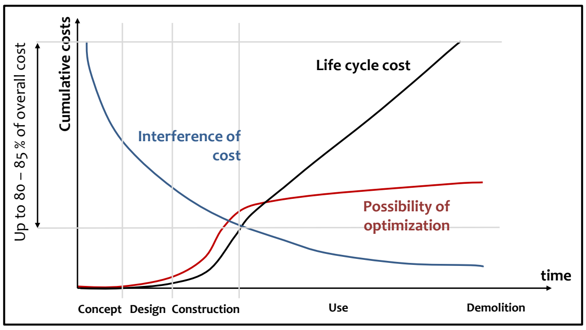


Figure 1. Life Cycle Cost of a Building (BMVBS, Jones Lang LaSalle 2012)

This paper describes the state of the art of operational and service–optimized planning, how FM is currently integrated within the design phase and where the according problems are. After having identified the problems, existing solutions and methodologies will be introduced and analyzed. Finally, conclusions and recommendations will be given at the end of the paper including advice about which methodologies can be used to obtain service-optimized construction and how they can be modified.

History of Life Cycle Consideration of Buildings

From a historical point of view, one of the first approaches that considered the building life cycle and its phases was introduced in the 1960's, when the U.S. Army established rules for public procurement that considered the life cycle cost (Koenig 2009). Further occurrences, such as toxic contaminated building materials from 1950 – 1980, led to sensitization on the whole life cycle of the building. These toxic contaminated building materials were harmful during the operational phase for users and increased the demolition cost disproportionately. The energy crisis from 1973 raised awareness for the energy performance of the building and its energy cost during the operational phase. At the end of the 20th century, the first Public Private Partnership (PPP) projects started. In a PPP project, the government awards a contract, which includes funding, construction and the operation of a building as one project. The contract has a duration of 20 – 50 years and all phases of the life cycle have to be considered.

Consideration of FM Cost in Addition to Energy Cost

Within the operational phase there are a lot of costs besides energy cost. But until the end of the 20th century the optimization of the operational phase focused mainly on energy costs. With the start of the commercial crisis in 2007 it became more apparent that it was not enough just to consider energy cost during operational phase. Designers have to take into account the whole FM cost of the operational phase. As a result, by the example of Germany, standards such as DIN 18960 "Nutzungskosten im Hochbau" (2008) and the Green Building label DGNB, which considers FM during the operational phase, were implemented. Another effective way to decrease FM costs during the operational phase is its integration already during design and construction phase. With the integration, an operational and service-optimized building design can be obtained.

State of the Art

Comparison to Mechanical Industry and the Reason for a Missing Adaption

In the field of mechanical industry, the whole production is adapted to the product and its usage (e.g. car-series or industrial production in general). For buildings, this usage oriented and optimized production is missing. During the design and construction phase, the biggest target is optimized construction cost. The usage oriented production is disarranged in a second row. The reasons for this fact may be the following:

- Defining the role of a building is difficult, because this changes during its life cycle. The building itself is a product while the life cycle of a building is a process (König *et al.* 2009). Therefore the definition of building usage can be different.
- In industry, the aim of the project group is to develop a product for certain groups of customers. But for the building sector, there are many stakeholders with different aims and expectations including the owner, architects, the structural designer, external consultants, the building operator, the contractor, tenants, etc. And each of them might have different aims. For example, the owner's or investor's aim is a low investment and a high profit. The architect is usually focusing on aesthetics. The structural designers have to achieve a safe structure and the building operator needs enough space and routes for the building operation. The various stakeholders also have different time expectations (table 1) and different involvement time in a building.
- Each building is unique and a standardization is difficult

Due to the reasons above, a building project is complex and a definition of one role and one costumer is difficult. Further, an overview of all stakeholders and action throughout whole life cycle of a building is missing. Therefore a usage oriented production of a building is a challenge throughout all building phases.

Table 1. Excerpt of Time Expectation of a Building (König *et al.* 2009)

Participants	Time expectation
Tenants (residents)	5 - 30 years
Tenants (non residents)	1 - 20 years
Estate agent	1 – 2 years
Building contractor	1 – 5 years (warranty)
Facility Manager	1 – 5 years (contract)
Designer	1 – 25 years (1st Repair)
PPP – Participants	10 – 50 years (contract)
Owner	25 – 50 years (generation)

Usage Oriented Production in Building Sector and Related Problems

Treating the usage of a building as operation of a building, the course for an optimized usage is already set during the concept and design phase. In that time, the significant stakeholders for operation (e.g. user, building operator, Facility Manager) are not involved in the project team and the other participants pursue different goals. And at that time usually the most important type of cost is the invest cost of a building. This fact leads to design decisions without the consideration of the consequences on the operational phase. Therefore an optimization of the operational phase of a building is generally hard to be reached. Some of the decisions, which are done without consideration of operation are wrong and make future building operation, difficult or even impossible. Examples for these wrong decisions in practice are as follows:

- Not cleanable façade or windows or façade
- Façade or windows are only cleanable by special workers (climbers) or by special utilities
- Long routes for service providers
- Transport of wares, such as office supplies or hygiene products, can only be done by special utilities or machines
- Missing plug sockets for vacuum cleaner (usually in open space offices)
- Corners and places, which cannot be cleaned

These wrong decisions can be seen as design failures, even if there are no errors in construction or design. Currently, there are several approaches to eliminate such design failures and to avoid wrong decisions during design and construction phase. In the following paragraph these approaches will be shown, classified, explained and analyzed.

Existing Approaches

Existing approaches can be classified into three groups (figure 2). These approaches are usually done in bigger building projects of office buildings. The project size should be big enough to allow a Green Building labelling.

The approaches are acting in different phases of life cycle of building. The three groups are:

- Methodologies of Green Buildings
- Integration of consultants and experts of operational phase during design and concept phases
- Calculation methods, such as Life Cycle Analysis, Life Cycle Cost, Benchmarks and single variant-calculations

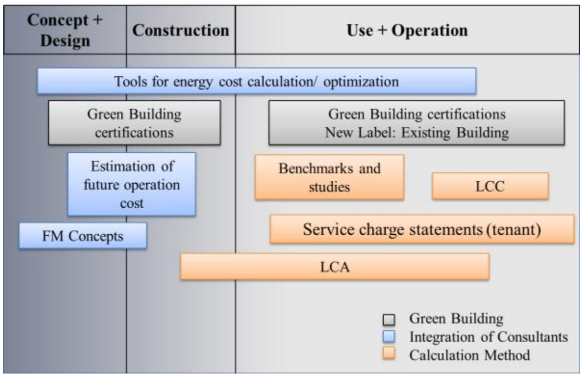


Figure 2. List of Existing Methodologies for Operation Oriented Planning

Methodology of Green Buildings

There are more than 60 Green building labels worldwide. The oldest certification label is BREEAM (Building Research Establishment Environmental Assessment Method) launched in 1990 in the UK. BREEAM considers nine categories (Management, Health & Wellbeing, Energy, Transport, Water, Materials, Waste, Pollution and Land Use & Ecology.), which are called qualities in Green building labels. BREEAM focuses on environment (Luft 2009). The most common Green building label worldwide is LEED (Leadership in Energy and Environmental Design), which was founded in 1993. LEED considers seven qualities (Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials & Resources, Indoor Environmental quality, Innovation in Design and Regional Priority) and focusses also on environment (Luft 2009). The most modern label of the three major green building label is the DGNB (German Society for Sustainable Building), which was founded in 2007. It considers 6 qualities (Environmental, Economic, Sociocultural and Functional, Technical, Process and Site). Unlike the two aforementioned labels, DGNB focuses on sustainability. Therefore, this paper will discuss in detail on the Green Building Label DGNB and examines its methods for operational and service-oriented planning.

The Green building label DGNB has 37 schemes for buildings (e.g. Office and administration buildings in use, Office new buildings, retail buildings, etc.) (DGNB 2014). For the evaluation of these schemes 41 core criteria are given (figure 3). Out of these 41 core criteria, following eight criteria deals with FM and will be explained and examined in this paper:

- Life Cycle Cost (Number ECO 1.1)
- Flexibility and Adaptability (Number ECO 2.1)
- Safety and Security (Number SOC 1.7)
- Cleaning and Maintenance (Number TEC 1.5)
- Integrated Design (Number PRO 1.2)
- Design Concept (Number PRO 1.3)
- Documentation for FM (Number PRO 1.5)
- Systematic Commissioning (Number PRO 2.3)

Criterion: Life Cycle Cost (Economic Quality)

This criterion has a high importance factor (3) as well as a large share of overall evaluation (9.6% of the overall). It examines the whole life cycle cost of a building starting with construction cost and ending with recycling cost. The obvious aim is to consider the whole life cycle of a building and to make decisions, which considers some operational cost as well. The costs are structured by standard. For the structure of construction cost, the German standard DIN 276-1 (2008) is used. The basis for the structure of operation cost is also a German standard DIN 18960. The calculation basis for these costs is the cash method which also includes price development. Finally these costs will be compared with the benchmarks of DGNB and evaluated.

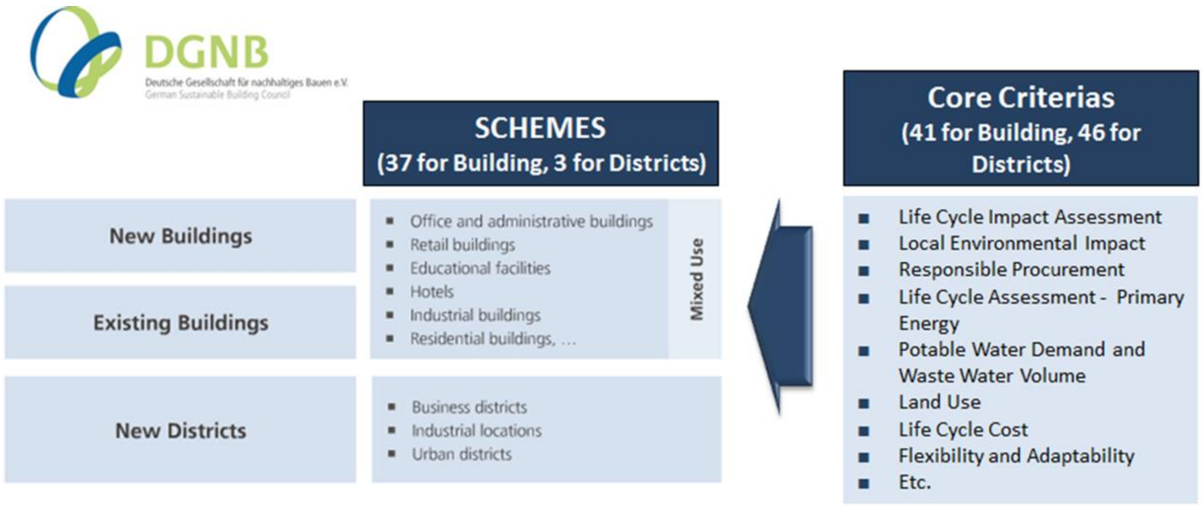


Figure 3. Application of the DGNB Certification System (DGNB 2014)

For the operational cost, the following costs will be evaluated:

- Supply and disposal cost
- Cleaning and care of the building
- Operation, inspection and maintenance
- Repair

This criterion is an important criterion regarding the topic of this paper as it forces the applicant to consider operational costs to obtain a Green building label. It also tries to find a way to make buildings comparable with each other.

Criterion: Flexibility and Adaptability (Economic Quality)

This criterion evaluates the feasibility of conversion and has also a high importance factor (3) as well as a large share of overall evaluation (9.6% of the overall). The idea is that if a conversion is easily done, the usable area can be easily adapted and optimized to the type of usage. By optimizing space allocation, significant savings of resources can be achieved.

If the conversion and the flexibility of usage are considered, the consideration of the usage and operation is obligatory. Therefore this criterion can be used to consider the usage and operation of future building already in concept and design phase.

Criterion: Safety and Security (Sociocultural and Functional Quality):

The criterion Safety and Security deals with subjective feeling of safety of the user and has a share of overall evaluation of 0.9%. Provisions, such as clear routing, sign-posting, safety lighting, technical safety devices, security services help to achieve credit points for the certification. Accordingly, security measures for cases of damage or emergency are also mentioned in this criterion, such as guide books for ventilation and air conditioning installations and evacuation plans.

This criterion forces the planners to issue building security aspects already during the design phase and to develop a security concept, which combines the technical safety devices with security services already at the time of certification.

Criterion: Cleaning and Maintenance (Technical Quality)

This criterion deals with cleaning and maintenance friendliness of a building and has a share of overall evaluation of 4.1%. The cleaning and maintenance friendliness has a high impact on the operation cost, as well as on the environment. For the evaluation of this criterion, the building is divided into the following three types of components:

- Supporting structure
- Non-loadbearing external structure including windows and doors
- Non-loadbearing construction inside.

The different types of components of the building are considered separately.

This criterion is an important one regarding the topic of this paper. Buildings, which cannot be cleaned and maintained due to non-accessibility, have design failures. Through this criterion such non-accessible areas can be found already in the design phase and if possible, eliminated. Unfortunately, not the whole building but single components are considered separately and therefore a holistic consideration of accessibility is missing. Additionally only accessibility is considered.

Criterion: Integrated Design (Process Quality):

With this criterion, DGNB recognizes the importance of integrated design. The share of overall evaluation of this criterion is 1.4%. This criterion considers the integration and improved coordination on all participants and optimization of the planning process.

It evaluates the following four aspects on the basis of an evaluation scale:

- Interdisciplinary planning team
- Integration of user (user's planning partner/ building operator/ Facility Manager)
- Participation of the public
- Development of functional specification

Being a part of the planning team, a Facility Manager and user can improve the design and has the opportunity to optimize it.

Criterion: Design Concepts (Process Quality):

Since there is no standard solution for the construction of a sustainable building, concepts and variant studies are important methods for optimization. Therefore this criterion list needed concepts for sustainability. It has a high importance factor (3) and a share of overall evaluation of 1.4%. Out of listed concepts, following concepts are related to FM:

- Safety concept
- Energy concept
- Disposal concept
- Concept for cleaning and maintenance friendliness
- Life Cycle cost planning during design phase

In addition to the criteria mentioned above, this criterion ensures the consideration of FM concepts during the design phase.

Criterion: Documentation for FM (Process Quality):

One of the common problems at the commissioning phase and at the beginning of the operation phase of a building is missing documentation for operation. Having involved the operator or Facility Manager during the design phase or tendering phase, this problem can be solved. This criterion, which has a share of overall evaluation of 1.0% manages the documentation of used materials, auxiliary supplies and safety data sheets for the life cycle phase and possibly conversion and dismantling for the building during the design phase so that these documentation can be provided for the operation.

Systematic Commissioning (Process Quality):

This criterion deals with commissioning and start of the operation, which has to be planned and managed in advance. It also considers the first optimization of operation after 10 – 14 months after commissioning. It has a high importance factor (3) and a share of overall evaluation of 1.4%. This criterion helps to optimize the commissioning, but plays a minor role in operational and service-optimized construction.

Conclusion

The percentage of evaluation of these eight criteria is nearly 30% of overall criteria of this Green Building scheme "New Office and Administrative Buildings" (DGNB 2012). Consequently, the impact of FM on DGNB Green Building level is high. Thus, an applicant of a Green Building label DGNB is forced to consider FM (consequently operation) to obtain a certificate.

Integration of Consultants and Experts

An integration of consultants and experts at the right time during the concept and design phase is the most effective method to prevent design failures. This approach is known as "FM during the design and construction phase". FM during the design and construction phase begins with requirements management and ends with the introduction of the operator in the building.

Generally, FM during the design and construction phase starts with FM - concepts. The FM - concepts generate constructional, technical and organizational requirements according to operational and service-optimized planning and are basis for the estimation of future operation cost (figure 4). The development also contains the building operation simulation so that wrong decisions and design failures (according to operation) can be found at an early phase. Thus, these failures can be avoided in advance in most cases through simple measures or changes in the design. If this is not possible, at least the potential consequences can be verified. The following concepts are usually considered within FM - concepts (Häusser 2012):

- Building access concept
- Security concept
- Cleaning concept
- Disposal concept
- Supply chain/ ware and logistic concept
- Maintenance and operation concept

To develop these concepts plans are analyzed and evaluated from the perspective of FM.

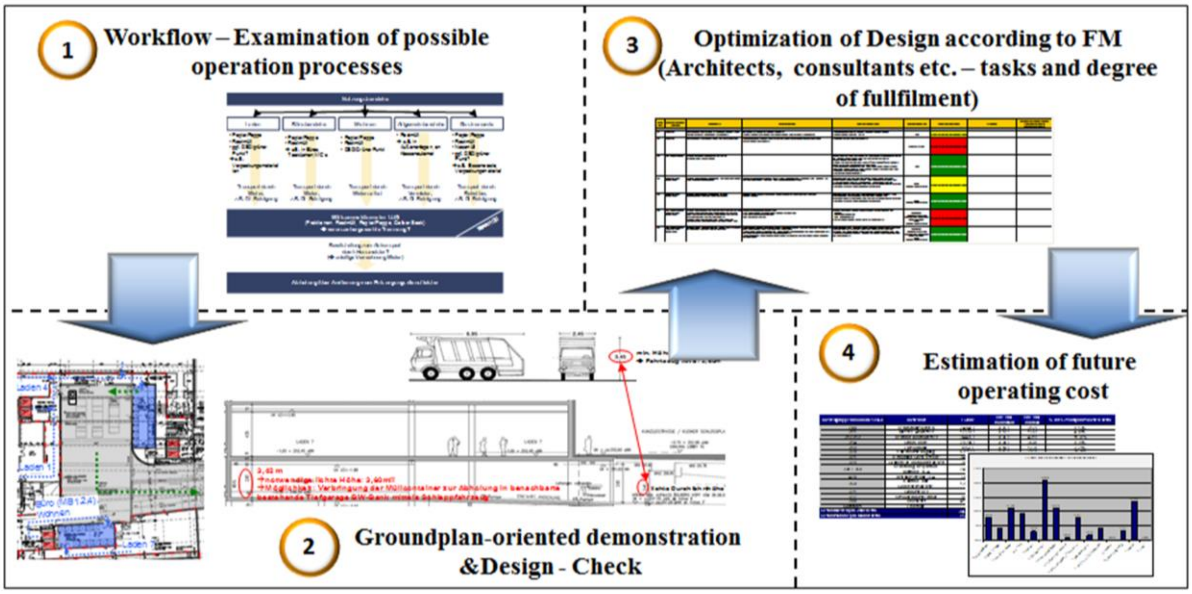


Figure 4. Process of Facility Management During Design and Construction Phase (Häusser 2012)

Building Access Concept

In the building access concept, access routes of various user groups (e.g. visitors, service operator, workers, etc.) and various transport access possibilities (e.g. public transport, car, bicycle, etc.) are investigated. Also barrier-free access, signage concept and reception workstations play a crucial role in this concept.

Security Concept

The safety concept identifies different security zones in the building and gives suggestions about the possible technical safety equipment. Here, special attention is paid to separation of operation and public zones, so that no security vulnerabilities occur due to unauthorized access.

Cleaning Concept

The cleaning concept plays an important role. This is because most design failure exist in the façade concept where some walls or glass parts cannot be reached easily for cleaning. This has to be verified and possible solutions have to be found so that all parts can be cleaned. Accordingly, the feasibility of routine cleaning, e.g. to existing facilities, fittings, door mats is investigated. The cleaning concept includes also green space maintenance, winter maintenance and possible service levels for the routine cleaning, which is helpful for future tendering.

Disposal Concept

Apart from the design failure of non-reachable façade parts, the second most common design failure is the wrong-sizing and wrong concept development of waste spaces. This is examined in a disposal concept. A disposal concept plays also a major role in Green building Certification because most of the Green building labels require it. The disposal concept also includes processes of disposal from work station to collection point where waste containers were collected by disposal companies. The abidance by the requirements of hazardous waste and as well as barrier–free disposal routes is mandatory in disposal a concept.

Supply Chain/ Ware and Logistic Concept

Same as disposal route, the supply route and supply area have to be also barrier-free and easily reachable. These barrier–free routes as well as further access possibilities for supply (e.g. lifts) were examined within the supply chain / ware and logistic concept. Accordingly the dimensions of supply area and dock possibilities for trucks are investigated.

Maintenance and Operation Concept

The maintenance and operational concept manages the feasibility of the technical operations as well as the existing rooms and tools for maintenance.

Estimation of Future Operation Cost

If FM-concepts are developed and necessary information about future operation given, the future operation cost can be simulated and calculated. For example, future price lists for operation services such as cleaning, security, reception, etc. can be filled with average costs to determine a realistic cost of future operation.

The German standard DIN 18960 (2008) “Nutzungskosten im Hochbau”/ User costs of building or GEFMA Standard 200 gives a good overview of possible operation cost. The most important ones are:

- Electricity, water and heating supply
- Waste and sewage
- Cleaning (routine cleaning, glass cleaning, façade cleaning)
- Cleaning and maintenance of outdoor facilities (paved surfaces, plants and green space)
- Operation, inspection and maintenance (operation of technical facilities, inspection and maintenance of technical and construction facilities)
- Security services
- Repair (construction and technical facilities)

FM during the design and construction phase can be optimized by continuous consulting throughout the concept, design and construction phases by a FM consultant.

Integration of consultants and experts is the most effective method to optimize the future operation, but this method is also the most expensive one. And each solution is a unique solution depending on each project. Currently a standardization method for FM is not available.

LCA and Other Calculations

There are lots of methodologies and calculations that deal with operational costs. The most common calculations are:

- Life Cycle Cost Calculation
- Service charge statement of tenants
- Benchmarks (e.g. Oscar, etc.)

But since these calculations deal with past operational costs, which occurred already, none of these methods can be used to detect design failures.

The Life Cycle Assessment (LCA) is a good basis to consider the life cycle of a building. But usually LCA is just an environmental life cycle assessment and focusses just on energy.

Conclusions and Recommendations

Sustainable planning for operational and service-optimized building design is still a challenge in each building project and is not considered in every project even though there are some attempts to push operational and service-optimized planning such Green Building labels, FM-consultants and various calculations.

Nowadays, a Green Building label acts as a marketing tool for the buyer and investor of a building. New buildings without a Green Building label will have difficulties in selling. And, as shown in this paper, Green Building labels consider Facility Management with several of its criteria. Therefore they can be a door opener for considering FM during concept and design phase. But if more detailed information and further requirements of future operation and FM are needed, Green Building labels are not enough because not all design failures due to operation and FM can be found and solved with only the application of Green building labels. Thus, the Green building label is a trendsetter and driver of operational and service-optimized planning.

The best method to find and correct design failures is the integration of FM consultants and experts by developing FM-concepts. But this method is unique and has to be developed for each project. Standardization in advance is not possible.

Other methodologies are calculations, such as Life Cycle Analysis or Life Cycle Cost. None of these calculations deal directly with sustainable planning for operational and service-optimized construction. But these data can be used to obtain a basis for an optimization.

The main challenges in the future will be the standardization of a method that verifies design failures according to operation and numbers them in advance in the design phase. Accordingly the awareness of operational and service optimized planning must be increased. To increase this awareness, the following approaches can be taken:

- Increase of importance factor of some FM related criteria in Green Building labels. This option might be a way to lead buyers and investors to spend more money during the design and construction phase for FM optimization.
- Creating a label for operating phase: Within a Green Building label, a new certification system can be developed where operation and service of a building will be evaluated.
- Definition of general baseline for building operation cost for comparison: To be able to measure FM optimization, which is related to the decisions during design and construction phase, a baseline of operation cost must be defined. The best solution is a possibility to collect real data easily, e.g. internet based platform, where the Facility Manager can enter his operation cost.
- Invest more in education, which deals with FM during design and planning phase: A great opportunity to force the operational and service-optimized building design would be a special subject, which deals with FM during design and construction phase. This subject can be integrated in a FM degree, architecture as well as civil engineering.

References

DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen - DGNB e.V.) (2013) certification system *"New Office and Administrative Buildings*, Version 2012 with Upgrade of 31st of July 2013"

Häusser, T. (2012) *Vorgehen Nebenkostenschätzung*, Drees & Sommer Advanced Technology GmbH, Stuttgart

König, H. (2009) *Entwicklung einer Methodik zur Bestimmung von Orientierungswerten für Lebenszykluskosten*, BMVBS, BBSR, BBR, Germany

König, H., Kohler, N., Kreißig, J., Lützendorf, T. (2009) *Lebenszyklus-analyse in der Gebäudeplanung*, Detail Green Books, München Germany

Luft, Christian (2013) Das DGNB System im internationalen Vergleich: ein Überblick, Retrieved June 30, 2014 from: www.dgnb.de/fileadmin/de/dgnb_ev/Veranstaltungen/eigene_veranstaltungen/dgnb-impuls/Vortraege_Impuls/Praesentation_Impuls_System_im_intern_Vergleich.pdf

DIN 18960 (2008-02) *Nutzungskosten im Hochbau/ User costs of building* (DIN 18960:2008-02)

DIN 276-1 (2008-12) *Kosten im Bauwesen – Teil 1: Kosten im Hochbau/ Building costs – Part 1: Building construction* (DIN 276-1:2008-12)

GEFMA 200 (2004-07) *Kosten im Facility Management - Kostengliederungsstruktur zu GEFMA 100* (GEFMA 200:2004-07)

BMVBS, Jones Lang LaSalle (2012-08) Lebenszykluskosten: Gebäude ganzheitlich planen und bewerten. Retrieved December 1, 2013 from: www.architektur-online.com/aktuelles/edv/1747-lebenszykluskosten-gebaeude-ganzheitlich-planen-und-bewerten

Integrating Indoor Climate, Daylight and Energy Simulations in Parametric Models and Performance-Based Design

Pil Kirstin Brix Lauridsen[1,2] and Steffen Petersen[*1]
pila@alectia.com, stp@eng.au.dk
[1] Department of Engineering, Aarhus University, Denmark
[2] Alectia A/S, Aarhus, Denmark

Abstract: This paper presents a method for using parametric models to generate design support for the performance-based design process regarding indoor climate, daylight and energy performance. The method is operationalised in the Grasshopper programming environment. In the method, the designer suggests a room design and decides a certain degree of parametric freedom of parameters defining the room e.g. based on an overall architectural idea, a conceptual thought or something third. The method then employs a system of simulation tools and an optimization algorithm to generate a range of design proposals fulfilling user-defined indoor climate, daylight and energy performance criteria. The geometries of these solutions are presented to the designer together with performance data for decision making. The system of simulation tools includes the thermal simulation tool called ICEbear which is a newly developed plug-in to Grasshopper. It is ICEbear that enables the integrated indoor climate, daylight and energy performance simulations of complex geometries.

Keywords: Parametric Design, Building Simulation, Complex Geometry, Indoor Climate, Low-Energy Buildings.

Introduction

The European Performance Building Directive states that all new buildings constructed after 2020 should consume "near zero energy" (EPBD 2010). This demand requires that design decisions in the early design phase are based on careful considerations about their potential impact on energy efficiency. Design decisions also have to respect other design issues such as thermal comfort, cost, aesthetics and other design issues. Choosing the appropriate combination of design options is therefore a complex task which requires the management of a large amount of information on the properties of design options and the simulation of their performance. Computer-based building simulation tools are ideal for facilitating these tasks.

There is a well-established research movement that seeks to enhance the use of building simulation tools in the early design stage and, consequently, there are many suggestions, experiments and examples on how to do this, e.g. Morbitzer (2003), de Wilde (2004) and Petersen (2011) to cite but a few. However, there seems to be a low uptake of these research efforts in professional design practice. Researchers are investigating the potential reasons for this, e.g. Attia (2011), Holst and Kirkegaard (2010) and de Souza (2011). Reasons can be divided into issues related to the capabilities of tools (interface, input/output, etc.) and issues related to the integration of tools in design practice (work flow, culture, eye of the beholder, etc.). The lack of integration in design practice is the major motivation for proposing the method described in this paper. Building simulation is mainly used for an evaluative purpose. The aim of this paper is to contribute to a development where building simulation is used for a generative purpose.

Parametric Design and Simulation Tools

The proposed method is based on the principle of parametric design. The basic principle of parametric design is to iteratively modify different parameters of the design while continuously evaluating its performance. The principle has been applied for design before the age of computers. It was for instance used by the architect Antonio Gaudi when he designed the Cathedral Sagrada Familia in Barcelona in 1910. Gaudi used physical parametric models to optimize the shape of the cathedral according to aesthetical or structural criteria. One of the more simple parametric models of Gaudi was the cylinder shaped by two circles connected with strings (figure 1). While rotating one of the circles the overall shape of the cylinder changed. In this case the rotation degree of the circle was the varying parameter in the parametric model.

Figure 1. Parametric Model of a Cylinder Made by Gaudi, 1910 (http://ilaba.wordpress.com/2009/06/14)

Today, parametric models with high complexity can be established relatively fast and easily in computer programs like Grasshopper (2014). According to Nembrini *et al* (2014), computational parametric models are furthermore an effective way to intertwine architecture with indoor climate and energy performance. Programs for handling computational parametric models are therefore a suitable platform for a new generation of generative building simulation tools embedded in geometrical model platforms which are already familiar to architects. There are already several tools available for these programs. In the Grasshopper environment, there are simple tools like Ladybug (2014) which provides climate visualizations, and more sophisticated ones like the daylight simulation tool DIVA-for-Rhino (2014). These evaluative plugins can be linked to optimization algorithms like Galapagos (2014) to become more generative. There are, however, still barriers for full integration of indoor climate, daylight and energy considerations in the generative design process. These barriers can often be linked to the limitation in the available simulation tools, such as a limited capability of indoor climate evaluation, lack of integrated daylight and thermal simulations, lack of the capability to evaluate natural ventilation concepts, and limited possibilities for adjusting operation schedules and HVAC systems. This paper therefore also presents a new plug-in tool for Grasshopper that accommodates these barriers.

Method

The proposed method is inspired by the paradigm of performance-based design as described by Kalay (1999), see figure 2a. Here, the first step is to define performance requirements, which for instance could be a maximum use of energy, desired amount of daylight, range of acceptable indoor temperatures, conceptual thoughts on architectural expression, structures etc. The next step is to make a design proposal. The performance of the proposal is then predicted and the designer determines whether the performance is desirable or not. If the design proposal is desirable, the design is completed. If not, the designer enters an iterative process where new designs are proposed, performance predicted and evaluated until a desirable solution emerges. In this rather traditional workflow, the designer uses intuition and pre-experienced knowledge to come up with design proposals. Consequently, an unexperienced designer has a distinct risk of making inexpedient design decisions resulting in an inefficient design process where iterations is running in (too) many loops.

To minimize the number of iterative loops, Petersen and Svendsen (2011) suggest using simulation-based performance predictions and parametric analysis to inform decisions made in this part of the process (figure 2b). This has an educational effect on the designers and will (hopefully) save some loops and thereby time. However, just as in figure 2a the workflow of figure 2b still heavily relies on the judgment of the designer who in each loop needs to consider which parameters to analyse and make decisions upon.

The method proposed in this paper is depicted in figure 2c. The method starts by setting performance requirements just as in figure 2a and 2b. The designer then proposes a design formulated as a parametric model with a number of parametric variables. The proposal could be based on an overall architectural idea, a conceptual thought or something third – a practice similar to the parametric works by Gaudi in early 20th century. The model is then linked to a system of simulation tools including the newly developed thermal plugin (see the section "Operationalization of the method"). These tools are linked to an optimization algorithm that automatically generates the optimal and a range of near-optimal geometrical solutions. These solutions are presented to the designer together with performance data for decision making. The parametric model can be adjusted accordingly if none of the geometries are desirable, and the performance of the new model can be predicted or a new range of design proposals can be generated.

The fundamental difference in this proposal compared to the methods in figure 2a and 2b is that the generation of design proposals fulfilling performance requirements has been automated. This means that designers no longer have to consider how to remedy any misfit to the performance requirements. Instead designers can concentrate on assessing the architectural quality of the automatically generated designs. The trade-off of this functionality is that the automation deprives the designer from the iterative learning process on indoor climate, daylight and energy as in case of figure 2a and 2b.

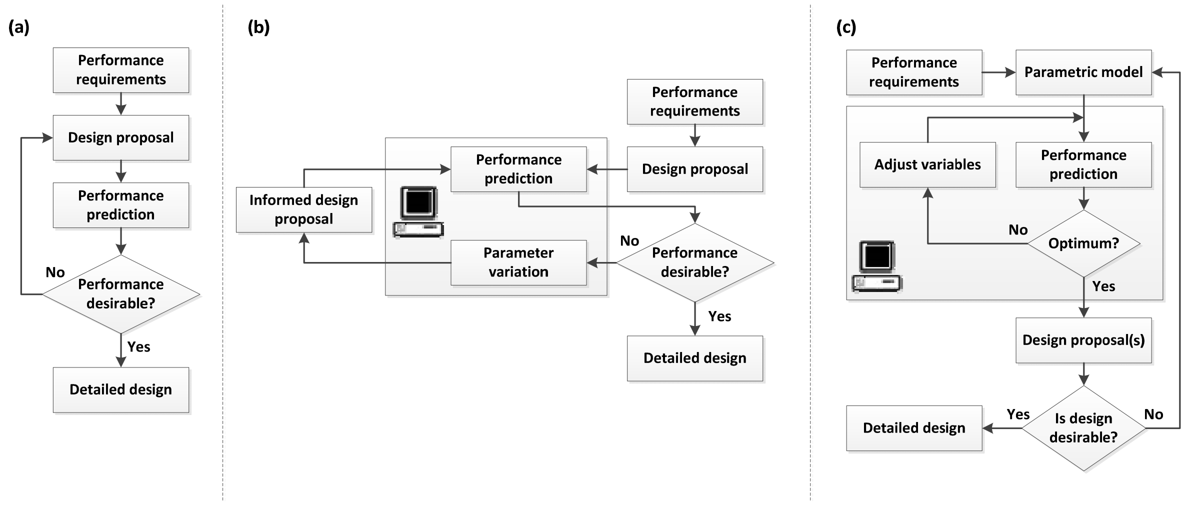


Figure 2. Development of the Performance-Based Design Paradigm, (a) Performance-Based Design (Kalay, 1999), (b) Implementation of Parameter Variation to Inform Design Decisions in Performance-Based Design (Petersen, 2010), (c) The Proposed Method that Automates the Generation of Design Proposals.

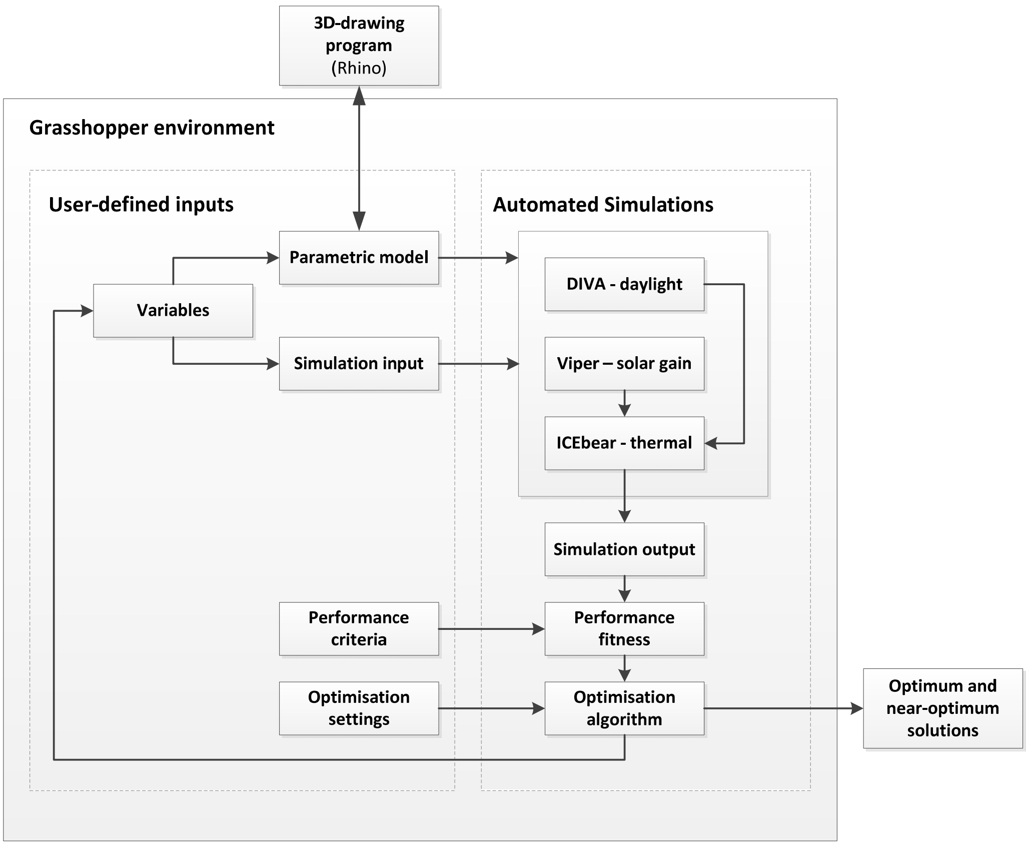


Figure 3. Flow Diagram of the Operationalized Method

Operationalization of the Method

The method is operationalized to automate the generation of room design proposals which fulfils user-defined performance criteria for energy efficiency, thermal comfort, air quality, and daylight levels. The operationalization is implemented in the parametric programming platform Grasshopper (2014) which is a plug-in to the 3D-drawing program Rhinoceros (2014). The flow chart in figure 3 illustrates the data flow of the implementation. The user first defines a basic geometry of the room. The user can choose to make the geometry of the design directly in the Grasshopper environment or as a parameterization of a Rhino model. The user also has to specify a range of simulation inputs used by the DIVA-for-Rhino plug-in (2014) and the newly developed thermal calculation plug-in. The new plug-in is based on the algorithms of the hourly-based thermal simulation tool BuildingCalc (Nielsen 2005) and a network model for natural ventilation combining stack and wind ventilation (SBi 2002). The plug-in is thus capable of predicting indoor climate and energy performance of design proposals.

The plug-in is called ICEbear: ICE is an abbreviation for “Indoor Climate and Energy” and the “bear” is added because the Grasshopper plug-ins often uses animal names. Furthermore an “ice bear” is close to a polar bear which has anatomic mechanism to keep the body in right temperature and is often associated with sustainability and climate change. The aim of the ICEbear plug-in is to generate more sustainable building designs and by that the name is found suitable.

The next user task is to decide which of the geometrical parameters and simulation input that are variables and to define their limitations e.g. as a possible ranges or movement patterns. Finally, the user has to specify performance criteria and optimization settings.

The geometric model and simulation inputs are sent to the automated simulation environment where the DIVA-for-Rhino component DIVA is used to calculate hourly illuminance levels in a reference point, and the component Viper is used to calculate hourly solar heat gain. The output from DIVA and Viper is then sent to ICEbear. Here, the DIVA output is used to determine the need for lighting in user-defined schedules which consequently leads to a heat load in the model, and the output from Viper constitutes the solar heat gain to the model. Other inputs to the thermal calculations such as schedules defining additional heat loads due to people and equipment, HVAC systems operation, weather data, and pressure drop characteristics for any natural ventilation are defined by the user in the simulation inputs. The DIVA/Viper/ICEbear complex then executes an hourly-based integrated daylight and thermal simulation with a simulation time of approx. 30 seconds. The simulation output (indoor climate, daylight and energy performance) is evaluated according to the performance criteria set by the user. This information is sent to the optimization plug-in Galapagos (2014) which is adjusting the user-defined variables and running simulations until an optimal solution is found. This solution is displayed together with range of near-optimal solutions. This way it is in fact the use of the Galapagos optimization algorithm that automates the generation of design proposals.

Practical Application of the Method

In the proposed method, the generation of design proposals that fulfil predefined performance criteria is automated. But the design freedom is still in the hand of the human designer who defines the solution space, i.e. the boundary conditions for the generation of design proposals. In other words, it is the human designer that freely defines the initial geometrical model, the geometrical and technical variables and their degree of freedom.

Figures 4, 5, and 6 show examples of user-defined parametric models ready for the automated generation of design proposals. The examples are divided into three geometrical design tasks: The façade, the room or the overall building. The rooms shown in figure 4 have the same room geometry but different conceptual ideas for the façade geometry, and figure 5 are examples of different geometrical issues on room level. The proposed method could in principle also be applied for generation of overall building shapes. As an example, the variable could be the rotation degree of the building torso similar to the idea of the high-rise “Turning Torso” in Malmö designed by Calatrava (figure 6). The degree of rotation could be optimized according to indoor climate, daylight and energy using the proposed method and its tools.

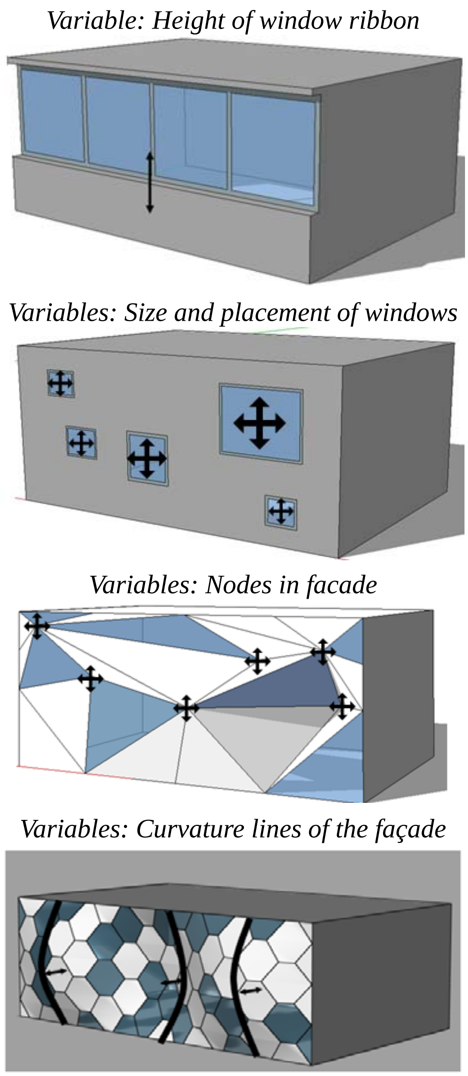
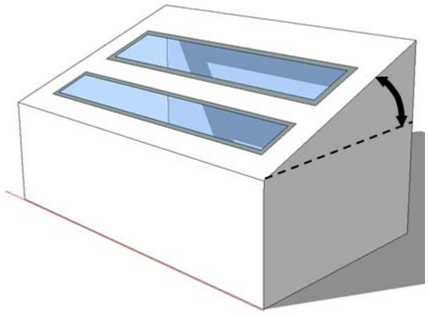


Figure 4. Examples of Parametric Models of Façade Concepts and Variable(s)

Variables: Height, depth and width of the room

Variable: Slope of the roof



Variables: Nodes defining room geometry

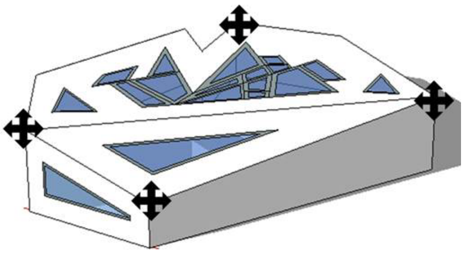


Figure 5. Examples of Parametric Models of Room Geometry and Variable(s)

Figure 6. Turning Torso by Calatrava, Malmö, Sweden. In the proposed method, the variable could have been the rotation of the building torso. (www.bizzbook.com/map/turningtorso2004.html)

Case

A case featuring the geometry of a façade was executed to illustrate how the operationalized method works in practice. It was decided that the aesthetical expression of the façade design should create a feeling of diamonds. Therefore the façade elements were made of triangles connected in six points, see figure 7. These six points could move in three directions (x, y and z) with boundary conditions of ±1m in y-direction and inside each $^1/_6$-part of the façade for the x and z directions (the dashed boxes in figure 7). The room was naturally ventilated through two bottom hung window near the ceiling. The placement of the two additional windows was to secure a view out. The room was in connection with an atrium where the ventilation exhaust was located at the roof. The performance criteria was to reach a maximum energy use for building operation 25 kWh/m2/year while fulfilling thermal class II according to DS/EN 15251 without having more than 100 hours above 26 °C, air quality class II (ibid.) and a minimum daylight autonomy of 60 % in a point in the middle of the room.

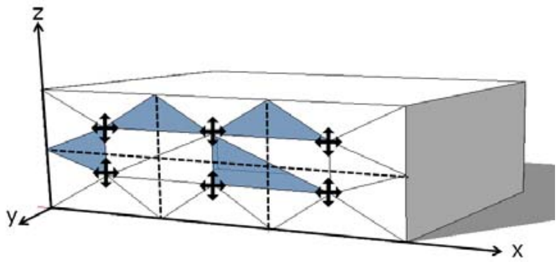


Figure 7. Case Example Featuring a Façade Design with Six Variable Nodes in the Façade.

Results

Optimization of the case was made for a north-oriented room and a south-oriented room. Figure 8 shows that the solution for the north-oriented room started to converge after approx. 160 iterations. The performance criteria regarding indoor climate were fulfilled but the energy criterion was never fulfilled. The minimum energy use of 34.8kWh/m^2/year was found after 254 iterations. This solution is visualised in figure 9.

No converged solution was found for the south-oriented room after 234 optimization iterations, see figure 10. Instead the optimization seems to oscillate between a few different shapes. The optimization algorithm has a hard time finding an optimum because the heat gain from direct sun is fluctuating a lot as it is very sensitive to the area and tilt angle of the windows. However, after 234 iterations there are a number of solutions that fulfil or almost fulfil the performance requirements. Some of these are pointed out in figure 10 (top) and illustrated in table 1 together with their performance data. An interesting aspect from an architectural point of view is that the solutions have different appearance even though the indoor climate and energy performance are quite similar.

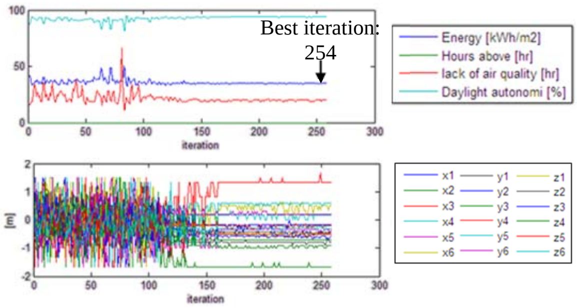


Figure 8. Optimisation of North-Oriented Room. Top: Performance. Bottom: The Relative Location of the Variables

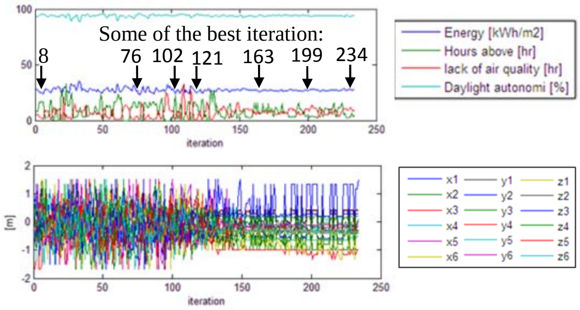


Figure 10. Optimisation of South-Oriented Room. Top: Performance. Bottom: The Relative Location of the Variables

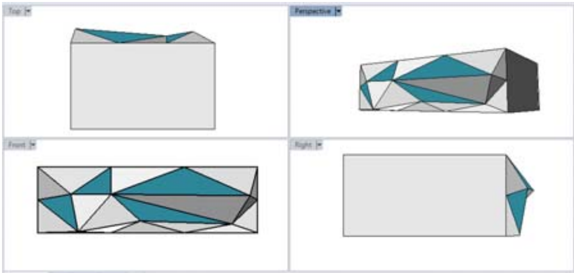
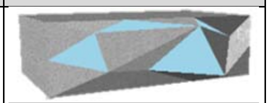
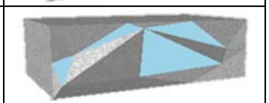
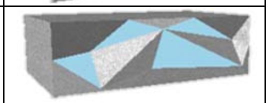
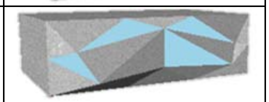
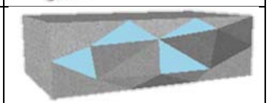
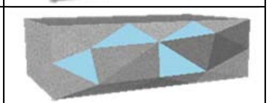
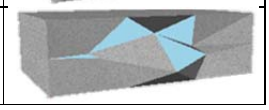


Figure 9. The Façade Geometry of Iteration No. 254 for the North-Oriented Room

Table 1. A Selection of Façade Design Proposal for the South-Oriented Room which Fulfils or Almost Fulfils the Performance Requirements

Iteration number	Energy Consumption [kWh/m2/year]	Above 26 ^{o}C [hours]	Poor air quality [hours]	Daylight Autonomy [-]	Visual appearance of the façade
8	25.3	20	1	0.95	
76	24.0	17	1	0.96	
102	24.8	17	1	0.95	
121	24.8	17	1	0.95	
163	26.8	7	6	0.94	
199	26.6	12	5	0.94	
234	26.1	3	8	0.95	

Discussion

In the proposed method, design proposals fulfilling certain performance criteria are generated automatically by a computer instead of a human designer. This might raise the question: Can computers replace the human designer? This method could be perceived as a small step in that direction. However, this is not the case as the method does not work without having a human designer stating the architectural idea and its boundary conditions. The few examples in section "Practical application of the method" illustrates that design freedom is practically unlimited. The only limitation is the imagination of the designer and how well the geometry can be described in Grasshopper. In the case of this method, computers are therefore merely a powerful tool for the human designer: $1.3 \cdot 10^{24}$ simulations were needed if all solutions in the example (section "Case") were to be simulated. This would take the same amount of time as ½ billion times the age of the earth. The computer found possible solutions after only 200 iterations (approx. 7 hours). Furthermore, the human designer always has the right to dismiss geometries generated by a computer for whatever reason. The ultimate power of design is thereby still in the hands of the human designer.

Conclusion

This paper presents a method for using parametric models to automatically generate design proposals that fulfils predefined performance criteria regarding indoor climate, daylight and energy performance. These proposals should be perceived as an input to a performance-based design process. The operationalization of the method includes a newly developed thermal calculation tool called ICEbear which is a plug-in to Grasshopper. ICEbear is able to simulate the annual indoor climate, daylight and energy performance of complex geometries based on hourly weather data. This tool is used together with an optimization algorithm for automatically generation of design proposals based on input from the human building designer regarding the conceptual idea. A case example illustrates that the method can generate a range of near-optimal solutions regarding criteria for indoor climate, daylight and energy performance. It is then up to the human designer to make the actual design decision on which solution to refine further.

Future work on this method includes investigations on whether the proposed method is useful to practicing designers working on real life building projects. Another task is to ensure that the information used for the simulations can be exported from the current sketching platform to any BIM model platform more suitable for the detailed design phase.

References

Aggerholm, S., Andersen, K.T., Heiselberg, P. (2002) *SBi 202: Naturlig ventilation i erhvervsbygninger* (in Danish), Hørsholm, Denmark, SBi.

Attia, S. (2011) *State of the Art of Existing Early Design Simulation Tools for Net Zero Energy Buildings: A Comparison of Ten Tools*, Technical report, Université catholique de Louvain, Louvain La Neuve, Belgium.

de Souza, C. B. (2011) Contrasting paradigms of design thinking: The building thermal simulation tool user vs. the building designer. Automation in Construction, Vol. 22, pp. 112–122

de Wilde, P. (2004) *Computational support for the selection of energy saving building components*, Ph.D. Thesis, Delft, The Netherlands, Delft University Press.

DIVA-for-Rhino (2014) Solemma, US, http://diva4rhino.com/

EN 15251. (2007) Indoor environment input parameters for design and assessment of energy performance of building-addressing indoor air quality, thermal environment, lighting and acoustics.

EPBD (2010) Directive 2010/31/EU of the European Parliament and of the Council of 19 December 2010 on the energy consumption of buildings (recast).

Galapagos (2014) Rutten, D., Austria, http://www.grasshopper3d.com/group/galapagos

Grasshopper (2014) Scott Davidson, US, http://www.grasshopper3d.com/

Holst M. K. and Kirkegaard, P. H. (2010) Computational Design Tools for Integrated Design, *1st International Conference on Structures and Architecture*, Guimarães, Portugal, pp. 1658-1665.

Kalay, Y.E. (1999) Performance-based design, *Automation in Construction*, Vol. 8, pp. 395–409.

Ladybug (2014) Roudsari, M.S., US, http://www.grasshopper3d.com/group/ladybug

Morbitzer, C. (2003) *Towards the Integration of Simulation into the Building Design Process*, Ph.D. thesis, University of Strathclyde, Glasgow, Scotland.

Nembrini, J., Samberger, S., Labelle, G. (2014) Parametric scripting for early design performance simulation. *Energy and Buildings*, Vol. 68, pp. 786–798.

Nielsen, T.R. (2005) Simple tool to evaluate energy demand and indoor environment in the early stages of building design, *Solar Energy*, Vol. 78, pp. 73–83.

Petersen, S. and Svendsen, S. (2010) Method and simulation program informed decisions in the early stages of building design. *Energy and Buildings*, Vol. 42, pp. 1113–1119.

Petersen, S. (2011) *Simulation-based support for integrated design of new low-energy office buildings*, Ph.D. thesis, Kgs. Lyngy, Denmark, DTU-Tryk.

Rhinoseros (2014) Robert McNeel & Associates, US, http://www.rhino3d.com/

Civil Engineering Capstone Design Courses Devoted to Structural and Architectural Renovation Projects

Yu-Chou Chiang, Shang-Hsien Hsieh, Wen-Cheng Liao, and Hervé Capart*

jerrold0625@gmail.com, shhsieh@ntu.edu.tw, wcliao@ntu.edu.tw, hcapart@yahoo.com

Department of Civil Engineering, National Taiwan University

Abstract: Engaging in a realistic design experience is widely seen as a fruitful way for engineering students to cap their undergraduate training. In industrial design, senior student projects often culminate in the fabrication of a functional prototype that can be evaluated by jury and tested by users. In civil engineering, however, real projects typically develop over time periods much longer than a single senior year, at scales too large to allow rapid prototyping. At the Department of Civil Engineering of National Taiwan University, our capstone courses of the last two years have sought to address this conundrum by various means. These include: focusing on building renovation projects of modest scale; working on campus projects for which there is a possibility of actual construction; using scale models and partial prototypes; involving professional architects and engineers, and starting capstone projects in the junior year to allow more time for students to pursue and materialize their designs. We describe one renovation project for which it was possible to complete the full cycle, from design to construction, over a span of two years coinciding with the junior and senior years of the student designers. The second project, likely to remain a simulation exercise, nevertheless incorporated various means to make the design process more realistic. For both actual and simulated projects, addressing the renovation of an existing structure in dialogue with users and owners help students ground their capstone design experience in reality.

Keywords: Capstone Design, Design to Construction, Structural and Architectural Renovation.

Introduction

Around the world, a number of civil engineering programs are seeking ways to integrate realistic design experiences in the undergraduate curriculum. These include programs at Stanford University (Fruchter, 2001), George Mason University (Arciszewski, 2009), the Technical University of Denmark (Jensen and Almegaard, 2011), and the Massachusetts Institute of Technology (Einstein, 2013). At the Department of Civil Engineering of National Taiwan University, we started experimenting in 2010 with a sequence of cornerstone, keystone, and capstone design projects, targeted respectively at freshman, sophomore, and junior/senior undergraduates (Capart *et al.*, 2013). For these projects, one of our objectives has been to let students test their ideas in practice by combining digital design with material fabrication or construction.

For the mandatory cornerstone course, first year students use jet-cut aluminum to build and test scale models of their structural designs. The optional keystone course allows second year students to design and build 5 m span wood bridges, in cooperation with architecture students from Shih-Chien University (Hsu and students, 2013), and to design and fabricate functional pneumatic toys (Capart et al., 2013). For the capstone course, however, we have found it more difficult to complement design with a meaningful material component. Our first attempts (Wu et al., 2011) sought to ground projects in reality by targeting real sites: Xitou Forest, for the design of a cableway system, and Wushe Reservoir, for the design of sedimentation countermeasures. The design process included user and field surveys, and some lab experimentation, but the final result of students' work was limited to written and oral reports, without a material product. Scaled physical models were produced in later editions, but did not greatly improve on the scale models that students can already produce in their first and second years.

In 2012, an opportunity arose for students to pursue a real project, when the department considered renovating a student space in our own building. The large first floor space, previously devoted to laboratories, had become a space for student activities, but had not been transformed in any way to meet the new user requirements. A planning stage in which students participated produced attractive proposals (Mu and students, 2012), and we decided to devote a capstone course to the design of a feasible structural and architectural renovation. Although the course was open to both junior and senior students, only juniors enrolled (save for one senior), and this allowed student designers to get involved in the project over more than one year. In this contribution, we describe the resulting capstone experience, which culminated in actual construction.

We also describe a new edition of this capstone course, currently in progress with a new generation of juniors and seniors. It again involves the renovation of an aging campus building, but is likely to remain a simulation exercise. Nevertheless, a number of lessons learned from our experience with a complete design-to-construction project have allowed us to improve the realism of this new edition. Below, we first describe the contents and approaches of the capstone courses. We then evaluate the courses in light of the four capstone aims proposed by Gardner, Van der Veer and Associates (1997) and adopted as guidelines by National Taiwan University (Center for Teaching and Learning Development, 2012). These four aims are integration, closure, reflection, and transition.

Student Space Renovation Project

Student Assessment of Structural Retrofit Schemes

The student space renovation project involved two components: first, a retrofit of the existing reinforced concrete (RC) structure, to allow some alterations to the building yet increase safety against earthquakes; secondly, the design of new elements, in particular a new mezzanine floor to allow more diverse uses of the large space. For both components, structural and architectural considerations were to be jointly taken into account.

To explore different ways of shoring up the structure, student teams first investigated various retrofit schemes (figure 1). For each scheme, students fabricated a 1:14 scale model of a single building frame strengthened by their proposed retrofit. Analogue materials were used (soldered copper substituted for reinforcement steel, and a sand-gypsum mix substituted for concrete), to facilitate fabrication at small scales yet produce scaled behaviors similar to real RC frames (Harris and Sabnis 1999; Lu et al., 2007; Knappett et al., 2011).

Students then subjected the model frames to quasi-static pushover tests. In these tests, vertical loads are kept constant, but lateral loads are gradually increased until failure to model the effects of horizontal ground motions. These experiments allowed students to acquire a better feel for the way reinforced concrete structures behave under earthquake loads, and to compare the performance of their different retrofit approaches compared to a reference bare frame (no retrofit) constructed using the same model materials.

Based on those tests, supplemented by advice from experienced structural engineers, a scheme involving wing walls and a new grade beam was selected. To investigate whether this scheme could more than compensate for the removal of a wall infill, students learned to simulate frame behavior using hand calculations and professional structural analysis software (ETABS). To check actual conditions below grade, an exploration pit was dug at this stage. Students then performed a new round of scale model tests using the verified dimensions and calculated wing wall sections. The experiments and calculations confirmed the suitability of the proposed scheme, which the students defended in the final design review of the semester. The conclusions of the student assessment were not altered by the subsequent professional analysis, performed by the practicing engineer in charge of the final renovation design.

New Architectural and Structural Components

For the second component of the course, students developed designs for new architectural and structural components, including a mezzanine floor and its staircase. This took place in parallel with the development of structural retrofit schemes over the Fall 2012 semester. At the end of the semester, however, proposals were not nearly as mature as the structural retrofit schemes. We therefore extended the effort beyond the Fall semester. A group internship at a professional wood workshop took place during the Winter. This allowed student designers to work with craftsmen to developed prototypes of possible components of the mezzanine and staircase. The ability of students to produce feasible designs that could actually be constructed progressed greatly as a result (for a detailed description, see Chung *et al.*, 2013).

In the Spring 2013 semester, the students who participated in the Winter workshop then continued to develop their designs, in dialogue with professional architect and structural engineer, and with the future student users of the renovated space. Five teams of students were responsible for different components of the design, and also met regularly to seek consensus on how to assemble the parts together into a coherent proposal. This culminated in the drafting by students of detailed construction drawings, including both wood and steel components, carefully integrated together (figure 2).

By the end of the Spring semester, student designs had progressed markedly, and convinced the department to go ahead with implementing the scheme. Architect and structural engineers were commissioned to professionalize the designs, including structural safety calculations and the preparation of bidding documents. Upon securing funding, the work was subdivided into three parts, assigned respectively to a general contractor, a specialty steel contractor, and the wood workshop which hosted the Winter internship (which forms part of the Experimental Forest of National Taiwan University).

Figure 1. Assessment of existing structure and retrofit options for the student space project. Top to bottom and left to right: students survey the existing structure, composed of parallel RC frames; fabricate scaled RC beams composed of soldered copper and a gypsum mix poured into wood formwork; conduct pushover tests on a scaled model of a single frame, strengthened by wing walls and a new grade beam; discuss experimental model response with an experienced teacher; simulate frame behavior using professional software, guided by practitioners; report the results of their retrofit assessment. After further professional involvement, the option investigated by students was adopted for actual implementation.

Figure 2. Design of new structural and architectural components for the student space project. Top to bottom and left to right: concept sketch developed by students prior to the course; preliminary student designs for a mezzanine structure and staircase; design review by a professional architect; fabrication of a flitch beam prototype during a winter internship at a professional wood working facility (for a detailed description of this workshop, see Chung *et al.*, 2013); discussion of steel assembly details with a practicing structural engineer; student drafting of the construction drawings, taking professional input into account; 3D view of the final student design combining wood (brown) and steel (gray).

Actual Construction

Actual construction started in August 2013, and provided many opportunities for continued involvement by the student designers (figure 3). Two of the students interned as junior worksite engineers. They were tasked with documenting the progress made by the general contractor, and with following up on design changes, some due to new information which emerged during the construction process. As an example, one of the brick walls to be removed turned out to include an unexpected RC column, which was not removed for the sake of structural integrity.

Other students participated in incorporating design changes suggested by the structural engineer, steel and wood contractor. Although no essential feature of the student designs was altered by engineer and contractor, many small changes were made. This included details of the steel assembly, improvements to the interface between wood and steel components, and dimension adjustments to fit the actual geometry of the space after completion of the retrofit work by the general contractor. An interesting change to the staircase was the contractor's recommendation to switch from an even to an odd number of steps, in line with construction practices deemed auspicious by traditional Taiwan builders.

Last but not least, student designers had the joy of seeing their designs gradually materialize over the semester. Milestones included the partial demolition and excavation, the pouring of concrete for the new grade beams and wing walls, the fabrication and erection of the steel structure, pull-out tests to verify the anchorage of the steel columns onto the RC footings, and the fitting of the wood elements of the mezzanine structure, deck and staircase. The renovated space was inaugurated on January 10, 2014. The happy occasion was attended by the student designers and many of the craftsmen, professionals and instructors who contributed to the project.

Old Library Renovation Project

Project Background

Building on our experience with the student space project, a new capstone course centered on renovation was offered in the Spring 2014 semester to a new generation of students. The project focuses on the hypothetical renovation of an aging campus building: the old library of the College of Management. This building was originally constructed by the US army when it operated an air station near National Taiwan University. It was later incorporated into the university campus and used as a college library. For many years, the aging building has hosted the student associations of the College of Management. The building has not been significantly adapted to suit this new function, its roof leaks, and the structure is only marginally safe. No renovation is currently being considered by the school because the building may be torn down to make way for a new development. Nevertheless, the building is attractive as an interesting case for a simulated renovation project.

Structural Assessment

Focused on this building, the new edition of the capstone project again included two components: a structural assessment of the existing structure, and the development of renovation proposals including new roof designs (figure 4). Two sections were opened to accommodate the increased number of students wishing to enroll in the course. For the structural component, student teams initially conducted a survey of the existing building. As the building is more complex than the student space, different groups were tasked with assessing different frames of the building, taken respectively in the longitudinal and transverse directions.

Improving upon the more ad hoc training provided previously, tutorials were organized to teach students how to assess the structural safety of RC buildings. Students learned to calculate loading cases and pushover curves using hand calculations, as well as using professional structural analysis software (ETABS). The earlier student space project was used as a great source of examples for presentation and practice, before students applied what they learned to the old library case. To help students get a feel for the construction and behavior of RC structures, each team constructed a 1:12 scale model of the frame they were tasked with. Models were again constructed from soldered copper and gypsum mixes, and subjected to laboratory pushover tests. Based on their calculations and experimental results, students presented their assessment for technical review by instructors and practicing structural engineers.

New Architectural and Structural Components

In parallel with the structural assessment, student teams developed proposals for structural and architectural improvements to the existing building (figure 5). Teams subjected their evolving concept to peer review, then professional review by practicing architects. After making changes in light of these reviews, students prepared draft proposals for presentation to the current users and manager of the building (student association representatives and the Vice-dean of the College of Management). Although the proposals concerned a simulated renovation not currently considered for implementation, a lively discussion ensued, offering student a quite realistic experience of meetings between clients and designers (figure 6).

Figure 3. Implementation of the structural and architectural renovation scheme for the student space project. Top to bottom and left to right: design presentation to future users of the space; wall demolition; construction of the wing walls and new grade beams, including footings supports for the mezzanine structure; student monitoring of worksite progress; on-site erection of the mezzanine steel structure; anchor bolt pullout tests; fitting of the wood components of the flitch beams; student designers examine the nearly completed mezzanine deck. The steel contractor redrew the students' steel construction drawings, but the wood contractor worked directly from the student drawings.

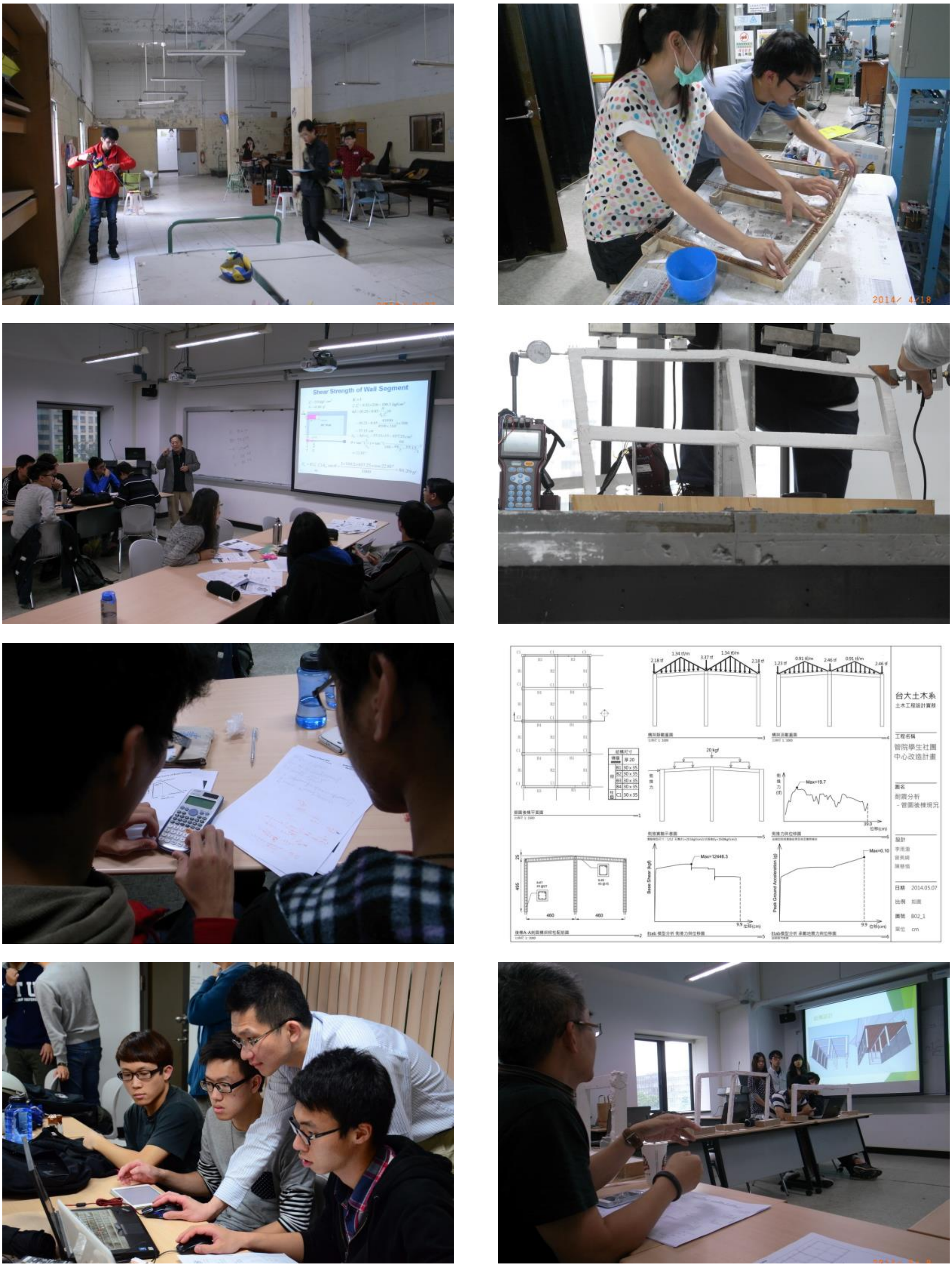


Figure 4. Assessment of existing structure for the old library building project. Top to bottom and left to right: students survey the existing structure, learn how to calculate the seismic capacity of typical RC structures, using the student space project as example; calculate the seismic capacity of the old library structure by hand, and using professional software; build structural scale models using soldered copper and a gypsum mix; conduct pushover tests of their model frames; report the results of their structural assessment using a CAD sheet summarizing their assumptions, calculations, and experimental results; discuss their assessment during a technical review session with a practicing structural engineer.

Figure 5. Development of renovation proposals for the old library project. Top: peer review of preliminary proposals for renovated roofs. Bottom: white board design of key structure details.

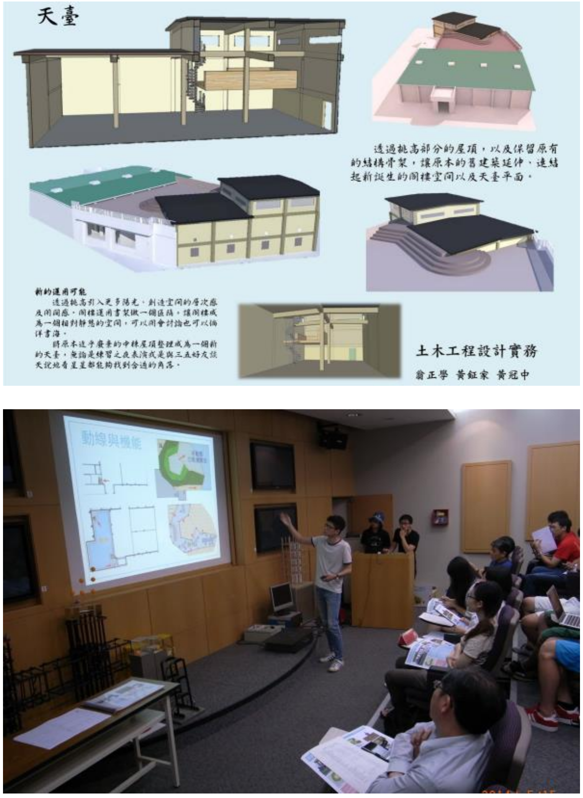


Figure 6. Student renovation proposals for the old library project. Top: draft student proposal poster. Bottom: presentation of draft student proposals to users and manager.

Evaluation

How much do such design projects contribute to the students' capstone experience? Gardner, Van der Veer and Associates (1997) and the NTU Centre for Teaching and Learning Development (CTLD, 2012) recommend that important dimensions of the capstone experience should include integration, closure, reflection, and transition. The design projects described above address some, but not all of these dimensions.

Regarding integration, design projects focused on building renovation are an excellent way to achieve vertical integration of skills and knowledge acquired by students at various stages of their undergraduate education. These include operational skills acquired by students in their freshman year, such as surveying and engineering graphics, basic analytical abilities acquired in the sophomore year, in courses on structural mechanics, and their application to the most common structural elements and materials learned in the junior year, in courses on reinforced concrete. Likewise, a course on construction management has equipped students with knowledge of the organizational and budgetary context of civil engineering projects. The capstone design project further connects these skills and domain knowledge to design abilities developed during cornerstone and keystone design projects. The joint consideration of structural and architectural issues also encourages students to bridge between a core sub-discipline of civil engineering (structural engineering), and a discipline beyond the strict confines of civil engineering (architecture). The above design projects, however, do not address the horizontal integration between different civil engineering sub-disciplines (geotechnical, hydraulic, transportation engineering, etc.)

The capstone design projects contribute to closure by allowing students to demonstrate the mastery they have acquired with various skills and disciplines. Students have the opportunity to produce technical drawings, craft scale models, and develop design proposals that approach or attain professional quality. For the student designers who participated in the student space project, an exceptional degree of closure was achieved when students saw their designs actually constructed. Even when projects cannot be brought to such degree of completion, the products of the capstone courses supply a strong closing chapter to students' design portfolio.

Reflection is a dimension not currently targeted by our capstone design projects. The capstone projects emphasize creation over reflection, and their primary aim is to encourage students to actively practice design. Some reflection does occur when students evaluate their designs jointly with instructors and professionals, but this evaluation typically focuses on design products rather than design process. Neither do the capstone projects aim to let students reflect on their broader learning itinerary since their freshman year.

Transition is addressed in various ways by the capstone projects. The most important transition they seek to achieve is one between passive reception and active practice. Ill-defined problems must be identified and solved, using resources that students must actively corral from various sources. The projects also seek to bridge between individual learning and team work, with opportunities for students to develop their skills as leaders and contributors to team efforts. A transition toward professional attitudes is sought by challenging students with realistic problems and tasks, and allowing students to interact with the professionals who intervene as mentors and reviewers.

Complementing the capstone design projects, our department has developed other initiatives which contribute to a more comprehensive capstone experience. This includes a summer internship program, typically pursued by students between their junior and senior years. Internships are preceded by a semester-long seminar, which provide opportunities for students to reflect upon their strengths and interests, and meet with a variety of guest professionals to discuss the skills and attitudes needed to thrive in engineering practice.

The senior year is also an important transition between undergraduate and graduate study: students apply for graduate programs in the middle of their senior year. In the second semester, those who go on to graduate school in our own department often start to work on research projects with their future graduate advisors. Those who aim to transfer to other programs, on the other hand, typically enlist in elective courses related to their target field of graduate study. Finally, a number of seniors participate in international exchange programs. Because of these competing demands on students' preoccupations during their senior year, our experience is that the junior year and first semester of the senior year are the time periods most suitable for intense student involvement in capstone design projects.

Conclusion

Capstone projects focused on structural and architectural renovations feature a number of advantages. Because projects target existing buildings, students must directly engage realistic construction issues. Design efforts, moreover, can be conducted in dialogue with users and managers of the building. The projects allow a strong vertical integration of skills and knowledge acquired by civil engineering students at various stages of their undergraduate education, from engineering graphics to reinforced concrete. They also involve architectural considerations beyond the strict confines of civil engineering. These advantages accrue regardless of whether renovation projects can actually by implemented or only be simulated. The perspective of actual implementation, of course, provides a strong motivation to develop proposals further, and new opportunities for learning occur during the construction stage.

To provide opportunities for greater degrees of completion, possibly up to actual construction in exceptional cases like the student space project, and to avoid conflict with the many competing demands faced by senior year students, we recommend starting capstone projects in the junior year. Also, cornestone and keystone projects pursued in the freshman and sophomore years constitute an important preparation for successful capstone projects. The student designers who completed the student space project were the first generation of students who experienced the full sequence of cornerstone, keystone, and capstone projects. This allowed them to take their design efforts much farther than earlier students for whom the capstone course was the first design experience.

Acknowledgements

Many professionals and academics contributed to these capstone courses, including structural engineers K. Chang, Y.Y. Lu and L.Y. Wu, architect C.C. Chang, contractors C.W. Chen and J.C. Shen, applied researchers T.C. Chiou, M.J. Chung, and F.P. Hsiao, and university instructors L.L. Chung, S.J. Guo, S.J. Hwang, S.Y.J. Lai, F.C. Lin and S.M. Mu. The contributions of wood and steel craftsmen, student designers, student teaching assistants, and project assistants are also gratefully acknowledged. The courses benefited from exceptional support by the Dept of Civil Engineering, chaired by Prof. L.J. Leu, and by the Ministry of Education.

References

Arciszewski, T. (2009) *Successful education: How to educate creative engineers.* Successful Education LLC, Fairfax, USA.

Capart, H., Hsieh, S.-H., and Leu, L.-J. (2013) Cornerstone, keystone, and capstone design project courses for civil engineering students. *Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering*, Worcester Polytechnic Institute, USA, pp. 137-144.

CTLD (2012) *Capstone Course Manual*. Centre for Teaching and Learning Development, National Taiwan University.

Chung, M.-J., Hung, C.-Y., and Capart, H. (2013) Design to fabrication of wood and steel prototypes for a structural and architectural renovation. *Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering*, Worcester Polytechnic Institute, USA, pp. 121-129.

Einstein, H.H. (2013) Design education in civil and environmental engineering. *Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering*, Worcester Polytechnic Institute, USA, pp. 112-120.

Fruchter, R. (2001) Dimensions of teamwork education. *International Journal of Engineering Education*, Vol. 17, Nos. 4 and 5, pp. 426-430.

Gardner, J.N., Van der Veer, G.., and Associates (1997) *The senior year experience: Facilitating integration, reflection, closure, and transition*. Jossey-Bass Publishers, San Francisco, USA.

Harris, H.G., and Sabnis, G. (1999) *Structural Modeling and Experimental Techniques*. CRC Press, Boca Raton, USA.

Hsu, T.H. and students (2013) SCU + NTU Bridge design and fabrication workshop. Student work portfolio. Department of Architecture, Shih-Chien University, and Department of Civil Engineering, National Taiwan University.

Jensen, L.B., and Almegaard, H. (2011) Integrated structural design education. *Proceedings of the First International Workshop on Design in Civil and Environmental Engineering*, KAIST, Korea, pp. 74-79.

Knappett, J., Reid,C., Kinmond, S., and O'Reilly, K. (2011) Small-scale modeling of reinforced concrete structural elements for use in a geotechnical centrifuge. *ASCEJ. Struct. Engng*, Vol. 137, No. 11, pp. 1263-1271.

Lu, X., Zou, Y., Lu, W., and Zhao, B. (2007) Shaking table model test on Shanghai World Financial Center Tower. *Earthquake Engng Struct. Dyn*., Vol. 36, pp. 439-457.

Mu, S.-M. and students (2012) Fundamental Environmental and Architectural Design. Student work portfolio, Institute of Building and Planning, National Taiwan University.

Wu, E.Y.H., Capart, H., and Lin, M.L. (2011) Design with or without expert guidance? Lessons from a new capstone course at NTU-CE. *Proceedings of the First International Workshop on Design in Civil and Environmental Engineering*, KAIST, Korea, pp. 88-93.

The Role of the Customer in Building Design: A Literature Review

Marianna Marchesi[*1] and Irene Paradisi[2]

marianna.marchesi@natec.unibz.it, irene.paradisi@fraunhofer.it

[1] Faculty of Science and Technology, Free University of Bozen-Bolzano, Italy

[2] Fraunhofer Italia Research, Italy

Abstract: Although nowadays building design as well as other design disciplines recognize the decisive role of the customer and the necessity of the early user needs identification to guarantee the effectiveness of solutions and design process, in building design this activity is not yet well-defined. In Italy the traditional approach based on dimensional standards and type solutions is widely applied even though a new approach based on customer requirements and corresponding performances is available. Besides, various experiences in the building sector show attempts to formalize the activity for the collection of the overall needs or requests for specific purposes. Building design may benefit from the introduction of well-established procedures for identifying customer needs. In order to evaluate contributions for the improvement of such activity, this study reviews the role of the customer in building design throughout the years and provides an overview on experiences and available design procedures developed in building and product design.

Keywords: Customer Needs, Building Design, Design Standards.

Introduction

Starting from the second half of the twentieth century, manufacturing companies have conceived their production to fulfill the identified customers' needs. The product is designed to satisfy specific needs. Therefore the understanding of the customer groups' needs is decisive for the success of the product and specific procedures are adopted in order to gain this knowledge. Throughout the centuries, buildings have always been products highly customized to specific customers' needs. However in Italy during the twentieth century, the active customer involvement began to be lost and came to increasing evidence starting from the post-war period. The primary necessity of dwellings to be available in a short time facilitated the establishment of standardization as one of the characteristics of the period since it allowed reaching a minimum dwelling quality at a feasible cost. It affected not only design solutions but even design activities in general and the customers' need collection in particular. Although recently identifying the customer needs has become important even in the building design and a new approach has been developed according to it, the traditional one is still applied in the current building design activity. Among other reasons, the design through dimensional standards and type-solutions was easily accepted even because the 80% of dwellings in big Italian cities was rented flats. Meanwhile in the last decades the tendency de-trended: the number of owned dwellings has strongly increased and nowadays the third-quarters of the Italian families own the dwelling where they live. In Italy the dwelling demand has become similar to durable goods such as cars and furniture rather than goods of investments. Therefore the dwelling has acquired a "communication value": it expresses the personality of the owner. This aspect further expands the heterogeneity of the demand, which is a current trend among all the artifacts. Such heterogeneity creates a segmented building market which requires the introduction of specific procedures to understand the needs of different customer groups and thence design customized buildings. Some recent procedures in building design intend to formalize the collection of the overall customer needs or needs for specific purposes. Other design disciplines such as product design have already well-established such activity in the design process because they have started managing this issue earlier.

This study intends to review the role of the final users and some available procedures within the design process in building and other disciplines. Both these aspects are required to attain a wholly involvement of the customer in a building design.

Customer Needs in Building Design

Different Approaches to Customer Needs

In Italy two different approaches to customer needs in building design are defined during consecutive phases of development: a descriptive approach and a performance approach. In the initial phase, it is established the descriptive approach. It is based on quantitative standards defined according to the number of expected occupants, and it provides descriptions of good solutions and models which designers and manufacturers should reproduce accurately as much as possible. Design solutions are evaluated by comparison with these standards and type-solutions. Such approach is not flexible regarding variations of the dwelling demand since many quantitative standards are the same for all distribution types, and there is a strict relation between number of habitants and minimum dwelling surface without involving other parameters related to different contexts, different users and demands (Regione Emilia-Romagna 1981). As a result the descriptive approach cannot regulate the building quality and it is not able to support the design innovation. These standards were fixed by the Italian government for no-profit house projects starting from 1896. Even in other European countries comparable dimensional standards were established for dwelling based on user number and minimum surface (Regione Emilia-Romagna 1981). In 1975 in Italy dimensional standards are updated: every inhabitant has the right to a minimum dwelling surface as well as to a minimum area for single, double and living rooms (Regione Emilia-Romagna 1981). In the '70, on the basis of dimensional standards, the Italian government entrusts the development of technical specifications to each Region in order to diversify the design of dwelling according to specific context. Unfortunately only few regions such as Emilia Romagna decide to perform studies and researches for the development of local technical rules (Regione Emilia-Romagna 1981).

In the meantime starting from the 1976, a new approach was introduced due to emerging differentiated dwelling demands and the need for the customization of the building process. This new approach analyzes the building as a system able to satisfy specified needs by performances. Different user needs reflecting variable lifestyles and contexts are collected and translated in requirements. Then the specified requirements are reached by building performances. To be effective, such perspective needs requirements and performances measurable by parameters (Regione Emilia-Romagna 1981). This approach is able to address specified level of quality and to support the design innovation because no solution is suggested. It is based on the definition of goals that might be achieved through different solutions (Regione Emilia-Romagna 1981). National and regional building rules traditionally based exclusively on quantitative standards are progressively integrated with qualitative requirements (Regione Emilia-Romagna 1981). Crucial research for the development of this type of approach is carried out by Emilia Romagna region starting from 1978. It intends to elaborate a regional technical regulation for no-profit residential buildings laying the foundations for the new approach based on needs and requirements. The experience finds a large consensus at the national level and in other regions. In 1995, the Emilia-Romagna region defines the building regulation type (RET) on the basis of the new approach in order to provide a regional guide for each local building regulation. The document is then updated in 2000 following the large revision of the national building rules: voluntary requirements are added to mandatory ones updating the previous version. Unfortunately the spreading process of such approach is long and national and local building regulations are not everywhere adapted to it (Rossini *et al*. 2000).

The Role of the Customer

Initially the attention is paid to the object-product, and the customer is merely considered the buyer of the house. Therefore its real involvement on the decisions influencing the quality of the product is missing (Regione Emilia-Romagna 1982). The basic standard on a minimum dwelling space per user is the leading rule. The main reasons are two: the need of planning resource usage in relation to the real necessity and the need of assuring minimum privacy and hygiene conditions with respect to number of user and space dimensions.

Because the dwelling need evolves from a quantitative demand for survival typical of the post war periods to a qualitative demand typical of the globalization era, a different approach for the customers' need collection arises driven by new business development strategies more focused on the market rather than on the product. The attention shifts from the object-product to the subject-user: the customer becomes a user. The user behavior and its demand are analyzed in order to orient the house production offer towards the customers' needs. According to it, new regional technical regulations are developed in order to promote a new strategy and support the conversion of the production toward the satisfaction of the current needs. The performance approach is developed starting from the analysis and classification of the users through their involvement in the definition of user profiles, user needs and for the evaluation/validation of the existing standards (Regione Emilia-Romagna 1981).

During the last decades, while public bodies are generally resilient at changing to the subject-user approach, society and market evolve at a different, faster speed. In Italy the dwelling demand has become similar to durable goods such as cars and furniture rather than goods of investments. Therefore the dwelling has acquired a so called "communication value": it expresses the owner's personality (Castaldo and Sabbadin 2009, Sabbadin 2011). The sector leadership was traditionally taken by the construction company whereas now the private customer is gaining importance and represents a "new" segment of the market. All the stakeholders within the construction value chain are competing to become its preferential speaker (Sabbadin 2007). Both these aspects, 1) the house as a durable good and 2) the attraction of a new sector, increasingly involve the owner but even highlight its actual weakness among the stakeholders in construction. It is due to the heterogeneity of the demand which is a current trend among all the artifacts and to the lack of information coming from experience in such acquisition as happens with other goods (Sabbadin 2007). Moreover actual technologies require a deep consciousness in choices which highly impact the building management and user behavior. A great improvement in marketing might balance the situation. Particularly, the introduction of specific procedures to understand the needs of different customer groups and thence to design customized buildings is necessary.

Identifying Customer Needs

In some design disciplines such as in building design, clients' needs are seldom clearly expressed and collected in a structured way at the early phase of the design process. In building design usually initial statement of design objectives is brief and rather vague. Some objectives are expressed during the design brief; others are obtained by interviewing the clients or by discussion within the design team. This activity is usually performed by the architects using their experience and knowledge without the support of methods. However, the need for identifying customer needs in architectural design is likely to expand due to the increasing complexity of buildings and building systems (American Institute of Architects 2000). Some experiences show the need to format such activity. On the contrary, in product and engineering design, identifying customer needs is already a well-defined activity due to the primary need of offering mass customized products and because it is common knowledge that identifying customer needs in an organized manner facilitates effective design process (Ulrich and Eppinger 2008).

Following the change of the attention from the object-product to the subject-user started in different design sectors, a new approach in the building one emerged in Italy at the end of 70s. This approach focused on the definition of products that satisfy the needs of the users. In order to define the dwelling demand in terms of users and their qualitative and quantitative dwelling needs, the Emilia-Romagna Region experiments a different approach. It is developed starting from the collection of data from no-profit housing habitants via questionnaire and interviews. Data are analyzed and classified for the definition of user profiles (Regione Emilia-Romagna 1982). Afterwards user profile representatives are involved in small group meetings and workshops to collect data regarding user dwelling needs. In order to stimulate the definition of their needs, technical tools such as projects of different plan solutions, drawings and videotape are used. The behavior of user samples are examined and classified and the results are directly checked and validated by comparison with the involved users. By applying this procedure, the users are directly included in the design process and in the validation of the existing dwelling standards (Regione Emilia-Romagna 1981).

The American Institute of Architects (AIA) considers the customer need collection (called architectural programming) as a predesign service related to, but distinct from architectural design (American Institute of Architects 2000). It aims at a systematic evaluation of organizational and project values, goals and needs of clients, users and surrounding community. According to AIA analysis, government agencies use programming service extensively to provide a fully program for the design procurement. Even owners of complex institutional facilities and developers recognize the need for a careful analysis of design issues unlike residential clients who are concerned by additional design cost (American Institute of Architects 2000). It focuses on value identification, project goal setting, discovery of related facts (constraints and opportunities) and development of specific project requirements. This phase may be preceded by preliminary studies (financial feasibility, site suitability and master planning services). The architectural programming is a team process that involves several persons according to the scale of the project, type of facilities, functions and possibly constraints: at a minimum, the programmer, the client and the user, but even sometimes community participants (American Institute of Architects 2000). Five types of information gathering are proposed in architectural programming: literature search/review, interview, observation, questionnaire/survey and group session. The collected data should be organized to be retrieved and analyzed quickly and easily. Therefore only the decisive information in making design decisions should be sought and recorded. Performance and design criteria are identified analyzing all the gathered information. Usually criteria encompass space requirements, space relationships, circulation, ambient environment, safety and security, needed surfaces, furnishings, flexibility and site information. Moreover matrixes showing space allocations and relationships and bubble diagrams showing adjacency relationships are developed. Some preliminary ideas about solution options are then proposed in order to support the evaluation and to recommend the most effective alternatives. The deliverable may be a written architectural program report composed of the methodology documentation, the executive summary, the value and goal statements, the relevant facts, the data analysis conclusions and the program requirements. It also includes project cost estimation and a project schedule (American Institute of Architects 2000).

HOK, an international architectural, engineering and planning firm, has developed a problem analysis method in order to improve the requirement seeking process. This method intends to clarify, to understand and to state the problem that will be solved by design which starts after an exhaustive problem statement. In order to define the whole architectural problem, it is specified in terms of function, form, economy and time (Peña and Parshall 2012). Problem seeking method proposed by HOK intends to support the requirement analysis covering the wide range of factors that influence the design of different building types and also to incorporate sustainable requirements in order to determine the level of sustainability of design and construction (Peña and Parshall 2012). To perform these activities, the method establishes five steps: establish goals, collect and analyze facts, uncover and test concepts, determine needs and state the problem. It provides techniques on how to collect, organize and analyze data, then on how to interview users for data gathering and finally on how to use that information during the decision-making work sessions. An information index is used as a key-word checklist of questions to retrieve appropriate information and to classify them. The process involves the client and the architect group since the early phase of the activity to determine organization needs related to a proposed building project. Before interviews and work sessions, the main decision makers are identified. When a variety of design options is developed, games and simulation techniques support project team and client in taking decisions (Peña and Parshall 2012).

Other experiences involve the customers in the initial phase of the design process to collect specific needs in order to address specific aims during the design process. Fraunhofer IAO (Spath *et al.* 2010) developed a methodology to provide concepts and guidelines for designing optimized space office. The procedure consists of 3 steps: the analysis of work structure and user requirements; the development of user scenarios for the new working environment; the definition of the new work structure and the final work space concept. The first work package takes place in group sessions and workshops at two different settings, the management level (top-down) and the worker representative level (bottom-up). Work structures and processes are analyzed to define the current space usage and possible future evolution, to identify spaces and equipment requirements, to collect and to evaluate qualitative and quantitative user requirements. Then working activity types are defined considering culture, communication, organization, IT concept, knowledge management and economical aspects. On the basis of the defined working activity types, the second work package (work space management strategy) develops office module types, specifies common spaces (project area, meeting-room and connections), and identifies IT integrated support, lighting, acoustics, arrangements and aspects regarding the needs of concentration, communication and brand identification . The final work package provides functional and distribution guidelines for designing to the design team (Spath *et al.* 2010).

The Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) has developed several models to assess water needs in the pre-design phase and to provide objectives, strategies and targets for designing sustainable water usage in the functional recovery of an urban industrial area in Bologna (Italy). These models refer to corresponding design activities: investigation, data acquisition, data analysis and scenarios development. First a specific web-based survey tool is set to record indoor and outdoor water needs. The survey is organized on the basis of expected activities. For each activity, any possible furniture and equipment are indicated with relative water consumption and water waste features in order to assess the water usage on the basis of survey results. Then an assessment tool is set to rank input data and to develop scenarios. Finally the resulting data is evaluated for selecting opportunities of greater efficiency in each major usage category and cost-effective possibilities of usage from one process to another.

A different experience regarding user need analysis in the building design is led by Experientia. This is an Italian design consultancy that supports companies and organizations in designing valuable user experiences through the understanding of how people really live nowadays and how they will live in the future. Experientia took part in designing a sustainable urban district in Helsinki. Because sustainable buildings require sustainable living practices, Experientia’s responsibility among the design team was the delicate topic of how to address behavioral change to support a sustainable style of living in a new urban district. Since it is clear that technology is not sufficient to guarantee sustainability, the aim was to perform the reduction of energy demand and carbon emissions by enabling residents and workers to make better choices about their consumption maintaining a high quality of life (Experientia 2009). Experientia developed strategies to empower people’s change, including engagement and awareness programs, through several measures: services aimed at creating social actions based on green values; technology to assist people in making decisions, such as smart energy meters and dynamic pricing systems; reinforcement loops (with incentives and benefits) for people who live in, work in and visit this building block; and using the community as a knowledge network to share best practices. Therefore potential inhabitants of the new district were involved in the development of their future environments, through the design of sustainable services, and through the creation of behavioral change programs (Experientia 2009). In order to create the behavioral change concepts, Experientia drafted hypothetical profiles of the people who might inhabit the area and the kind of lifestyles they might live. Looking at the hypothetical day-to-day movement of these profiles, Experientia generated ideas on the type of needs and attitudes they might have, the type of services and products they might want, and how their behaviors should and may change for them to become more sustainable (Experientia 2009).

While the experiences mentioned above witness the already started process of establishing customer needs' collection in building design, in engineering and product design there are well-established methods to perform such activity. Some of them are analyzed in order to identify suitable references which can improve the identification of customer needs in building design. In manufacturing, connecting the customers to the product design has become essential to respond to the needs of current dynamic and competitive markets. An analysis of well-known and structured methodologies to capture and organize customer needs in the product design is provided by Kurniawan *et al.* (2004). The proposed framework is composed of 3 phases: customer need elicitation, customer need translation and utility analysis. In order to perform the first step the following methods developed in the marketing research are available: Voice of Customer, Kano Diagram and Web-based Consumer Elicitation Methods. The Voice of Customer is a set of customer needs hierarchically organized. The needs are collected by group or one-to-one interviews, then structured and organized in an importance rating according to the customer preference. The Kano diagram is used to categorize the customer needs on the basis of the level of customer satisfaction into three different customer need categories (expected, revealed and exciting). It supports the identification of design strategy according to different segment of market. The Web-based consumer elicitation method consists of web-based surveys and statistical analyses that provide information about customer needs, preferences and buying behavior. In order to perform the second step, designers can adopt Kansei Engineering method and Quality Functional Deployment (QFD) method. Finally in the third step the customer needs are analyzed using the Conjoint Analysis method in order to identify the product space in the market (Kurniawan *et al.* 2004).

Ulrich and Eppinger (2008) propose another structured method to gather data from customers. It intends to foster the interaction between product developers and customers in the target market. This connection is essential for the innovation and the deep fulfilment of the customer needs. The method consists of 5 steps: gather raw data from customers; interpret raw data in terms of customer needs; organize the needs into a hierarchy of primary, secondary and tertiary needs; establish the relative importance of the needs; reflect on the results and the process (Ulrich and Eppinger 2008). Gathering raw data from customers is performed via interviews, focus groups and the observation of existing products. Interviews are considered the primary data collection method because inexpensive and able to provide information on the use environment of the product. Peculiar useful data source are those customers called lead users. They experience needs months or years in advance with respect to the average customer and they may have already invented new solutions. Data should be gathered from product end users and from any other type of customers and stakeholders decisive in the process (Ulrich and Eppinger 2008). The raw data provided by the customer should be collected in terms of statements and translated in terms of needs. Since the number of need statements may be too high to be directly used in the following design activities, a hierarchical organization of these needs is required for each market segment. A list is developed by designers throughout a step-by-step procedure and consists of a set of primary needs each of which may be characterized by a set of secondary needs. The secondary needs may be broken down into tertiary needs in case of complex products. Secondary and tertiary needs express needs in detail. Then the relative importance of the identified customer needs is established by numerical quantified weights through further customer surveys (Ulrich and Eppinger 2008). In order to verify their consistency, the results are finally compared using the information that the team has gathered during the surveys as well as a certain amount of intuition. The resulting customer needs are used to guide the team in establishing product specifications, generating product concepts and selecting the final solution concept (Ulrich and Eppinger 2008).

Discussion and Conclusions

This paper focuses on the role of the customer and on the identification of customer needs in building design. An historical overview has shown the customer involvement through the last century. It has highlighted the attempt to move from the house as an object to the user as the main reference of the design.

A literature review regarding existing experiences and related procedures on identifying customer needs has been provided. Although the issue of customers' need assessment has grown in importance over the last decades, the study of methods to aquire them has been mostly neglected by mainstream literature. For this reason relevant sources on this topic are limited. Since the new role of the customer is not yet acquired in the building design, this study has considered some procedures developed in product design where the customer involvement is well-established. In order to ease the comparison between such design fields, a scheme is introduced (table 1). The structure is based on the aims, the subjects involved in the procedure, the intended building type to design, the adopted procedure and suggested methods and techniques.

Table 1. Comparison Among Procedures for Identifying Customer Needs in Building and Product Design

Building Design				
	A. aim/B. subjects/ C. object	*Procedure*	*Technique*	*Method*
Regione Emilia-Romagna (1981, 1982)	A define users and user requirements; B no-profit housing habitants and end user profile representatives; C no-profit housing	1 user data acquisition	interview, questionnaire - survey	(not available)
		2 user data analysis	statistical analysis	(not available)
		3 user profile and need definition	group session and workshop	participation methods
American Institute of Architects (2000)	A define human, environmental, cultural, technological, temporal, economic, aesthetic, safety requirements; B clients, end users and community; C different building types	1 preliminary studies (financial feasibility, site suitability, master planning services)	(beyond the aims of the paper)	(beyond the aims of the paper)
		2 client and user value identification and prioritization	literature search review, interview, observation, survey, questionnaire, group session	(not available)
		3 design goal setting	data analysis	(not available)
		4 constraints and opportunity discovery	data gathering	(not available)
		5 development of program requirements	design team analysis	(not available)
HOK (Peña and Parshall 2012)	A define function, form, economy, time requirements; B client and end user; C different building types; entire design process	1 establish goals	interview, questionnaire, work session for data gathering; data management	Problem Seeking Process
		2 collect and analyze facts		
		3 uncover and test concepts	work session, space list, visualization and simulation tools for summary and decision making	
		4 determine needs		
		5 state the problem		
IAO Fraunhofer (Spath *et al.* 2010)	A optimize space use; B managers and office workers; C offices	1 analysis of work structure and user requirements	group session and workshop	Fraunhofer Workspace Innovation
		2 development of user scenarios	data analysis made by design team	
		3 new work structures and space concept	(belongs to next design phase)	(belongs to next design phase)
ENEA (Clerici Maestosi *et al.* 2012)	A assess water need; B workers and researcher; C research laboratories and offices	1 investigation	design team analysis	(not available)
		2 data acquisition	web-based survey	(not available)
		3 data analysis	(not available)	(not available)
		4 project scenarios development	(beyond the aims of the paper)	(beyond the aims of the paper)

Experientia (2009)	A reach sustainability by involving potential residents; B end users; C urban district	1 drafting hypothetical profiles of potential inhabitants and their lifestyles	stakeholder interviews, ethnographic research	Participation methods
		2 test and refine initial concept designs	user participatory design workshop	
Product Design				
Kurniawan *et al.* (2004)	A capture and organize customer needs; B end users; C products	1 customer need elicitation	group or one-to-one interview; web-based survey	Voice of Customer, Kano Map, Web-based elicitation method
		2 customer need translation	consumer behavior investigation, ergonomic experiment	Kansei Engineering, Quality Function Deployment
		3 utility analysis	customer interview	Conjoint Analysis, statistical analysis methods
Ulrich and Eppinger (2008)	A capture and organize customer needs; B end users and lead users; C products	1 gather raw data from customers	interview, focus group and observation of existing products	Product Design and Development
		2 interpret the raw data in terms of customer needs	data clustering and interpretation	
		3 organize the needs into a hierarchy	design team workshop	
		4 establish importance	customer survey made by design team	
		5 reflect on results and process	design team analysis	

Relevant results of this analysis are that some procedures are available to support the identification of user needs for different types of buildings, but the analyzed building experiences are not able to involve all different stakeholders. As the specific characteristic of the building sector is complexity, the final user is part of a group of different stakeholders that influences the building output. Their involvement and impact need to be analyzed and coordinated in a structure. Since well-established procedures are not yet available in building design, in the next future the research intends to test and eventually codify methods and procedures to address such challenge.

References

American Institute of Architects (2000) *The Architect's Handbook of Professional Practice*, John Wiley & Sons Inc. Retrieved from http://www.aia.org.

Castaldo, S., Sabbadin, E. (2009) *Innovazione e collaborazione nella filiera delle costruzioni*, Milano, Tecniche Nuove, p. 1.

Clerici Maestosi P., Farina, R., Stante, L. Valpreda, E., Parenti, A., Stojkov, I. (2012) "Functional recovery in an urban industrial area: methods and tools to integrate efficiency and sustainability in the pre-design phase", in Pacetti, M., Passerini, G., Brebbia, C. A., Latini, G. (ed.). *The Sustainable City VII: urban regeneration and sustainability*, Southampton, Boston, WIT Press, Vol. 1, pp. 169-180.

Kurniawan, S. H., Zhang, M., Tseng, M. M. (2004) "Connecting Customers in Axiomatic Design", *Proceedings of ICAD2004: The 3rdInternational Conference on Axiomatic Design*, Seul.

Experientia (2009). Low2No. Retrieved May, 2014 from http://www.experientia.com.

Peña, W. M., Parshall, S. A., (2012) *Problem Seeking: An Architectural Programming Primer*, John Wiley & Sons Inc.

Regione Emilia Romagna (1981) *La qualitá dell'abitare. Domanda abitativa, esigenze, situazione produttiva, risorse, standard,* Milano, Franco Angeli.

Regione Emilia Romagna (1982) *Gente, famiglie, case. Trasformazioni sociali e demografiche e nuove esigenze abitative*, Milano, Franco Angeli.

Rossini, U., Cremonini, I., Vitali, V., Facchini F., Grandi, G., Mazzoli C. (2000) "La normativa prestazionale del regolamento edilizio tipo della

Regione Emilia-Romagna: esperienze, problemi, prospettive", *Atti Convegno Tematico ATI*, Firenze.

Sabbadin, E. (2009) *Mercato e distribuzione nell'edilizia*. Milano, Tecniche nuove, pp. 7-8.

Sabbadin, E. (2011) "La casa nell'epoca del mercato globale dei beni immateriali", in Ghini A.(ed.), *Casa, tecnologia, ambiente: architetture e prestazioni per la residenza contemporanea*, Sant'Arcangelo di Romagna, Maggioli Editore, pp. 71-81.

Spath, D., Bauer, W., Rief, S. (2010) *Green Office: Ökonomische und ökologische Potenziale nachhaltiger Arbeits- und Bürogestaltung*, Springer.

Ulrich, K. T., Eppinger S. D. (2008) *Product Design and Development*, McGraw Hill.

Indicators as Tool for Evaluating the Sustainability of Ørestad Nord and Ørestad City

Christian Nygaard Sørensen*[1], Anne-Sofie Lütken[2], Christina Erikshøj[1], Mathilde Landgren[1] and Caroline Uebel[3]

cnygaard86@gmail.com, a_lytken@hotmail.com, christina@erikshoj.dk, mathildelandgren@gmail.com, uebel.caroline@gmail.com

1 Department of Civil Engineering, Division of Architectural Engineering, Technical University of Denmark

2 Department of Energy Conversion and Storage, Technical University of Denmark

3 Department of Management and Engineering, Linköping University - Institute of Technology, Sweden.

Abstract: Developing a new city and making it sustainable at the same time is a complex matter as sustainability itself combines environmental, economical and sociological aspects. These aspects connect sustainability to both the daily city life and the urban development through numerous factors, including transportation, infrastructure and small-scale factors such as local park environments, design and sizes. In this paper two neighbourhoods in Ørestad, a new district in Copenhagen, Denmark, are studied and their sustainability from a planning perspective is evaluated using indicators that cover four areas: density, mixed land use, green areas and public spaces. The study was done as a comparative analysis of indicators for the two finished neighbourhoods Ørestad Nord and Ørestad City. The study describes the methodology of creating the indicators and presents an evaluation scale for ranking the data assembled. The data indicated differences in sustainability between the two neighbourhoods and even though the sustainability was found to be pretty satisfying, it could have been considerably higher in both neighbourhoods.

Keywords: Indicators, Sustainability, Urban Planning, Ørestad.

Introduction

Sustainability is a matter that most countries, cities, districts, neighbourhoods and individual persons have interest in, and people constantly compare their local environment with others, whether it is the adjacent neighbourhood, similar cities or other countries. It is a difficult task to compare areas or cities in terms of sustainability due the multiple factors influencing sustainability within the environmental, economical and sociological domains, and thus it can be quite difficult to obtain specific data to evaluate sustainability against.

The use of indicators as a sustainability evaluation tool can be a way of converting a fuzzy concept of sustainability into specific and quantified data with measurable units and scales (MacLaren 1996; Azapagic *et al.* 2000). Sustainability indicators are typically used for determining progress towards sustainability and can only provide indications on sustainability and not a full picture. But if the indicators reflect the three sustainability domains mentioned above, are forward looking in measuring progress and possibly produced by multiple stakeholders of the given community, they can be a solid measurement of sustainability (MacLaren 1996).

Multiple cities have developed their own tools and methods to evaluate sustainability from indicators, and among them is Copenhagen Municipality with their "Sustainability tool" for measuring of potential sustainable development in the city. The sustainability tool developed for Copenhagen consists of 14 different subtopics within the fields of social, environmental and economical domains. In the sustainability tool it is stated that a living and dynamic city is a dense city, that benefits from strategic placement of functions, public spaces and public transport, which will decrease the need for transportation. Green and blue areas should be improved in a way that increases biodiversity along with recreational areas that provide opportunities for leisure and activities (Københavns Kommune 2014). In this study, the Copenhagen sustainability tool and MacLaren's indicator method framework are used as basis for producing indicators that are used to evaluate the progress towards sustainability for the new city part in Copenhagen, Ørestad.

Ørestad is an interesting city part, since it has been a subject of intense discussions in the Danish media, involving citizens, authorities and experts. Many of the contributions to the debate have addressed the building sizes, sizes of surrounding areas and building design in Ørestad, all subjects that can be assigned to an overall theme of sustainability and urban environment of a city. In the light of these ongoing discussions, it's interesting to actually examine whether Ørestad is developing towards a more sustainable city district and whether it is meeting some of the critique that has been pointed towards it, or not.

Ørestad as a city district is divided into 4 smaller neighbourhoods which are in different stages of development. The neighbourhoods Ørestad Nord and Ørestad City are almost completed which makes comparison of the neighbourhoods possible. The investigation of the progress towards sustainability for Ørestad in this study is thus carried out as a comparison between Ørestad Nord and Ørestad City, since it is assumed that Ørestad Nord was built before Ørestad City. The main reason for comparing two neighbourhoods within Ørestad is the fact that the district of Ørestad isn't fully developed yet. It is therefore not possible to compare it with another neighbourhood of Amager for instance or any other city district of Copenhagen. It wouldn't be fair, since Ørestad is a new city district and the other districts of Copenhagen have been developed for numerous decades or even centuries.

The evaluation of the progress towards sustainability of Ørestad is focused on the topic *land use*, which again is splitted into four subtopics: density, mixed land use, green areas and public spaces. Indicators for these four subtopics will be produced and evaluated.

Visions of Ørestad

The Master Plan of Ørestad from 1995 has been the main outline for developing the new district. The overall vision of Ørestad is to link Copenhagen city centre to the connection of international traffic passing between the southern part of Europe and the northern part of Scandinavia. The idea of Ørestad was to create a modern counterpart to the old city centre, following newer strategies for urban planning and creating the possibility for having a lot of new and modern architecture gathered in one area (Book *et al.* 2010)

To fulfil Copenhagens ambitions concerning a dense city and to accommodate all the desired functions of a city, the building percentage were set to 100%. In order to make an attractive location for businesses as well as residential housing a new metroline was planned as the main vein connecting Ørestad with the rest of Copenhagen.

Figure 1. Air photo of Ørestad Nord. Picture source: Ole Malling, By & Havn.

Ørestad Nord (figure 1) is mainly defined as a university area, since it contains the existing part of Copenhagen University's Faculty of Humanities and the IT-University. The area also contains business, residences and cultural facilities. The green areas and the canal through the neighbourhood are meant to gather students, inhabitants and business people during the days of good weather, and are planned in that way to bring life to the urban space. Ørestad Nord was the first area to be built, since it was supposed to contain some very important functions for the new city area, and to start attracting people to the new city district as early as possible (Book *et al.* 2003).

Figure 2. Air photo of Ørestad City. Picture source: Ole Malling, By & Havn.

Ørestad City (figure 2) was the next neighbourhood to be developed, since it had a very important place in the overall strategy of the Ørestad district, where the link between the Øresundsbro connection and the city centre has a crosspoint. Ørestad City mainly contains business, cultural facilities including the big shopping centre Field's and residential flats (Book *et al.* 2003).

For both areas a significant approach has been to integrate the green areas (figure 3) and the water into the urban spaces (figure 4). The green areas are seen as broad green fingers, bringing the green Amager Fælled into the built areas. The water is visible in the canal in a long nerve through Ørestad Nord and Ørestad City (Book *et al.* 2003). Buildings were designed in high quality and all with the aim of having less than 10 minutes for pedestrians to a metro station. This means that big, tall buildings were established to create large people densities close to the metro (Block, K, personal communication, March 25, 2014).

Figure 3. Diagram of the Final Competition Winning Solution. [Interview, By&Havn], Picture source: Received by Kresten Bloch, By & Havn.

Method

Indicator Method

The method used for creating the indicators is based on Maclaren's (1996) 9-step-method for urban sustainability reporting. The method used here has however been slightly adjusted according to the purpose.This was due to the fact that the paper is an independent study, which means that data was limited and that data availability as a consequence was a main criterion when choosing the final set of indicators.

To ensure indicators that both cover a wide range of sustainability issues and can be directly measured, two different categories of indicators were identified: soft and hard indicators. Soft indicators are indicators that cannot be measured without a rather high subjectiveness. To ensure a higher validity for these soft indicators, a scale with ranking from 1 to 5 were created. The higher ranking the better indication of sustainability. Hard indicators can be measured only by numbers, but are also graded on a 5-point scale.

Numerous indicators within the four main subjects were created and evaluated. For each subject the ranking for each indicator is summed up on a radar diagram to get an overview of the sustainability in relation to the specific subject.

Data Collection

Data was collected both for background information about the planning and development of Ørestad and for the indicators. Four types of data collection methods were mainly used: literature search, data collection via online available maps (distance and area measurements), interviews and field trips (light measurements, facade evaluation, etc.). For many of the indicators, distances and areas were necessary to measure. These were measured with Google Earth Pro and the distances were measured as the air distances.

An interview with architect Kresten Bloch from By & Havn, a fraction group of the disestablished Ørestad Development Cooperation (ØDC) which started the planning of Ørestad, was carried out and used as a knowledge source for the building and planning process of Ørestad as well as the different planning choices made by the ØDC. Some of the indicators are evaluated against these choices.

A field trip to Ørestad was carried out to get some general impressions of the city parts. The different impressions were written down and pictures were taken for documentation. The light at nighttime was measured using a luxmeter-app.

Developing the Indicators

The indicators developed in this study are based on the four main areas within land use: density, mixed land use, green areas and public spaces. The sections below describe the basis on which the indicators were built and briefly explain the underlying grading scales that were used to obtain the radial diagrams, in which the indicator results are presented. In general, the specific indicator numbers and grading scales can be found in the report plus the supplementary material (Sørensen *et al.* 2014) that constitute the basis for this article.

Density

According to Jan Gehl (2010), urban density can be compared with a party: When planning a longer party you want to collect the guests and the event in as few rooms as possible, preferable at the same level. The same principle can be applied for urban planning. The people should be collected in as few "rooms" as possible with a suitable size and on the same level. According to Jan Gehl, too many and too "big rooms", that is the public urban spaces, are created in modern urban planning. As one of Jan Gehl's beliefs are that "people like to go where people are" (Hayter 2004, p. 29) he means that the "too big room"-scenario creates a situation where no people visit the public spaces as they feel deserted. So in order for people to feel comfortable in an urban space, a certain building density and people density must be present. Llewelyn-Davis (2000) express this as a critical mass of people that must be present in order to support local shops, schools and public transport (Carmona 2010), thereby creating life. The positive effects of density thereby count ease in the access to community services and access to transport, but also things as lower energy consumption and an increased feel of safety (Carmona 2010). Peter Newman (1996) suggests a minimal people density of 30 to 40 people per hectare. A number of 2000 inhabitants can be estimated to have been present in the early organic cities in the 20th century (Gehl 2010) and can approximately be considered as an optimal value, since these cities can be thought of as ideal (indirectly expressed by Newman (1996)).

But density expressed in terms of people density is not the same as density expressed in terms of buildings. A high people density can easily be achieved through few, very tall building. But according to Jan Gehl (2010) many high buildings with big spaces around do not necessarily describe a healthy density even though the urban density still high. This is primarily related to the scale of the buildings; large-scale buildings are out of the "human scale", as Gehl expresses it (2010).

The above considerations were taken into account when developing the density indicators and this resulted in indicators, which describe the number of inhabitants, size of living spaces, building geometry and architectural footprint. Following final five indicators could be obtained through the available data: urban density, average residential area per person, number of small apartments (<60 m2), building height and building size in relation to the surroundings.

The indicators were evaluated through a 5 point scale, where a high urban density, a high ratio of small apartments (40-60%), a low building height, low residential area per person and a proper architectural footprint area were considered best and hence graded highest. The resulting indicator evaluation is shown in figure 4.

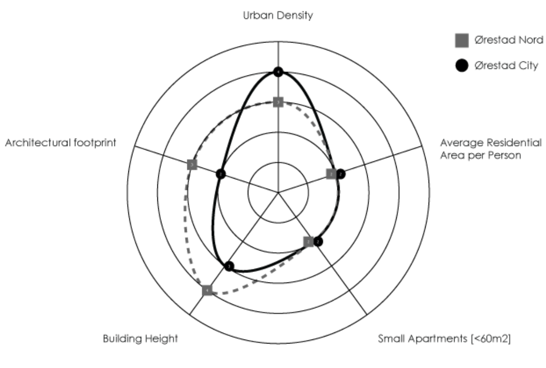


Figure 4. Result of Graded Density Indicators

Mixed Land Use

In Copenhagen, the agenda has for a long time been to take room from cars and give it to pedestrians and bikers, to create a city that is dominated by people and not cars. In relation to this, the locations of the different functions in the city are crucial factors to consider. A normal citizen can be expected to be in need of five main functions in the city in his or hers everyday life: a residence, a workplace (offices/businesses), grocery stores and public institutions and transportation if needed.

In order to invite people to walk or bike, these functions should be available within a walking distance. Peter Newman (1996) expresses a quality city like this: "the streets are filled with people walking and all major local destinations are within a short walk. The keys to this are density and mixed land use, which grow from the need to have sufficient people living nearby and sufficient work, shops, schools, etc. within walking distance". Peter Newman mentions the term mixed land use, which can be interpreted as a more or less evenly distribution of the cities main four functions throughout a neighbourhood. This is also expressed in Jan Gehl's (2010) view on scale, when he states that it is more useful to have 1 m^2 space available next to the home, than $10m^2$ available just around the corner. This sums up the concept behind mixed land use quite well. All the necessary functions should be accessible locally; rather small and local functions than a larger central function cluster. Ultimately, when a dense local city with mixed land use is achieved, people can quickly move between their daily activities to an extent, where cars become unnecessary.

Furthermore, an area with a well-mixed land use has activities all day and the connected feeling of safety and the excitement of experiencing such a neighbourhood by foot are improved enormously.

Based on these observations and the principles of Peter Newman and Jan Gehl, indicators for mixed land use and its functionalities have been developed. Ten subindicators were developed in order to evaluate the mix of functions in all scales. The 10 indicators concerned the distances between the four functions: residences, grocery stores, transportation and public institutions and included the degree of mixed land use for the overall neighbourhoods and for subdivisions of the neighbourhoods, individually divided for Ørestad Nord and Ørestad City.

The indicators were graded on a 5 point scale, where short distances between the functions were favoured as well as the degree of mixed functions, where a 50:50 ratio between housing and commercial functions (businesses, stores and public activities) was considered to be optimal (By og Havn 2012). The result is shown in figure 5.

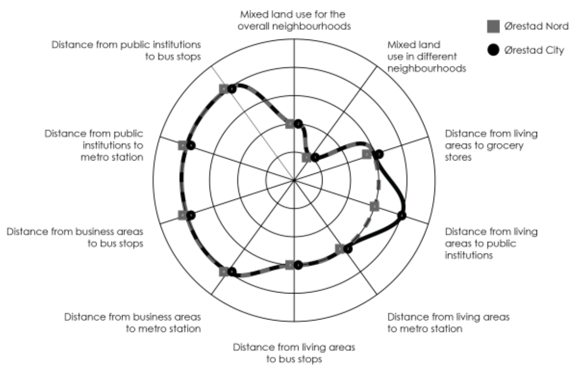


Figure 5. Result of Graded Mixed Land Use Indicators

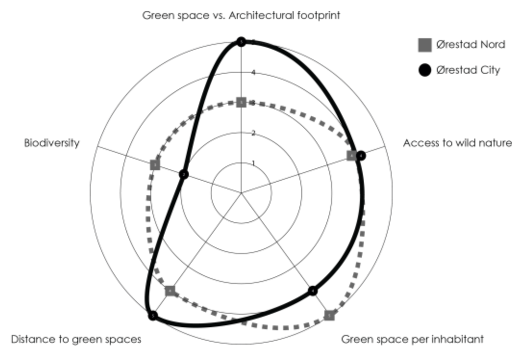


Figure 6. Result of Graded Green Areas Indicators

Green Areas

The presence of green areas is highly related to the perception of a great sustainable urban area. Green areas allows for pleasure, play, and relaxation. A study on green spaces, urbanity and health showed that the presence of green public spaces enriched the overall health of the citizens in larger cities (Maas *et al.* 2006). The study showed that the lower socioeconomic classes benefitted more from these areas than others.

Green spaces influence businesses, economy and are important for their employees' happiness and productivity (CABE Space 2003). Furthermore residential prices increase if a park or other green public space is located nearby (CABE Space 2003).

Based on these findings, it is evaluated that it is important to consider the amount of green spaces compared to the total area and per capita living in the area when evaluating the green areas of a city. This is important because it gives an indication of how green the area is and how populated it is. Furthermore the distances, especially from residential areas, should be analysed, since the distance is crucial for the use of the green space.

The size of green areas should also be considered, as it is related to the daily use; a small area may feel more suited for relaxation and sedentary activities where a large open space invites play, sports and physical activities.

Based on these considerations, indicators have been developed and include the distance from housing and green areas, green areas per inhabitant, access to wild nature, biodiversity and green space vs. architectural footprint.

In general the indicators are evaluated against the 5 point grading scales that favour large amounts of green, large green areas, short distance to them from housings, a large biodiversity and a short distance to wild nature. Figure 6 shows the result of the indicators.

Public Spaces

Public spaces in the cities are the centre for all kinds of activities, physical as well as social. They provide the basic needs which can not be fulfilled in the private homes; socializing with other people, experiencing the nature, outdoor activities, etc., and therefore they contribute to the overall quality of life. The spaces have to be inviting and attractive in order for people to use them. A lot of elements influence the attractiveness of public space and these elements have to co-exist, since over-dominating elements might have a bad influence on the perception of the public space. Jan Gehl has studied public spaces for decades and made general guidelines for what qualifies as a good public space. He has developed a tool for evaluating public spaces, where the public space should fulfill 12 quality criterias (Gehl 2010). The quality criterias is parted in 3 main subjects; protection, comfort and enjoyment/delight. Based on the 12 quality criterias the indicators used to evaluate public space have been generated. This has resulted in indicators describing safety, wind conditions, sun conditions, sitting possibilities.

In each neighbourhood, two public spaces; a green space and a public passage, are selected and evaluated based upon the indicators, described in the next section.

The safety of pedestrians, cyclists and other soft individuals is crucial for a great public space. In order to quantify this protection, measurements and analysis of roads, biking paths, pavements and their location is investigated. Another aspect of feeling safe is the occurrence of crime and the fear of crime – which is likely to occur in dark and deserted places. Precautions to prevent this could be an increased amount of streetlights. Examples show that this can lead to reduced crime rates and fear (CABE Space 2003). This means that indicators concerning safety could be simple measurements of the lightings in a neighbourhood. The lighting levels are measured in lux for the different public spaces in the night in order to compare and evaluate on their effect. Both effect of emitted light and distance between light sources should be taken into consideration.

Climatic effects have a great influence on the use of public spaces. When the wind is blowing it can feel colder to be outside, while sitting in the sun makes you feel warmer. In the design and use of the public space there should be awareness of these climatic effects, and how they will affect and shape the public space. This means that an indicator concerning wind and sun conditions is made. The public spaces are investigated in concern to this and simulations showing the wind conditions (figure 8) are made as well as diagrams showing the conditions for sun/shadow (figure 7).

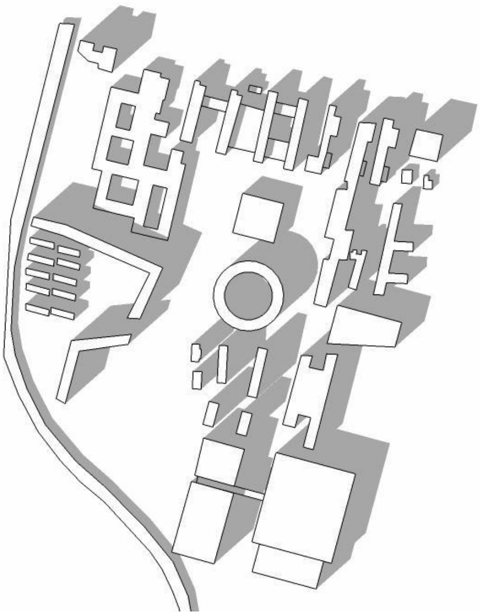


Figure 7. Shadow Analysis of Ørestad Nord

Figure 8. Wind Analysis of Ørestad Nord

Enjoying the weather in the public space, people like to have different possibilities to sit and enjoy the weather. The possibilities are evaluated. Benches are an obvious possibility for sitting down, but in public spaces alternative solutions are often made, where people for example can sit on the edge of a flower bed etcetera and these possibilities are included as well.

Attractions, activities and architecture can all contribute to the public space and the perception of a space. The presence of such has been investigated in order to evaluate the public space.

As mentioned the evaluation of public spaces is being subdivided into two categories (a green space and a public passage) in order to grasp the complexity of this subject. The reason for “zooming in” on these locations is that the perception of public space cannot be generalised from a bird perspective. The feeling one will get in one area of a neighbourhood might be very different from another part of the neighbourhood. The selected green space and public passage in Ørestad Nord and Ørestad City are all evaluated based upon the following specific 10 indicators: street lights, pedestrian safety, bicycle friendliness, wind conditions, sun conditions, possibilities to enjoy the weather (sitting possibilities), sub spaces (smaller spaces in the city), attractions, aesthetic quality and crime rate. The indicators gradings can be seen from figure 9.

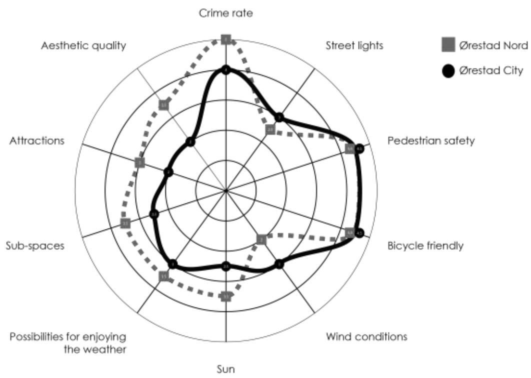


Figure 9 - Result of Graded Public Spaces Indicators

Findings and Discussion

We can see that in terms of the density, Ørestad Nord and City have almost the same indicator results – and are generally graded low from a sustainability perspective. Ørestad Nord was found to perform better in terms of building height and architectural footprint. The building heights is in both areas in general too high when comparing with the thoughts of Gehl (2010), and a high people density (in tall buildings) is prioritized over a high building percentage with a more widespread people density. Furthermore the tall buildings affect sun and wind conditions and the human scale in both areas are lost due to massive building complexes.

In terms of the mixed land use indicators, both Ørestad Nord and City are holding low distances to public transportation systems making both districts walkable in terms of distances. It is obvious that the metro and city districts have been planned together. A transit oriented development makes public transportation easily accessible. When considering the grade of mixed land use, it is very poor on a local level. Functions are gathered in clusters; education, residential and business are all gathered in individual areas, which make the city less varied in terms of day and night shifts in city life. This could for instance affect the feel of safety during night. The city life is also affected, when playing kids aren't mixed with office people, subdividing the neighbourhood with respect to social and functional classes. It is clear that the required sociological mix of people and functions that Gehl (2010) and Newman (1996) mention have not been met in either neighbourhood. This is consistent with the fact that some of the subgoals for Ørestad were to attract people with a solid economy, and hence lots of bigger apartments were and are offered in Ørestad, making less room for people with a lower income.

When it comes to green areas, Ørestad Nord and Ørestad City are very similar. They are characterized by large open parks surrounded by the massive buildings as one would see it in Central Park, New York. The green areas connect the wild nature of Amager Fælled with the citizens of Ørestad. Especially the green areas in Ørestad City are characterized by its youth, where low vegetation seems odd taken the scale of the park into consideration. Ørestad City is however more sustainable in terms of green spaces since the area is easily accessible and better planned for the locals.

The evaluation of the public space indicators shows that Ørestad Nord is the most sustainable. This can be explained in accordance to the overall development of Ørestad district, where Ørestad Nord was developed a bit ahead of Ørestad City, and hereby the public spaces are more developed as well. Ørestad City differs from Ørestad Nord according to street lighting and wind, which have better conditions in Ørestad City. Ørestad Nord is better in relation to the indicators concerning architecture and possibilities for urban activities in the public space.

Several of the indicators show that the green areas and buildings in the two neighbourhoods of Ørestad are big scale, for which they were designed. The areas are wide, and the surrounding buildings very tall. In ‘Byer for mennesker’ (Gehl 2010) a social field of vision is mentioned, which reaches a length of 100 meters where movement can be spotted. When decreasing the distance, our other senses are awoken and by the distance of 50-70 meters distance, the sense of hearing is included in addition to the vision sense. At 20-25 meters it is possible to communicate and read expressions and feelings. The senses increase with shorter distances and at 7 meters the sense of smelling works. These distances clearly show at which dimensions the human senses are starting to be stimulated and in which scales cities should be build to invoke interactions like communication and general sensing. And the numbers also show which senses that are in use in Ørestad: mainly the vision sense, sincen the area of the green space in Ørestad City for instance is 170 meters wide and 430 meters in length. This indicates a poor city life and hints that the connection between the green public spaces and the adjacent buildings should be improved in order to improve the city life of Ørestad. Furthermore, the facades are closed off and no direct opening is available in Ørestad Nord and City, which was one of the drawbacks in connection with the aesthetic quality indicator. The façades should rather be inviting and inspiring to walk along.

Ørestad Nord and City are built within the same decade, which causes the buildings to have the same architectural history and expression. The existing community is often the expert of the area and can provide details for historical aspects and what is valuable for the people living there (Project for Public Spaces 2014). But what do you do, when the community is going to be built from scratch? Then there’s no architectural history or well-established public spaces to take a starting point from. The history of Ørestad is being written now and perhaps in the future the public spaces and architecture will grow and end up having a story to tell.

The Indicators

The indicators did in general prove useful for evaluating sustainability for Ørestad and gave nuances to the analysis of two quite similar neighbourhoods. However, there are some shortcomings to the method and indicators used for this study. The study seek to evaluate the sustainability of an urban area for which the definitions or ideas of sustainability often are very loosely defined, and where the theory behind only gives vagues numbers or only indications of scales. This means that every indicator has been normalized in order to be able grade and compare properly. In order to grade the indicators each individual indicator has been equipped with a scale. The scales are produced from of our own knowledge, observations and judgement with theories from Jan Gehl and Peter Newman in mind and were limited by the deficiency of precise enough theoretical values. The subjectiveness of this approach adds insecurities to the grading of the indicators. These insecurities could have been minimized by only using existing data as done in the DPL-Copenhagen (Duurzaamheid Prestatie voor een Locatie, ‘Sustainability-Profile for Districts’) by among other Danish Building Research Institute, which would strengthen the reliability of the results and increase the trust and belief in the results amoung politicians (Jensen 2009).

This study chose not to limit the amount of indicators to already existing facts, but attempted to generate further indicators in order to grasp the entire sustainability aspect in Ørestad Nord and City. These indicators were treated as soft indicators.

Some challenges were also connected to the production of indicators. It could either be difficulties in setting the grading scales if the outcome of an indicator in theory didn't follow a linear development (for instance the density indicator, where an increase in building density for a neighbourhood after a certain level doesn't necessarily bring any additional benefits for the respective neighbourhood).

For other indicators, it was difficult to set a scale if the indicator in the theory was measured against more than one scale and indicators' use were also very limited without the results from other indicators. This was the case with mixed land use and green areas, where distances were measured. In accordance to Gehl, the perception of distances is highly dependent on how exciting the environments surrounding the walking paths are. But the grading scale for distances was done without this consideration. The same goes for the indicators for green areas where the amount of public green areas should be considered with care. Green areas have been proved beneficial in multiple ways, which would indicate that the more green the better. This is however not always the case, which is also one of the critiques of Ørestad City. The areas are too large and the human scale is lost. Where to draw the line for how large a green area should be hasn't been clarified, since factors such as population, accessibility, park planning, vegetation and many more aspects have a say in this matter.

Other indicators were dismissed by the difficulties to measure them in an objective way. "Biodiversity in green areas" was such an indicator. This indicator was also difficult to measure, since the time for data collection was in the early spring. In countries with variation in climate, and therefore also greenery, during the year the visible impression can vary tremendously. In such cases, the results from some indicators can be affected.

Conclusion

When comparing Ørestad Nord to Ørestad City in terms of sustainability, we see a clear picture formed, but not the anticipated one. Both of the neighbourhoods generally have the same score on the sustainability scales made for the comparison, and hence the overall conclusion must be that there hasn't been a progression towards a greater degree of sustainability in the process of going from Ørestad Nord to Ørestad City. This result reflects and underlines the fact that Ørestad Nord and City both were planned and build in connection to each other, which means that experiences from the earlier phases perhaps hadn't had time to settle before the next building phase was initiated. This can also be seen in the planning visions for the two neighbourhoods. They are more or less the same, where short distances to the metros are prioritised, creating high buildings with a high local people density but surrounded by big green areas.

Even though the indicators didn't show a significant difference in sustainability for Ørestad Nord and Ørestad City, they can still be used to evaluate the overall sustainability of Ørestad as a city district. In regard to this, it was shown that Ørestad in general was sustainable in some aspects of the green areas, but wasn't when it came to density and mixed land use.

This was primarily due to some overall flaws in the urban planning prioritisation, if measured against the sustainability goals of Copenhagen Municipality, Jan Gehl and Peter Newman:

- Prioritising of transport time rather than urban building density
- Prioritising of attractive housing near green areas rather than a dense, lively city scapes
- Prioritising of a uniform population group rather than a more complex one
- Prioritising of peoples need for green over peoples need to look at other people

In general, indicators proved useful for evaluating sustainability of two urban areas in Copenhagen and gave some nuances to the analysis even though the areas were quite similar. The method for grading the indicators, however, could be revised, since the majority of the indicator gradings were done on the basis of subjective assumptions and evaluations due to the lack of precise theoretical values. The creation of indicators was done from a general point of view and could in principle be applied for any city, but some of the indicators could vary with time and place and hence, the forming of urban planning sustainability indicators should always be corrected to apply to the given city - and even more so, since the indicators also should reflect the interests and needs of the city and the stakeholders involved.

References

Azapagic, A. and Perdan, S. (2000) Indicators of sustainable development for industry: A general framework. *Trans IChemE*, 78, pp. 243-261.

Book, K., Eskilsson, L., Khan, J. (2010) Governing the Balance between Sustainability and Competitiveness in Urban Planning: the Case of the Orestad Model. *Environmental Policy and Governance*, 20, pp. 382–396.

By og Havn (2012) *Nordhavnen: From idea to project.* By og Havn.

CABE Space (2003) *The Value of Public Space.* London: CABE Space

Carmona, M. (2010) *Public Places, Urban Spaces: The dimensions of urban design*, Routledge

Gehl Architects (2004) *Places for People - Melbourne 2004*. Copenhagen: Gehl Architects.

Gehl, J. (2010) *Byer for mennesker*. Bogværket.

Hayter, J. A. (2004) Places for People 2004 - Melbourne, Australia. Places – EDRA/Awards 2006, 18 (3), ss. 28-32.

Jensen, J. O. (2009) Sustainability Profile for Urban Districts in Copenhagen. *Sustainable Cities and Regions: Enabling Vision or Empty Talk?*, Örebro University, Sweden

Københavns Kommune (2014) De 14 bæredygtighedshensyn. Københavns Kommune. [Online]. [Accessed 14 March 2014]. Available from Naturstyrelsen: http://naturstyrelsen.dk/media/nst/Attachments/KBHDe14bredygtighedshensynashx.pdf

Maas, J., Verheij, R. A., Groenewegen, P. P., De Vries, S., & Spreeuwenberg, P. (2006) Green space, urbanity, and health: how strong is the relation?. *Journal of epidemiology and community health*, 60(7), 587-592.

Maclaren, V. W. (1996) Urban Sustainability Reporting. *American Planning Association*, 62 (2), pp. 184-202

Minneapolis City Council (2014) [Online]. [Accessed 19 June 2014]. Available from: http://www.ci.minneapolis.mn.us/sustainability/indicators/index.htm

Melbourne Sustainable Society Instutute (2014) [Online]. [Accessed 19 June 2014]. Available from: http://www.sustainable.unimelb.edu.au/content/pages/sustainability-indicators-local-government/

Project for Public Spaces (2014) Eleven Principles for Creating Great Community Places. [Online]. [Accessed 1 April 2014]. Available from Project for Public Spaces: http://www.pps.org/reference/11steps/

Sørensen, C., Lütken, A. Uebel, C., Erikshøj, C. and Landgren, M. (2014) Sustainable Development of Ørestad Nord and Ørestad City

Flow-Induced Energy Harvesting: Conceptual Design and Numerical Analyses of a Piezoelectric Bender for Smart Building Applications

Sara Ferri, Konstantinos Gkoumas*, Francesco Petrini and Franco Bontempi
sara_ferri86@yahoo.it, konstantinos.gkoumas@uniroma1.it, francesco.petrini@uniroma1.it, franco.bontempi@uniroma1.it
Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Italy

Abstract: This study focuses on the conceptual design and the numerical analysis of an Energy Harvesting (EH) device, based on piezoelectric materials, for the sustainability of smart buildings. Before that, a comprehensive literature review on the topic takes place. The device consists in an aerodynamic fin attached to a piezoelectric element that makes use of the airflow to harvest energy. The principal utilization of this device is for energy autonomous sensors, with applications in smart buildings. A performance-based parametric analysis is conducted (in ANSYS®) in order to assess the optimal values of some design and operating condition parameters, including length, width, thickness, constitutive material of the bender and velocity and turbulence intensity of the incoming airflow. The response parameters used for evaluating the performances include the bender maximum tip displacement, the bender vibration frequency, and the rms of the voltage generated by the device. Considerations are made on possible applications in other sectors (structures and transportations infrastructures).

Keywords: Energy Harvesting, Piezoelectric Materials, Parametric Analysis, FEM Modeling, Building Automation.

Introduction

Engineers, designers and planners, are nowadays very sensitive to issues related to the sustainability of structures. To this end, one of the primary aims of civil engineering design in particular, is to design and build structures with low environmental impact and with an optimal energy performance. Therefore, in the last few decades, the concept of Smart Building was born. This requires buildings equipped with additional subsystems for managing and controlling energy sources and house appliances, and minimize energy consumption, often using wireless communication technology (Morvaj *et al.* 2011). Among these, typical examples are Building Automation Systems, or centralized, interlinked networks of hardware and software that monitor and control the environment in commercial, industrial, and institutional facilities. One of the objectives of Building Automation is to automatize the systems present in the building through the monitoring of ambient parameters using sensors installed in the structure. These sensors can be powered through the mains or in alternative, can be self-powered. The latter is advantageous because it makes their installation easier and it reduces the cost of cabling. An alternative is the use of batteries, which, however, considering their limited lifetime, need to be replaced at regular intervals, so, in addition to having a high environmental impact, their use affects maintenance costs in the long term. Therefore, the best solution is to employ wireless autonomous sensors powered by Energy Harvesting devices.

On the other hand, energy harvesting, i.e. the process of extracting energy from the environment or from a surrounding system and converting it to useable electrical energy, is a prominent research topic, with many promising applications nowadays in buildings, transportation infrastructures and bridges. Its areas of application are currently focused - though not limited - to powering small autonomous wireless sensors (thus eliminating the need for wires), while more recently proposals have been made concerning higher power energy harvesting devices, in the upward trend of renewable energy growth.

Regarding applications for building automation, the trend is very positive in the last years, especially after issues regarding the wireless network frequency allocation have been resolved.

In this paper, a device for converting mechanical energy into electrical energy has been studied. This device can be used to power sensors for building automation, and in particular, for sensors placed inside HVAC (Heating, Refrigerating and Air Conditioning) systems, present in centralized form in many commercial, industrial and constitutional buildings. The device exploits the airflow inside the HVAC ducts. A conceptual design of a bender with piezoelectric material (a material that changes its shape when subjected to an electric field, or, focusing on the opposite effect pertinent to this case, generates an electric field when it is deformed), is studied inside an HVAC duct and subjected to Vortex Shedding phenomenon. The latter occurs when a body, immersed in a current flow, produces a wake made of vortices that periodically detach alternatively from the body itself with a certain frequency.

A parametric study of the bender has been conducted in order to find the configurations capable of generating resonant conditions that produce the highest level of power for the range of velocity typical inside HVAC ducts (2-5 m/s). A Finite Element Model has been created with the program ANSYS® 13, which treats piezoelectric materials, in order to find the optimal configuration for power wireless sensors.

Literature Review

Micro-scale energy harvesting aims to the powering of sensors or other small electronic devices, including those based on MEMS (Micro Electro Mechanical Systems) that require small amounts of energy. The research carried out in the last decade on micro-scale energy harvesting is massive. Applications in the last decade in the civil engineering field focus on the Structural Health Monitoring (SHM) of long span bridges and skyscrapers.

Harb (2011) and Gkoumas (2012) provide an overview, while an extensive review of methods, technologies and issues is found in Priya and Inman (2009). Gibson (2010) provides a review of multifunctional materials, some of which can be deployed in energy harvesting applications. Belleville et *al.* (2010) lay a framework for the functioning of energy autonomous systems, and provide estimated power output values for different harvesting principles. Chalasani and Conrad (2008) provide a survey of different energy harvesting sources for self-powered embedded devices. Gilbert and Balouchi (2008) review the characteristics and energy requirements of typical sensor nodes, indicate possible application, provide potential ambient energy sources and compare energy harvesting devices found in literature. Gammaitoni *et al.* (2011) discuss issues for kinetic (vibration) energy harvesting. At present, piezoelectric energy harvesting has gained most of the attention; however, there are other promising forms of mechanical energy conversion (e.g. using magnetostrictive materials). Davino *et al.* (2011) discuss issues related to the latter.

Even though a great progress took place in the last decade, there are still issues to be solved and margins for improvement in the efficiency of micro-scale energy harvesting. Some of the key issues (power storage efficiency, communication standards, integration of devices, cost of ownership) are discussed in Kompis and Aliwell (2008). The same authors provide a list of international centers of expertise in this field.

Regarding research on energy harvesting using a piezoelectric bender, in many cases, the bender is integrated with an added tip mass and subjected to mechanical vibrations induced by external forcing. In some cases, like the one of this study, the external forcing is represented by an airflow acting on the structure.

Ly *et al.* (2011) study a piezoelectric cantilever sensor with a mass at the free end, both by means of finite element modeling and experiments. The model and the experiment indicate that the second mode of resonant frequency provide a voltage and a bandwidth much higher than the first mode. Zhou *et al.* (2012) study a shear mode piezoelectric cantilever with a proof mass at the free end, and have evinced that the output peak voltage is maximum when the frequency is resonant (63.8 Hz), while it decreases after that. The output peak power has the same trend and it reaches the maximum of 9 mW at the resonance frequency. Wang and Wu (2012) conduct research on the optimal design of a piezoelectric coupled beam structure. In particular, they observed the effects of the size and the location of the piezoelectric patch as well as the excitation frequency on the power-harvesting efficiency. They find that the efficiency decreases when the location of the piezoelectric patch changes from the fixed end of the beam to its free end. The peak value of the voltage is 0.62 V with an angular frequency of 30 rad/s and an excitation amplitude of 0.1 N. Diyana *et al.* (2012) investigate both single and comb-shaped piezoelectric beam structures, obtaining better results in terms of output voltage for the comb-shaped structure. Blazevic *et al.* (2010) propose a modal model of the dynamic behavior of a piezoelectric cantilever beam. They compare the measured performance of commercially available energy scavenger with the results obtained from a FEM, establishing that the device with larger piezoelectric material volume, outputs more power and that the output power is proportional to the tip-mass. Li *et al.* (2010) compare the behavior and the outputs of a piezoelectric cantilever beam with a curved L-shaped mass with the conventional block-shaped mass, and test it on a shoe under walking conditions. The curved L-shaped mass lowers the fundamental frequency and improves the power density in comparison with conventional cantilever piezoelectric power harvesters. Wang and Ko (2010) develop a FEM model of a new piezoelectric energy harvester from flow-induced vibration in order to estimate the generated voltage of the piezoelectric laminate subjected to a distributed load. The experimental results show that an open circuit output voltage of 2.2 VPP (Peak-to-Peak Voltage) and an instantaneous output power of 0.2 mW are generated, when the excitation pressure oscillates with an amplitude of 1.196 kPa and a frequency of about 26 Hz. Zhu *et al.* (2010) present a design study on the geometric parameters of a piezoelectric cantilever beam with a seismic mass attached to the tip. For the beam, a shorter length, larger width, and lower ratio of piezoelectric layer thickness to total beam thickness provide better results in the case of a fixed mass. For the mass, a shortened mass length and a higher mass height provide better results in the case of variation in the mass length and a wider width and small mass height are better in the case of variation in mass width and height. For the case of a fixed total length, a shorter beam length and longer mass length provide better results. Gao *et al.* (2013) study a Piezoelectric Flow Energy Harvester (PFEH) based on a piezoelectric cantilever with a cylindrical extension. Prototypes are tested in both laminar and turbulent air flows, showing how PFEHs generate higher voltage and power in the turbulent flow rather than in the laminar flow. The turbulent excitation was the dominant driving mechanism of the PFEH with additional contribution from Vortex Shedding excitation in the lock-in region. Up to 30 mW and 4.5 VOC (Open Circuit Voltage) are obtained at 5 m/s wind velocity in a fan test. Song *et al.* (2012) investigate the feasibility of a piezoelectric cantilever beam for converting mechanical vibrations of an operating high-speed Korean train to useful electricity. They have increased the sensitivity of the system by designing thinning cantilever beams and increasing the piezoelectric material dimensions. The peak power output for a piezoelectric system composed by a 43 x 33 x 0.25 mm^2 piezoelectric material on 69 x 37 x 0.25 mm^2 stainless steel, with four masses of 4.75 g each, is 7.76 mW. Ovejas and Cuadras (2011) study a multimodal piezoelectric wind energy harvester. They use commercial films with different areas and thickness. The energy generated is rectified through a diode bridge and delivered to a storage capacitor. They investigate two different wind flows (laminar and turbulent flows) and also two wind incidences (parallel and normal), obtaining better results in terms of power generation by increasing the thickness and by keeping the area in the effective area range characterized by turbulence. The piezoelectric coupling under wind flow in presence of turbulence is better. The power generation is in the order of 0.2 mW.

In literature, two studies present similarities to the performed analyses in this study. Wu *et al.* (2013) develope a cantilever attached to piezoelectric patches and a proof mass, for wind energy harvesting from a cross wind-induced vibration. They study the influence of the length and location of the piezoelectric patches as well as of the proof mass, on the generated electric power, concluding that the optimal location of the piezoelectric patches is close to the middle lower part of the cantilever harvester when the vortex shedding frequency is close to the second resonant frequency of the harvester. The optimal length of the piezoelectric patches depends on their location and the resonant frequency of the harvester can be adjusted by changing the proof mass attached on the top of the cantilever. Weinstein *et al.* (2012) conduct an experimental study of a cantilevered piezoelectric beam excited in a HVAC duct. In their case, the excitation is amplified by the interactions between an aerodynamic fin attached at the end of the piezoelectric cantilever and the vortex shedding downstream from a bluff body placed in the air flow ahead of the fin-cantilever assembly. They find that the addition of this fin to the tip of the piezoelectric bender improves significantly the power generation of a vortex shedding induced energy harvester. Power generation between 100 and 300 μW for flow speeds in the range of 2-5 m/s are sufficient for powering a sensor node of HVAC monitoring systems or other sensors for smart building technologies.

Modelling Approach and Issues

As stated before, this study focuses on a bender in piezoelectric material under Vortex Shedding flow excitation placed inside an HVAC duct. The purpose is to design a bender in a specific material with a piezoelectric patch, which can enter in resonance with the external force deriving from the Vortex Shedding phenomenon. This is because the resonance conditions produce the highest level of power. From a design point of view, this approach is in contrast with traditional civil and mechanical engineering design, since normally the aim is to avoid the resonance conditions.

Vortex Shedding Excitation

The Vortex Shedding phenomenon occurs when a body, immersed in a current flow, produces a wake made of vortices that periodically detach alternatively from the body itself with a certain frequency n_s. This body enters in resonant conditions when the frequency n_s is equal to the natural frequency of the system.

The detachment of alternating vortices causes a transversal force to the flow direction. This force can be expressed by the harmonic law:

$$f_{sL}(t) = F_{L,i}(s) \cdot \sin(2\pi \cdot n_s t)$$

where $F_{L,i}(s)$ is the equivalent static action:

$$F_{L.i}(s) = m(s) \cdot \left(2 \cdot \pi \cdot n_{i,L}\right) \cdot \phi_{i,L}(s) \cdot y_{pL,i} \cdot C_{TR,i}$$

where:

s is the structural coordinate; $m(s)$ is the element mass per unit length; $\phi_{i,L}(s)$ is the modal shape of the i-eigenmode in the transversal direction, normalized to 1 in the $\bar{s}$ coordinate of maximum displacement , $\phi_{i,L}(\bar{s}) = 1$; $y_{pL,i}$ is the peak value of the transversal displacement of the element, evaluated at the $\bar{s}$ coordinate; $C_{TR,i}$ is an adimensional parameter related to the possibility that critical values of the average wind velocity occur for elevated values of the return period T_R; n_s is the Vortex Shedding frequency which comes from the Strouhal law:

$$n_s = \frac{St \cdot v_m}{b}$$

where St is an adimensional parameter, called Strouhal parameter, which is function of the section shape and the Reynolds number, v_m is the a average flow velocity, and b is the characteristic dimension of the cross-section.

The most critical conditions occur when the frequency n_s is equal to the natural frequency of transversal vibration of the body $n_{i,L}$, in particular when it is equal to the first frequency associated to the eigenmode of vibration perpendicular to the wind direction. When $n_s = n_{i,L}$, the average velocities of the wind are the critical ones and the structure enters in resonant conditions. These conditions produce the highest level of power. Thus, the Vortex Shedding critical velocity for the *i*-transversal eigenmode, is defined as the average wind velocity that produces resonant conditions, $n_s = n_{i,L}$. The critical velocity can be expressed as:

$$v_{cr} = \frac{n_{i,L} \cdot b}{St}$$

The difficulties arise from the fact that the sinusoidal force generated form the Vortex Shedding, and, therefore, the frequency n_s, depend from the dimensions of the body on which the flow impacts, as well as from the average velocity of the air flow in the HVAC duct. The value of this velocity lies in the range of 2-5 m/s. Therefore, to ensure that the bender enters in resonant conditions, flow velocity must be the critical one for the bender. Following that, if the bender configuration is changed, its eigenmodes of vibration will change, as well as its natural frequency, and hence, its critical velocity. Vice versa, if the flow velocity is changed, the optimal configuration that induces the resonance will change.

Numerical Modeling

The configuration of the piezoelectric bender is shown in figure 1. The object of the research is a cantilever bender with a piezoelectric patch, placed inside an HVAC duct (figure 1a).

The incoming wind flow impacts the bender and the detachment of alternating vortices produces a sinusoidal force acting in transversal direction to the wind flow (figure 1c). This force causes the vibration of the bender (figure 1b). Initially, a simple bender with piezoelectric patches has been studied, and, after the initial results, its configuration was changed, by adding a tip-mass (figure 1b). The geometric parameters of the bender, the patch and the tip-mass are shown in figure 2 and in table 1.

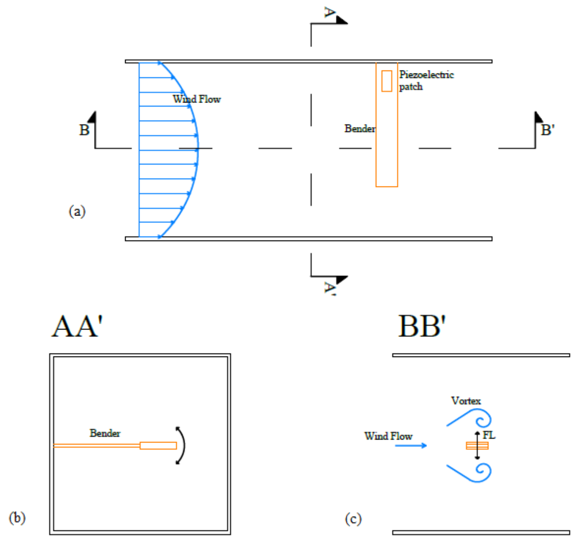


Figure 1. Piezoelectric Bender Inside the HVAC Duct

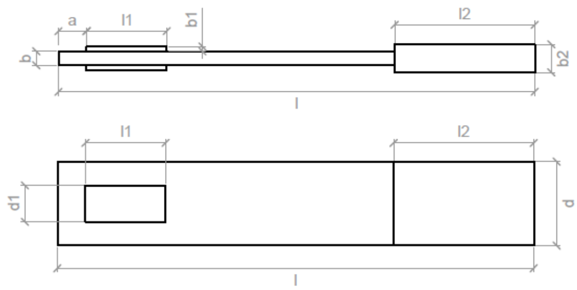


Figure 2. Geometric Parameters

Table 1. Values of Geometric Parameters

ELEMENTS	DIMENSIONS	VALUES (m)
BENDER	l	variable
	b	variable
	d	variable
	a	0.01
PIEZO - ELECTRIC PATCH	l_1	0.0286
	b_1	0.0017
	d_1	0.0127
ADDED MASS	l_2	variable
	b_2	0.01
	d_2	d

As shown in table 1, some dimensions are fixed while other can vary. The (fixed) dimensions of the piezoelectric patch have been chosen according to the piezoelectric elements currently available in the market. For the added mass, a fixed thickness of 0.01 m was chosen. The width of the added mass is the same as the one of the bender, while the length has been modified in order to study how it affects the entire model, as well as the bender dimensions.

In addition, and regarding the materials, the material properties of the piezoelectric patch are fixed while those of the bender can vary. In total, three materials have been considered, in order to identify the one with the optimal characteristics of weight and stiffness for the specific case. The materials and their characteristics are reported in table 2.

Table 2. Material Properties

MATERIAL	E (N/m^2)	ρ (kg/m^3)
Balsa	$3.3 \cdot 10^{12}$	175
Aluminum	$6.4 \cdot 10^{10}$	2700
Lead	$4 \cdot 10^{10}$	7400

LEAD ZIRCONATE TITANATE	
Density ρ	7800 kg/m^3
Young Modulus E	6.6 x10^3 N/m^2
Poisson ratio υ	0.2
Relative dielectric constant k^T_3	1800
Permittivity ε	1.602 x10^{-8} F/m
Piezoelectric constant d_{31}	-190 x10^{-12} m/V (C/N)

Numerical Results

In the first instance, and in order to find the most suitable density and stiffness characteristics, the Vortex Shedding parameters and bender modal characteristics have been studied for three different materials, which have been chosen for their different properties. After that, and after deciding that the best configuration is the one with the added tip mass, the length of this mass was calculated for multiple bender dimensions. Finally, the voltage and power outputs are reported as a function of the added mass and as a function of the bender dimensions.

Dimensions and Natural Frequencies

Table 3 provides the range of three variable bender dimensions. For each value, modal analysis was conducted and the Vortex Shedding parameters calculated. A bender modeled in aluminum was implemented in this case; the configuration is not the right one, but it was desired to show only to highlight the dependency from the bender dimensions of the parameters.

Table 3. Bender Dimension Range

Dimension	Range
Length l	0.06÷0.20 m
Thickness b	0.001÷0.008 m
Width d	0.02÷0.05 m

In the following figures, the frequency dependence from the bender dimensions is shown. As can be seen, the frequency increases with the bender thickness (figure 3) and it decreases with the length (figure 4) and the width (figure 5) of the bender.

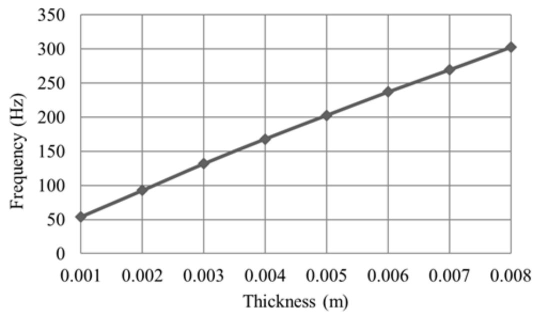


Figure 3. Frequency as a Function of the Thickness

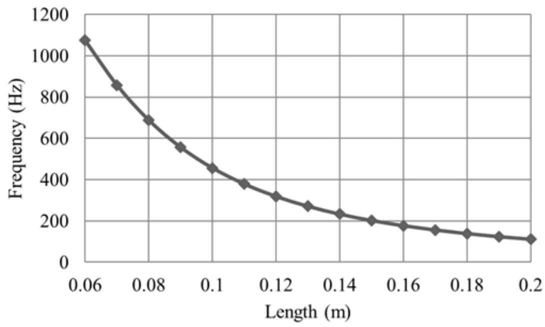


Figure 4. Frequency as a Function of the Length

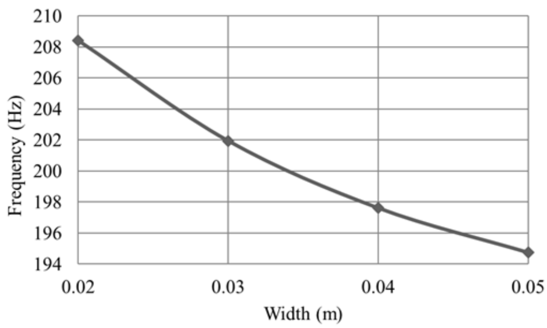


Figure 5. Frequency as a Function of the Width

Critical Velocity and Static Force

Figures 6 to 11 report the results.

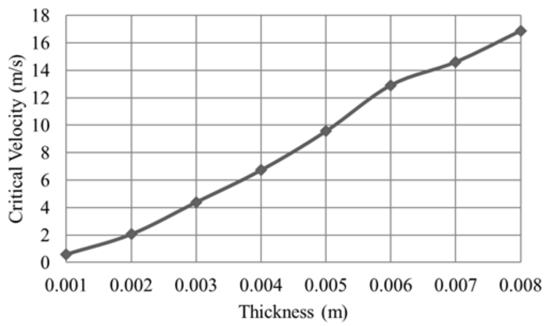


Figure 6. Critical Velocity as a Function of the Thickness

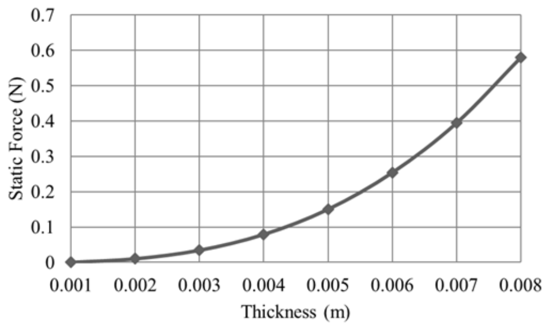


Figure 7. Static Force as a Function of the Thickness

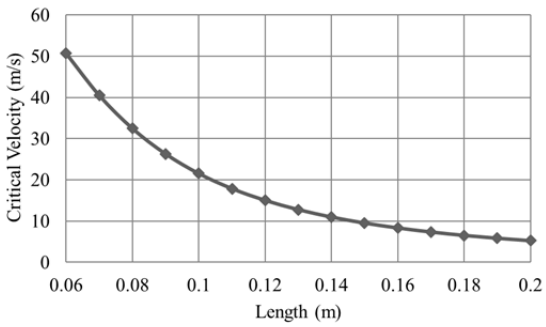


Figure 8. Critical Velocity as a Function of the Length

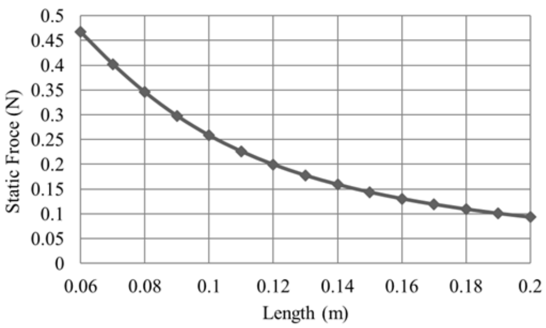


Figure 9. Static Force as a Function of the Length

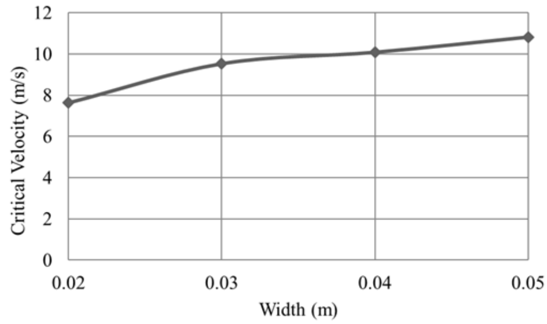


Figure 10. Critical Velocity as a Function of the Width

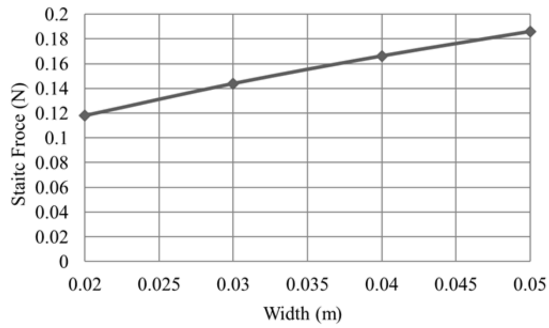


Figure 11. Static Force as a Function of the Width

The critical velocity and the static force are strongly interdependent and, for this reason, they have a similar tendency. They increase according to the thickness and the width, whereas they decrease according to the length of the bender.

Materials

After testing different material, the results of analysis with two materials in particular (aluminum and lead) are reported. The characteristics of the materials are those shown in table 2.

It was decided to show the results with these two materials because of their different densities and stiffness, so it is possible to comprehend the bender behavior to density and stiffness variations. In table 4, the values of the bender dimensions used in this case are reported.

Figures 12 and 14 show the frequency for the model in aluminum and lead respectively, while figures 13 and 15 show the critical velocity for the same materials.

Table 4. Values of Bender Dimensions

Dimension	Values
Length *l*	0.15÷0.20 m
Thickness *b*	0.003÷0.006 m
Width *d*	0.03 m

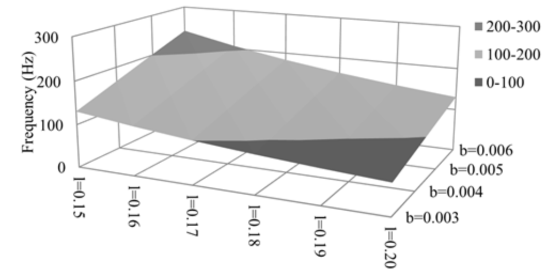


Figure 12. Natural Frequency as a Function of the Length and the Thickness for the Aluminum Model

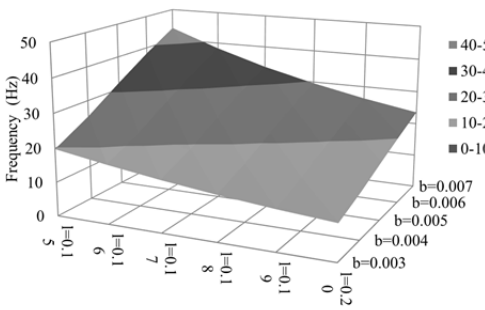


Figure 13. Natural Frequency as a Function of the Length and the Thickness for the Lead Model

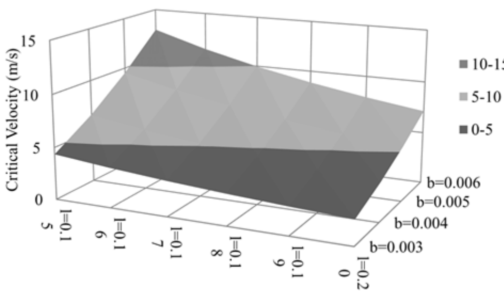


Figure 14. Critical Velocity as a Function of the Length and the Thickness for the lluminium Model

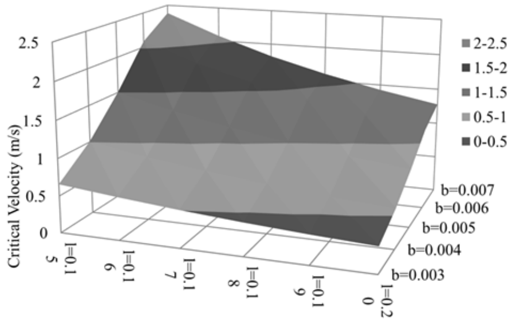


Figure 15. Critical Velocity as a Function of the Length and the Thickness for the Lead Model

In addition to the relationship of the parameters with the bender dimensions, these figures show that the configuration entirely in aluminum is very light. In fact, the critical velocities and the frequencies are too high. On the contrary, the configuration entirely in lead is very heavy and, consequently, the critical velocities are too low. Therefore, an additional configuration is studied in order to obtain the required global density and stiffness: a bender with a tip mass. The addition of the mass allows tuning the natural frequency of the bender and, therefore, the critical velocity.

Addition of a Tip Mass

For the calculation of the tip mass, as well as of its dependency from the dimensions, the following considerations are made.

The critical velocity range is imposed (2-5 m/s), which corresponds to the range of the average velocity in the duct, and from it the Vortex Shedding frequency n_s was calculated. The latter must be equal to the natural frequency n_i of the first eigenmode in order to obtain resonant conditions. Therefore, from the difference between these frequencies (n_s and n_i), the mass size is calculated. Fixing two dimensions, the width and the thickness of the mass, only the mass length was calculated, for each couple *l*-*b* of the bender.

Table 5 shows the values of the bender dimension with which the results are obtained.

Figures 16, 17, and 18 show the required mass length for different values of the critical velocity bender length and the bender thickness respectively.

Table 5. Bender Dimension Range

Dimension	Values
Length *l*	0.15÷0.20 m
Thickness *b*	0.003÷0.006 m
Width *d*	0.03 m

The lower the velocity acting in the duct (which is imposed equal to the critical one), the greater the required mass size must be (figure 16). This is because, by increasing the mass, the frequency decreases, and for lower values of the critical velocity lower frequency values are required.

In addition, the results shown in figures 17 and 18 are compatible with what reported before. For example, regarding the length variation, when it increases the natural frequency of the bender without the tip mass decreases. Therefore, the mass to be added in order to lower the natural frequency to the required value decreases. The exact opposite thing happens when considering the thickness variation (figure 18).

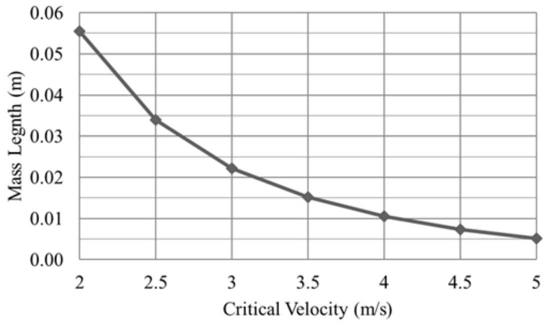


Figure 16. Required Mass Length for Different Critical Velocities

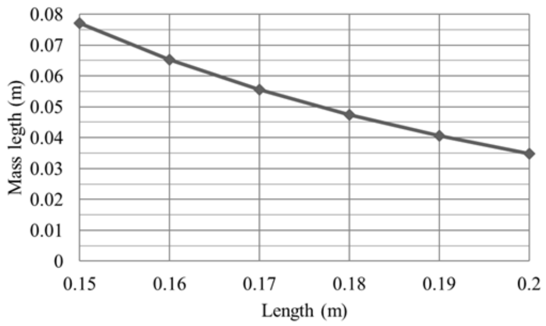


Figure 17. Mass Length as a Function of the Bender Length

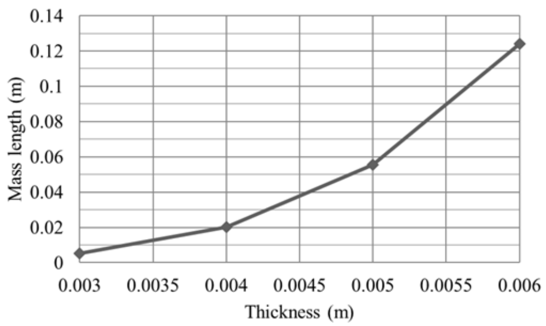


Figure 18. Mass Length as a Function of the Bender Thickness

Voltage and Power Output

The voltage and power outputs obtained by the application of the sinusoidal force derived from Vortex Shedding phenomenon are illustrated. For both parameters, the peak values and the RMS (Root Mean Square) values were calculated. Results for different configuration are reported in order to understand how outputs vary with the considered parameters. For the calculation of the power a resistance of 1000 Ω was used.

Model with Bender in a Material with Intermediate Properties

In order to study how the voltage and power outputs vary with the bender dimensions only (without considering the tip mass), a bender in a material with properties in-between those of aluminum and lead is studied. Table 6 reports the characteristics of this material.

Table 6. Properties of the Fictitious Material

Dimension	Values
Young Modulus E	3.45×10^{10} N/m^2
Density ρ	7000 kg/m^3

The voltage and power outputs have been calculated both in the center (identified in the figures with “1”) and in the corner (identified in the figures with “2”) of the piezoelectric patch. The maximum values are measured in the corner, where the stress is maximum. Figures 19, 20 and 21 show RMS and peak values of the voltage for different values of the bender length, the bender thickness and the critical velocity respectively.

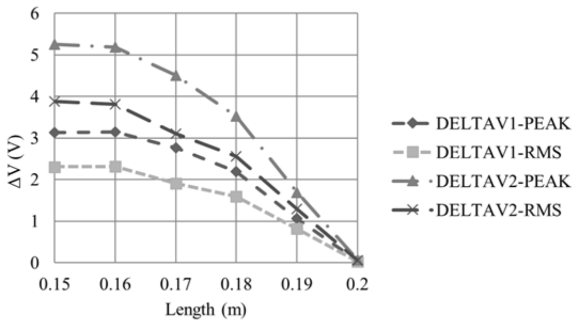


Figure 19. Peak Values and RMS Values of the Voltage for Different Bender Lengths

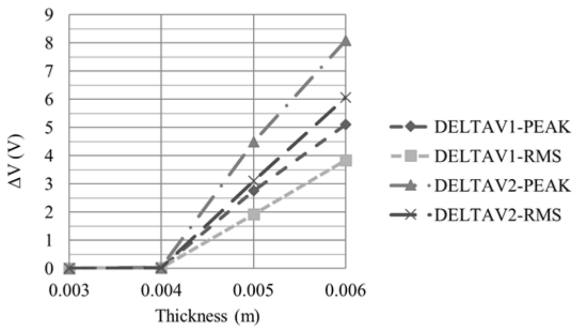


Figure 20. Peak Values and RMS Values of the Voltage for Different Bender Thicknesses

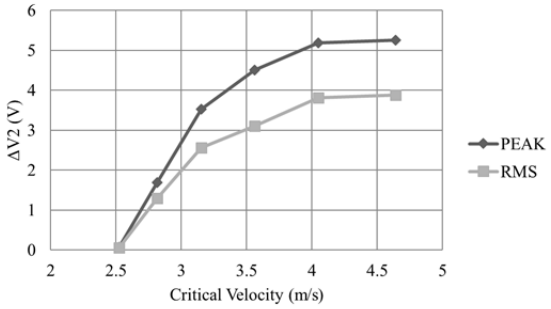


Figure 21. Voltage Output for Different Values of the Critical Velocity

Figures 22, 23 and 24 show the same measures in relation to power.

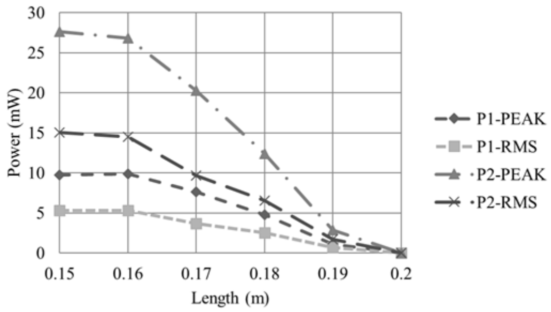


Figure 22. Peak Values and RMS Values of the Power for Different Bender Lengths

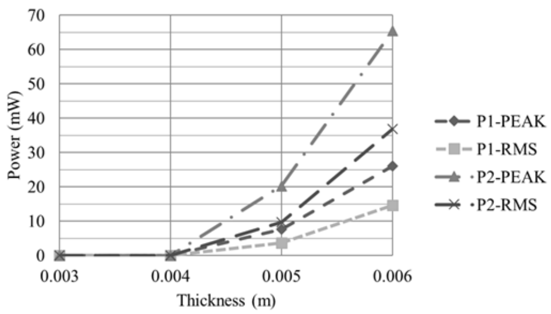


Figure 23. Peak Values and RMS Values of the Power for Different Bender Thicknesses

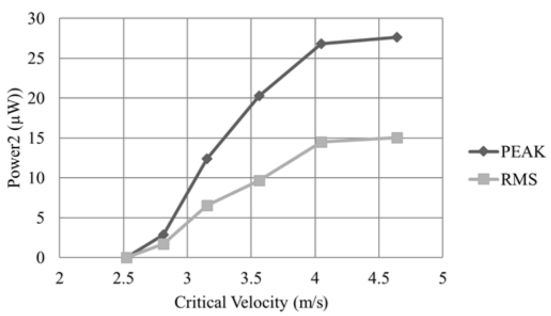


Figure 24. Power Output for Different Values of the Critical Velocity

From the results, it is clear that the voltage output, as well as the power output increase when the thickness increases and the length decreases. The magnitudes of these results are not taken into account, but only the tendencies, because they are obtained through the study of a configuration with a fictitious material. As it is expected, the voltage and the power increase with the critical velocity.

Model with Different Mass Lengths

As a last step, the voltage and power outputs were calculated for a fixed aluminum bender with variable tip mass. The bender dimensions and tip mass dimension are shown in tables 7 and 8 respectively.

Table 7. Bender Dimensions

Dimension	Values
Length *l*	0.17 m
Thickness *b*	0.005 m
Width *d*	0.03 m

Table 8. Added Mass Dimensions

Dimension	Values
Length l_2	variable
Thickness b_2	0.01 m
Width d_2	0.03 m

The peak and RMS values are illustrated in figure 25, for the voltage, and in figure 26, for the output power, which was calculated with a resistance R=1000 Ω. These results show a voltage trend increasing with the added mass, though the trend is not linear but fluctuating. This is caused by the fact that the added mass affects not only the total structure mass, but also the moment of inertia and, therefore, its global stiffness.

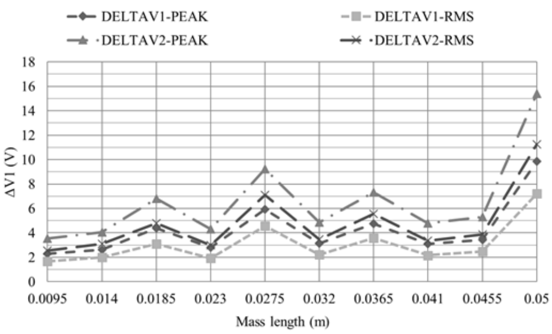


Figure 25. Peak Values and RMS Values of the Voltage for Different Mass Lengths

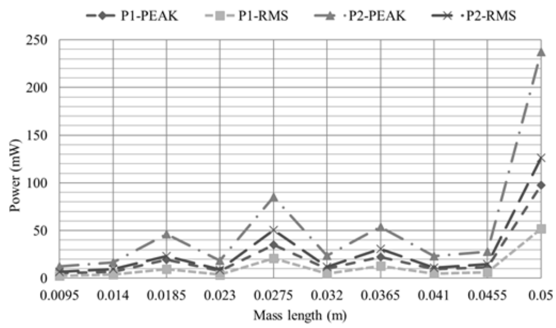


Figure 26. Peak Values and RMS Values of the Output Power for Different Mass Lengths

The maximum voltage output, as well as the maximum power output, occur for the higher mass value (table 9).

Table 9. Maximum RMS and Peak Values of the Voltage and Power Outputs

	VOLTAGE (V)	POWER (mW)
PEAK	15.4	237.20
RMS	11.23	126.25

The above power generation is in line with the energy requirements foreseen in a reference study by Rabaey *et al*. (2000), for the powering of a "PicoNode", a wireless sensing, communication, and computation node that, among else, would consume less than 100 μW on average.

Conclusions

A piezoelectric bender under Vortex Shedding flow excitation placed inside an HVAC duct has been studied. The laws by which the parameters vary have been found, as well as the optimal configuration of the bender and the one that produces the resonance conditions for each value of the airflow velocity acting inside the duct. Finally, the voltage and power outputs have been calculated for different dimensions and configurations. It is found how the critical velocity, the static force and the natural frequency vary with the bender dimensions. The optimal configuration of the bender has also been obtained: a bender made of aluminum with a tip mass made up by lead. The materials were chosen for their stiffness and density characteristics. The added mass allows adjusting not only the total mass of the structure, but also its global stiffness and, as such, it allows tuning the natural frequency of the structure.

The voltage and the power increase when the bender thickness and the critical velocity increase, whereas they decrease when the bender length increases. Furthermore, the voltage and power outputs increase when the added mass increases. The calculated values of the voltage and power are sufficient to power a wireless sensor node in order to monitor ambient parameters inside an HVAC duct.

Of course, there are limitations to this study. In this phase, only the characteristics of the fictitious material have been obtained. For an eventual physical test, a readily available material should be identified. In addition, the results can be considered as preliminary. For an eventual validation, advanced numerical models should be prepared (for example, models based on CFD – Computational Fluid Dynamics), that can better capture the flow-bender interaction. After that, a physical model should be tested in laboratory conditions.

More generally, it is possible to state that energy harvesting technologies make the easy installation of wireless self-powered sensors possible. These can monitor the environmental condition in order to automatize and optimize the operation of specific systems like lighting systems, HVAC (Heating Ventilation and Air Condition) systems, etc. Therefore, the integrated implementation of Building Automation Systems and Energy Harvesting technologies can provide a resolution to the problem of high-energy consumption and elevated cost for maintaining normal function of buildings.

Acknowledgements

This paper presents results from the Master in Science Thesis of one of the authors (Sara Ferri), successfully defended to the Department of Structural and Geotechnical Engineering of the Sapienza Univerity of Rome. The other authors co-advised different parts of this Thesis. Furthermore, the www.francobontempi.org research group at the Sapienza University of Rome is gratefully acknowledged. This study was partially supported by the research spin-off StroNGER s.r.l. (www.stronger2012.com) from the fund "FILAS - POR FESR LAZIO 2007/2013 - Support for the research spin-off".

References

Belleville, M., Fanet, H., Fiorini, P., Nicole, P., Pelgrom, M.J.M., Piguet, C., Hahn, R., Van Hoof, C., Vullers, R. and Tartagni, M. (2010) Energy autonomous sensor systems: Towards a ubiquitous sensor technology. *Micro electronics Journal*, Vol. 41, No. 11, pp. 740-745.

Blazevic, D., Zelenia, S. and Gregov, G. (2010) Mechanical analysis of piezoelectric vibration energy harvesting devices. *MIPRO, 2010 Proceedings of the 33rd International Convention*, pp. 122-126.

Chalasani, S. and Conrad, J.M. (2008) A Survey of Energy Harvesting Sources for Embedded

Systems. *IEEE Proceedings of Southeastcon 2008*, pp. 442–447.

Davino, D., Giustiniani, A. and Visone, C. (2012) Effects of hysteresis and eddy currents in magnetostrictive harvesting devices. *Physica B: Condensed Matter*, Vol. 407, No. 9, pp. 1433-1437.

Dyiana, N. H., Muthalig, A. G. A., Fakhzan, M. N. and Nordin, A. N. (2012) Vibration energy harvesting using single and comb-shaped piezoelectric beam structures: modelling and simulation. *Procedia Engineering*, Vol. 41, pp. 1228-1234.

Gammaitoni, L., Vocca, H., Neri, I., Travasso, F. and Orfei, F. (2011) Vibration Energy Harvesting: Linear and Nonline-ar Oscillator Approaches, Sustainable Energy Harvesting Technologies - Past, Present and Future. Yen Kheng Tan (Ed.), InTech, Retrieved May 27, 2014 from: http://www.intechopen.com/articles/show/title/vibration-energy-harvesting-linear-and-nonlinear-oscillator-approaches

Gao, X., Shih, W-H. and Shih, W. Y. (2013) Flow energy harvesting using piezoelectric cantilevers with cylindrical extension. *IEEE Transactions on Industrial Electronics*, Vol. 60, No. 3, pp. 1116-1118

Gibson, R.F. (2010) A review of recent research on mechanics of multifunctional composite materials and structures. *Composite Structures,* Vol. 92, pp. 2793–2810.

Gilbert, J.M. and Balouchi, F. (2008) Comparison of Energy Harvesting Systems for Wireless Sensor Networks. *International Journal of Automation and Computing*, Vol. 5, No. 4, pp. 334-347.

Gkoumas, K. (2012) Energy harvesting in bridges and transportation infrastructure networks: state of art, recent trends and future developments. *Proceedings of the Sixth International IABMAS Conference*, pp. 1527-1533.

Harb A. (2011) Energy harvesting: State-of-the-art. *Renewable Energy*, Vol. 36, No. 10, pp. 2641-2654.

Kompis, C. and Aliwell, S. (eds.). (2008) Energy Harvesting Technologies to enable remote and wireless Sensing. Sensors and Instrumentation KTN Report, Retrieved May 27, 2014 from: ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/necs/20090306-05-eharvesting-ck_en.pdf

Li, R., Rguiti, M., D'Atorg, S., Hajjaji, A., Courtois, C. and Leriche, A (2011) Modeling and characterization of piezoelectric cantilever bending sensor for energy harvesting. *Sensors and Actuators A: Physical*, Vol. 168, No. 1, pp. 95-100.

Ly, W. G., He, S. and Yu, S. (2010) Improving power density of a cantilever piezoelectric power harvester through a curved L-shaped proof mass. *IEEE Transaction in industrial electronics*, Vol. 57, No. 3, pp. 868-876.

Morvaj, B, Lugaric, L. and Krajcar, S. (2011) Demonstrating smart buildings and smart grid features in a smart energy city. *Proceedings of the 2011 3rd International Youth Conference on Energetics (IYCE)*, pp.225-232.

Ovejas, V. J. and Cuadra, A. (2011) Multimodal piezoelectric wind energy harvesters. *Smart Materials and Structures,* Vol. 20, 8pp.

Priya, S. and Inman, D.J. (eds). (2009) *Energy Harvesting Technologies*, New York, Springer.

Rabaey, J., Ammer, J., da Silva, J., Patel, D. and Roundy, S. (2000) Picoradio supports ad-hoc ultra-low power wireless networking. *IEEE Computer Magazine*, Vol. 33, No. 7, pp. 42–47.

Song, D., Yang, C. H., Hong, S. K., Kim, S. B., Woo, M. S. and Sung, T. H. (2012) Feasibility study in application of piezoelectricity to convert vibrations of Korea Train Express. *Proceedings of IEEE Applications of Ferroelectrics (ISAF/ECAPD/PFM).*

Wang, D-A. and Ko, H-H. (2010) Piezoelectric energy harvesting from flow-induced vibration. *Journal of Micromechanics and Microengineering*, Vol. 20, No. 2, 9pp.

Wang, Q. and Wu, N (2012) Optimal design of a piezoelectric coupled beam for power harvesting. *Smart Materials and Structures*, Vol. 21, No. 8.

Weinstein, L. A., Cacan, M. R., So, P. M. and Wrigth, P. K. (2012) Vortex shedding induced energy harvesting from piezoelectric materials in heating, ventilation and air conditioning flows. *Smart Materials and Structures.* Vol. 21, 10pp.

Wu, N., Wang, Q. and Xie, X. (2013) Wind energy harvesting with a piezoelectric harvester. *Smart Materials and Structures*, Vol. 22, No. 9.

Zhou, L., Sun, J., Zheng, X. J., Deng, S. F., Zhao, J. H., Peng, S. T., Wang, X. Y. and Cheng, H. B. (2012) A model for the energy harvesting performance of shear mode piezoelectric. *Sensors and Actuators A: Physical,* Vol. 179, pp. 185-192.

Zhu, M., Worthington, E. and Tiwari, A. (2010) Design study of piezoelectric energy harvesting devices for generation of higher electrical power using a coupled piezoelectric-circuit finite element method. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency control,* Vol. 57, No. 2, pp. 427-437.

Sustainable Agricultural Building Design Using Locally Grown Danish Timber

Olga Popovic Larsen*1, Daniel Lee[1], and Torben Lange[2]

Olga.larsen@kadk.dk, Daniel.lee@kadk.dk, TLA@tlaticon.dk

[1] Royal Danish Academy of Fine Arts School of Architecture, Denmark

[2] ATICON, Denmark

Abstract: The paper describes an ongoing project, a sustainable design of an agricultural building, part of an ecological meat production farm on the island of Glænø in Denmark. It is a low-cost design using local skills and materials. The building is resource saving on every level; it also utilizes excess heat and sun energy. The paper presents the overall sustainable design approaches and mainly concentrates on the design of the optimized timber roof truss which uses locally grown timber. The main design criteria for the timber roof structure are structural efficiency, buildability and aesthetic appearance of both the concept and detailing.

Keywords: Sustainable Design, Local Timber, Reciprocal Frames, Optimized Design.

The Design Context

In Denmark there is a great tradition in agriculture, especially production of meat, which is mostly produced in intense farming conditions. In recent years there are increased tendencies of ecological meat production, where the animals are let to graze freely in free-range farms. Undoubtedly the quality of meat produced this way is better, but often the cost of such ecological meat production is higher due to increased health risks for the animals, need for more space on the farms, the volume of meat production which is rather small in comparison to the intensive production etc. Although the government supports such initiatives, it is often that the most persistent farmers who through daily struggle manage to keep up the ecological farming. Despite the government's efforts to help ecological farming, its volume in comparison to intensive farming is still lower.

In the context of the above the task was to design a building, a new cowshed that would replace an existing one and provide home for the ecological meat production. The client strongly believes in sustainable approaches. Thus the building had to be designed to minimize resources both for construction, also to reduce operational energy use. The materials used in construction had to be local, also the building should use as much as possible local skills and easy to construct methods without any machinery beyond what is available on a typical farm. Lastly the building structure should be something other farmers could copy, almost build it themselves because it is easy to construct, it is efficient and beautiful. The building structure should challenge the existing approaches of designing and building farm buildings and offer new, improved and more sustainable ways.

The Brief

The brief was to design a building that would measure 16 x 32 meters in plan (figure1, bottom) without any internal vertical supports. As the aim was to create a new approach for farm buildings an important requirement was that the building from outside must have a conventional 30 deg. roof, (figure 1, top) just like any other typical farm building in Denmark would have.

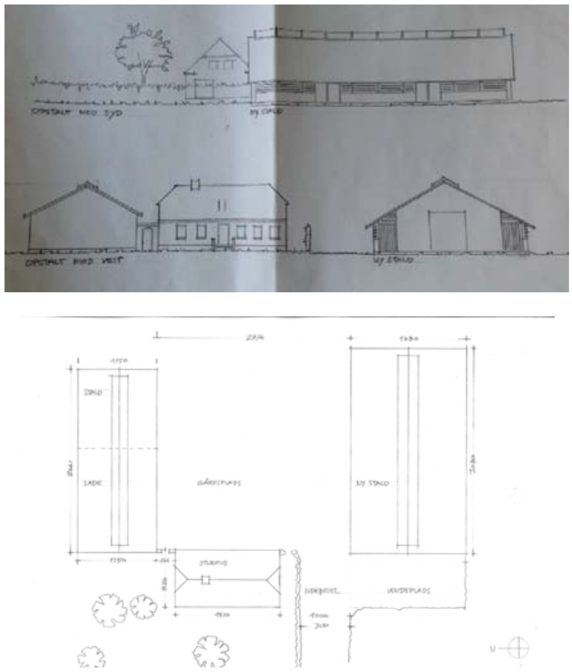


Figure 1. The Arangement of the Buildings Showing the Position of the New Cowshed (The Largest Building)

The client thought that if we challenged the external expression by offering a completely new form, the building would not fit in a conventional Danish farm setting. Furthermore, it would be unlikely that other farmers would use the idea for the roof structure. This gave a clear constraint to the possible geometry of the roof.

The Design

The building will be designed using concrete foundations and a concrete floor. The building design will be used as an experiment by trying to utilize the heat that is produced in the fermentation of the feces from the animals mixed with straw. The heat will be stored and transported through the concrete floor and utilized for heating. There will be a special system of pipes in the floor that resembles an above ground heat pump situated in the floor. The system is new and the client is developing it together with researchers from the Danish Technological Institute.

The roof has a good orientation and it will be used for solar energy with panels that will be fully integrated in the structure and not as an add-on often seen on farm buildings.

These, as well as the sustainable roof design, will make the building a showcase for sustainable design of an agricultural building in the Danish context.

The Timber Roof

A common approach when building an agricultural building in Denmark would be to use a prefabricated timber truss roof structure. This would be a relatively cheap and fast way to build a roof over a column-free space. A prefabricated timber truss was not an option for this project because it would have not followed a sustainable design approach, something that the client could not accept. The truss uses:

- C24 timber most likely imported
- Fully dried timber, thus has used additional heat for drying the timber
- Engineered connections that require a specialized construction team for assembly (often provided by the truss supplying company)
- Purely engineering aspects for structural performance thus has no consideration of aesthetic appearance of the overall structure and the details of the connections.

The prefabricated timber truss as a recognized structurally efficient option during the design process was used as a benchmark for comparison. In the design development, during each step of the process, each new design option was compared to the truss in terms of efficiency and the design was optimized continuously and accordingly. The comparisons guided the optimization process. During the design development the optimization was carried out to achieve minimal use of timber (Heschler *et al.* 2011) by achieving an efficient structural design concept, but also a design that was aesthetically pleasing with simple, efficient and beautiful detailing and a building that could be constructed with out machinery almost in a DIY way. It was a challenge!

The Design Development

The first initial ideas came from structures using small timber members that combined form stable assemblies (Larsen 2014). More specifically a structure inspired by Leonardo da Vinci's temporary bridges (figure 2) forming an Reciprocal Frame (RF) arch structure was the starting proposed design.

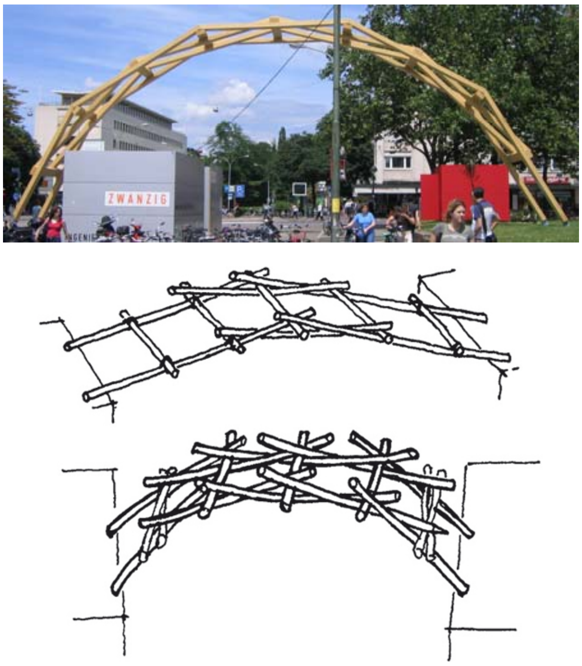


Figure 2. Leonardo da Vinci's Temporary Bridges

The idea to use a Reciprocal frame (RF) structure came because RFs are:

- Easy to construct due to the interlocking of the RF members (Baverel and Larsen 2011)
- Easy to handle because the members are small thus weigh less (Larsen 2013).
- The weaving effect of the interlocking structure offers a possibility of creating a distinct aesthetic

We all liked the appearance of the structure. After modeling the structural behavior we made a crude 1:10 physical model, which suggested ease of construction of the interlocking members and also, showed a very interesting aesthetic (figure 3).

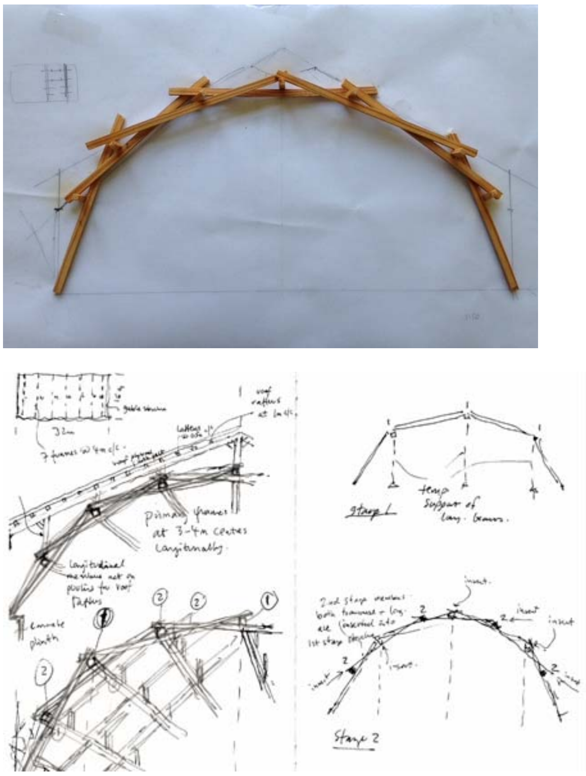


Figure 3. The First RF Arch Structure Proposal

Then we carried out a comparison to the prefabricated truss used as a benchmark. As we knew that we would be using locally grown timber (most of it fast grown spruce), as shown in figure 4, we could not count on more than C18, in some cases even less, yet the prefabricated truss was C24. We therefore modeled the RF arch both in C18 and in C24 and the volume of wood in C24 was compared to the volume of wood (also in C24) used in the prefabricated truss. It was clear when comparing the structural efficiency of the RF arch to the prefabricated truss, that the truss would be more efficient, so that did not come as a surprise. However, when looking more closely to the design, a further problem was that not only an arch was structurally less efficient, but had to be loaded with a secondary structure creating the 30 deg. sloping roof appearance to the roof. A simple solution of reducing the dead load would have been to clad the roof in a segmented arch form and not follow the 30 deg. sloping roof. The suggestion was not accepted by the client. He felt that a form like that would not fit into the context. We were back to the drawing board!

Several other concepts were considered and each time the concept was modeled and compared to the benchmark structure. It was clear that it would be difficult to fully match the structural efficiency of the benchmark structure because we were using local timber with lower grade, thus the design required larger sections. Furthermore an important consideration was the ease of construction and an

Figure 4. Locally Grown Timber (Spruce) Will Be Used for Construction

important compromise was to come up with a structurally optimized design that was aesthetically pleasing and easy to build. Although our design is using more timber, it is sustainable because:

- The timber is locally grown, comes from 400 meters away from the farm
- The timber will be dried outside and will not use any additional energy for drying
- The design avoids complicated construction methods.

At present the design development (figure 5) has achieved a design that is very close (about 10-15% more) to the use of timber of the benchmark structure. This was achieved through many iterations and design development. The final design (figure 6) is a Reciprocal Frame truss. Thus it is more efficient than an arch, avoids the dead load of a secondary structure by using the top cord of the structure for forming the required 30 deg. roof.

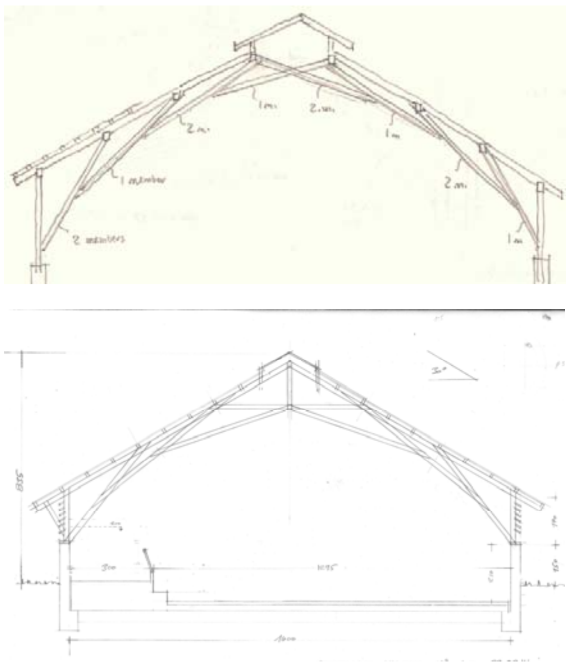


Figure 5. Steps in the Project Development – A RF Truss

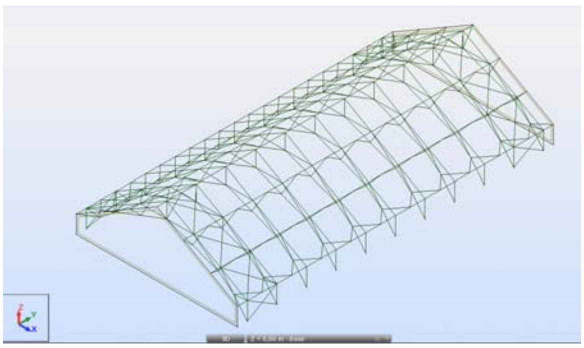


Figure 6. 3-D View of the Roof Structure

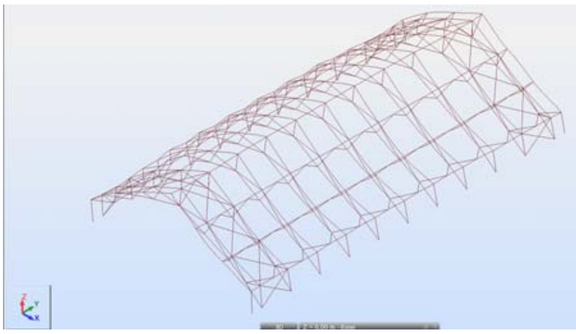


Figure 7. Perspective View of the Deformed Structure under the Wind Load

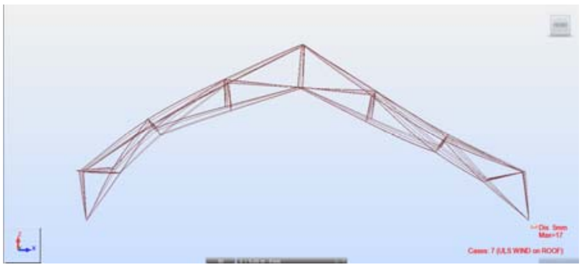


Figure 8. Elevation View of the Deformed Structure under the Wind Load

The following information is relevant to the design:

- The 3D computer model is constructed to analyze the overall stability of the structure under the combinations of loads, including s wind and snow loads (figures 7 and 8).
- All elements are assigned to pinned support condition (free to rotate at ends). Though the actual timber connections may transfer moments between the elements, they will become loose over years due to local compression deformations of the timber and eventually no moments would be possible to be transferred; thus they are calculated as pinned supports.
- In the computer model, the loads are applied on each frame as line loads, and the wind load on the gables are applied on pseudo-panels.
- The calculation is in accordance with the Eurocode with Danish National Annex.
- The structure is checked against the limit state design criteria, and the overall displacements of the structure are not critical as for the building does not include any brittle components.
- The material strength of the elements is specified to C18 with Service Class 2, although in some cases it may be lower.

To Be Done

At present the wood has been felled and imminently will be cut to the required sizes. It will then be left to dry for about a year. As the building will be an unheated space there is no need to fully dry the timber, but it will be sufficient to reach 18-20 %. To achieve that level it will be sufficient to dry the members in a covered, well-ventilated space (most likely a tent will be constructed over the timber). It will take some effort to cut the timber – about 16040 meters in total length. As the logs are in different diameters, drawings (figure 9) have been made for all the timber log sizes, suggesting how to cut the timber so that most is used and least is wasted.

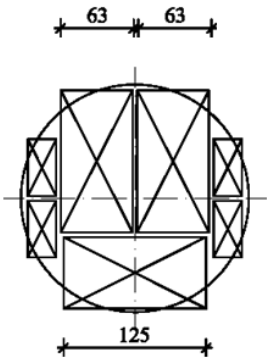


Figure 9. Example Drawing Suggesting How to Cut the Timber so the Least is Wasted and Most is Used

During the period while the timber is drying the design of the connections (Rizzuto and Larsen 2010) will be finalized. The final design details will follow the overall design strategy of achieving an efficient, easy to construct and crisp/beautiful expression simultaneously.

It is envisaged that work on site will start approximately one year from now. It is likely that the construction will give opportunities to involve students. Workshops in real scale and on a real project will give an opportunity to teach about the design process, optimization, the RF structural system and about how to work with wood. In that sense the project has a great educational potential.

Beyond the Project

There are several benefits and agendas that the project can influence:

1. Exploring the potential of RF trusses as a development from single layer RF structures to double layer structures. A study of the structural efficiency, geometry, aesthetic potential and applicability will give an overview of the real potential. Double layer RFs have not been researched in any depth yet.
2. Developing a new way of building agricultural buildings in the Danish context using local materials and local skills.
3. Using this and further projects for combined interdisciplinary educating of students (engineers, architects, carpenters, material scientists, timber education students, etc.)
4. Influence Denmark/EU to support small farms in the ecological meat production.
5. Influence more sustainable design and construction.

It will be a great success if only even a small part of these agendas are influenced by the project.

Conclusions

The paper presented an ongoing design project of an agricultural building to be constructed out of local timber. The roof structure uses an optimized RF truss system. The paper presented the design process of the roof structure and gave an overview of the future potentials of the process.

Acknowledgements

The authors would like to acknowledge the client Henrik Terkelsen, for giving us an excellent research opportunity to explore double-layer minimal RF trusses on a real project.

References

Baverel, O., & Larsen, O. P. (2011) A review of woven structures with focus on reciprocal systems-nexorades. *International Journal of Space Structures,* 26(4), 281-288.

Heschler O., Larsen O.P. and Nielsen, S. (2011) Sustainability of Constructions: Integrated Approach to Life-Time Structural Engineering. *Volume 2: Integrated Approach to Life-Time Structural Engineering - Summary Report of the Cooperative Activities of COST Action C25*, European Science Foundation, pp. 339-354.

Larsen, O.P (2013) Design and Construction of Three-dimensional lightweight Timber Grid Strictures Explored through a Mass-Customized Approach, *Mass Customisation and Personalisation in Architecture and Construction*. Routledge, pp. 105-113.

Larsen, O. P. (2014) Reciprocal Frame (RF) Structures: Real and Exploratory. *Nexus Network Journal*, 16(1), 119-134.

Rizzuto, J. P., & Popovic Larsen, O. (2010) Connection systems in reciprocal frames and mutually supported elements space structure networks. *International Journal of Space Structures*, 25(4), 243-256.

From Structures to Automation in Freshman Civil Engineering Projects

Yin-Nan Huang, Albert Y. Chen, Jiing-Yun You, and Hervé Capart*
ynhuang@ntu.edu.tw, albertchen@ntu.edu.tw, genejyu@ntu.edu.tw, hcapart@yahoo.com
Department of Civil Engineering, National Taiwan University, Taiwan

Abstract: For the last four years, we have offered a cornerstone design course to first year students of civil engineering at National Taiwan University. This mandatory course is centered on design-build-test projects, blending digital design with physical model fabrication and testing. For the first two editions of the course, the project scope was limited to structures, and centered on scale models of roof structures made of jet-cut aluminum. These last two years, we have supplemented structural aspects with a transportation automation component, including system design, motor control, and Arduino board programming. In this contribution, we describe this new version of the course, and extract some lessons on how to enrich students' learning experience. Strategies we have found useful include self-paced tutorials and peer review, theory-based design aids, and an enlivened load testing process.

Keywords: Freshman Design, Project-Based Learning, Structural Engineering, Transportation Engineering.

Introduction

These last four years, our Department of Civil Engineering has been engaged in a sustained effort to enrich the undergraduate curriculum with stronger design and practice-oriented components. Building on pilot tests (Ni *et al.*, 2011), we now offer a sequence of project-based courses called cornerstone, keystone, and capstone courses, directed respectively at first, second, and third or fourth year undergraduates (Capart *et al.*, 2013). The sequence works well overall, with each course allowing students to acquire skills that they can build upon in later courses. Within this sequence, the cornerstone design project offered the second semester of the first year is especially important. As a mandatory core course, it aims to provide a foundation in terms of design skills, and motivate interested students to pursue design and practice-oriented projects in subsequent optional courses. At other schools, related approaches to civil engineering design education have been described by Arciszewski (2009), Thompson (2010), and Einstein (2013).

Our department therefore allocates to this course an unusual level of resources. Instead of the three sections adopted for most courses, the course splits our class of 120 students into six separate sections, with each section addressing a smaller group of 20 students. The course is taught by a team of six instructors, aided by teaching assistants, student teaching assistants, and technical staff. Support from our alumni and the Ministry of Education also allows us to support the course with the requisite materials and equipment, including a computer-controlled water jet cutting machine, used to transform students' digital designs into functional parts. To make the most of these resources, we have devoted considerable efforts to designing course contents and approaches that seek to maximize student learning and achievement. For the first two editions of the course, the project scope focused on structures, and culminated in the construction of scale models of roof structures made of jet-cut aluminum and poured gypsum. These last two years, we have sought to further improve and enrich the course, by refining the structural design-build-test component, and by including a new transportation automation component. One key goal of the course is to let students learn how to navigate between the digital and physical world, from digital design to the construction of structural and mechanical prototypes and back to digital control.

To tie in with the cornerstone project, two mandatory courses which used to be offered in the third year of the curriculum have been moved up to the first year. The first is engineering graphics, now taught in the first semester of the first year, which equips students with the basic skills needed for digital design. The second is computer programming, now taught in the second semester in parallel with the project, which equips students with the logical design and computer coding skills needed for the design and programming of automated systems. As the project now includes both static and dynamic components, it also ties in more fully with the engineering mechanics course, also taught in the first year.

In this contribution, we describe the structure-to-automation projects proposed these last two years. Although both projects combined structures and automation, the two design briefs differed a great deal, and we discuss the corresponding advantages and drawbacks. We also describe strategies adopted for both projects that we found particularly useful, including self-paced tutorials and peer review, theory-based design aids, and an enlivened load testing process.

Project Briefs

Space Structures Linked by a Conveying System

The project brief for the Spring 2013 edition of the course was our first attempt to integrate structural issues with an automated transportation component (figure 1). For the first part of the semester, pairs of students were tasked with designing, building and testing a functional scale model of a large span roof structure. Mounted on a wood base of size A1, the roofs were to span a footing-free area of size A2. Students were to build their structures from aluminum components of their own design, cut from a single plate of size A3 and thickness 4 mm, complemented by bolts and steel cables.

The load-bearing requirement was the ability to support metal blocks weighing 2.5 kg each, at least 105 mm above ground, and distributed over as wide an area as possible for a total of minimum 50 kg and maximum 100 kg. In addition to this functional requirement, the brief challenged students to design elegant and expressive structures.

For the second part of the semester, aggregated teams of four students were tasked with designing, building and testing an automated conveying system linking their two space structures. The payload to be delivered back and forth was a single steel sphere, using a system composed of a programmable Arduino board (Motoduino), electrical motors and switches, jet-cut aluminum components, steel cables and aluminum rods that could be used as rails for spheres to roll on.

Earthquake-Resistant Automated Parking Tower

For the Spring 2014 edition of the course, a new project brief was developed, challenging students to design, build and test an earthquake-resistant automated parking tower (figure 2). Students worked in stable teams of three throughout the semester. In the first part of the semester, students designed and constructed a three-story earthquake-resistant tower.

To be mounted on an A3 wood plate, the structures were to be assembled from student-designed aluminum components, jet-cut from an A2 plate of thickness 4 mm, complemented by three viscous piston dampers. Although viscous dampers of identical specifications were provided to all groups, students were free to choose damper positions and configurations which they thought would give the best energy dissipation properties.

Figure 1. Spring 2013 cornersone project: space structures linked by a conveying system, fabricated from jet-cut aluminum and steel cables. Top: completed structure and load-testing. Bottom: automated system shuttling spheres back and forth.

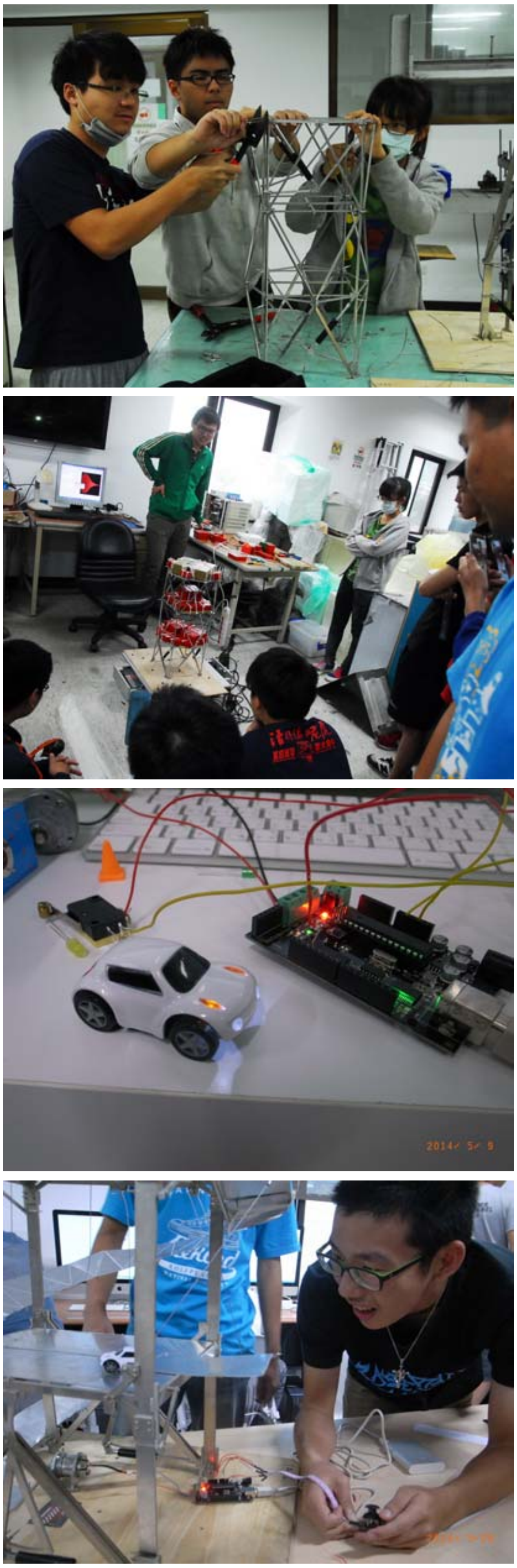


Figure 2. Spring 2014 cornersone project: earthquake-resistant automated parking tower. Top: tower assembly and load testing using a shaking table. Bottom: Arduino-controlled model cars and their test drive up and down the tower.

The structural load-bearing requirement was to support steel blocks on three floors, and resist earthquake loads of up to 0.5 g peak ground acceleration generated by a shaking table.

For the second part of the semester, students were to equip their tower with a car access ramp, allowing the up and down circulation of remote-controlled model cars (ZenWheels R/C Microcar). Although these cars were originally designed for control by an iPhone, students were tasked with wiring and programming an alternative control system composed of an Arduino board, blue tooth connection, and joystick. In addition to these functional requirements, students were again challenged to design expressive and attractive towers

Advantages and Drawbacks of the Two Briefs

Although the two structural briefs focused on different types of structures (large span roof versus multi-story tower), they have a number of common advantages. First, they allow repeating elements (parallel beams or stacked floors) yet provide a large range of possible variations in structural configurations and assembly details. The prescribed dimensions (spans, heights, size and thickness of aluminum plates from which components were cut) were carefully chosen to require relatively slender structures for which differences in design would lead to large differences in behavior.

Load testing produced a variety of failure modes, including overall instability, large deformations, bending failure, element buckling, and connection failures. The large span roofs required students to carefully consider how to combine aluminum members and steel cables (for elegant examples, see Saitoh and Okada, 1999). The earthquake-resistant tower required students to think about how their structure would respond to dynamic loading, and how best to use viscous dampers to damp shaking-induced oscillations (for background, see Hwang et al., 2005). The opportunity for students to find out how structures of their own design respond to static or dynamic loads is certainly one of the highlights of the course.

For the automation component of the course, the two briefs feature more contrasted advantages and drawbacks. Building an automated sphere conveyer system required students to devote much time and effort to mechanism design and tinkering. To help students, we provided a tutorial example consisting of an elevator device, and many groups chose to include this as a component of their design with only minor variations. Other groups, however, chose to explore very different types of mechanisms including swings, cable cars, a staggered staircase, a catapult, and rotary conveyers.

It turned out that mechanism design and implementation had a much greater influence on success than the computer coding aspects of system control. Although some Arduino controlled systems did well, the best system by far was a student-designed rotary belt conveyer which required no programming at all, with the motor operated continuously to handle a payload of multiple spheres. Adventurous students, therefore, learned more about mechanisms and mechanical systems than about computer programming, which had been our original target. Other drawbacks were a low need for integration between the space structure and transportation components of the project, and a lack of realism of the brief. Who needs to send spheres back and forth between space structures anyways?

For the automated parking tower, the use of a model car as basic transportation vehicle had a number of advantages. First, it reduces greatly the mechanical complexity of the project, and allowed students to devote more effort to the wiring and coding aspects of car control. Integration of the vehicle ramp with the structural tower also required students to produce more integrated designs. Finally, the project benefited from a much greater degree of realism. Civil engineers do wish to design earthquake-resistant structures through which cars can smoothly circulate.

On the downside, the range of possible variations for car ramp designs is more limited than for sphere-conveying mechanisms, providing fewer opportunities for creative invention. Moreover, it again turned out that good ramp geometry (with a grade not too steep and few sharp turns) has a greater influence on successful car circulation than the coding of the car remote control system. We have thus not yet found the brief which will truly reward student efforts to design good software as well as good hardware. In a future edition, one option we may pursue is to require software control of the cars, without human intervention. The project could thus involve designing a piece of infrastructure for self-driving cars.

Useful Strategies for Student Projects

Self-Paced Tutorials and Design Review Sessions

In project-based courses, most learning occurs as students actively engage in design, construction and testing. The time devoted to exposition and instruction should therefore be limited to a minimum. Nevertheless, students need to master many skills and absorb a great deal of information to produce digital designs that can be successfully fabricated from their digital files, and to write code that successfully interfaces with electrical and electronic components. Instead of standard classroom instruction, we provide the requisite material to the students in the form of step-by-step tutorials, posted online (figure 3). In class or at home, students can go through these tutorials at their own pace, and use them as reference as they go about their design work. Instructors and teaching assistants can then focus their time on helping students address the specific difficulties they encounter, without holding up or interrupting everyone's work. Compared to a typical course preparation, the investment required to prepare these tutorials is considerable, but it is repaid many times over. Prepared to a high quality standard and made available to each of the six sections, they allow 120 students to work asynchronously and autonomously.

In addition to letting students work in teams on their projects, time freed up in this way can also be used for design reviews (figure 4). These are formal and informal sessions during which students discuss their evolving designs with instructors and peers. When given the opportunity and encouraged to do so, we have found that students can provide helpful suggestions and constructive criticism to their peers. For instructors, informal discussions with students as they work provide great opportunities to get to know students better and provide tailored feedback and encouragement.

Figure 3. Self-paced tutorial allowing students to learn how to wire Arduino boards.

Figure 4. Design review session during which students present their evolving design and obtain feedback from instructors and peers.

Theory-Based Design Aids

The project briefs and model-making technology adopted for the course encourage students to integrate cables or dampers into their designs (figures 5 and 6). To help students identify good ways of using these elements, short theory-based lessons were scheduled in the first weeks of the semester. The emphasis is on operational knowledge that students can apply to their own design. For the Spring 2013 roof project, we taught students to analyze constant chord force trusses using form and force diagrams (Allen and Zalewski, 2010; Lachauer and Kotnik, 2010).

For the Spring 2014 tower project, we taught students how to estimate damper amplification factors for different toggle brace configurations using small deformation analysis (Costantinou *et al.*, 2001; Hwang *et al.*, 2005).

Both types of analysis can be performed graphically using pencil, ruler and protractor, and can be applied to a great variety of geometrical configurations. They can be learned by first year civil engineering students in a matter of hours via teacher instruction, in-class exercises and homework.

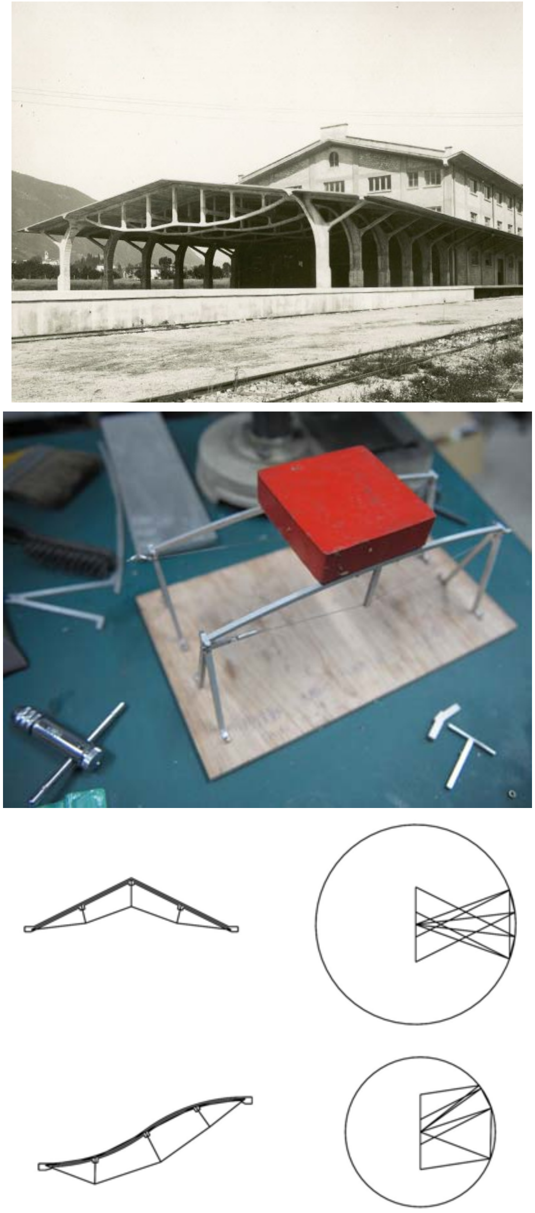


Figure 5. Constant chord force trusses and their graphic statics analysis. Top: Robert Maillart's Chiasso Shed (Source: ETH Bildarchiv). Middle: a demonstration structure using jet-cut aluminum and steel cable. Bottom: form and force diagram analysis.

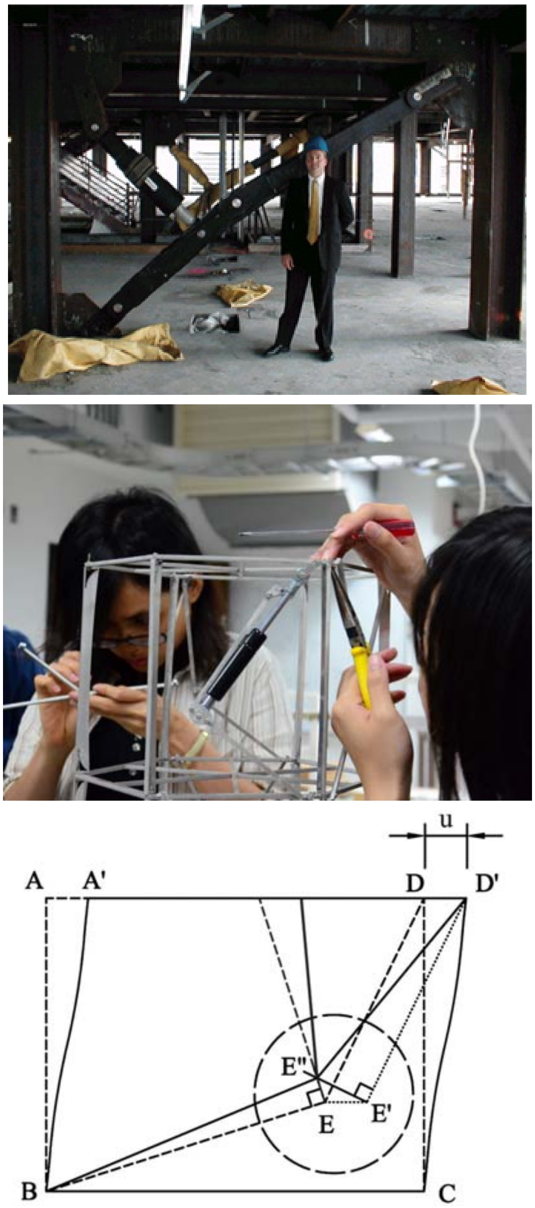


Figure 6. Toggle brace configuration improving the performance of viscous dampers. Top: real example at the Yerba Buena Tower (Source: Teratec). Middle: students integrate a toggle brace into their tower structure. Bottom: graphical analysis.

After practicing on structural configurations supplied by instructors, students can analyze new configurations of their own design. Requiring only a few hours of semester time, these design aids provide an early opportunity for students to connect theoretical analysis and practical design.

Decision-Based Load Testing

One of the highlights of the course is the load testing session, during which students subject their scale models to static or seismic loads. In the first two years of the course, we adopted a one-dimensional load testing procedure, in which a rod suspended from a single point at the centre of the structure was gradually loaded with heavier and heavier weights. The score was then calculated from the maximum load before failure or, for structures that did not fail, from the deformation monitored at the loading point. Although it does allow assessment of structural behavior, the loading process conducted in this way is rather mechanical and reduces the students to passive observers (save for adding weights and taking deformation measurements).

For the last two years, we have used a different approach: a decision-based loading process during which students decide at each step where and how much they want to continue adding loads to their structure. For the roof project (figure 7), this was done by letting students add standard weights (2.3 kg steel blocks) anywhere over the surface of their roofs. To encourage well-distributed loads, a score of 1 point per block is given to the first layer of blocks, a reduced score of 1/2 point per block for each block piled over another to form a second layer of blocks, a score of 1/4 for the third layer, etc. For the tower project (figures 8 and 9), students added weights to the floor of their choice (second, third, or fourth floor), scored respectively by a weighting factor of 1, 2 or 3, and decided on the level of ground acceleration they wanted to subject their tower to, with the total score calculated as the product of factored mass by peak ground acceleration.

The decision-based load testing process has turned out to be much more engaging than the former procedure. During testing, students are intensely concentrated on identifying optimal ways of loading their structure, maximizing their performance score before the structure fails. As different students have different appetites for risk, students of the same group must also negotiate among themselves to decide how far they wish to push the tests. Many groups tested their structure to total failure, either because they overestimated its capacity, or because they were curious to see how far it would go and how it would fail. Students from other groups also enjoy witnessing the process, usually encouraging greater risk taking.

Figure 7. Load testing of the roof structures, Spring 2013. Top: students decide to add one more steel block, leading to collapse. Bottom: students argue whether to continue adding weights. They stopped before the structure suffered more than local damage.

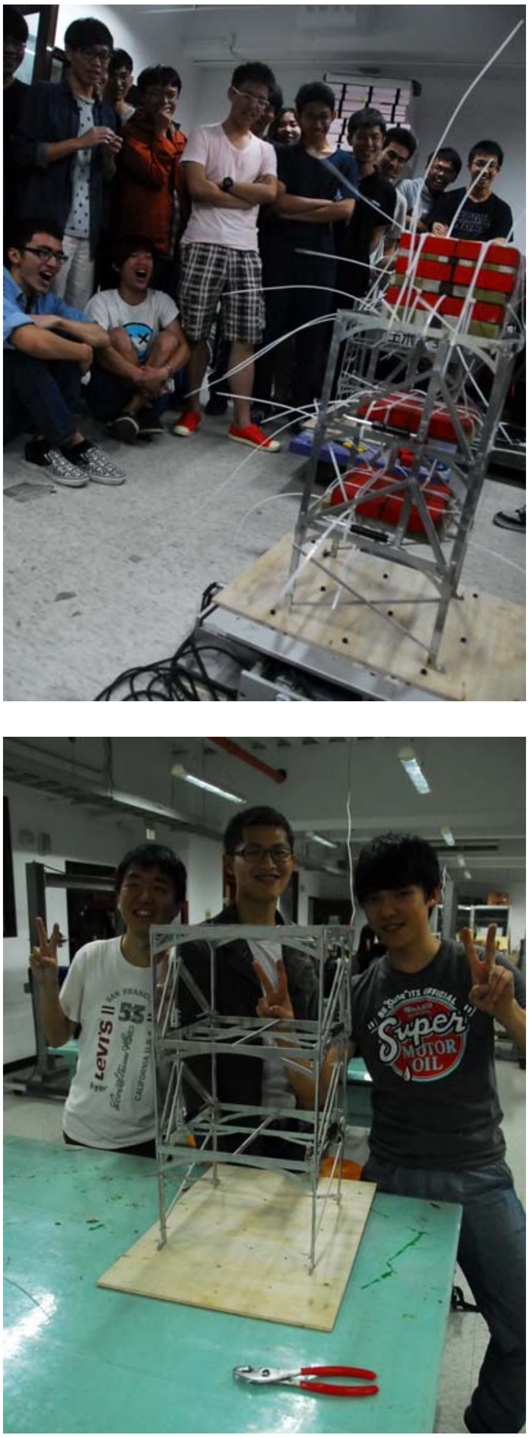


Figure 8. Decision-based load testing of the tower structures, Spring 2014. These students decided to heavily load the top floor of their structure… yet it survived seismic shaking.

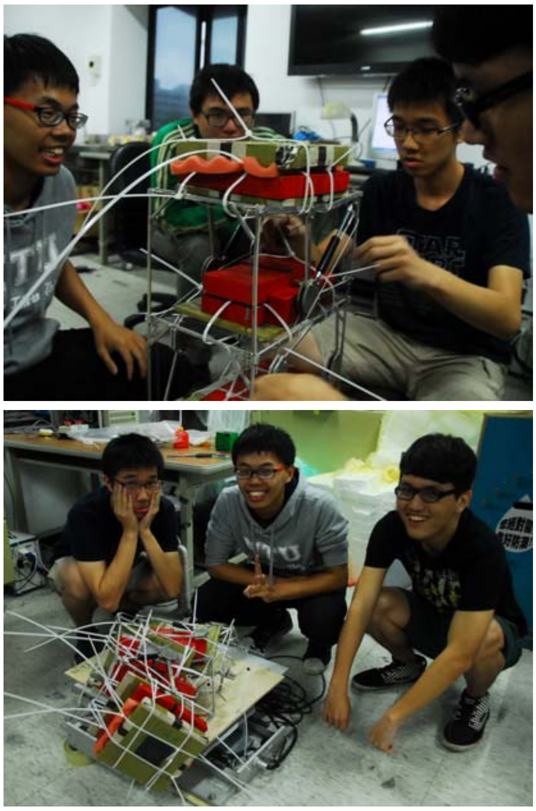


Figure 9. Decision-based load testing of the tower structures, Spring 2014. These students were more conservative, but earthquake shaking caused their tower to suffer complete collapse.

Conclusions

Results from student evaluations for the Spring 2014 semester are not yet available, making it difficult to compare how students have experienced the two structure-to-automation projects conducted so far. Nevertheless, the Spring 2013 edition of the course, combining structures with automation, generated substantially higher levels of student satisfaction than the previous editions focused on structures alone. As another indication of heightened interest, students who experienced that edition of the course were more likely to enroll in the optional keystone design project course offered in the second year. Whereas in previous years, about 25 students signed up for this very time intensive follow-up course (described in Capart *et al*., 2013), this year 50 students signed up (unfortunately, enrollment had to be capped at 35). Compared with previous classes, moreover, this crop of students showed greater fluency with system and mechanism design. Although further efforts will be needed to improve the automation component of the course and its integration with structural aspects, combining these two components is proving to be a fruitful way to enrich our cornerstone design course.

Acknowledgements

In addition to the authors, co-instructors of the cornerstone course included Wen-Cheng Liao (Spring 2013), James Chih-Yuan Chu and Yu-Ting Hsu (Spring 2014). The technical staff, teaching assistants, and student teaching assistants also contributed greatly to the course. Extraordinary institutional support by the Civil Engineering Department, chaired by Professor Liang-Jenq Leu, and financial support by alumni and the Ministry of Education are also gratefully acknowledged.

References

Allen, E., and Zalewski, W. (2010) *Form and Forces*. Wiley.

Arciszewski, T. (2009) *Successful education: How to educate creative engineers*. Successful Education LLC, Fairfax.

Capart, H., Hsieh, S.-H., and Leu, L.-J. (2013) Cornerstone, keystone, and capstone design project courses for civil engineering students. *Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering*, Worcester Polytechnic Institute, USA, pp. 137-144.

Costantinou, M. C., Tsopelas, P., Hammel, W., and Sigaher, A. (2001) Toggle brace damper seismic energy dissipation systems. *ASCE J. of Struct. Engng*, Vol. 127, No. 2, pp. 105-112.

Einstein, H. H. (2013) Design education in civil and environmental engineering. *Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering,* Worcester Polytechnic Institute, USA, pp. 112-120.

Hwang, J. S., Huang, Y. N., and Hung, Y. H. (2005) Analytical and experimental study of toggle brace damper systems. *ASCE J. of Struct. Engng*, Vol. 131, No. 7, pp. 1035-1043.

Lachauer, L., and Kotnik, T. (2010) Geometry of Structural Form. *Advances in Architectural Geometry,* 193-203.

Ni, W. J., Capart, H., and Leu, L.-J. (2011) Design to Build: Pilot Tests for a New Keystone Project Course at NTU-CE. *Proceedings of the 1st International Workshop on Design in Civil and Environmental Engineering*, KAIST, Daejon, Republic of Korea, pp. 79-87.

Saitoh, M., and Okada, A. (1999) The role of string in hybrid string structure. *Engineering Structures* Vol. 21, pp. 756-769.

Thompson, M. K. (2010) Green Design in Cornerstone Courses at KAIST: Theory and Practice. *Int. J. Engng Ed*., Vol. 26, No. 2, pp. 359-365.

Sustainability Concepts in the Design of High-Rise Buildings: The Case of Diagrid Systems

Giulia Milana, Konstantinos Gkoumas* and Franco Bontempi
giuliamilana@live.it, konstantinos.gkoumas@uniroma1.it, franco.bontempi@uniroma1.it
Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Italy

Abstract: One of the evocative structural design solutions for sustainable tall buildings is embraced by the diagrid (diagonal grid) structural scheme. Diagrid, with a perimeter structural configuration characterized by a narrow grid of diagonal members involved both in gravity and in lateral load resistance, has emerged as a new design trend for tall-shaped complex structures, and is becoming increasingly popular due to aesthetics and structural performance. Since it requires less structural steel than a conventional steel frame, it provides for a more sustainable structure. This study focuses on the structural performance of a steel tall building, using FEM nonlinear analyses. Numerical comparisons between a traditional outrigger system and different diagrid configurations (with three different diagrid inclinations) are presented for a building of 40 stories, with a total height of 160m, and a footprint of 36m x 36m. The sustainability of the building (in terms of structural steel weight saving) is assessed, together with the structural behavior.

Keywords: Diagrid Structures, Tall Buildings, FEM, Sustainability, Design Criteria.

Introduction

Tall building structural design developed rapidly in the last decades, focusing among else on the sustainability improvement. In fact, sustainability in the urban and built environment is a key issue for the wellbeing of people and society, and sustainable development is nowadays a first concern both for public authorities and for private investors. One of the evocative structural design solutions for sustainable tall buildings is embraced by the diagrid (diagonal grid) structural scheme.

This study focuses on the Sustainability of Structural Systems, within two specific topics:

- The use of steel in high-rise buildings;
- The conception and design of sustainable diagrid high-rise buildings.

The inspiration for this study arises from the impact that the construction industry has on the environment, in terms of use of resources and production of waste, and the social need that calls for investigating sustainable solutions.

Sustainability in the Urban Environment

Sustainability is a difficult and complex issue, and an elusive one. It is enormously important since it has to do with the chances of humankind surviving on this planet. At the rate that the human race is using scarce and limited resources it appears that, unless measures are taken now - and if there is still time - the future of civilization, at least as we understand it now, is uncertain. It leads to a better life for the present generation and survival for generations to come, enhancing their ability to cope with the world that they will inherit. Per current level of understanding, sustainability covers the following elements (Adams 2006):

- Economic benefit;
- Resource efficiency;
- Environmental protection; and,
- Social development.

A process that is designed for only economic and environmental concerns is classified as viable; a process that is designed for only environmental and social concerns in classified as bearable; and a process that is designed for economic and social concerns is equitable. Thus, a sustainable process in one that covers all three dimensions (figure 1).

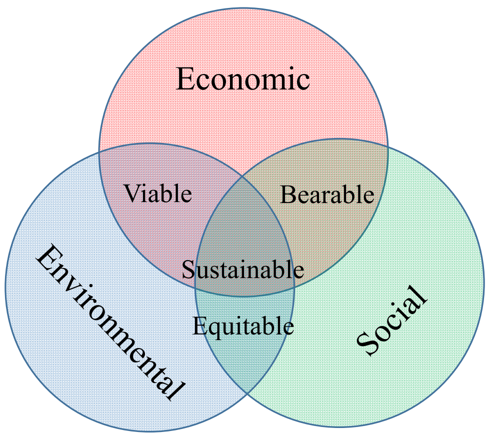


Figure 1. Triple Bottom Line of Sustainability - Adapted from Adams (2006)

Sustainability in the urban environment is a key issue for the wellbeing of people and society.

Sustainable development, defined as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN 1987) is nowadays a first concern for public authorities and the private sector, and is shaped by incentives and sanctions. Although sustainability goals are not uniquely identified, a total plan for sustainability requires, in a cost efficiency balance (ISE 1999):

- Reduction of emission of greenhouse gases;
- More efficient use (and reuse) of resources;
- Minimization and constructive reuse of waste;
- Reduction of harmful effects from construction activities and building occupation.

The above goals find their application in the construction and built environment sector.

Sustainability in the Construction and Built Environment Sector

In the recent years, the construction sector is more and more oriented towards the promotion of sustainability in all its activities. The goal to achieve is the optimization of performances, over the whole life cycle, with respect to environmental, economic and social requirements. According to the latest advances, the concept of sustainability applied to constructions covers a number of braches such as life-cycle costing, ecology durability and even structural design. Several procedures and design tools are proposed in different international frameworks. Indeed, the current trend in civil engineering is moving towards lifetime engineering, with the aim to implement integrated methodologies that consider as a whole all the sustainability requirements according to time-dependent multi performance-based design approaches (Sarja *et al.* 2005).

The design, construction and operation of "green" buildings is nowadays regulated by international guidelines, codes and standards (see for example the green building evaluation and certification system USGBC, 2009). What emerges is a variety of widely acknowledged and recognizable standards, especially for what regards ranking and certification systems (Nguyen and Altan 2011). In fact, the entire concepts of "sustainable development" and "sustainable building" are cumbersomely defined, with different and sometimes contrasting definitions. Berardi (2013) discusses in detail several aspects of sustainable development (namely its time dependency, its multi-space and multi-scale levels, its multiple dimensions and its social dependencies) and arrives at a definition of what is a sustainable building by means of a number of principles.

It is important to add that even though sustainability has mostly a social character, benefits of sustainable design are not only to the general public but also for the building stakeholders, including owners, who benefit from the increased value of the property.

Sustainable design leads to innovation since it demands inventive solutions, and eventually is sup-ported by a cultural shift, evident from national level reviews and surveys (Robin and Poon 2009; Tae and Shin 2009).

Sustainability issues are wide-ranging, but the main focus in the building industry is the reduction of energy consumption in construction and use. Although the trend is to arrive to a so-called Net Zero Energy Buildings, for which a balance between energy flow and renewable supply options is established, the path to this goal is still very long (Srinivasan *et al.* 2011). Ramesh *et al.* (2010) provide a breakdown of energy use in the various phases of building lifecycle (manufacture, use and demolition), and highlight the higher contribution of the operating phase, and the variability of the results for different climates, different building uses etc. This is especially important for structural parts and systems, where recycling, reusing and material minimization can be important aspects (Vezzoli and Manzini 2008). The possibility to implement active systems for the energy efficiency of buildings is also an alternative, providing energy by sustainable resources (see for example Gkoumas *et al.* 2013).

The role of steel structures towards sustainable development has been also recognized, due to several advantages such as the offsite prefabrication and the consequent reduction of site waste and impacts, the easy dismantling process, the high recycling rates of the material and components, etc. (figure 2). Nowadays, the steel construction industry has been giving more attention to the questions related to life-cycle costing, ecology, durability and sustainability of steel products and components (Landolfo *et al.* 2011).

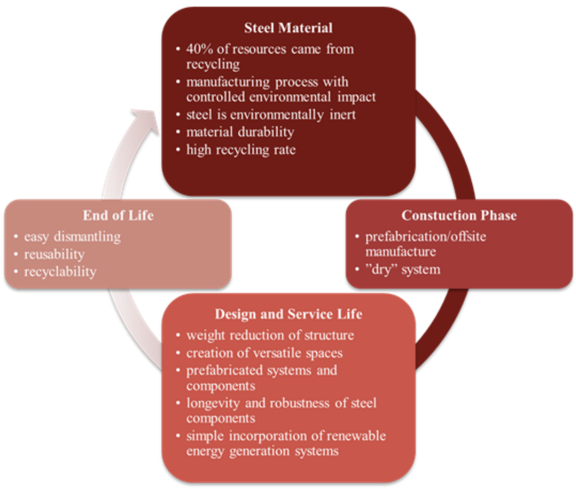


Figure 2. Environmental Advantages of Steel Construction –Adapted from *http://arcelormittal.com*

When evaluating the sustainability of a building, the life cycle approach is required, taking into account all phases of a building's life, including material production, transportation to the construction site, construction, operation, demolition or deconstruction, and end of life.

Sustainability and Tall Buildings

The number of tall buildings designed and build is increasingly always more rapidly. They are evolving in height, construction materials, use and compartmental composition. The driving forces behind this progression are inevitably financial, political and environmental, but it is modern technological developments, both structural and material, which have truly enabled the continued evolution of these buildings. The tall building of today is a completely different entity to that of a decade ago, with the propensity for change even greater in the immediate future. Advancements in structural engineering have arisen to make possible the increase in height, size and complexity, the reduction of cost and carbon footprint as well as architectural imagination and economic versatility of these buildings (Cowlard *et al.* 2013).

Two of the most important design requirements for any building structural design are strength and stiffness, while for very tall buildings with a high height-to-width aspect ratio, stiffness constraints generally govern the design. The structural systems with diagonals, such as braced tubes and diagrids, are generally very stiff and, in turn, very effective in resisting lateral loads among various structural systems developed for tall buildings.

Two modes of deformation, bending and shear deformation, contribute primarily to the total deformation. In general, as a building becomes taller and its height-to-width aspect ratio becomes higher, the contribution of the bending deformation becomes more important. Technically, there are infinite numbers of bending and shear deformation combinations that can meet the design parameter. This also means that there are numerous design scenarios possible to meet the stiffness requirements (Moon 2008).

Historical Perspective

In the late nineteenth century, early tall building developments were based on economic equations - increasing rentable area by stacking office spaces vertically and maximizing the rents of these offices by introducing as much natural light as possible.

In terms of structural systems, most tall buildings in the early twentieth century employed steel rigid frames with wind bracing. Their enormous heights at that time were achieved not through notable technological evolution, but through excessive use of structural materials (for example the Empire State Building of the early 1930s). Due to the absence of advanced structural analysis techniques, they were quite over-designed. The mid-twentieth century, after the war, was the era of mass production based on the International Style defined already before the war, and the previously developed technology.

Structural systems for tall buildings have undergone dramatic changes since the demise of the conventional rigid frames in the 1960s as the predominant type of structural system for steel or concrete tall buildings. With the emergence of the tubular forms still conforming to the International Style, such changes in the structural form and organization of tall buildings were necessitated by the emerging architectural trends in design in conjunction with the economic demands and technological developments in the realms of rational structural analysis and design made possible by the advent of high-speed digital computers. Beginning in the 1980s, the once-prevalent Miesian tall buildings were then largely replaced by the façade characteristics of postmodern, historical, diagrid and deconstructivist expressions. This was not undesirable because the new generation of tall buildings broke the monotony of the exterior tower form and gave rise to novel high-rise expressions. Innovative structural systems involving tubes, mega frames, core-and-outrigger systems, artificially damped structures, and mixed steel-concrete systems are some of the new developments since the 1960s.

The primary structural skeleton of a tall building can be visualized as a vertical cantilever beam with its base fixed in the ground. The structure has to carry both the vertical gravity loads and the lateral wind and earthquake loads. The gravity loads are principally the dead and live loads, while lateral loads tend to snap the building or topple it. The building must therefore have an adequate shear and bending resistance and must not lose its vertical load-bearing capacity.

The quantity of materials required for resisting lateral loads, on the other hand, is even higher and could well exceed other structural costs if a rigid-frame system is used for very tall structures. This calls for a structural system that goes well beyond the simple rigid frame concept. Khan (1973) argued that the rigid frame that had dominated tall building design and construction so long was not the only system fitting for tall buildings. Because of a better understanding of the mechanics of material and member behavior, he reasoned that the structure could be viewed in a holistic manner, that is, the building could be analyzed in three dimensions, supported by computer simulations, rather than as a series of planar systems in each principal direction. Feasible structural systems, according to him, are rigid frames, shear walls, interactive frame-shear wall combinations, belt trusses, and the various other tubular systems.

Structural systems of tall buildings can be divided into two broad categories: interior structures and exterior structures (figures 3 and 4).

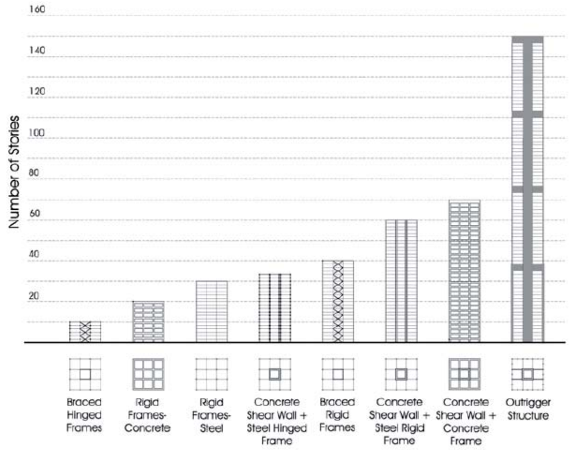


Figure 3. Interior structures (from Ali and Moon 2007)

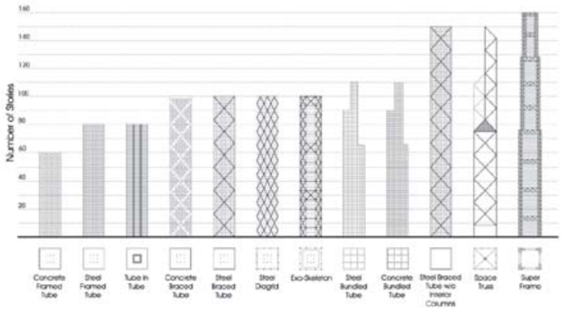


Figure 4. Exterior structures (from Ali and Moon 2007)

This classification is based on the distribution of the components of the primary lateral load-resisting system over the building. A system can be referred to as an interior structure when the major part of the lateral load resisting system is located within the interior of the building. Likewise, if the major part of the lateral load-resisting system is located at the building perimeter, a system can be referred to as an exterior structure. It should be noted, however, that any interior structure is likely to have some minor components of the lateral load-resisting system at the building perimeter, and any exterior structure may have some minor components within the interior of the building (Ali and Moon 2007).

In plain words, steel-framed buildings with a rigid frame can be economical for medium rise buildings up to 20 stories. A vertical steel shear truss at the central core of the building can be economical for buildings up to 40 stories. Finally, a combination of central vertical shear trusses with horizontal outrigger trusses is most suited for up to 60-stories, this being the most common form of tall building structure in the US for example. For even taller buildings, it becomes essential to transfer all gravity loads to the exterior frame to avoid overturning effects. Rigid framed tubes, braced tubes and bundled tube structures have been developed to reach up to over 100. There are many ways to construct tall buildings and in practice it is the desired use of a building, which predominantly determines its design. The exterior shape and the materials of the façade have the greatest impact on the outside public, whilst the arrangement of spaces inside determines the efficiency of a building's use by its occupants. The choice of materials for the structural frame is determined primarily to satisfy those requirements, with comparisons made of the most economical form that will do the job (Pank *et al*. 2002).

Diagrid Structures

Diagrid is a perimeter structural configuration characterized by a narrow grid of diagonal members that are involved both in gravity and in lateral load resistance. Since it requires less structural steel than a conventional steel frame, it provides for a more sustainable structure

The diagrid system is not a new invention. In fact, an early example of today's diagrid-like structure is the 13-story IBM Building in Pittsburg of 1963. However, the implementation in a larger scale of such tall building was not practical due to high cost related to the difficult node connections. It is only in recent years that technology allowed a more reasonable cost of diagrid node connections (Leonard 2004).

With specific reference to tall buildings, diagrids are increasingly employed due to their structural efficiency as well as architectural suggestion. In fact, diagrid structures can be seen as the latest mutation of tube structures, which, starting from the frame tube configuration, have increased structural efficiency thanks to the introduction of exterior mega-diagonals in the braced tube solution.

The perimeter configuration still holds the maximum bending resistance and rigidity, while, with respect to the braced tube, the mega-diagonal members are diffusely spread over the façade, giving rise to closely spaced diagonal elements and allowing for the complete elimination of the conventional vertical columns.

The difference between conventional exterior-braced frame structures and current diagrid structures is that, for diagrid structures, almost all the conventional vertical columns are eliminated. This is possible because the diagonal members in diagrid structural systems can carry gravity loads as well as lateral forces due to their triangulated configuration in a distributive and uniform manner. Compared with conventional framed tubular structures without diagonals, diagrid structures are much more effective in minimizing shear deformation because they carry shear by axial action of the diagonal members, while conventional tubular structures carry shear by the bending of the vertical columns and horizontal spandrels (Ali and Moon 2007).

Diagrid Module

A diagrid structure is modeled as a vertical cantilever beam on the ground, and subdivided longitudinally into modules according to the repetitive diagrid pattern. Each module is defined by a single level of diagrids that extend over multiple stories.

Being the diagrid a triangulated configuration of structural members, the geometry of the single module plays a major role in the internal axial force distribution, as well as in conferring global shear and bending rigidity to the building structure.

The analysis of the diagrid structures can be carried out in a preliminary stage by dividing the building elevation into groups of stacking floors, with each group corresponding to a diagrid module (Moon 2011).

As shown in the studies by Moon *et al.* 2007 and Moon, 2008, the diagrid module under gravity loads G is subjected to a downward vertical force, $N_{G,mod}$, causing the two diagonals being both in compression and the horizontal chord in tension (figure 5a).

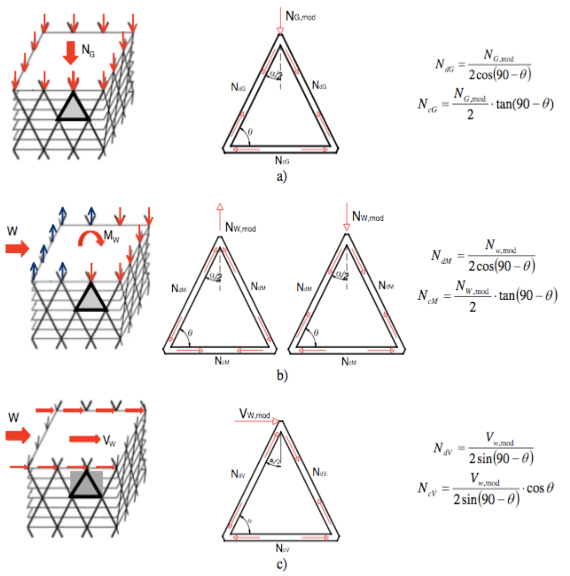


Figure 5. Diagrid Module: (a) Effect of Gravity Load, (b) Effect of Overturning Moment and (c) Effect of Shear Force –from (Mele *et al.* 2014)

Under a horizontal load W, the overturning moment M_W causes vertical forces in the apex joint of the diagrid modules $N_{W,mod}$. The direction and intensity of this force depends on the position of the diagrid module, with upward/downward direction and maximum intensity for the modules located on the windward/leeward facades, respectively, and gradually decreasing values for the modules located on the web sides (figure 5b). The global shear V_W causes a horizontal force in the apex joint of the diagrid modules, $V_{W,mod}$,, which intensity depends on the position of the module with respect to the direction of wind load, since the shear force Vw is mainly absorbed by the modules located on the web façades, i.e. parallel to the load direction (figure 5c).

In the formulations provided in figure 5, for deriving internal forces in the diagrid elements, it has been implicitly assumed that the external loads is transferred to the diagrid module only at the apex node of the module itself (Mele *et al.* 2014).

Geometry and Design Criteria

Diagrid structures, like all the tubular configurations, utilize the overall building plan dimension for counteracting overturning moment and providing flexural rigidity. However, this potential bending efficiency of tubular configurations is never fully achievable due to shear deformations that arise in the building 'webs'; with this regard, diagrid systems, which provide shear resistance and rigidity by means of axial action in the diagonal members, rather than bending moment in beams and columns, allows for a nearly full exploitation of the theoretical bending resistance. This is the main reason underlying the extraordinary efficiency of diagrid systems.

Being the diagrid a triangulated configuration of structural members, the geometry of the single module plays a major role in the internal axial force distribution, as well as in conferring global shear and bending rigidity to the building structure. As shown in the study by Moon *et al.* (2007), while a module angle equal to 35° ensures the maximum shear rigidity to the diagrid system, the maximum engagement of diagonal members for bending stiffness would correspond to an angle value of 90°, i.e. vertical columns. Thus, in diagrid systems, where vertical columns are completely eliminated and both shear and bending stiffness must be provided by diagonals, a balance between these two conflicting requirements should be searched for defining the optimal angle of the diagrid module (Mele *et al.* 2014).

Structural Analysis

The considered structure is a 40-story building, for a total height of 160m, and a footprint of about 36mx36m. Its function is for not-public offices. The building is located in Latina (Lazio, Italy). Regarding local wind and earthquake loading conditions, the area where the building is placed is characterized by a class of roughness "B" (urban and sub-urban areas) and a class of exposition to wind "IV"; the seismic zone corresponds II seismic level (PGA 0,15-0,25).

During the conceptual design, two different structural design solutions were proposed: outrigger and diagrid. Consequently, comparisons are performed to select the most efficient structural system and to reduce the material used. Objective of the study is to verify advantages and disadvantages, both in direct economic terms (limited to the amount of structural steel) and in structural performance. Figure 6 outlines the different structural configurations.

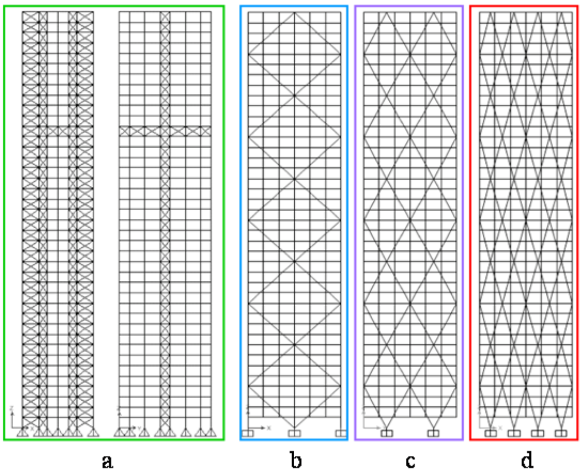


Figure 6. Structural Models (a- Outrigger Structure; b- Diagrid Structure α=42°; c- Diagrid Structure α=60°; d- Diagrid Structure α=75°)

Outrigger Structure

The building plant is symmetric with respect to the X axis; it has an octagonal footprint, approximated by a square of 35m x 35 m. The overall height of the structure is 160 m, while the distance between two consecutive floors is 4 m. The structure (and the model) have been realized in order to make a diagonal bracings system resists horizontal actions of the wind. The diagonal elements of the system consist in St. Andrew cross-bracings.

In order to reduce the building deformability, a rigid plane is introduced. This plane is called outrigger; this reinforcement, located at the 29th floor (between 112m and 116m), is realized by introducing braces expanded vertically for all façades in exam. These outriggers are located on two facades in direction X and on two cross-sections in direction Y at X=4m and X=31m.

Diagrid Structures

The plant of the buildings is symmetric with respect to both the X and the Y axis, and it has a square footprint of 36mx36m. The overall height of the structure is 160 m, while the distance between two consecutive floors is 4 m.

Some generic considerations are necessary. Typically, a diagrid structure is subdivided longitudinally into modules according to the repeated diagrid pattern. Each module is defined by a single level of diagrid that extends over multiple stories. In the building here presented, there are 4-story modules. The structural efficiency of diagrid for tall buildings can be maximized by configuring them to have optimum grid geometries.

The optimal angle of diagonals is highly dependent upon the building height. Since the optimal angle of the columns for maximum bending rigidity is 90 degrees and that of the diagonals for maximum shear rigidity is about 35 degrees, it is expected that the optimal angle of diagonal members for diagrid structures will fall between these angles. This study introduces three intermediate angles: 42, 60 and 75 degrees respectively.

Numerical Modelling and Results

The three diagrid buildings have two structural systems working in parallel: the first is internal and it is made of a rigid frame system which only reacts to gravity loads, while the second is perimetral and it is made of a diagonal grid system which reacts both to vertical and horizontal loads.

The internal structure, as any other ordinary frame structure, is composed by columns and main and secondary beams, while, the external one is composed by diagonal and horizontal elements (without columns).

All the components of the internal system are placed at a distance of 6m in plant, thus creating square footprints of 6mx6m. The internal columns transmit vertical loads to the ground, while the perimetral ones do not; in fact their function is to link the generic diagrid module to the floors included in it. In more details, the external columns receive the loads from the perimetral beams and they transfer these loads to the horizontal elements of the module. The extension of the external columns is four-story length as the diagrid module. Passing from one module to the consecutive one, the perimetral beams are replaced by the horizontal diagrids. In this way, the two structures "communicate" every four floors.

All of the vertical elements are tapered every four stories, since the size of each diagrid module changes. While Italian profiles are used for interior structure, American ones are used for the perimetral structure.

The computational code SAP2000 (version 16.0.0) has been used for all analysis. The structural model takes into count the real distribution of the masses, while the effect of non-structural elements on the global stiffness has not been considered. Figure 7 provides an overview of the deflected diagrid configurations.

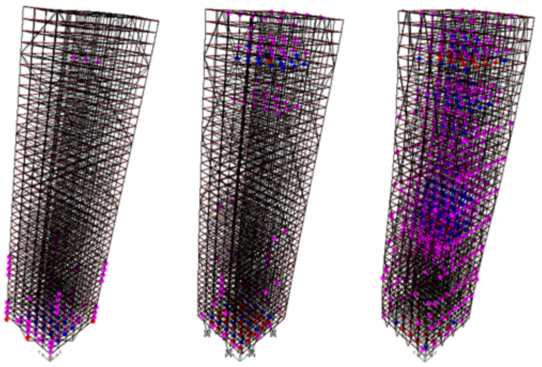


Figure 7. Different Diagrid FEM Models

Weight and Structural Periods

In this research the weight saving is the most important issue, since this is considered as the most important sustainable aspect. For all diagrid buildings an important weight saving occurs, therefore, in all cases the diagrid system results better than the ordinary outrigger for what regards sustainability.

The weight of the structures is calculated without considering the floors. This is due to the fact that all the structures have the same number of floors.

In table 1 and figure 8 the comparison among the structures is presented. The percentage of savings is calculated compared to the weight of the outrigger structure.

Table 1. Weight and Weight Saving

Structure	Weight (ton)	Weight-Saving (%)
Outrigger	8052	-
Diagrid 42°	6523	19
Diagrid 60°	5931	26
Diagrid 75°	5389	33

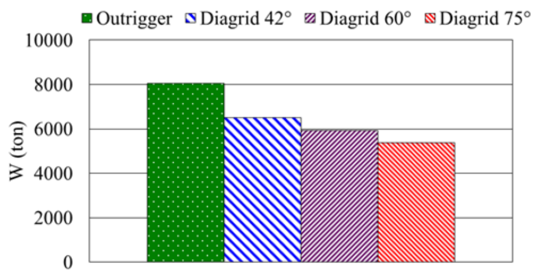


Figure 8. Comparison of Weights

Verifications

It is important to verify the structural configurations for both Serviceability Limit States (SLS) and Ultimate Limit States (ULS). To this aim, displacements are confronted with thresholds provided in codes and standards, and pushover analyses are performed.

SLS: Horizontal Displacements

For the verification of the service limit states, the absolute horizontal displacements are considered. The points of control used are placed every four stories (16m). Figure 9 presents these displacements, together with the threshold values provided by the Italian Building Code (NTC 2008). Is easy to see that all structures are verified by a great margin.

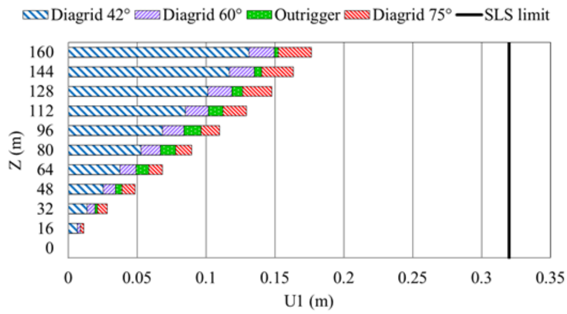


Figure 9. Comparison of Horizontal Displacements

ULS: Pushover Analyses

In order to evaluate the ductility of the structures, a non-linear static (Push-Over) analysis is conducted. A lamped plasticity model has been implemented taking into account the material non-linearity. For simulating this non-linearity, plastic hinges are used. The Pushover analysis is conducted on the 3D model for all structures with the same static loads and hinges, in order to have a direct comparison of the results.

The horizontal (wind) load applied to the structure is a triangular load, increasing with height.

The concentrated forces, are applied to the geometric centers of each floor and represent the equivalent static forces normalized.

To simulate the non-linearity of material, plastic hinges are introduced. Two different kinds of hinges are considered: axial hinges, used for all elements of the outrigger structures and the perimetral system in the diagrid structures, and, bending hinges for the internal columns in the diagrid structures.

In addition, and in in order to consider the effect of geometric non-linearity in the structural behavior, another kind of non-linear static analysis is introduced: P-Delta analysis. The P-Delta effect refers specifically to the non-linear geometric effect of a large tensile or compressive, direct stress upon transverse bending and shear behavior.

In order to take into account the effect of gravity loads upon the lateral stiffness of building structures, a non-linear case is created considering only permanent vertical loads 'VertNonLin'. Another load case, 'DeadNonLin', is also considered, in which only the dead loads of the structure are accounted for.

Figures 10-12 report the comparison of the capacity curves of all structures. In order to simplify the reading of results all graphs are presented with the same scale axis. The curves are divided according to the different types of analysis: with or without P-Delta effects; in the P-Delta cases, two load-cases are considered.

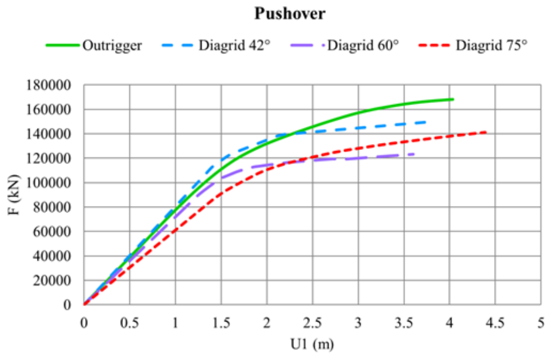


Figure 10. Comparison of 'Pushover' Curves

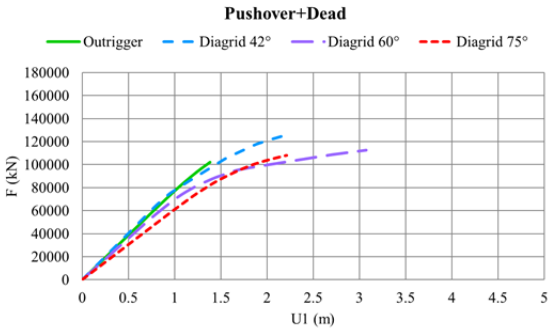


Figure 11. Comparison of 'Pushover+Dead' Curves

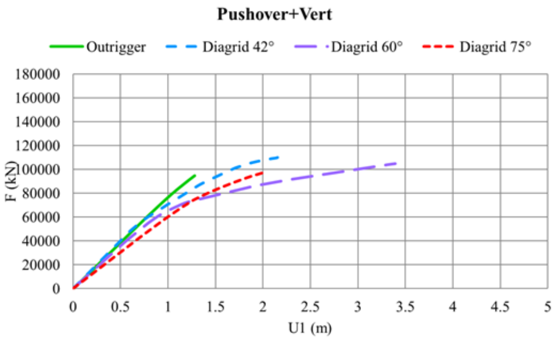


Figure 12. Comparison of 'Pushover+Vert' Curves

Comparison and Choice of the Best Model

Based on the capacity curves of the previous paragraph, it is possible to obtain three of the four values from which we can identify the model with the best behavior.

These properties are:

- Strength (R)
- Stiffness (K)
- Ductility (μ)

For the analyses, the same considerations made in the previous section remain valid.

In the chart of figure 13 the features for calculating these properties are identified. The capacity curve in the figure is an example of the realization of the features.

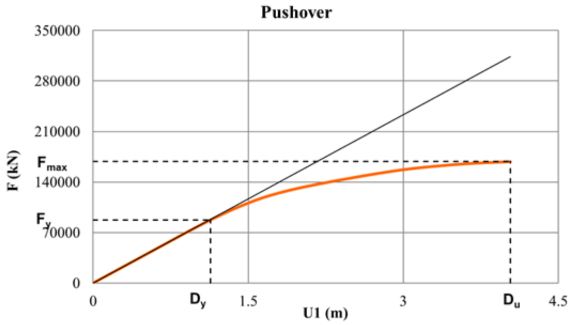


Figure 13. Definition of the Main Features

The features represented in the chart are:

D_y: yield displacement
D_u: maximum displacement
F_y: yield force
F_{max}: maximum force

From these features, it is possible to obtain the mechanical properties of interest in the following way:

$R = F_{max}$: Strength

$K = \frac{F_y}{D_y}$: Stiffness

$\mu = \frac{D_u}{D_y}$: Ductility

Using these properties as well as the weight of the structure, the buildings are compared and the best structure is chosen through an equation defined in the following paragraph.

All these features are calculated just for the 'Pushover+Vert' curve, because it is the most realistic case.

Definition of a Performance Equation

An equation that helps to identify the structure with the best behavior is defined below. All terms of this equation are normalized to the features of the outrigger structure, that is, the reference building. These terms are multiplied with amplification coefficients. For the weight, a coefficient equal to 1.2 is considered, while for the other terms the coefficients are equal to 1. In fact, weight is very important for the sustainable aspect. The higher the outcome, the better the behavior of the structure.

$$Eq.: \frac{R}{R_0} + \frac{K}{K_0} + \frac{\mu}{\mu_0} + 1{,}2\left[\frac{(P - P_0)}{P_0} + 1\right]$$

In the above equation, the subscript "0" identifies the features relative to the outrigger structure. Given that the behavior improves for a reduced weight a higher expression is used.

In table 2 the results of this equation are provided for each structure.

Table 2. Weight and Weight Saving

	OUTRIGGER	DIAGRID 42°	DIAGRID 60°	DIAGRID 75°
	P+V	P+V	P+V	P+V
R (kN)	94775	110185	104972	97131
K (kN/m)	77143	80615	71306	60897
μ	1,535	3,587	5,681	2,564
P (kg)	8052	6523	5931	5389
Eq.	4,20	5,06	**5,52**	4,67

In order to have a clearer view, is possible to represent the terms of the equation, multiplied for the relative coefficients, on the axes of a radar chart.

In figure 14, the chart is reported in accordance to the performed analyses.

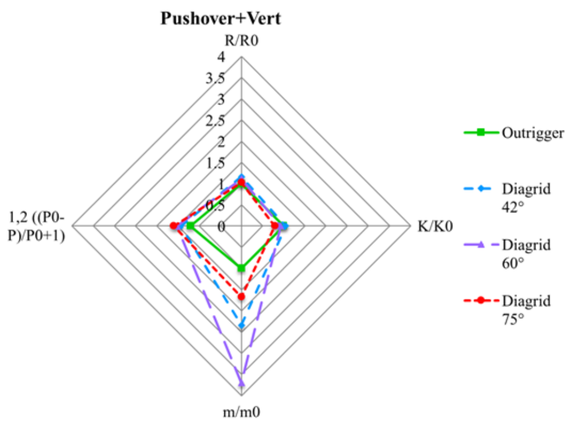


Figure 14. Comparison of Models for the 'Pushover+Vert' Case

From the results of the equation and the examination of the chart, it is possible to observe that the model with the best behavior is the diagrid structure with diagonal members having an inclination of 60°.

Thus, the diagrid structure with an intermediate inclination results as the best model; in fact this structure leads to an important saving of weight while at the same time, offers a high performance in terms of strength, stiffness and ductility.

Conclusions

In this study, the Sustainability of a complex structural system has been inquired, focusing on two specific topics:

- The use of steel, an intrinsically sustainable material, especially for high-rise buildings;
- the conception and design of sustainable diagrid high-rise buildings.

The inspiration for this study arises from the impact that the construction industry has on the environment, in terms of use of resources and production of waste, and the social need that calls for investigating sustainable solutions.

Among the finding, it has been shown and quantified the way in which diagrid structures lead to a considerable saving of (steel) material compared to more traditional structural schemes such as outrigger structures. Furthermore, the performance of diagrid structures has been assessed, not only in terms of material reduction, but also in terms of safety, serviceability and structural robustness.

In particular, different diagrid structures were considered, namely, three geometric configurations, with inclination of diagonal members of 42°, 60° and 75°. These configurations, in addition to allowing a considerable saving of weight, guarantee a better performance in terms of strength, stiffness and ductility.

Among the diagrid structures considered the one with the best overall behavior results to be the one with 60° diagonal element inclination.

Of course, there are limitations to this study. Additional loading scenarios should be accounted for, in order to have a broader insight on the structural behavior. In addition, the defined performance equation is calibrated with specific coefficient values that highlight the sustainability aspect.

Nevertheless, the initial results provide a starting point, and together with the proposed methodology, contribute obtaining a preliminary assessment of the sustainability of diagrid structures.

Acknowledgements

This study presents results from the Master in Science Thesis successfully defended from one of the authors (Giulia Milana), to the Department of Structural and Geotechnical Engineering of the Sapienza Univerity of Rome, with the other authors co-advising. The www.francobontempi.org research group from Sapienza University of Rome is also gratefully acknowledged. Finally, the study was partially supported by the research spin-off StroNGER s.r.l. (www.stronger2012.com) from the fund "FILAS - POR FESR LAZIO 2007/2013 - Support for the research spin-off".

References

Adams, W.M. (2006) The Future of Sustainability: Re-thinking Environment and Development in the Twenty-first Century. *Report of the IUCN Renowned Thinkers Meeting*, 29-31 January.

Ali, M. M., Moon, K. S. (2007) Structural Development in Tall Buildings: Current Trends and Future Prospects. *Architectural Science Review*, Vol. 50, pp. 205-223.

Berardi, U. (2013) Clarifying the new interpretations of the concept of sustainable building. *Sustainable Cities and Society*, Vol. 8, pp. 72-78.

Cowlard, A., Bittern, A., Abeccassis-Empis, C., Torero, J. (2013) Fire safety design for tall buildings. *Procedia Engineering*, Vol. 62, pp. 169-181.

Gkoumas, K., Petrini, F., Arangio, S. and Crosti, C. (2013) Energy harvesting for the sustainability of structures and infrastructures. *Research and Applications in Structural Engineering, Mechanics and Computation Alphose Zingoni (ed.),* CRC Press, pp. 2457-2462.

ISE - Institution of Structural Engineers (1999) *Building for a sustainable future: Construction without depletion*, ISE/SETO, London, UK.

Khan F. R. (1973) Evolution of Structural Systems for High-Rise Buildings in Steel and Concrete, *Proceedings of the 10th regional conference on tall buildigs-planning, design and construction*, Bratislava.

Landolfo, R., Cascini, L. and Portioli F. (2011) Sustainability of steel structures: towards an integrated approach to life-time engineering design. *Frontiers of Architecture and Civil Engineering in China*, Vol. 5, No. 3, pp. 304-314.

Leonard, J. (2007) *Investigation of Shear Lag Effect in High-rise Buildings with Diagrid System*, Master's thesis, Department of Civil and Environmental Engineering, MIT.

Maunsel, F. (2002) *Tall Buildings and Sustainability*, Corporation of London.

Mele, E., Toreno, M., Brandonisio, G. and Del Luca, A. (2014) Diagrid structures for tall buildings: case studies and design considerations. The Structural Design of Tall and Special Buildings. *Wiley Online Library*, Vol. 23, No. 2, pp. 124-145.

Moon, K. S. (2008) Sustainable Structural Engineering Strategies for Tall Buildings. *The Structural Design of Tall and Special Buildings*, Vol. 17, No. 5, pp. 895-914.

Moon, K. S. (2011) Diagrid Structures for Complex-Shaped Tall Buildings. *Procedia Engineering*, Vol. 14, pp. 1343-1350.

Moon, K.S., Connor, J.J., Fernandez, J.E. (2007) Diagrid structural system for tall buildings: characteristics and methodology for preliminary design. *The Structural Design of Tall and Special Buildings*, Vol. 16, No. 2, pp. 205-230.

Nguyen, B. K. and Altan H. (2011) Comparative Review of Five Sustainable Rating Systems. *Procedia Engineering*, Vol. 21, pp. 376-386.

NTC - *Norme Tecniche per le Costruzioni/Italian Building Code* (2008) Decreto Ministeriale del 14/1/2008, Suppl. ord. n. 30 alla G.U. n. 29 del 4/2/2008 (in Italian).

Pank, W., Girardet, H. and Cox, G. (2002) *Tall Buildings and Sustainability*, The Corporation of London, London. Retrieved May 29, 2014 from: http://www.cityoflondon.gov.uk/services/environment-and-planning/sustainability/Documents/pdfs/tall-buildings-sustainability.pdf

Ramesha, T., Prakasha, R. and Shuklab, K.K. (2010) Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, Vol. 42, pp. 1592-1600.

Robin, C. P. Y. and Poon, C. S. (2009) Cultural shift towards sustainability in the construction industry of Hong Kong. *Journal of Environmental Management*, Vol. 90, pp. 3616–3628.

Sarja, A., Bamforth, P., Caccavelli, D., Chevalier, J., Durucan, S. (2005) *Lifetime Engineering of Buildings and Civil Infrastructures*. Retrieved May 9, 2003 from: http://lifetime.vtt.fi/lifetime_deliverable_3_1.pdf

Srinivasan, R. S., Brahamb, W. W., Campbell, D. E. and Curcija, C. D. (2011) Re(De)fining Net Zero Energy: Renewable Energy Balance in environmental building design. *Building and Environment*, Vol. 47, pp. 300-315.

Tae, S. and Shin, S. (2009) Current work and future trends for sustainable buildings in South Korea. *Renewable and Sustainable Energy Reviews*, Vol 13, pp. 1910-1921.

UN - United Nations. (1987) Report of the World Commission on Environment and Development. General Assembly Resolution 42/187, 11 December. Retrieved May 29, 2014 from: http://www.un.org/documents/ga/res/42/ares42-187.htm

USGBC - United States Green Building Council. (2009) *LEED for New Construction and Major Renovations*, version 3.0. Green Building Council, Washington, D.C.

Vezzoli, C. and Manzini, E. (2008) *Design for Environmental Sustainability*. Springer-Verlag London.

Planetarium Sorrow

Kristjan Plagborg Nielsen[*1], Klaas de Rycke[2], and Marie Boltenstern[3]
kpn@kpne.dk, kderycke@bollinger-grohmann.fr, m.boltenstern@hotmail.com
[1] RCD, Ramboll UK Ltd, UK
[2] Bollinger-Grohmann Sarl, France
[3] Institut für Architektur, Technische Universität Berlin, Germany

Abstract: The Planetarium Sorrow was a project that involved parametric design, combined with new materials, manufacturing and construction considerations and perhaps most of all aesthetics. The project is an art piece temporary exhibited at the 2013 FIAC exhibition in the Jardin des Tuileries, developed by Bollinger + Grohmann in collaboration with architects and artists Berger&Berger. The piece resembles a geodesic dome, left with no function whatsoever and minimised to its very minimum. The starting point was a geodesic geometry with some 270 elements, which needed to be reduced to about one third. Culling elements according to which could best be left out, led to a design with a big hole in the top, and therefore not an aesthetically pleasing solution. The aim of the design team was to digitally engineer a way to achieve solutions that had "randomness". Various approaches where tested and compared, to in the end find the most optimal solution regarding weighted parameters of aesthetics, internal stresses and structural performance, and erection process. The project also included design and manufacturing of 3D-printed connection as well as new and innovative magnetic connection methods. The dome is manufactured with bars of 3 different lengths and customised 3D printed nodes. The project is 6 by 4.5m and weighs only 73kg and fits into two boxes so that two people can easily transport it. The art piece was after the exposition bought by a collector and is to be rebuilt soon elsewhere.

Keywords: Parametric Design, Computational Design, Holistic Design, 3D-Printing, Magnetic Connectors.

Figure 1. Architect's Rendering of the Structure Before Start of Collaborative Design Development

Site and Boundary Conditions

Since 1974 the French organisation FIAC (Foire Internationale d'Art Contemporain) has held an annual art fair in Paris, where galleries from around the world exhibit their upcoming art and artists. In recent years the fair has been continuously expanding in size, with expositions growing out of the Grand Palais into the Jardin des Tuileries, the garden in front of the Louvre Museum. Through Paris based Galleri Torri, artist and architect brothers Berger&Berger were asked to participate in the 2013 exhibition.

Their idea was a broken dome: the Planetarium Sorrow (see figure 1). The design concept was a geodesic dome with random elements removed. The geodesic dome was invented, first patented and built by Walther Bauersfeld in 1929 for a planetarium for the optical company Carl Zeiss in Jena, Germany. After The Second World War the Americans acquired all of Germany's patents, and it was allegedly through Bauersfeld's old German patent that Buckminster Fuller found the Geodesic principle and started to redevelop dome structures - for later to acquire his own American patent on the principle. Berger&Berger contacted the engineering consultancy Bollinger+Grohmann to participate in the development of the art piece in everything from overall stability to erection methods.

The geodesic dome is the geometric principle of recreating a sphere using straight elements, thereby creating triangles or heptagons and hexagons. The higher the number of subdivision, or "frequency", the closer the geodesic structure is to the original sphere. The overall size of the dome was decided in accordance with the context of the site and the budget. For the Planetarium Sorrow Berger&Berger had already chosen a geodesic dome with a frequency of 3, with 3 different nodes connecting 5, 5, or 6 elements. The dome was to be around 4.5 meters in diameter and 6 meters high. This design requires approximately 270 elements of 3 different lengths to recreate a full sphere. The sphere was cut slightly below its middle point and rotated around its center point to create the feel of randomness, see figure 2. Berger&Berger chose to use ceramic tubes with an enameled finishing. Berger&Berger had prior to the integrated design process bought 120 tubes of 1,5 meters with a diameter of 2 cm. They were made of Alumina Alsint 99,7%, a ceramic material (see figure 3), and by an enameling process the tubes would obtain a white glossy finish. The elements of the dome were therefore given beforehand and were the first fixed boundary.

Figure 3. Ceramic Tube Before Enamelling

To evoke the feeling of randomness, the basic geodesic geometry was slightly rotated around its center point. Berger&Berger had decided on an initial geodesic sphere with 270 elements, which was supposed to be reduced to around 115. The number of elements was the second boundary condition.

Removing random elements brought along another boundary condition; almost all nodes were to become a different shape. In a regular geodesic dome three different nodes connect either 5 or 6 elements. When removing elements of the regular geodesic dome the design of the nodes becomes more complex; nodes could in principle be connecting 2, 3, 4, 5 or 6 elements. A solution to manufacture some 50-60 different node connections had to be found, as well as a way to make the node-connections with a similar finish to the enameled ceramic.

A fourth boundary condition was related to the assembling. The 2013 FIAC exhibition was only a temporary event from 24th to 27th October, and the sculpture therefore had to be disassembled fast and easily.

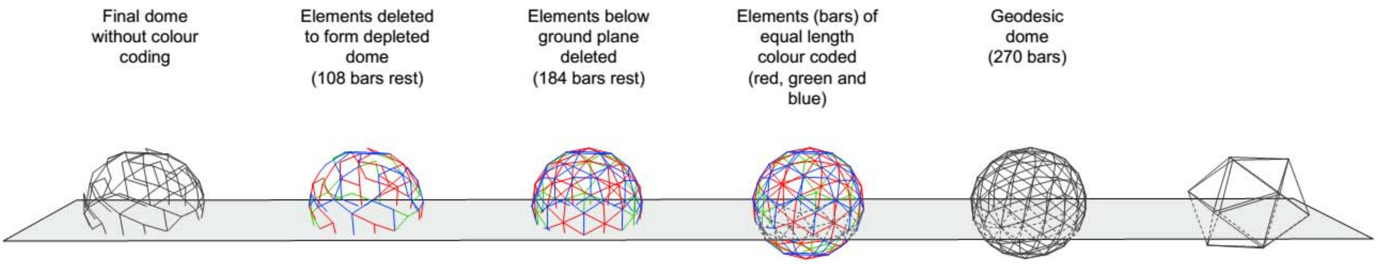


Figure 2. Development of the Geodesic Structure

Form Finding Through Generative Optimisation

To find the optimal structural shape of the broken dome, the internal forces in the elements and in the nodes had to be limited. To search for an optimised solution an algorithm was developed by the use of parametric modeling tools.

Figure 4. Visualisation of Generative Optimisation in Grasshopper using Evolutionary Solver Galapagos

The algorithm was developed in Grasshopper, a graphical algorithm editor tightly integrated with the NURBS software Rhinoceros 3-D. With the use of the Finite Element Modeling (FEM) tool karamba, a live test of the broken dome's stability could be performed. Combining structural analysis made with karamba with the evolutionary solver Galapagos (figure 4), it is possible to computer-generate several optimised designs. Galapagos first produces a given number of random species, then measures each of them against a chosen optimisation parameter and then tries to combine the good genes from each species into mutations.

Computational design is not cleverer than the input it gets. Initially no restrictions were built into the algorithm, and the optimised output did not have the random visual expression which the design team sought. Asking the initial script to take out the elements that it could best do without resulted in a Pantheon-like shaped dome with a large hole in the top. In general the geometries that came out of the initial algorithm had the tendency to be clumped together leaving big holes in the dome.

To achieve the randomness asked for by Berger&Berger, the script was further developed and different approaches were investigated. Some options were made by manipulating the geometric input; for instance by dividing the initial geodesic geometry into zones. Other options were based on a completely rewritten algorithm, which instead of culling elements connected nodes with either 3 or more elements.

The different geometric approaches were tested with different optimisation parameters as total deformation, maximum deformation, normal forces or bending forces.

3D-Printing and Node Design

The design of the nodes was carried out in parallel to the form finding process described above. Berger&Berger had initially imagined the nodes made of steel tubes welded together in the right angles, but it would be hard to obtain a result precise enough with this technique. It would also take a lot of time to produce that many different nodes. Instead 3D-printed nodes were proposed; each node could be different as all the "hard work" of various angles from node to node would all be done digitally.

In collaboration with *Materialise* several test pieces were printed to test strength and finish. Recent years' advances within 3D-printing techniques have made it possible to print new materials, for instance titanium. For budget reasons it was chosen to use a material called Alumide. 3D-printed alumide models are constructed from a blend of aluminum dust and nylon plastic, making it relatively strong but also quite elastic (see figure 6).

Figure 5. 3D-Printed Node with Magnetic Female Connector Part Glued Inside

A magnetic screw solution originally developed for connections in wood was proposed instead – a solution called *Invis Lamello* (figure 5). As ceramic - like wood - is a non-magnetic material it was possible to glue in a male connector part inside each tube and a female part in the arms of each 3D-printed node. The male parts have magnets placed around the thread, and with a special magnet "bit" for a screwing machine, the thread can be turned when it is placed inside a ceramic tube. Another advantage of the system was the ability to completely hide the male thread inside the tube, so the last element of a triangulation can easily be placed.

Figure 6. Photo of 3D-Printed Node Connection

Choosing the Final Shape

The generative form finding process resulted in some thirty different optimised options, some more optimised for internal forces and others had a limited deformation. Each option was calculated in karamba with continuous elements rigidly connected to each other. The parametric modeling did not take into account the varying stiffness between the 3D-printed nodes and the ceramic tube elements. This assumption was purposely made before the final design of the nodes was found, so in order to equitably compare options developed later in the process, this error was not corrected along the way. All options therefore contained this fault.

To test the impact of the stiffness difference between nodes and elements all options were calculated in RSTAB - a commercial FEM structural analysis program - with the correct material properties. One could imagine that the impact of the error would vary from option to option; an option where less stiff nodes placed in areas with a concentration of forces would not perform very well compared to other options.

The deformation found through karamba calculations was compared with one found in RSTAB. The factorial difference between deformations should lie within the same area, otherwise the impact of the less stiff nodes was too high and the options had to be excluded from further comparison. It was to verify that the optimised form was still optimised when taken the less stiff nodes into account. The final solution was intended to still work as a dome, though the geodesic geometry was broken up. A dome structure primarily has normal forces, and higher bending moments would cause higher deflections. It was chosen to leave out the 75th percentile (figure 7).

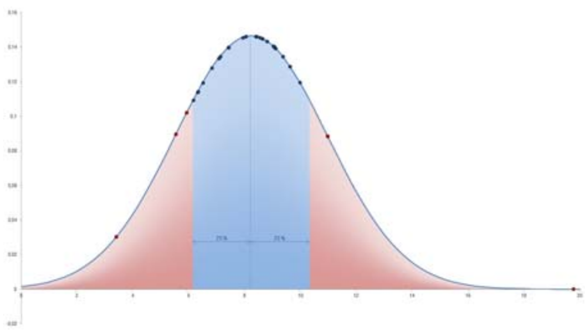


Figure 7. 25th Procentile of the Developed Designs was Kept for Further Study

Finally the von Mises stress was calculated for both the 3D-printed nodes and the ceramic tubes for various load cases - some loading situations even included the weight of pigeons. The maximum stresses were compared to find the option which could spread the forces in the most optimised way. The option with the least amount of internal forces also responded to excitation with the least amount of energy, and was in that sense the most optimised form of the some thirty different options initially found.

Figure 8. Photo from During Construction at Jardin des Tuileries

Prototype

To solve eventual construction problems or questions before the assembling a 1:5 scaled prototype model was made. All 57 nodes and 122 elements of the chosen option were 3D-printed in-house and assembled in the office of Bollinger+Grohmann. The prototype helped clarify erection sequences and assembling methods. The team of architects, engineers and builders could discuss the process of assembling around the model. The 3D-printed prototype helped all to reach a greater understanding of the complex geometry of the broken geodesic dome during the actual erection process (figure 8).

Conclusion

Through a collaborative process the art piece Planetarium Sorrow was developed by the use of cutting edge technologies. From a set of given boundary conditions, the design team developed a solution optimised in the dynamic 3D-modelling software Grasshopper, and the FEM plugin karamba. The final design was the most optimised design for the given aesthetic requirements set out not only by the artists but the engineers as well.

The Planetarium Sorrow consists of 122 ceramic tubes with three different lengths and a diameter of 2 cm.

Innovative methods were used for the design of the nodes and the connectors. The derived solution used newly developed 3D-printing material with strengthening aluminum dust to create custom made, high strength 3D-printed nodes.

Invisible magnetic connectors, originally developed for high-end furniture in wood, were used for the creation of a seamless transition between ceramic tubes and 3D-printed nodes.

The final result was exposed for two weeks at the 2013 FIAC exhibition in the Jardin des Tuileries (figure 9).

Figure 9. Photo of the Planetarium Sorrow Exhibited at Jardin de Tuileries

Report for the 2014 DCEE Working Group Meeting

Summary by: Lotte Bjerregaard Jensen and Mary Kathryn Thompson

Introduction

The DCEE 2014 meeting at the Technical University of Denmark focused on interdisciplinarity in design processes while embracing the central issues of the previous workshops: design tools / methods and design education in Civil and Environmental Engineering (CEE).

Interdisciplinarity

Interdisciplinarity runs through design in civil and environmental engineering and links all of the associated disciplines. For example, architects are not interested in HVAC. They are interested in how the building looks and where and how to place the windows. However these design choices influence the design of the HVAC system. The HVAC system design can, in turn, influence how a building's internal support structure must be designed and built and vice versa. The order in which these decisions are made sets the constraints that affect the decisions to come. But they often do not need to be made in a specific order. This places all of the disciplines at an equal level and requires them to work together instead for each other.

Since the earliest decisions impact all of the decisions to come, it is important that the decision making process is infused with engineering and scientific knowledge from the beginning. The many levels of decisions that need to be made over long periods of time must be based on broad and deep knowledge that cannot be held by a single person or discipline.

Larger civil design projects are usually commissioned and funded by the public. The politicians overseeing this process are aware of the complexity involved and also require a higher level of information to support their decision making processes. Thus, it will benefit all internal stakeholders to enhance transparency by advancing systematic interdisciplinary design processes and by developing and improving tools to inform the design process.

Finally, Civil and Environmental Engineering design processes are complex from the very beginning due to their scale and site specificity. Design methods which incorporate interdisciplinary perspectives are needed to help understand and manage this complexity.

One of the most important questions in this context is: Who are the stakeholders and the participants in interdisciplinary design processes in Civil and Environmental Engineering? While social scientists are needed to add knowledge and perspective, often the social scientists working in these areas have an engineering background. If interdisciplinarity work requires multidisciplinary participants, the cost associated with educating those people will be very high and their availability will be relatively low. Does this make interdisciplinarity then out of reach for many projects?

Finally, is interdisciplinarity in design processes a question of evidence-based design? Does evidence based design lead to overly conservative decisions since they can only be based on well documented and proven ideas? Does this represent a design dilemma?

The interdisciplinary approach, its requirements, and its implications could be the focus of forth coming workshops. Design methods could then be viewed as a broader subject. Perhaps this approach would allow design methods to be more precise in meeting current demands.

Grand Challenges

The 2014 workshop highlighted the fact that the world and its climate are changing. Thus, the types of design problems that currently need to be addressed and that will need to be addressed in the near future are changing. This increases the need to focus on improving design tools and processes to meet these needs.

Climate Change

From the technical presentations and from the breakout sessions, it is very clear that climate change related flooding is occurring all over the world. This changes the nature of our cities temporarily when impacted by more frequent micro bursts and 100-year or 1000-year rain events. It will also change the nature of coastal cities permanently as sea levels rise. This means that main stream solutions are no longer applicable. New requirements and constraints have been and will be added and new design parameters are and will be needed to address those needs.

Renewable Energy

Another grand challenge facing CEE engineers is the demand for 100% renewable solutions. The production of renewable energy depends on natural phenomena (sun, wind, waves, etc.). Although the long term availability of these resources is reasonably well known and can be used for planning, natural resources tend to have more short term fluctuations than fossil fuel or nuclear energy sources. Thus, it is more difficult to plan for and to meet the needs of the population and of industry.

These sorts of challenges are disruptive to the status quo. They require new design methods and new disruptive technologies to be developed to address these needs. Therefore we need to think more and differently about design processes in Civil and Environmental Engineering.

Globalization

Civil and Environmental Engineering projects are always related to and influenced by their location, the local climate, economy, and culture, and so on. Therefore, globalization changes our views on design processes. Historically, Asia had one tradition for design and one framework for design processes. Europe had another. The US had a third way to perform design. Now we are literally and figuratively speaking the same language. This enables us to share ideas and information internationally far more than before. But it also means that our designers and our construction industries have to work together and to compete with each other in a new way. The implications of this are not yet well understood and could be addressed in future workshops.

Teaching

Students in CEE are usually highly motivated and want to help address important problems and grand challenges associated with climate change, energy, environment, water and sustainability. Universities are good at teaching the fundamentals that will allow students to address the aforementioned problems. But many programs lack integrative experiences that provide students with the experience to do so. The working group asked: should design challenges by addressed by a design tradition, by a systematic design methodology, through practice via integrative experiences, by a combination, or using some other approach? Would it be valuable for this community to explore design tools and methods in an interdisciplinary environment by offering joint project-based grand-challenge-focused international short or summer courses?

Mapping of Related Fora: What is Unique in Design in Civil and Environmental Engineering?

Design applications in the fields within Civil and Environmental Engineering (water treatment, structural engineering , etc.) can be, and currently are being, presented at conferences and in journals related to those fields. Design within the ‘silos’ are usually well represented in the associated literature.

Papers related to Civil and Environmental Engineering education and curriculum development have established fora within engineering education. For example, the American Society for Engineering Education (ASEE) has a division dedicated to civil engineering and another dedicated to design education.

In addition, there are already conferences associated with topics that are related to design such as Building Information Management (BIM) and digital design tools in general. These topics are part of and support advanced design processes.

What we believe is unique about DCEE is its holistic perspective. This workshop provides a forum that welcomes design from all of the disciplines within CEE, that allows an integrated and interdisciplinary perspective and approach to design, that is independent of any given tool or technique, and that emphasizes the design process and design methods. DCEE must preserve this openness in order to continue to foster the interdisciplinarity necessary to address specific projects from CEE related technical and scientific fields as well as the grand challenges that cross them.

DCEE Community

Finally, the working group addressed the status and evolution of the DCEE community. A question was raised about the need to formalize the DCEE community. For example, does DCEE need to form or join a professional society of some sort? This seems to be a critical question for the next few years.

Publication Options

Similarly, the group discussed the need for and the founding of a civil design journal. This would help to formalize the community and would greatly increase the visibility and the impact of the community. However, it is also a substantial undertaking. There is great enthusiasm and support to do this. But it is not yet clear that there is critical mass for a dedicated civil design journal. For now, the participants agreed to investigate options to increase the visibility and impact of the workshop proceedings and to organize a special issue related to design in CEE in an existing journal.

DCEE Meetings

The group discussed the format of future meetings. Participants like the single (plenary) sessions that are currently offered. But this limits the meeting to a maximum of 60 to 80 participants. The consensus is to try to keep the workshop character for now but also to ensure that the meeting is open and inclusive. If this requires parallel sessions, an increase in poster presentations, or other adjustments, these will be made. The participants of the 2014 meeting also liked the breakout sessions and wanted to continue to invite and embed industry in the workshop.

Benefits and Challenges for the Hosting Organization

Finally, the team from DTU noted that organizing and hosting the workshop provided a valuable opportunity for self-reflection and a platform for communication about design research that has been conducted in CEE over the past 15 years. The workshop showed both local and international participants how much work has been done in integrated design and integrated energy design at DTU. It also showed that there have been different cycles of research in design methods in different parts of the university over the years.

Participants who are interested in hosting the workshop in future years noted that it is important to ensure a smooth and easy transition from one team to the next. Resources are always limited. They should be spent on the technical issues and building the community, rather than on replicating work that has been done by others.

Activities Outside of the DCEE Workshops

DCEE has not yet settled into an annual or biannual format. Members of the community stressed the importance of meeting once a year, even if the workshop is held biannually. If this is not possible, an online discussion or platform might be necessary to ensure that the bonds between the members are maintained and strengthened.

Several options for participation outside of the workshops were discussed. It was concluded that collaboration was likely to take place pairwise and outside of the workshop framework. No formal action is needed for these types of activities. However, formal exchanges of students, PhD summer schools and other types of short courses are all concrete and relatively easy ways to remain active and explore specific issues related to design in CEE between workshops. Special sessions on design in CEE can also be organized at other meetings related to the CEE domains or special topics such as BIM.

Editors

Lotte Bjerregaard Jensen
Mary Kathryn Thompson

DTU Danmarks Tekniske Universitet

COWIfonden

ISBN 9780989465830

9 780989 465830