NORDISK ARKITEKTURFORSKNING
NORDIC JOURNAL OF ARCHITECTURAL RESEARCH

1

ISSUE 1 2017

NORDISK ARKITEKTURFORSKNING

Nordic Journal of Architectural Research

1–2017

Nordic Journal of Architectural Research
ISSN: 1893–5281

Submitted manuscripts
Manuscripts are to be sent to Madeleine Granvik (Madeleine.Granvik@slu.se) and Claus Bech-Danielsen (cbd@sbi.aau.dk) as a text file in Word, using Times New Roman font. Submitted papers should not exceed 8 000 words exclusive abstract, references and figures. The recommended length of contributions is 5 000–8 000 words. Deviations from this must be agreed with the editors in chief.
See Author's Guideline (http://arkitekturforskning.net/na/information/authors) for further information.

Subscription
Students/graduate students
Prize: 27.5 Euro.
Individuals (teachers, researchers, employees, professionals)
Prize: 38.5 Euro.
Institutions (libraries, companies, universities)
Prize: 423 Euro.

Membership for the association
5.5 Euro (for individuals who get access to the journal through institutions).

Students and individual subscribers must inform about their e-mail address in order to get access to the journal. After payment, send the e-mail address to Trond Haug, trond.haug@sintef.no.

Institutional subscribers must inform about their IP-address/IP-range in order to get access to the journal. After payment, send the IP-address/IP-range to Trond Haug, trond.haug@sintef.no.

Payment
Sweden, pay to: postgirokonto 419 03 25–3
Denmark, pay to: Danske Bank 16780995, reg.nr. 3409
Finland, pay to: Danske Bank 800013–70633795, IBAN code FI30 8000 1370 6337 95
Norway, pay to: Den Norske Bank 7877.08.13769

Outside the Nordic countries pay in Euro to SWIFT-address: PGS ISESS Account no: 4190325–3, Postgirot Bank Sweden, SE 105 06 Stockholm.

Published by SINTEF Academic Press
P O Box 124 Blindern, NO-0314 Oslo, Norway.

CONTENTS

Photo on the front cover: "Urban Bike Scapes, New York: Architectural analysis for a new urban typology".
Photographer: Line Marie Bruun Jespersen

NORDISK ARKITEKTURFORSKNING
NORDIC JOURNAL OF ARCHITECTURAL RESEARCH

DESIGNING AND CONTROLLING ADAPTIVE LIGHTING USING NETWORK-BASED AGENTS METHODOLOGY

TONI ÖSTERLUND AND HENRIKA PIHLAJANIEMI

Abstract

The rapid development of lighting technologies, especially the introduction of LED and the integration of computation and sensing technologies into our everyday environments, have opened up new opportunities for lighting design. The driving force for introducing adaptive lighting solutions to urban and indoor environments has been to conserve energy through automated systems and optimised solutions. Although these types of Ambient Intelligence (AmI) systems are technologically sophisticated, they do not consider the role of design and aesthetics, and currently, there is untapped potential in using adaptive lighting in improving the functional and experiential quality of architectural spaces. This paper discusses a design framework called VirtuAUL, which is developed for the design, control and real-world implementation of adaptive lighting. The aim of this paper is to present the details of the developed methodology, where network-based agents are used for designing and controlling adaptive lighting, and to discuss the benefits, opportunities and shortcomings of the developed method. Based on the control methodology, computational agents move in a designer-defined network topology and interact with the physical environment. Information on the environment and its users is conveyed from real to virtual through sensors, and lights reveal the composition of the virtual system. The lighting response is part of a creatively designed adaptive scenario. The use of the design and control methodology and its function is illustrated in the context of a real-world lighting demo called Urban Echoes.

Keywords:
adaptive lighting, network-based agents, lighting design, lighting control, design framework

1 Introduction

1.1 Background

The appearance of new lighting and sensing technologies on the market is changing the paradigm of urban lighting from static to more dynamic and adaptive lighting. Conventionally, lights stay fully lit through their operational hours, which results in static lighting environments and excessive use of energy. The introduction of controllable LEDs and the integration of technology into our everyday environments have opened up new opportunities for lighting design. Lighting solutions can adapt intelligently and dynamically to the presence of people through data transmitted by integrated sensing technology (Hughes and Dhannu, 2008).

Adaptive lighting can be seen as an intelligent and adaptive system processing data about the presence of people and current environmental conditions according to the rules defined by a designer. The processing of information dynamically affects the luminaires in the system, thus creating an adaptive lighting environment (Pihlajaniemi, 2016, p.16). The behaviour of the adaptive lighting system is defined through a creative design process, which can also entail aesthetic qualities and artistic expression (see Figure 1). Adaptive lighting system can be considered as an Ambient Intelligent system, characterised as being responsive, sensitive and adaptive (Cook, Augusto and Jakkula, 2009).

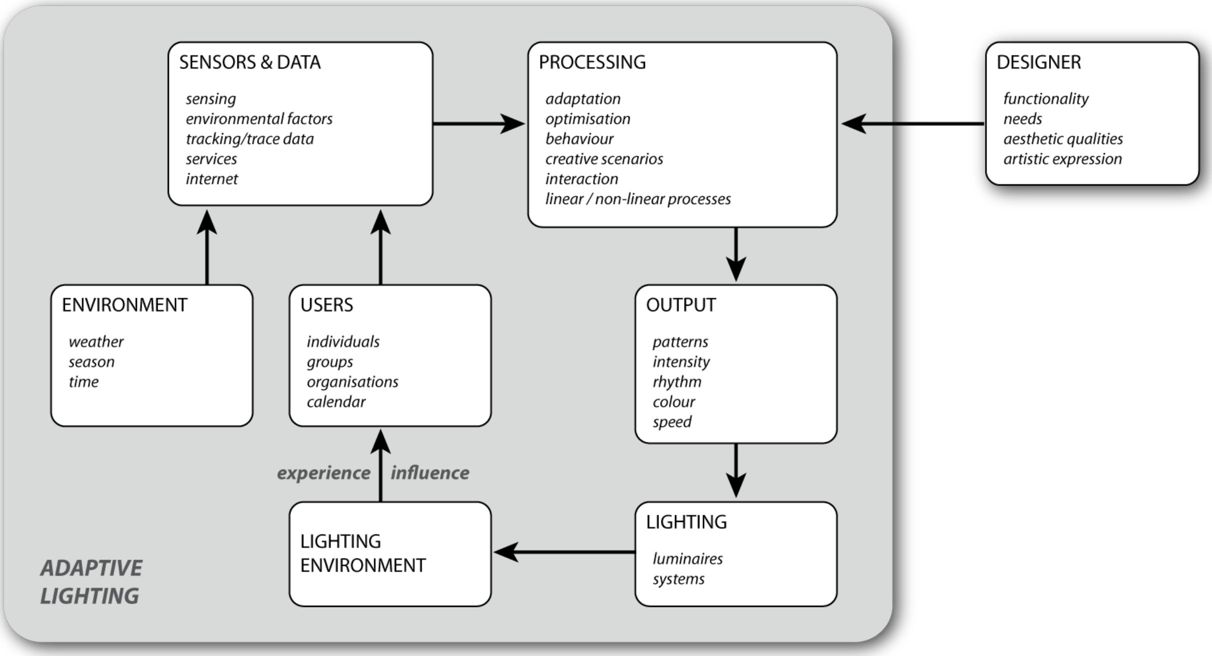


Figure 1
Diagram depicting the components of adaptive lighting, where the adaptation process in addition to purely functional aspects entails aesthetic qualities and creative design decisions.

Ambient Intelligence (AmI) is an emerging discipline, which embeds intelligence into architectural spaces through the integration of computation and sensing technologies. AmI offers the technical basis for environments that are sensitive to people, perform context-aware actions and appreciate social interactions. (Shadbolt, 2003; Cook, Augusto and Jakkula, 2009) This involves the integration of several computing areas, such as *ubiquitous computing* (Weiser, 1991), intelligent systems research and *pervasive computing* (McCullough, 2004), among others. With the use of ubiquitous technology, computation is no longer separated from architecture; it allows people to interact directly with their environment.

The AmI approach focuses on the users and their experience, allowing the environment to proactively support them in their endeavours, and overcome the device and function oriented paradigm (Bullinger, 2006). As technology is becoming more integrated into our social infrastructure, it demands design consideration through social, psychological, aesthetic and functional factors (McCullough, 2004, p.3). The challenge is to design the experience through advanced interaction concepts (Aarts & Encarnação, 2006, p.XII).

So far, the driving force for introducing adaptive and intelligent lighting solutions for traffic environments, urban spaces and buildings has been to conserve energy. The applications have been mainly focused on technology: concentrating the design on automated systems and optimised solutions (see e.g. Lau, Merrett and White, 2013; Hughes and Dhannu, 2008; Siddiqui, et al., 2012). Although these types of AmI systems are technologically sophisticated, they do not consider the role of design and aesthetics (Röcker, et al., 2012).

Energy conservation is an important task of future lighting systems; however, there is untapped potential in using adaptive lighting in improving the functional and experiential quality of architectural spaces. Instead of considering adaptation processes for automating lighting behaviour and optimising energy usage, this paper discusses new possibilities for its creative design. Adaptive lighting can be seen to have experiential value and convey artistic expressions through light patterns, rhythms and colours; communicate, convey information and offer opportunities for social interaction (Pihlajaniemi, Österlund and Herneoja, 2013).

The aim of our research has been to develop a design and control methodology for the design of adaptive lighting processes without the need for programming. The development has been related to a larger research endeavour of several projects at the Oulu School of Architecture, studying the design processes and methods of adaptive lighting, as well as users' experiences of environments with adaptive lighting solutions; see, for example, Pihlajaniemi (2016). The specific aim of this paper is to present the details of the developed solution, where network-based agents are used for designing and controlling adaptive lighting, and to discuss the benefits, opportunities and shortcomings of the developed method.

1.2 Designing adaptive lighting processes

In order to design dynamic lighting patterns and adaptive processes, the designer has to define the lighting system's behaviour and its actions according to sensor stimuli and external data. Due to the sheer amount of data and its complexity, the focus of the design process shifts – from the formulation of isolated and individual sensor triggers or animated lighting actions, to defining algorithmic processes and behavioural rules. Through the use of *algorithm-aided design* methods (also known as algorithmic, generative or computational design), computation is utilised in creative systems through algorithmic logic and generative processes (Terzidis, 2006; Österlund, 2013). Designers become the formulators of algorithms and creators of design tools, rather than just the end users of self-contained applications (Davis and Peters, 2013). Understanding how the system operates and how the designer can predict the performance of any design alternative they may generate computationally is fundamental (Ahlquist and Menges, 2011).

The level of "predictability" in the designed lighting process, from the user's point of view, is also a significant factor. In this context, predictability refers to the amount of perceived complexity or *nonlinearity* (Mitchell, 2009) in the designed lighting patterns. Nonlinearity in lighting design is not a trivial question, as the system could be used in many levels of perceived user control. Increasing the nonlinearity of the design might decrease the readability of the logic thus affecting the perceived influence of user control. The level of interaction in lighting systems may also vary, as the control can range from fully automated solutions (with a decreased perceived feeling of control) to full user control through different interaction methods (van Essen, Offermans and Eggen, 2012).

Depending on the functional requirements and the will of the designer, the lighting behaviour should be able to scale from linearly logical to nonlinear processes, increasing the unpredictability of the lighting solution respectively. From an experiential point of view, the use of nonlinear dynamics brings forth new aesthetic qualities of unpredictable and seemingly organic factors into adaptive lighting. The qualities are present in natural lighting conditions, due to changing weather and winds, as well as in the swarming behaviour of birds and fish. In our research and through our developed methodology, we do not attempt to define the aesthetic properties of adaptive lighting, but to provide means for designers to define it for themselves. The possibility to decide light colours, intensities, pathways, patterns and rhythm of changes provide the tools for design.

The system interacts with the physical environment and its users by creating appropriate lighting patterns that are constantly changing and dynamically evolving. It is hard to predict the exact composition of the lighting patterns as they are the emergent outcome of the designer-defined adaptive solution and real-world interactions that involve users, as individuals or collectively, in the feedback loop. Users can interact with the lighting environment *explicitly*; with a conscious effort to tell the system what to do, or *implicitly*; with actions that are not primarily aimed for interaction, but which the system understands as inputs (Schmidt, 2000; Pihlajaniemi, 2016).

Through implicit interaction, users affect the adaptive lighting by moving around or by entering certain locations, and in response, the lighting can attract and influence people's behaviour (Pihlajaniemi, et al., 2014a). Interaction is bi-directional, as humans interact with technologies and these technologies mediate their behaviour (Verbeek, 2010). Thomsen describes these kinds of interactive environments as performative, where "actors" engage with designed landscapes through bottom-up processes: a time-based process with interactive contacts between all actors and the possibility to include complex parameters and influences in the design process (Thomsen, 2009).

The commercial tools currently available for the design of dynamic lighting require knowledge and skills in programming in order to formulate solutions that are more complex. Yet the creative professionals, who are designing functional and experiential lighting, may not possess these skills, which might lead to overly simplified solutions, as the intentions are lost to the complexities of programming. The field is heavily dominated by technical professionals, and there is a need for new concepts, generalizable design methodologies and tools for the creative design of adaptive and intelligent lighting (Karamouzi et al., 2013; Hakulinen, Turunen and Heimonen, 2013; Magielse, 2014, pp.92–93).

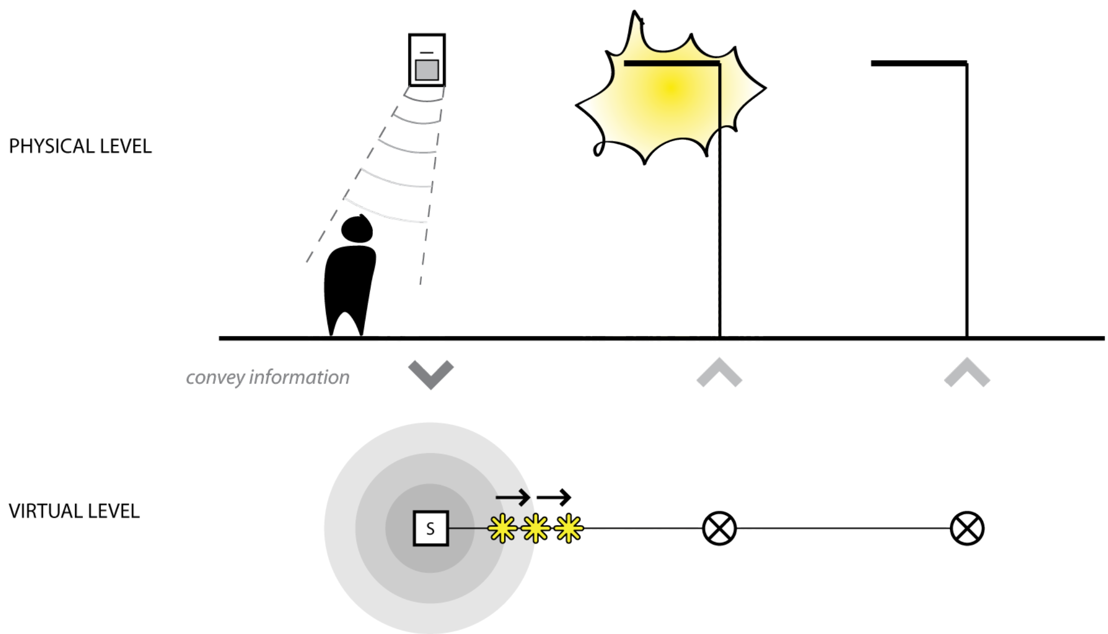
1.3 Network-based agents

We have developed a design framework called *VirtuAUL* (Virtual Adaptive Urban Lighting) for the creative design, adaptive control and real-world implementation of adaptive lighting (Österlund and Pihlajaniemi, 2015; Österlund and Pihlajaniemi, 2016). The framework incorporates a novel *network-based agents* methodology for the design and control of adaptive lighting processes, which mediates the implicit interactions between the user and the system. The lighting scenarios are designed with a graphical design tool, allowing the designer to define adaptive processes without the need for programming. The designed scenarios are implemented and operated in real-world settings by using a centralised lighting controller.

In the network-based agents methodology, computational agents move and operate within a designer-defined network topology. The network topology (i.e. the configuration of links connecting the nodes) defines pathways in which the agents can move from node to node. The network defines the agents' virtual environment, which corresponds to the real-world environment through the nodes' representing the physical sensors and luminaires of the lighting system.

The flow of computational agents within the virtual network emerges as dynamic and adaptive lighting patterns in the real world, when the lighting system interacts with its users (see Figure 2). Sensor nodes emit agents to the network, and are triggered by presence or other environmentally sensitive data. As the agents move in the network, the light nodes react to their vicinity and properties, thus affecting the luminaires' intensity and colour.

Figure 2
Sensors convey information to the virtual system, which operates accordingly. The composition of the virtual system and the agents is revealed through the dynamic lighting patterns.



1.4 Related work

The field of adaptive and intelligent lighting research has previously been approached from multiple perspectives, such as methods for user interaction, effects on energy consumption and safety. Magielse (2014) researched concepts for user interaction through specially built luminaires and control hardware. Offermans, van Essen and Eggen (2014) provide insight to the general principles of explicit light control interfaces and user needs, while Dugar, Donn and Marshall (2012) have researched the design of tangible control interfaces by using immersive virtual environments. By using implicit interaction methods, the authors implemented and studied the use of adaptive lighting in retail environments (Pihlajaniemi, et al., 2014b). Offermans, van Essen and Eggen (2013) proposed the use of hybrid methods in order to find the dynamic balance between optimised automated lighting behaviour and user preferences.

Researching the effects on energy consumption, Lau, Merret and White (2013) developed an adaptive lighting scheme for road traffic, adjusting luminaire brightness based on traffic speed and volume. By measuring the energy consumption in office environment, Hughes and Dhannu (2008) found substantial energy savings in using an adaptive lighting scheme compared to a static one. Haans and de Kort (2012) investigated the effect of different adaptive lighting distributions on perceived safety of pedestrians.

Information processing of a lighting system can happen within a centralised controller unit that receives data, is knowledgeable of every component connected to the whole system and controls all light sources. Ceriotti, et al. (2011) has used this type of centralised closed-loop control system together with wireless sensor networks to adaptively set lighting levels of a road tunnel. Yeh, et al. (2010) propose an autonomous centralised lighting control system based on the feedback from wireless light sensors carried by people in office surroundings. Another approach is to use decentralised information processing, where computation is distributed among different autonomous and intelligent hardware components. In this approach, the system components do not have an overall view of the global configuration, yet they can be locally aware of their neighbourhood. Bandini, et al. (2011) used purpose-built hardware including sensors and light sources, and component communication based on cellular automata, in order for the lighting system to adapt to pedestrians. Rao, et al. (2012) propose the use of autonomous light and sensor hardware agents that communicate local changes with each other in order to synchronise the global view.

Österlund (2013) has discussed the design possibilities of complex systems with emergent properties in adaptive lighting control, where the spatial model used in the network-based agent system is also presented. Hakulinen, Turunen and Heimonen (2013) also discuss the need for a spatial model in interactive lighting systems, where they argue that a lighting system should be aware not just of the locations of the light fixtures and their rotation, but also of the area they can illuminate.

Different design tools have been created in order for the users of the environment to participate in the design process. The LightStories installation by the authors used an online design tool, where people could create their own light animations to be displayed on a pedestrian street (Pihlajaniemi, et al., 2012). The responsive urban lighting installation by Poulsen, et al. (2013) used custom-built software with predesigned lighting behaviour, which' parameters users could modify through a mobile interface. Custom tools have also been created in order to visualise the changes in design parameters without changing the underlying lighting behaviour. For the light art project "Silo 468", Lighting Design Collective (2011) created a graphical tool for simulating and defining the parameters of dynamic lighting on the façade of an old oil silo, based on swarm algorithm and wind speed. Bandini, et al. (2011) created a graphical design environment, which allowed to configure the system and to simulate the behaviour of the cellular automata based adaptive lighting.

The development of the VirtuAUL design framework together with the design development of Urban Echoes lighting installation has been discussed in a previous paper by the authors (Pihlajaniemi, Österlund and Herneoja, 2014). Our proposed approach to the design of adaptive lighting, compared to the related work presented here, is to allow the designer to creatively define the adaptive processes. The lighting behaviour is not predefined, but the design method and tool allows the designer to freely envision complex adaptive scenarios. We implement centralised controller that regulates the lighting conditions, sensor information and processing. The use of centralised controller reduces the scalability of the system (Rao, et al., 2012), but it makes it possible to use "unintelligent" off-the-shelf hardware and luminaires, allowing the implementation on existing lighting infrastructure as well. It also enables the top-down design of the global behaviour, instead of configuring the inherently emergent bottom-up local interactions for a desired global effect, which in itself is a significant research problem (Bandini, et al., 2011).

2 Developing a new design and control methodology

2.1 Objectives and methods

The objective of the research was to develop a design and control methodology for the creative design of dynamic and nonlinear lighting that adapts based on external information and sensor data. One of the main goals in defining the methodology was that the design of adaptive processes should not require coding skills from the lighting designer. By using the developed software tool, a designer could graphically define the processes and parameters of the control methodology, which then computes and manages the adaptive lighting solution. One part of the research interest was to develop a centralised control system that utilises aspects of distributed computational intelligence as part of the adaptation process (Österlund, 2013). The aim was to open up new possibilities for the creative design of adaptive lighting patterns.

The research questions for the development of the design and control methodology can be formulated as:

- How can the control methodology be applied in designing presence-based adaptation processes of lighting?
- What kind of design elements and parameters are essential in the design process that allows versatile design solutions and sufficient freedom of design?
- What elements of the design and control methodology support the creation of linear and nonlinear processes?

Methodologically, the development process has to be described as part of the larger research entity, which aimed at understanding the design and experience of adaptive lighting. The design and control methodology was developed as an integral part of the research process consisting of designing, realizing and evaluating real-world demos. (Pihlajaniemi, Österlund and Herneoja, 2013; Pihlajaniemi, 2016)

Our research concerns various research disciplines such as lighting design research, HCI and architectural research. Typical to all of these disciplines is that their research problems are not usually set within one singular disciplinary framework. In addition, the research problem and its knowledge production operate within a context of practice. Our research can thus be defined as transdisciplinary research. (Pihlajaniemi, Österlund and Herneoja, 2014; Gibbons, et al., 1994)

In our research process, the framework of methods used in the tool and system development was developed and modified throughout the process. We followed a mixed-method or combined strategies approach, where multiple methods from diverse traditions are applied in one research. This approach is suitable for researching complex phenomena, in our case the design process and experience of adaptive and interactive lighting in a real urban context. (Pihlajaniemi, Österlund and Herneoja, 2014; Groat and Wang, 2013, pp.441–449)

Table 1 presents the combination of methods used in different phases of the research process. The development process is described in detail in Pihlajaniemi, Österlund and Herneoja (2014); a short summary is presented in the next section. The creation of the VirtuAUL design framework and the methodology stemmed from the need to solve specific challenges concerning the design and development of two real-world lighting demos: 1) *Urban Echoes*: adaptive and communicative lighting in an urban park environment, and 2) adaptive and intelligent lighting in a retail environment. The Urban Echoes demo is presented in this paper as a background for the functionality of the VirtuAUL design framework, and the second demo is discussed in Pihlajaniemi, et al. (2014b). The results of the experience evaluation are presented and discussed in Pihlajaniemi (2016) and Luusua, Pihlajaniemi and Ylipulli (2016). The performance evaluation of the design tool is presented in detail in Pihlajaniemi, Österlund and Herneoja (2014) and only referred briefly in this paper.

Table 1. Research methods used in the different phases of the research process.

Phase	*Methods*
Design Tool and System Development **Design and Realization of Pilots**	▪ State-of-the-art literature surveys ▪ Use Scenarios ▪ Research & Development by Design ▪ Real-world testing ▪ *Video documentation ** ▪ *System data logging and analyses ** ▪ *Design tool performance evaluation **
Experience Evaluation	▪ Semi-structured interview * ▪ Experience gauging walking interview in-situ * ▪ Evaluation probe method used in the test site * ▪ Questionnaires (online and printed) containing multiple choice and open-ended questions * ▪ System data logging and analyses *

* = research material is not included in this paper.

2.2 Development process

The VirtuAUL design framework was developed in an iterative design process, where the control methodology and design tool development progressed simultaneously. The design and realisation process of the Urban Echoes adaptive lighting demo was used as a development tool and test-bed for the design framework. The main methods used in the development process were 1) state-of-the-art literature surveys concerning algorithm-aided design methods and lighting design; 2) use scenarios; 3) research and development by design; and 4) real-world full-scale testing.

Figure 3
Otto Karhi park at the city of Oulu, Finland. The approximately 100-meter route, where the Urban Echoes lighting demo was set up, is marked here.

Urban Echoes was a temporary park lighting installation at the Otto Karhi park in the centre of Oulu, a city in northern Finland (see Figures 3 and 4). The demo's purpose was to study different adaptive lighting scenarios from the perspective of a park visitor's experience, as well as the communicative potential of urban lighting. The design process of the demo and its use scenarios acted as a method for developing the VirtuAUL design framework's functionalities and the design methodology. The functionality of the framework, from the use of the design tool and method to transforming the design into an intelligently controlled lighting scheme could be tested in the installation. The park lighting installation was a flexible system that could produce both even distributions of light and more uneven distributions consisting of different sized patches of light on the park pathway. The lighting reacted to the park visitors' movements via motion sensors, pursuant to the adaptive processes graphically defined with the design tool.

Figure 4
Urban Echoes lighting demo.
PHOTO: HENRIKA PIHLAJANIEMI

In the development process, a selection of scenarios of different adaptive lighting patterns (see Figure 5) were conceived and then created using the VirtuAUL design tool. The main design intentions for the scenarios were: 1) to support the perception of the route and safety of movement, 2) to support the perception of the route and the visual detection of other people, 3) to create lively lighting for the route and 4) to create an experiential route lighting that would highlight elements of the scenery. In the intended lighting behaviour of different scenarios, different combinations of linear and nonlinear interactive adaptation patterns were used. In section 5 of this paper, we describe the design of one scenario in detail in order to illustrate how the properties of the developed computational system can create experiential adaptive lighting behaviour.

The performance of the design tool and method was evaluated by comparing the initial design intentions, the design processes and simulations with the tool and the experience of real world lighting scenarios. The results of this evaluation and a description of the lighting system's communicative features is presented by Pihlajaniemi, Österlund and Herneoja (2014). This performance evaluation was carried out as part of a research-by-design process by a lighting designer who had been co-developing the tool. Larger scale tests with designers without any relation to the development process have not been carried out. Park users' experiences of the lighting scenarios were evaluated on site with a qualitative and ethnography-inspired method: experience gauging walking interview method. A description of the method and a wide qualitative analysis and discussion of the results is presented in Pihlajaniemi (2016).

2.3 Urban Echoes system description

The Urban Echoes adaptive lighting installation was implemented along one park path using 48 pieces of LED luminaires suspended above the path and positioned on the ground near trees and bushes. The selection of lights consisted of 44 pieces of RGB spotlights with varying beam angles and 4 pc. of 3000K LED luminaires with efficient street lighting optics.

Figure 5
Some adaptive lighting scenarios of the Urban Echoes demo. Altogether, more than 20 different scenarios were designed.
PHOTO: HENRIKA PIHLAJANIEMI

All the information processing, adaptive scenario modelling and light colour and intensity control took place in the global centralised lighting control unit (commercially available Pharos LPC2). The luminaires were controlled by a DMX protocol and identified by the control unit by their DMX addresses. The lighting controller unit directly controlled all the RGB LED luminaires through wirings and the other luminaires were controlled through a server link to their manufacturer's own master unit, and from there, via wireless radio control.

Seven IR motion sensors were distributed within the park pathway and were wired to the control unit inputs as close-circuit triggers. When detecting movement, the sensors triggered an immediate response from the lighting control unit and continued to do so for as long as they kept detecting movement and five seconds after motion had ceased.

3 Overview of VirtuAUL design framework

The developed VirtuAUL design framework (Österlund and Pihlajaniemi, 2015) is an end-to-end solution for designing, controlling and implementing adaptive lighting processes in real-world settings. It can be used in lighting systems of different sizes, effectively scaling up to an urban block or city district. The framework functions in real-world through a centralised processing unit, which receives information about the environment through sensors and other data sources, such as the city's online calendar. Based on the network-based agents control methodology combined with a purposefully designed lighting scenario and presence-based interaction with users, the central unit conveys control data to the luminaires. The resulting lighting environment adapts and reacts to the presence of people. The hardware connected to the system can be off-the-shelf and no special components are needed. The design framework has received a patent (Österlund and Pihlajaniemi, 2016).

The VirtuAUL design framework (see Figure 6) consists of four parts: 1) the base control methodology of *network-based agents,* 2) *VirtuAUL designer* software for defining and simulating adaptive control processes in urban settings, 3) *XML-based save file* and a method of information transfer between the design software and the central lighting controller unit, 4) *VirtuAUL controller* software that runs within the central lighting control hardware. The control methodology is explained in detail in section 4, and a brief overview of the other framework parts are given here for a better understanding of the framework in whole.

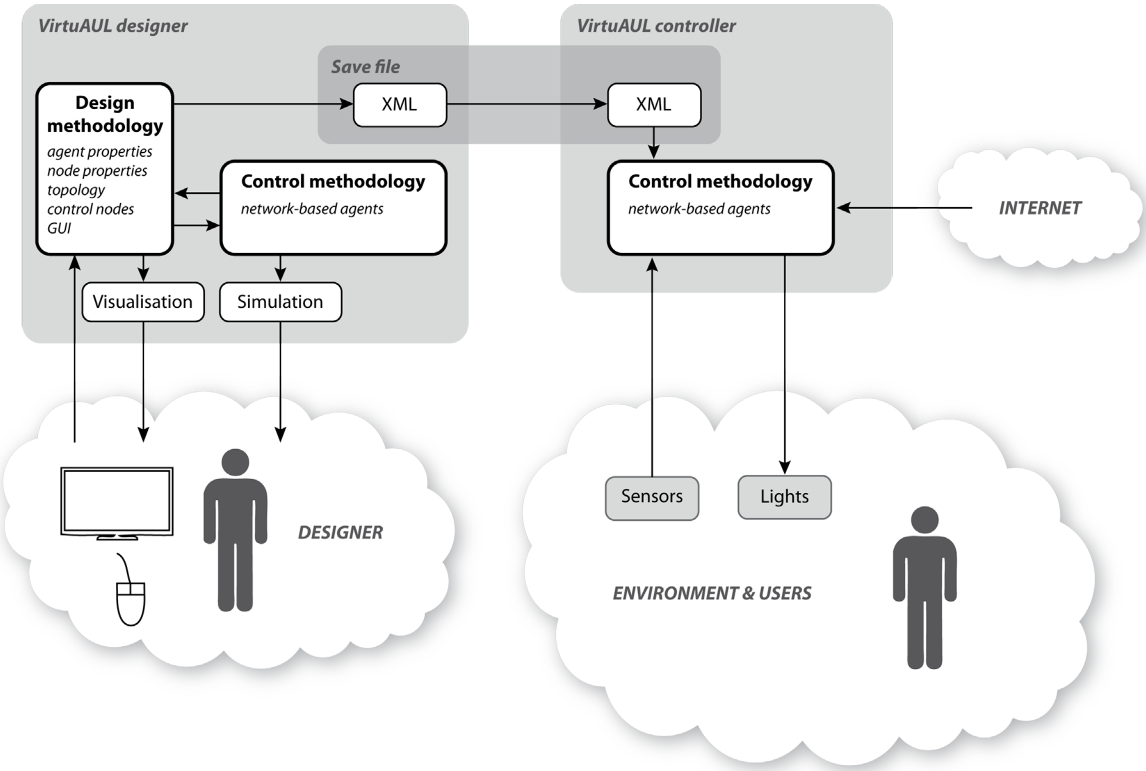


Figure 6
The VirtuAUL design framework.

For the design of complex adaptive lighting patterns, the current design tools require the processes to be defined through programming. Related to something that is very visual and dynamic, textual coding is unintuitive and cumbersome. The VirtuAUL designer software (see Figure 7) allows the designer to creatively and graphically define the adaptive processes that generate aesthetic lighting patterns without the need for programming (visual or textual). Yet the resulting lighting can reach high levels of sophistication in the level of interaction and complexity of the dynamic patterns. The effects can be simulated in real-time on top of a two-dimensional map of the design environment (see Figure 8).

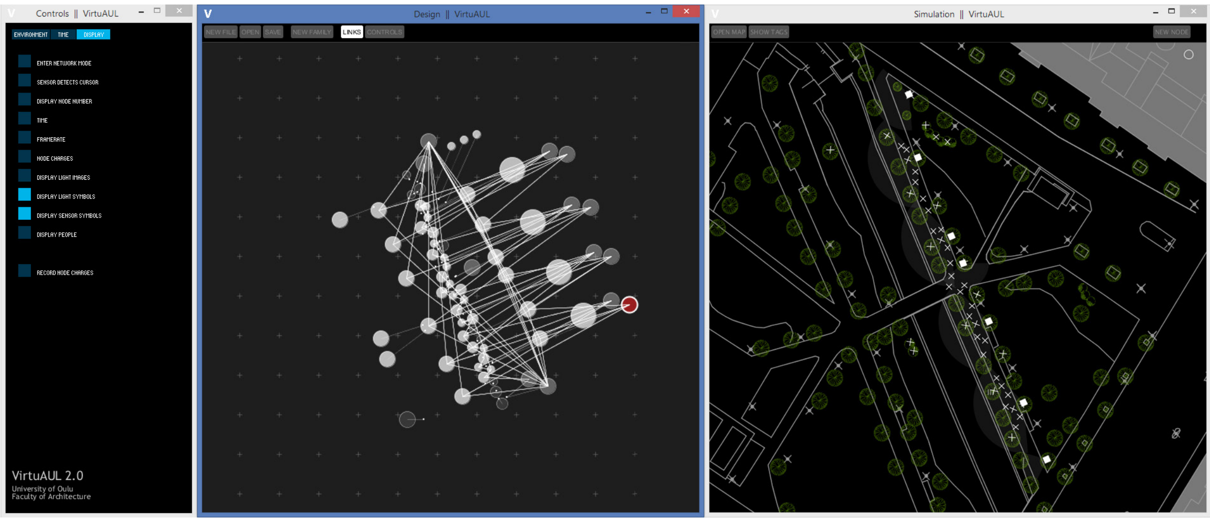


Figure 7
The VirtuAUL designer software during the design phase. The middle window is the design view, where the network topology as well as the design parameters are defined, using right-click menus that differentiate based on the node type and properties. The right window is the simulation view, where the effects of the defined process can be observed in real-time by using the mouse cursor to simulate a person. The left window contains the control options for the user interface.
ILLUSTRATION:
TONI ÖSTERLUND AND HENRIKA PIHLAJANIEMI

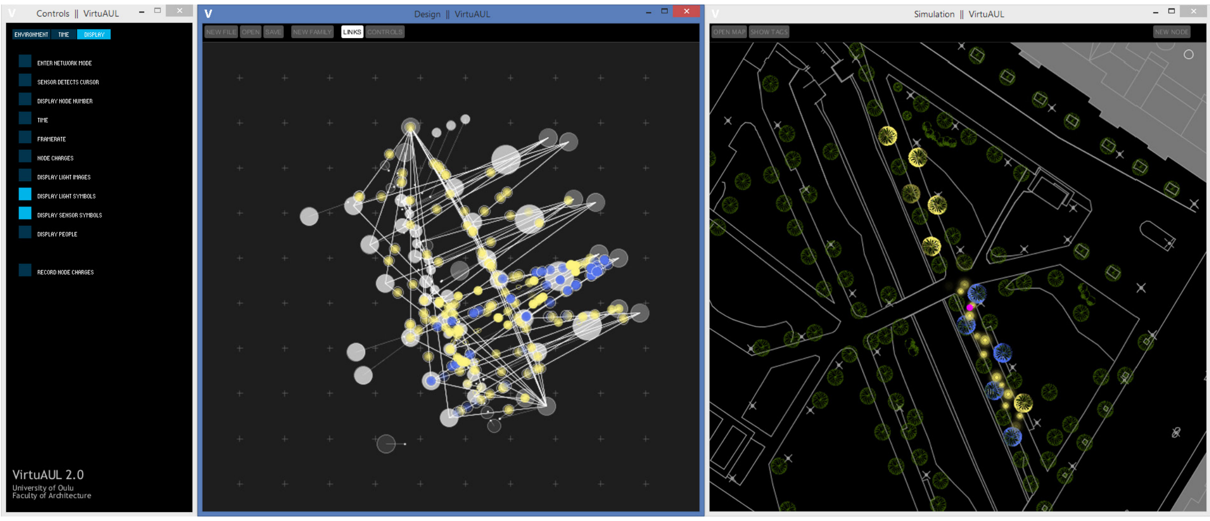


Figure 8. The VirtuAUL designer software with a simulation in progress, corresponding with the design in Figure 7.
ILLUSTRATION:
TONI ÖSTERLUND AND HENRIKA PIHLAJANIEMI

The lively light patterns emerge through interaction mediated by the control process, where dynamic virtual agents operate within a designer-defined network topology. The designed configuration of the system is saved as an XML-based textual file – a blueprint of the adaptive lighting process, which is then transferred to the central lighting control unit for processing in the real world. The XML-based blueprint itself does not define the control methodology, but it includes all necessary information for replicating the virtually designed configuration. The virtual lighting scenario matches the real world adaptive lighting process, as long as the urban surroundings, luminaires and sensors have been accurately modelled into the design tool.

The adaptive process is physically located in centralised lighting controller hardware that is running the VirtuAUL controller software. The controller software implements an identical process to the designer software, but without the graphical user interface and related components. The VirtuAUL controller is written in LUA scripting language and as such, it can function in various commercial lighting controllers as well as in a dedicated PC. All the sensors and lights in the system are connected to the centralised controller in order for the process to receive information on their status and convey lighting data.

In a centralised system, the adaptive process is aware of the global system configuration. This limits the scalability of the system (Rao, et al., 2012), as all new hardware have to be explicitly added and programmed to function as part of the process. In decentralised systems, the processing is distributed among the intelligent hardware components that behave through local rules and interact with each other. Decentralised systems are self-organising and the interaction with users happen autonomously through locally perceived changes; there is no global design to follow (Bandini, et al., 2011; Rao, et al., 2012).

From the design point of view, centralised control makes it easier to configure the desired global behaviour of the system, as each sensor and light behaviour can be explicitly set. It allows for a great deal of creative freedom, as the adaptive solution can be designed top-down: the global scenario defines different rules and behaviour for each connected component. The bottom-up design of local component rules in order to achieve a desired global behaviour is a significant research problem in decentralised, distributed systems (Bandini, et al., 2011), and as such very challenging for a lighting designer to design in a creative way. The centralised control also makes it possible to utilise "un-intelligent" hardware components and implement the adaptive scenarios to existing lighting infrastructures.

4 Control methodology

4.1 Computational model

The computational model of the *network-based agents* brings forth three main elements that together form the core functionality and main parameters of the control process: virtual *agents,* network *nodes* and network *links* (see Figure 9). These define the control process as well as serve as the main elements in the design methodology. The different elements of the computational model, their parameter settings and relational configuration define the resulting adaptive lighting solution. The model functions as a whole, with all elements affecting the lighting solution in some way. The conceptual boundaries of the different elements in defining the lighting solution are not so clear-cut, as the lighting output is affected by their interaction. Light itself is not considered as an individual element of the model, but it is the emergent end results of the system process in whole. The selected design parameters of the model elements emerged through the iterative design development process involving practical and theoretical knowledge from the fields of lighting design and computational design (Pihlajaniemi, Österlund and Herneoja, 2014).

Different node types exist, where, e.g., some receive sensing information (sensor nodes), and some process and output lighting information (light nodes) to be relayed to the real-world luminaires. The system is inherently dynamic and nonlinear, and it creates ever-changing lighting patterns. The agents are seen as dynamic information conveyers and are emitted by the sensor nodes as a consequence of change in environmental conditions.

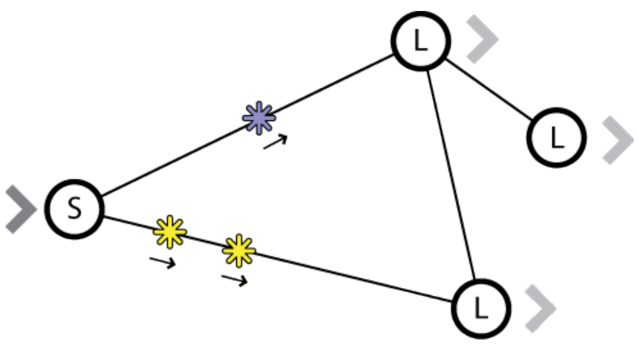


Figure 9
The main elements of the network-based agents methodology of controlling and designing adaptive lighting processes: dynamic agents (* symbol), network nodes (Sensors or Lights) and network links.

The network and its topology define the coordinate space and spatial structure of the agents' virtual environment as *graph-based coordinates* (Österlund, 2013). The location and direction of an agent is defined by three variables, $\langle N_s, N_e, P \rangle$, N_s is the node of origin, N_e is the target node and P is the position of the agent in percentage travelled from node to node. The graph-based coordinates together with the node-specific parameters define the adaptive lighting system's spatial model. The spatial model is a solution to the challenge of defining the spatial structure and dependencies of irregularly and sparsely located luminaires in real world space, where Cartesian coordinates cannot adequately describe their hierarchy or the relations of the lights to themselves or to their surrounding environment (Österlund, 2013).

The agents operate under simple rules, convey information and affect their environment in a M*ulti-Agent Syste*m (MAS) (Jennings, Sycara and Wooldridge, 1998). Multi-agent systems, contrary to *Agent-Based Modelling* (ABM), depict the design and development of "artificial" agents that do not try to model any existing human or organisational behaviour (Macal and North, 2009). Although agents are widely used in intelligent systems, modelling complex and emergent behaviour, there is currently neither a precise definition nor universal agreement of what an "agent" is (Macal and North, 2009; Jennings, Sycara and Wooldridge, 1998). For the purpose of this research, an agent is considered as a self-contained computational component that is capable of *autonomous* behaviour, *situated* in a virtual environment and capable of *interacting* with the real world through sensor information and lighting.

The network-based agent system can be described as a *multi-layered multi-agent situated system* (MMASS), referring to the MMASS system description by Bandini, Manzoni and Simone (2002). In MMASS, the environment where the agent lives, is explicitly structured and spatially related to the real-world environment, which makes the system situated (Bandini, Manzoni and Simone, 2002; Ferber and Müller, 1996). "Situatedness" is also defined by Jennings, Sycara and Wooldridge (1998) as agents that receive sensory input from their environment and perform actions that change that environment in some way. "Multi-layered" (Bandini, et al., 2009) in this context, refers to the fact that differentiated nodes, links and agents exist within the same system. It allows, for instance, multiple, completely separated networks with distinct agent types to exist within the same virtual system. In practise, this means that one adaptive lighting solution can define and simultaneously maintain very different kinds of behaviour of light.

Although the agents function as a part of a system that is capable of generating lighting solutions that interact with users and adapt to environmental changes, the agents themselves cannot be considered as adaptive. The agents do not learn from their environment, nor do they modify their rules or behaviour as a result of external input or internal computation (Macal and North, 2009).

4.2 Agent properties

An agent is a conveyor and a transmitter of information and is defined, in addition to its position, by six parameters: *colour*, *energy*, *speed*, *lifetime*, *fadetime* and *path selection behaviour*.

- *Colour* is used to store the RGB value of the agent and is depicted by three values (Red, Green and Blue) between 0 and 255. The colour information is translated directly as light colour as well as intensity when using RGB LEDs, and when using non-RGB LEDs, the first value stored (Red) is used to describe the intensity of light.
- *Energy* is the "signal strength", in which the agent transmits its colour information to the light nodes. At lower energy levels, the transmitted colour appears darker. The colour and the energy combined have an effect on the visible light colour and intensity. Transmitted colour is calculated as the energy percentage of each individual colour channel.
- *Speed* defines how fast the agent moves from N_s to N_e. Speed is not affected by the physical distance of luminaires or sensors, their Cartesian coordinates, nor the distance between nodes in the design view of VirtuAUL designer. The position *P* is a steadily increasing percentage, and the speed parameter defines the rate of progression in a way that speed indicates how many seconds it takes for an agent to travel the distance.
- The agent has two states: alive or dead, moving or stationary, dynamic or static. Using the analogy of a living agent, once the agent is born, it starts to move within the network for the duration of its lifetime, which is defined in seconds. Together with the speed parameter, the *lifetime* defines how far the agent can reach (i.e. how many nodes it can pass through) before it dies.
- Once the agent has died, it stops moving, yet it still transmits information. The signal strength slowly fades to zero, within the time defined by the *fadetime* parameter, and once it reaches zero, the agent is deleted from the system. This creates a fading intensity, so that lighting does not suddenly switch off, but has a gradient dimming factor.
- The *path selection behaviour* affects how the agent determines which link to move to next once it reaches its N_e. Possible options are that it:
  1. always turns back towards N_s
  2. randomly select new N_e (which can also be N_s)
  3. continue forward (do not use N_s) until a "dead-end" is reached (where N_s is the only option) and then turn back
  4. continue forward until "dead-end", then stop

The six parameters define an agent, its properties and behaviour, and multiple agents can share the same parameters. Agents that share parameters are described in the VirtuAUL framework as a *Family*. Agents of a certain family share some family traits: that is, they have very similar, yet not completely identical parameters. The stochastic parameter fluctuation between agents of the same family is defined automatically when they are created. Different families can be defined with their distinctive parameters (see Figure 10) and they can be used in defining different behavioural types. For instance, one family could consist of green-coloured agents that move fast, but die young, and another consisting of white agents that move slow, but live longer. When emitted to the system, their properties emerge as very different patterns of light.

Figure 10
The family parameters for family no. 0. The image shows the graphical controller interface for family parameters in the VirtuAUL design tool.
ILLUSTRATION:
TONI ÖSTERLUND AND HENRIKA PIHLAJANIEMI

Distinct sensor stimuli can be defined to create agents of certain families, so that different events trigger different lighting behaviour. The parameter fluctuation (in speed and lifetime parameters) between members of the same family creates variation in the movement of the individual agents, as otherwise, a group of identical agents would move in unison, indistinguishable from a single agent (except for their combined energy influence).

4.3 Network nodes

A single node can represent four different types of components: a *light fixture*, a *sensor* (physical or virtual, or another data source), a *control algorithm*, or it can be an empty *ghost* node.

- A *light fixture* node corresponds to an actual luminaire in the real world. The node entails information about the node's *ID number* (which equals to the luminaire's DMX address); *position*, *height* and *light distribution* bitmap (which are used in simulation); the bitmap *size* and *rotation*; whether the light can display *RGB colours*; and the *minimum* and *maximum* intensity values (restricting the light's intensity).

- A *sensor* node can represent either a physical or a virtual sensor. A physical sensor's parameters can include the *position*, *sensing area* and *rotation* (as in the implemented IR motion sensor type for the Urban Echoes). However, a physical sensor can also represent luminance or temperature sensors, for instance. The sensor nodes can also represent special types of virtual sensors, such as situated area hotspots. When a sensor node is triggered, it starts to emit agents based on the control algorithm and its parameters.
- A *control algorithm* node is a special type, as it does not act as an agent pathway. The node is a trigger connected to a sensor, also defining the agent's family and the amount emitted per timeframe, as well as on which *link layer* the agent resides. Different types of control algorithm nodes can exist and several can be connected to a single sensor at the same time, so a sensor can have different triggers with different settings and each one of them emitting different agent types.
- A *ghost* node is an empty pathway node. The node does not perform any action, nor does it correspond to any device. It can be used to extend the agent pathways.

Light nodes receive colour information from agents that are located on directly connected links. The system is updated at constant intervals, and if multiple agents approach a single light node at the same time, the cumulative effects are calculated as an average of colour information, weighed by their signal strengths (energy). The light nodes do not directly send the colour information to the physical light fixtures, but the information is gathered at the end of each interval as a list of luminaire addresses and their corresponding colour values. The lighting control unit then parses through this list and sends the control data to each luminaire.

When an agent is emitted onto a link connected to a light node, i.e. it is on the opposing end of the link (moved 0% of the distance), the colour of that agent does not yet affect the light colour. As the agent moves, the percentage gradually increases as it approaches the node, simultaneously increasing the intensity of the light colour. The movement of an agent from node to node creates a gradually increasing intensity of light. The speed of an agent affects the speed of the gradient effect. Similarly, when an agent moves onto a path away from a light, the energy decreases. The individual agent's signal strength determines how much a single agent affects the light intensity (at 100%, a light is at maximum intensity, when the agent is directly on the node).

4.4 Network links

As the network topology is a creative design decision instead of an automated or a hardware setting, it allows to generate a vast amount of different compositions. The network links have three parameters that have a profound effect on the movement of the agents, and thus, to the lighting patterns: *topology* of the network, link *directionality* and link *layer*.

- The *topology* of the network has a major influence on the level of nonlinearity and lighting patterns. Increasing the connectivity of the network (Miller, 2001) also increases the possible pathways an agent can take, and thus, increases the nonlinearity of the generated pattern.
- The *directionality* of a link controls the direction that an agent is allowed to travel through. A link can be defined as bidirectional (allowing movement in both directions) or unidirectional (allowing movement only in one direction).
- Different network topologies can be defined simultaneously as different *layers*, where only certain types of agents are allowed to move. Together with the layer-based link directionality control, it allows the designer to simultaneously define different types of behaviour within the same system.

5 Implementation in Urban Echoes project

5.1 Use scenario case study

In the Urban Echoes lighting demo, several different scenarios of adaptive lighting behaviour, which implicitly interact with the park visitors through their movements were designed, simulated and tested. One designed use scenario, which illustrates the possibilities of VirtuAUL in adaptive lighting design and control, is depicted here. The description presents the design intentions, the acts of the designer and the resulting lighting scheme.

The main design intention of the example scenario was to create an experiential route lighting that also highlights beautiful elements of the park scenery, such as trees and vegetation, along the route and further away. This creates an AmI environment, which interacts with its users through their location and movement. The dynamic adaptation of light should be perceivable by the user, so that it would enhance the atmospheric experience.

In addition, the aim was to create nonlinear lighting patterns in order for the lighting to act differently every time a person walks along the path and for a positive element of surprise for the park visitor, avoiding monotony. Even though the global appearance of light is nonlinear, it should include some predictability in its behaviour in order also to fulfil the functional needs of park lighting: the lively play of light on the park path should follow and even anticipate each park-goer, so that they could see the route and move safely.

5.2 Designing path lighting

The design commences with the opening of a template XML-file, where the light and sensor nodes are already present, matching the physical infrastructure of the installation. The first step is to design the lighting configuration to control path lighting (see Figure 11). In order to get lights brightened when a visitor is entering the path, the sensor node located at the start of the path (SN1) is linked to the nearest light node. Then, all the adjacent light nodes are linked consecutively (SN1 › LN1 › LN2 › LN3 › LN4 › ... › LN_n) until the end of the path. The last light node is linked to the sensor node on the other end of the path (SN6). Connecting the pathway light nodes to the sensor nodes at the ends serves people walking in both directions of the path.

The links are defined to be unidirectional on two different layers (L1 and L2): one direction is opened in each layer. This allows the agents to move to the same direction as the park visitor, when they enter the path from either end. Some “shortcuts” between non-consecutive luminaires are defined in order to add more possible pathways for the agents and more playfulness of light in the real world (for example, LN2 › LN5 and LN5 › LN8).

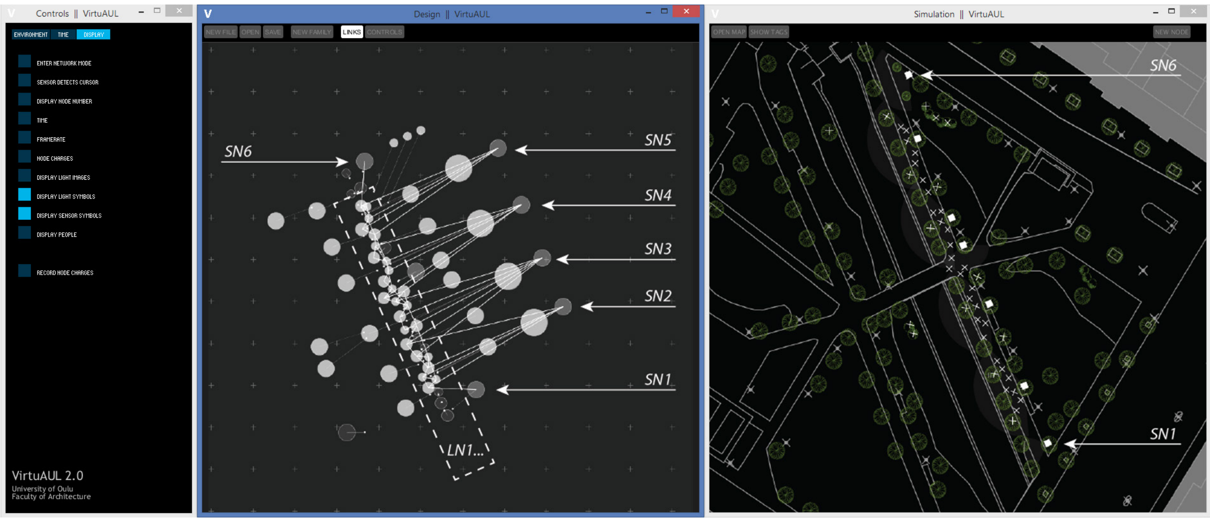


Figure 11
The left design view shows the light and sensor nodes of the Urban Echoes installation, with the luminaires and sensors in the simulation view on top of the map of the Otto Karhi park. The sensor node (SN) numbers are illustrated on the left, and the corresponding sensors at the ends of the path are also pointed out in the simulation view. Path lights (LN) are shown inside the dashed rectangle, with numbering starting from the bottom. Other light grey circles represent the tree lights (medium circle) and the 3000K LEDs with street light optics (large circle).
ILLUSTRATION:
TONI ÖSTERLUND AND HENRIKA PIHLAJANIEMI

A control node (CN1) is created and connected to the first sensor node (SN1). It triggers the sensor to emit agents into the network on the first layer (L1). A corresponding control node (CN2) is created and connected to the last sensor node (SN6), and defined to emit agents on the second layer (L2). Besides the end sensors, four motion sensors are located along the path with approximately equal intervals. Each corresponding sensor node is connected to four or five nearby light nodes. Both control nodes

(CN1 and CN2) are then connected to the four middle sensor nodes (SN2–SN5), and the amount of agents emitted per timeframe is set (see Figure 12). When an agent is emitted from the sensor, it randomly selects the pathway and then continues along the previously defined topology of the path lights. Agents are generated on both existing layers, so they can travel in both directions along the path.

The agent family (F1) properties (see Figure 10) are defined and tested in an iterative process of modifying the parameters and then simulating the results. Park visitors' movement is simulated using the mouse cursor. The light colour used is defined as warm white (3000K) by setting the colour parameter of the agents' family to RGB 255,240,110.

The simulated effect of the agents' movement in the network topology, emerge as a slowly altering, growing and diminishing swarm of light dots which gently follow the park visitor along the path. The patterns brighten and dim in a random rhythm in a pleasant pace and gradually fade away behind the visitor.

5.3 Designing tree lighting and colour effects

The next step is to configure the RGB-spot luminaires to illuminate the trees along the path, while the visitor enters the park. The first and last sensor nodes are linked to each tree luminaire node along the path, and bidirectional movement on the links is allowed. In order to "spill" some of the path lighting onto the trees, additional links are defined from some of the path lights to the tree lights. New control nodes (CN3 and CN4) are created and defined to emit agents on the existing layers 1 (CN3) and 2 (CN4). Their agent family (F2) is set to be different from the previously defined agents for other parameters except colour, which is still warm white. These control nodes are then connected to the sensor nodes linked to the tree luminaires (CN3 > SN1 and CN4 > SN6).

For some added interest and colour effect, which would draw the park visitors' attention towards the beautiful trees and shrubs nearby, a new control node (CN5) is connected to the four middle sensors (S2–S5). CN5 emits (see Figure 13) agents of magenta colour RGB 255,0,200 by defining a new family type (F3). The agents are emitted on a new layer (L3). The sensor nodes are connected to the tree and shrub light nodes, with some added links between them. All the defined links are opened as bidirectional on each three layers. In this approach, the tree and shrub lights will get illuminated with the magenta tone, and will occasionally fade to pink and warm white as F1 and F2 agents (coloured warm white) will access these links.

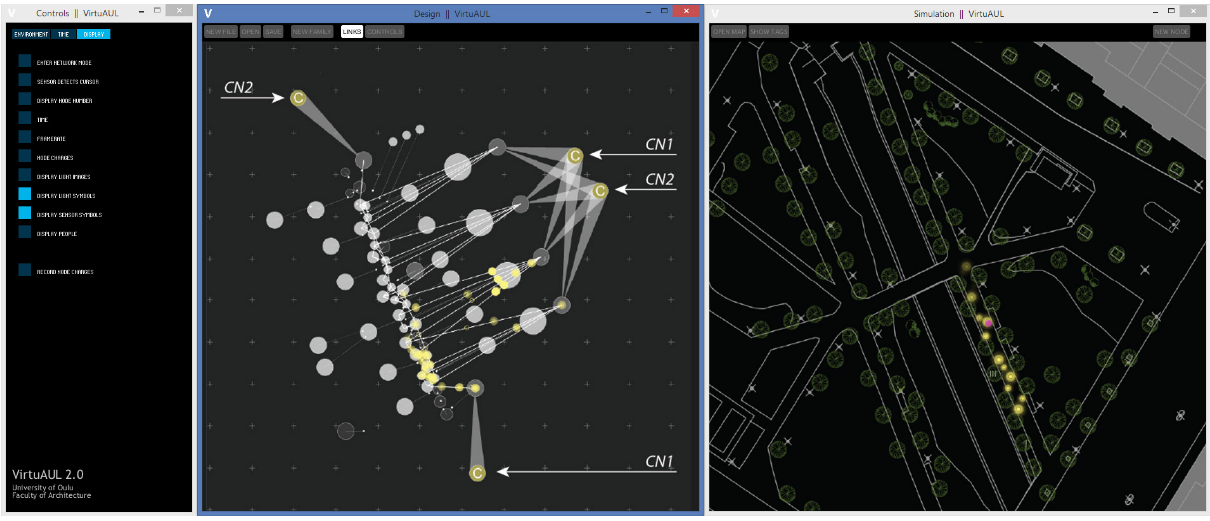


Figure 12.
The design view shows how the network-based agent system is visualised to the designer as it is simulated. The colourful agents move within the defined network topology. For readability purposes of the figure, multiple instances of the control nodes (CN1 and CN2) are created.
ILLUSTRATION:
TONI ÖSTERLUND AND HENRIKA PIHLAJANIEMI

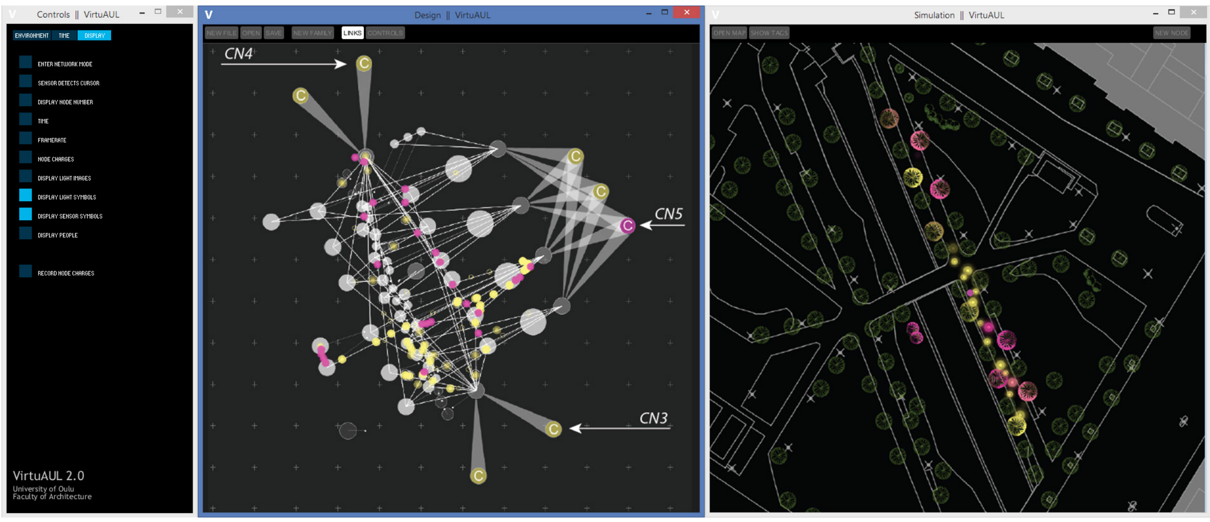


Figure 13
The entire designed scenario with all the control nodes and links. Simulation in progress.
ILLUSTRATION:
TONI ÖSTERLUND AND HENRIKA PIHLAJANIEMI

Finally, to let the colour effect flow into the trees along the path and on the path's surface, some bidirectional links for layer 3 agents are added between the middle sensors (S2–S5) and tree lights. Additionally, a selection of existing links from sensor nodes to light nodes on the path, as well as between the path light nodes, are opened to layer 3 agents' bidirectional movement. The visual appearance of the depicted scenario in the real world can be seen in Figure 14.

6 Discussion

We have presented a novel way to control and design adaptive lighting implementing the VirtuAUL design framework and, more specifically, the network-based agents methodology. The design methodology allows the design of adaptive, interactive and intelligent lighting processes with a graphical design tool. The adaptation process and corresponding flow of light is based on the movement of computational agents within a virtual designer-defined network. The users of the environment interact with the adaptive lighting system implicitly, through the system that senses movement and locations. The ambient intelligence of the artificial lighting environment is connected to the artistic aspirations of the lighting designer in creating visually aesthetic and experiential lighting.

The design framework was developed through the iterative design process of two real-world adaptive lighting installations. The resulting design and control elements were defined and gradually refined based on conceived lighting scenarios and their functional needs. The various design elements, their functionalities and parameters rose from this process and from the influence they would have on the resulting lighting solution. In the network-based agents methodology light is not considered as part of the model, but more as the end result of the process. The methodology serves the purpose of controlling the agents' movement and parameters in the network, as the lighting patterns are the emergent result of it. The visualisation of the process and its simulation are crucial and reveal the connection between the two.

The graphical design method, its visualisation and simulation, allows for the intuitive and fast design exploration of different behaviour of flowing agents, instead of hard to describe and hard to control coding of algorithmic processes. The adaptive process is both constructed and evaluated visually, and although it differs a lot from textual programming, it still requires the designer to conceive and create complex processes. As light is considered as energy flows from sensor to luminaire, or from luminaire to luminaire, the design process depends heavily on the visual representation of the process.

The simulation of the system's functionality within the design tool does not thrive for a physically accurate simulation, but it is used to convey the visual appearance of dynamic lighting. This is necessary for the designer in order to understand how the design parameters affect the lighting behaviour. For the simulation to functionally correspond with the real-world lighting process, the luminaires' and sensors' properties have to be accurately modelled in the design tool. If the properties do not match, for instance in the case of the sensing area, it might cause unexpected results in the real-world functionality.

The VirtuAUL controller software that runs the lighting scenarios in the real world can be implemented in off-the-shelf hardware controllers. It can readily be implemented in existing lighting infrastructures, assuming that the intensities and colours of the lights can be controlled dynamically. The centralised control approach has its limitations in scalability and for the amount of system components that it can effectively handle. Firstly, as every component has to be explicitly connected and programmed to function as part of the lighting scenario, the larger the system becomes, the more complex it becomes to define the design. Secondly, the process is computed in discrete time steps, where each change in system state takes some time to compute. Multitudes of sensors and lights mean increased computing time, which may prove to be a bottleneck in the currently available commercial lighting controllers.

As users interact implicitly through movement, which is translated as dynamic lighting patterns based on the designed scenario, the perceived feeling of control is greatly influenced by the level of "predictability", or how nonlinear the designed adaptive scenario is. In addition, when sensor stimuli affect luminaires at longer distances, or there are multiple users simultaneously, the lighting patterns might be conceived as random by the user, although the designed process would otherwise be very linearly logical (Pihlajaniemi, et al., 2014a). Due to the somewhat stochastic nature of the computation model, nonlinear lighting patterns are easier to define. Agents can take different routes through the network; the amount of possible pathways is determined by the connectivity of the network and by the agent's path selection behaviour. In order to achieve greater correlation between the design parameters and the system's behaviour in more linearly logical designs, restriction methods were specifically implemented in the system. The restriction methods include differentiated link layers, definition of the link directionality and the possibility to determine various path selection behaviours. By restricting the nonlinearity of the system, and thus limiting the number of possible outcomes, the emerging lighting patterns will always be the same, as long as similar (within some range) initial conditions apply.

The developed VirtuAUL design framework allows a designer to implement creative design intentions and aesthetic values into AmI lighting environments. The addition of emergent and nonlinear design elements adds to the playfulness of the light, but it still allows the design of linearly logical, functional and sustainable lighting. Several different types of lighting scenarios were developed for the Urban Echoes installation, with varying degree of nonlinearity. The design framework can be used in exploring the delicate balance between the artistic aspirations of the designer and the need for functional lighting.

Figure 14
The depicted scenario displayed in the real world.
PHOTO: HENRIKA PIHLAJANIEMI

Acknowledgements

The research has been carried out in the University of Oulu, Faculty of Architecture, as part of the *Adaptive Urban Lighting – Algorithm-Aided Lighting Design* (AUL) research project (2011–2013) led by D.Sc. (Tech.) Aulikki Herneoja. The AUL project was mainly funded by the Academy of Finland. The VirtuAUL design framework was developed in the project by the authors. The doctoral research of author Toni Österlund is funded by the University of Oulu Graduate School (UniOGS). We would like to thank all collaborators and sponsors of the Urban Echoes demo.

Aarts, E.H.L and Encarnação, J.L., 2006. *True visions: The emergence of ambient intelligence*. Berlin Heidelberg: Springer-Verlag.

Ahlquist, S. and Menges, A., 2011. Introduction: Computational design thinking. In: S. Ahlquist and A. Menges, eds. 2011. *Computational design thinking*. Padstow, Cornwall: John Wiley & Sons. pp.10–29.

Bandini, S., Bodomi, A., Vizzari, G. and Acconci, V., 2009. A CA-based self-organizing environment: A configurable adaptive illumination facility. In: V. Malyshkin, ed. 2009. *PaCt 2009, LNCS 5698*. Berlin, Heidelberg: Springer. pp.153–167.

Bandini, S., Bodomi, A., Vizzari, G. and Acconci, V., 2011. CA-based self-organizing environments – The case of a configurable adaptive illumination facility. *Journal of Supercomputing*, 57(2), pp.109–120.

Bandini, S., Manzoni, S. and Simone, C., 2002. Dealing with space in multiagent systems: a model for situated MAS. In: *Proceedings of the first international joint conference on Autonomous agents and multiagent systems: part 3 (AAMAS '02)*. Bologna, Italy, July 15–19, 2002. New York: ACM. pp.1183–1190.

Bullinger, H.J., 2006. Foreword. In: E.H.L. Aarts and J.L. Encarnação, eds. 2006. *True visions: The emergence of ambient intelligence*. Berlin Heidelberg: Springer-Verlag. pp.V–VI.

Ceriotti, M., Corrà, M., D'Orazio, L., Doriquzzi, R., Facchin, D., Guna, S.T., Jesi, G.P., Lo, C.R., Mottola, L., Murphy, A.L., et al., 2011. Is there light at the ends of the tunnel? Wireless sensor networks for adaptive lighting in road tunnels. In: *Information Processing in Sensor Networks (IPSN), 2011 10th International Conference*. April 12–14, 2011, Chicago, IL, USA. pp.187–198.

Cook, D.J., Augusto, J.C. and Jakkula, V.R., 2009. Ambient intelligence: Technologies, applications, and opportunities. *Pervasive and Mobile Computing*, 5(4), pp.277–298.

Davis, D. and Peters, B., 2013. Design ecosystems: Customising the architectural design environment with software plug-ins. *Architectural Design*, 83(2), pp.124–131.

Dugar, A.M., Donn, M.R. and Marshall, S., 2012. Designing tangible lighting control interfaces. *LEUKOS*, 8(3), pp.215–228.

van Essen, H., Offermans, S. and Eggen, B., 2012. Exploring the role of autonomous system behavior in lighting control. In: *DIS 2012, Workshop on Designing Interactive Lighting*. June 11, 2012, Newcastle Upon Tyne, UK.

Ferber, J. and Müller, J.-P., 1996. Influences and reaction: a model of situated multiagent systems. In: *Proceedings of Second International Conference on Multi-Agent Systems (ICMAS-96)*. December 9–13, 1996, Kyoto, Japan. California: AAAI Press. pp.72–79.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P. and Trow M., 1994. *The new production of knowledge. The dynamics of science and research in contemporary societies*. London: Sage Publications.

Groat, L.N. and Wang, D., 2013. *Architectural research methods*. Second edition. New Jersey, USA: John Wiley & Sons.

Haans, A. and de Kort, Y.A., 2012. Light distribution in dynamic street lighting: Two experimental studies on its effects on perceived safety, prospect, concealment, and escape. *Journal of Environmental Psychology*, 32(4), pp.342–352.

Hakulinen, J., Turunen, M. and Heimonen, T., 2013. Spatial control framework for interactive lighting. In: *Proceedings of International Conference on Making Sense of Converging Media (AcademicMindTrek '13)*. Tampere, Finland, October 01–04, 2013. New York: ACM. pp.59–66.

Hughes, R.F. and Dhannu, S.S., 2008. Substantial energy savings through adaptive lighting. In: *Electric Power Conference, 2008. EPEC 2008. IEEE Canada*. pp.1–4.

Jennings, N.R., Sycara, K. and Wooldridge, M., 1998. A roadmap of agent research and development. *Autonomous agents and multi-agent systems*, 1(1), pp.7–38.

Karamouzi, A., Papalexopoulos, D., Stavridou, A., Tzimopoulou, S. and Varoudis, T., 2013. DLD, Dynamic Lighting Design: Parametric interactive lighting software in urban public space. In: *9th International Conference on Intelligent Environments (IE13)*, Athens, Greece, July 18–19, 2013. pp.71–76.

Lau, S.P., Merrett, G.V. and White, N.M., 2013. Energy-efficient street lighting through embedded adaptive intelligence. In: *International Conference on Advanced Logistics and Transport (ICALT 2013)*. Sousse, Tunisia, May 29–31, 2013. pp.53–58.

Lighting Design Collective, 2011. Silo 468. [online] Available at: <http://www.ldcol.com/286/silo-468/> [Accessed August 18, 2016].

Luusua, A., Pihlajaniemi, H., and Ylipulli, J., 2016. Northern urban lights: Emplaced experiences of urban lighting as digital augmentation. In: N.S. Dalton, H. Schnädelbach, M. Wiberg and T. Varoudis, eds. 2016. *Architecture and interaction: Human computer interaction in space and place*. Switzerland: Springer. pp.275–297.

Macal, C.M. and North, M.J., 2009. Agent-based modelling and simulation. In: M.D. Rossetti, R.R. Hill, A. Dunkin and R.G. Ingalls, eds. 2009. *Proceedings of the 2009 Winter Simulation Conference – Wsc 2009*. December 13–16, 2009, Austin, TX, USA. pp.86–98.

Magielse, R., 2014. *Designing for adaptive lighting environments: embracing complexity in designing for systems*. [pdf] Eindhoven: Technische Universiteit Eindhoven. Available at: ‹http://alexandria.tue.nl/extra2/771846.pdf›.

McCullough, M., 2004. *Digital ground*. Cambridge, Mass.: The MIT Press.

Miller, L.E., 2001. Catalog of network connectivity models. [online] Available at: ‹http://w3.antd.nist.gov/wctg/netanal/netanal_netmodels.html› [Accessed October 24, 2014].

Mitchell, M., 2009. *Complexity: A guided tour*. New York: Oxford University Press.

Offermans, S., van Essen, H. and Eggen, B., 2013. Exploring a hybrid control approach for enhanced user experience of interactive lighting. In: *Proceedings of the 27th International BCS Human Computer Interaction Conference*. London, UK, September 09–13, 2013. Swindon: BCS Learning & Development. pp.1:1–1:9.

Offermans, S., van Essen, H. and Eggen, J., 2014. User interaction with everyday lighting systems. *Personal and Ubiquitous Computing*, 18, pp.1–21.

Pihlajaniemi, H., Österlund, T., Luusua, A. and Tanska, T., 2012. Light-Stories: Designing and Evaluating Interactive and Participatory Urban Lighting. In: *DIS 2012, Workshop on Designing Interactive Lighting*. June 11, 2012, Newcastle Upon Tyne, UK.

Pihlajaniemi, H., Österlund, T. and Herneoja, A., 2013. Towards adaptive urban lighting. In: A. Herneoja, H. Hirviniemi, S. Hirvonen-Kantola, A. Joutsiniemi, A. Luusua, R. Mäntysalo, A. Niskanen, K. Niskasaari, H. Pihlajaniemi, E. Rönkkö, A. Soikkeli, L. Soudunsaari, R. Suikkari and K. Tolonen, eds. 2013. *Proceedings of the 3rd Symposium of Architectural Research 2011: Research & Praxis (Arkkitehtuuritutkimuksen päivät 2011: tutkimus ja käytäntö)*. Publications A58. Oulu: University of Oulu. pp.164–180.

Pihlajaniemi, H., Österlund, T. and Herneoja, A. 2014. Urban echoes: adaptive and communicative urban lighting in the virtual and the real. In: *Proceedings of the 2nd Media Architecture Biennale Conference: World Cities*. Aarhus, Denmark, November 19–22, 2014. New York: ACM. pp.48–57.

Pihlajaniemi, H., Luusua, A., Markkanen, P., Herneoja, A. and Pentikäinen, V., 2014a. Experiencing adaptive retail lighting in a real-world pilot. In: *Proceedings of Experiencing Light 2014, International Conference on the effects of Light on Wellbeing*. November 10–11, Eindhoven, The Netherlands. pp.90–93.

Pihlajaniemi, H., Luusua, A., Markkanen, P., Österlund, T., Herneoja, A., Pentikäinen, V. & Sarjanoja, E., 2014b. Implicit interactions of intelligent lighting in a retail space. In: *Position paper for the workshop Beyond the Switch: Explicit and Implicit Interaction with Light in NordiCHI 2014 conference, 26 October, Helsinki, Finland.*

Pihlajaniemi, H., 2016. *Designing and experiencing adaptive lighting. Case studies with adaptation, interaction and participation*. Doctoral dissertation. University of Oulu Graduate School; University of Oulu, Oulu School of Architecture.

Poulsen, E.S., Morrison, A., Andersen, H.J. and Jensen, O.B., 2013. Responsive lighting: the city becomes alive. In: *Proceedings of the 15th international conference on Human-computer interaction with mobile devices and services*. Munich, Germany, August 27–30, 2013. New York: ACM. pp. 217–226.

Rao, S.A.B., Ozcelebi, T., van den Heuvel, M., Verhoeven, R. and Lukkien J.J., 2012. Dependable partitioning for autonomous agents in adaptive lighting environments. In: *IEEE International Conference on Consumer Electronics (ICCE)*. January 13–16, 2012, Las Vegas, NV, USA. pp.435–436.

Röcker, C., Kasugai, K., Plewe, D., Takashi, K. and Lugmayr, A., 2012. Aesthetic intelligence: The role of design in ambient intelligence. In: F. Paternò, B. De Ruyter, P. Markopoulos, E. van Loenen and K. Luyten, eds. 2012. *Ambient intelligence. Third International Joint Conference, AmI 2012, Pisa, Italy, November 13–15, 2012. Proceedings*. Berling: Springer. pp.445–446.

Schmidt, A., 2000. Implicit human computer interaction through context. *Personal technologies*, 4(2–3), pp.191–199.

Shadbolt, N., 2003. Ambient intelligence. *IEEE Intelligent Systems*, 18(4), pp.2–3.

Siddiqui, A.A., Ahmad, A.W., Yang, H.K and Lee, C., 2012. ZigBee based energy efficient outdoor lighting control system. In: *14th International Conference on Advanced Communication Technology (ICACT).* February 19–22, 2012, Pyeong Chang, Korea (South). pp.916–919.

Terzidis, K., 2006. *Algorithmic architecture*. Burlington, MA: Architectural Press.

Thomsen, B.S., 2009. *Performative environments.* [pdf] Aalborg University. Available at: <http://vbn.aau.dk/files/19929583/Bo_Stjerne_PhD_Performative_Environments_distribute.pdf> [Accessed August 1, 2013].

Verbeek, P.P., 2010. *What things do: Philosophical reflections on technology, agency, and design*. Pennsylvania: Penn State University Press.

Weiser, M., 1991. The computer for the 21st century. *Scientific American*, 265(3), pp.94–104.

Yeh, L.-W., Lu, C.-Y., Kou, C.-W., Tseng, Y.-C and Yi, C.-W., 2010. Autonomous light control by wireless sensor and actuator networks. *Sensors Journal, IEEE*, 10(6), pp.1029–1041.

Österlund, T., 2013. Design possibilities of emergent algorithms for adaptive lighting system. *Nordic Journal of Architectural Research*, 25(1), pp.159–184.

Österlund, T. and Pihlajaniemi, H., 2015. VirtuAUL – A design framework for adaptive lighting. In: B. Martens, G. Wurzer, T. Grasl, W.E. Lorenz and R. Schaffranek, eds. 2015. *Real time – Proceedings of the 33rd eCAADe Conference – Volume 1, Vienna University of Technology*. Vienna, Austria, 16–18, September 2015. pp.201–210. Available at: <http://papers.cumincad.org/cgi-bin/works/Show?ecaade2015_59>.

Österlund, T. and Pihlajaniemi, H., 2016. *Menetelmä mukautuvan ja älykkään valaistuksen ohjaukseen ja suunnitteluun*. Finland. Pat. FI125861B.

Biographical information

Toni Österlund
Oulu School of Architecture,
University of Oulu
Address: P.O. Box 4100, 90014 University of Oulu, Finland
E-mail:
toni.osterlund@oulu.fi
toni.osterlund@geometria.fi

Architect (M.Sc) Toni Österlund has been teaching courses and workshops in algorithm-aided architectural design at schools of architecture at University of Oulu, Tampere University of Technology and the Aalto University in Helsinki between the years 2008-2016. He worked as researcher in "Adaptive Urban Lighting – Algorithm Aided Lighting Design" project during years 2011-2013 He is currently finishing his Ph.D. in architecture at the University of Oulu, titled "Designing and Controlling Adaptive Lighting". Österlund has held international lectures and workshops for architects, designers, engineers and mathematicians on algorithmic design. He is a partner in Geometria Architecture Ltd, an office for architectural design, which specialized in realizing complex architectural structures and forms. Österlund was awarded the 2012 Pietilä Award (Lundén&Österlund) in recognition of the work done in reforming Finnish architecture, and the 2014 Bryggman prize by the Finnish Association of Architects (SAFA).

Biographical information

Henrika Pihlajaniemi
Oulu School of Architecture, University of Oulu
Address: P.O. Box 4100, 90014 University of Oulu, Finland
Phone: +358407089865
E-mail: henrika.pihlajaniemi@oulu.fi

Architect (M.Sc.), D.Sc. (Tech), lighting designer and researcher Henrika Pihlajaniemi (née Ojala) lectures and teaches Architectural Lighting in the Oulu School of Architecture, University of Oulu. She had a leading role in establishing architectural lighting education in the curricula in 2003. She worked during years 1999–2005 in the University of Oulu, Department of Architecture as project leader and researcher in several research projects concerning daylighting, housing façades and participatory design. During years 2011–2013, she worked as researcher in "Adaptive Urban Lighting – Algorithm Aided Lighting Design" project. In 2016, she defended her doctoral thesis "Designing and experiencing adaptive lighting – Case studies with adaptation, interaction and participation". Currently, she is leading "SenCity – Intelligent lighting as a service platform for innovative cities" research project in Oulu School of Architecture. Additionally, she works as lighting design consultant in her architectural office (M3 Architects). Her completed lighting projects include intelligent and adaptive lighting, urban lighting (e.g. Lighting Masterplan for the City of Oulu, 2010), public buildings (Church of St. Andrew, 2004), dwellings, light art and luminaires. She and M3 Architects have received numerous prizes in national and international architectural and urban design competitions, and the office was nominated for the Iakov Chernikhov International Prize 2012.