Bio-Modules

Cyber-physical modular responsive variations for dark urban areas using bio-degradable materials

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This paper documents the design and fabrication process of modular responsive lighting installation. The design and research led to a modular and transformable urban lighting concept, combining unique material behaviour and cyber-physical system. The main goal was to investigate how material characteristics, composition and performance could be programmed in order to generate a range of modular components. Modular tiles and joints combination designed of sustainable materials - bioplastics and cork sheets - were created and used together with number of sensors and micro-controllers. Furthermore, the installation concept links technical and psychological aspects that potentially could be used for the benefits of city dwellers. Paper consists of two parts. First part is the introduction of a broader urban night lighting design context to which the project belongs. This includes covering existing social issues related to urban darkness, as well as the need to increase biodiversity within built environment, through introducing new materials. The second part of the paper describes the design and fabrication process, that employs the conclusions discovered in the first part through set of material experimentations, design project and the reflections on the results.

Keywords: *modularity, material behavior, lighting installation, cyber-physical systems, perception*

PART I

The urban lighting design narrative

Project 'bio-modules' negotiates the dynamic relationship between darkness and urban environment; a seemingly urban barrier, that often shapes the behaviour and perception of a person in space. This urban barrier is often affected by personal experiences, cultural traditions, technological, environmental and climate factors *(Stone, 2017)*. The redefining of a healthy human-nature relationship is pursued by the proposed design.

The presented urban lighting concept spans a wide range of material experimentations, involving both physical material and digital feedback systems while tackling a phenomenal obstacle of urban darkness. Term "urban darkness" in this paper context is defined as a lighting condition in an urban environment of insufficient or non-existent light sources. Through interactive setting, it speculates on reciprocal relationships between users, cyber-physical systems and space. The five previously mentioned factors have direct consequences on each other, affecting reactions, sensations and occupational behaviour.

Subject, passing through the installation, is exposed to a situation that allows the comparison of its personal and prior subject's engagement with darkness, which overall can result in a more inclusive urban lighting design methodology. Light is the leading source, acting as a signal for someone to follow.

The broader field of research examines how a responsive modular lighting intervention, set in the urban environment, can be turned into a self-reflexive system, that questions the relationship between urban darkness and personal perception. Urban lighting interventions, especially in big cities, have led to the symbolic connection of night-time lighting to safety and security *(Schlor 1998)*.

Current urban situation and the problem of light

Two aspects are increasingly subject of debate in the (re)design and planning of urban environments; a) darkness, which can trigger crime, b) the necessity to use bio-degradable and sustainable materials in the construction of buildings and urban furniture.

The uninterrupted supply of light is the current rule, turning the non-illuminated points of cities into rarely ever visited places *(Dunn, 2016)*. This no-filtered light supply is increasing the demand of urban light sources, in as many areas as possible, and defines whether a place is "accessible" or not. In a very simplified way, we could say that darkness is mapped with danger or crime and light with safety *(Raynham, 2019)*. Fear of the dark is arguably an innate human quality, that has led to the evanescence of a variety of qualities of urban darkness in the cities *(Ekirch, 2005)*.

Apart from humans, other organisms that we share the city with, react to light, therefore, designing urban light should not only be approached through its human functional necessities but also through understanding it as a complex system with multiple actors *(Eisenbeis, 2006)*. The uninterrupted presence of light suppresses nature's fluctuations, disturbs the biorhythms while causing light pollution in the surrounding areas. Darkness acts as an important factor for nature's biological processes, required from living organisms physiologically and psychologically. Thus, the presence of light within the urban realm should be linked with its transient necessity and sensitive approach towards required luminosity *(Stone, 2018)*.

This means that the environmental impact of used materials, light intensity, distribution in space, circadian rhythms must be taken into consideration. Urban light and dark reaches beyond functional urban life needs. Alongside the physical need of light presence for the human eye, night-time lighting is strongly connected to psychological means, evaluating one's relationship with urban darkness. Light provides a notion of extended productive daytime, safety and exposure, whereas darkness, on the other hand, can mask various activities, identities or intentions. Furthermore, current city lighting systems are designed without sufficient variation in design, materiality, mobility and have to go through major transformations to fit in with trending smart city movement *(Pihlajaniemi, Österlund and Herneoja, 2013)*.

Even though new urban lighting installations or interventions are created and proposed, there is a tendency of fragmentation, small scale or implementation methods that often require advanced and complex technologies or fabrication. Cases where urban lighting design process would contribute to a circular economy, involve material behaviour and perception are even rarer.

One example is the project 'Get Home Safely' in Jätkäsaari district, Helsinki *[6]*. Here a modular temporary intelligent lighting system is installed in dark urban environments, where no permanent light is installed (e.g., construction of housing quarters, events). The light enables citizens to feel more secure and simultaneously adjusts to nature working as a responsive cyber-physical system.

Current urban environment context requires an interactive and responsive urban lighting design, which considers sustainability, materiality and human interaction. A comprehensive approach to the sustainable urban design used in this project addresses issues affecting safety and social well-being, as well as growing need to employ alternative, biodegradable materials in the pursuit of a more sustainable built environment.

PART II

Methodology. Utilizing Material Behaviour in Design and Fabrication
Step 1. Physical
Assembly geometry variations and distribution in space.

This design step consists of two sets of modular elements. Various free-form assemblies are possible between them - from individual objects to extensive surfaces. Extensive surfaces are suggested to cover long linear distances like sidewalks or fences, while individual objects are preferred when it is important not to obstruct natural setting with an emphasis on compactness. Therefore, as it comes to the selected area for the installation, a set of free-form modular objects were chosen, since it can be independently distributed in space. *Figure 1.* shows one individual lighting object entity.

The mentioned two assembly elements, as seen in the *Figure 1.*, are tiles and joints. Using parametric design tools *[1]*, more variations for each component were created. The average size of tiles varies from 20.0 to 25.0 centimetres, depending on the final deformation. Joint size is 7.0 by 7.0 centimetres. In total 50 pieces of tiles and 15 joints were produced for this project.

Figure 1
Individual lighting object

FRAME MATERIAL	THICKNESS	BENDABILITY	ABSORBABILITY
foam - (white) moosgummi	3mm	■■■□	■■■□
foam - (gray) moosgummi	2mm	■■■□	■■■□
rubber(black)	2mm	■■■■	■□□□
sylicon	3mm	■■■■	□□□□
natural cork buffed	3mm	■■□□	■■■■
natural cork buffed	2mm	■◧□□	■■■■

Figure 2
Frame material evaluation

Material choice and fabrication.

Through material investigation bioplastic infill in a cork frame were chosen as final materials for the tile component. Decision parameter for the choice of material was that both materials are biodegradable and easily accessible. *Figure 2.* shows the set of materials tested for the frame and its evaluation.

CORK. Cork is a renewable material that has a long history of sustainable industrial use, maintaining balanced ecological conservation and development *(Pereira, 2011)*. It is obtained from the cork oak tree (Quercus suber L.). Cork bar is composed of honeycomb structured cells, that are five folded - attribut-

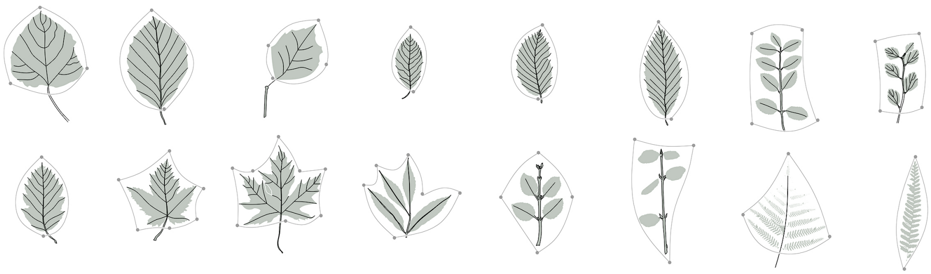


Figure 3
Nature driven inspiration for tile geometry

ing elasticity to the material- and allow it to recover its original shape when compressed. Furthermore, cells are filled mainly with gas making it extremely lightweight material *(Carther & Doran, 2013)*. Properties like bendability, compressibility, lightweight and possibility to recycle *(Pereira, 2011)* make it a good option for tile's frame when taking into consideration deformation caused by bioplastic and assembly's created loads. As a final product, 3 mm cork sheets were used to laser cut the frame variations.

The frame geometry investigations initially started by trying to resemble nature-like forms, taking inspiration from tree leaves. *Figure 3.* shows the simplified leaves geometry variations.

After comparing and analysing their former and final state we chose one according to on our preference. Then it was further developed, using parametric design tools, resulting in three variations, each having two, three or four connection points, as seen in *Figure 4.*

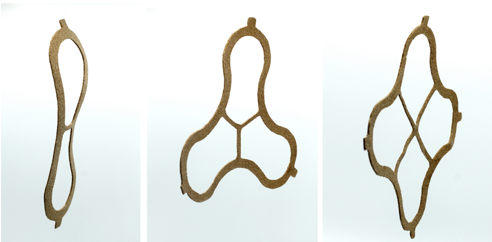


Figure 4
Frame geometry variations

It should be mentioned, that although the cork frame performs well as it comes to its bendability, it is very vulnerable in breaking or ripping apart in certain geometries. Thus, resistance to breakage should be enhanced e.g. by applying bioplastic on its surface to strengthen it, as observed. In all cases, during the tile fabrication process, the surface on which frame is laid needs to be covered in soap detergent or oily liquid before pouring the bioplastic to reduce the stickiness.

BIOPLASTICS. As it comes to the bioplastic infill, different recipes, produced by a range of materials, were tested. Gelatine-based bioplastics fulfilled most desirable features, therefore, further testing and final material design focused on it *[4]*.

Gelatine-based bioplastic is a renewable material, based on biomass *(Mekonnena, et al., 2013)*. It consists of three main ingredients: gelatine (biopolymer for strength), glycerine (plasticizer for flexibility) and water (for solubility). While water is self-explanatory, it is useful to define gelatine's and glycerine's main characteristics and role in bioplastic production.

Gelatine is a biopolymer, that consists of protein polymer chains of amino acid monomers, commonly known as a by-product of the meat industry. However, gelatine production from other species and plants is gaining importance *(Gómez-Guillén, Pérez-Mateos, et al., 2009)*. Its high hydrophilic nature explains the tendency to swell or dissolve in high moisture content *(Neelam, et al., 2018)*.

Figure 5
Recipe evaluation

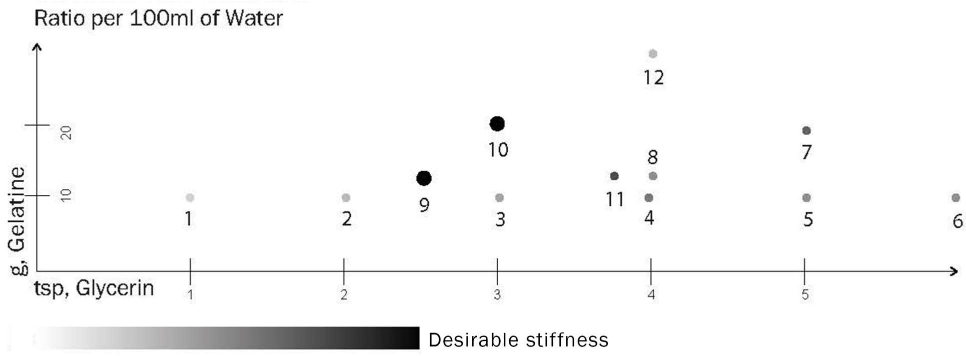
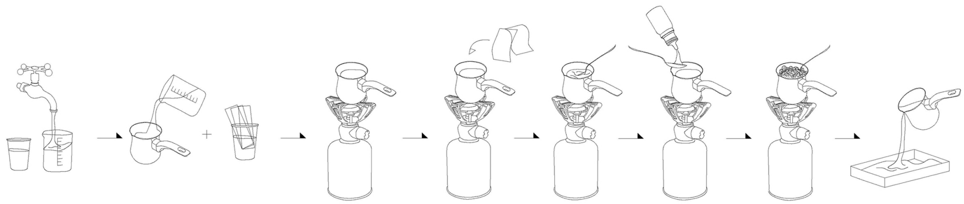


Figure 6
Bioplastic cooking process



Glycerine acts as a lubricant in bioplastic and makes the polymers within gelatine move easier. Glycerine is virtually nontoxic to human health and to the environment *(Gu, Jérôme, 2010)*. It is commonly used in food, chemistry and cosmetics industry *(Pagliaro, Rossi, 2008)*. In the recipe it controls the pliancy of the final-dehydrated material, varying from highly elastic to stiff.

Cooking bioplastics.

Preparation of bioplastic: gelatine powder/or sheets were purchased from a regular grocery shop, while glycerine was accessible in any pharmacy. When the water reached medium temperature on a stove, according to the chosen recipe, for every 100ml of water, a teaspoon of glycerine and 20 gr. of gelatine was poured in. The selected recipe was chosen after trials of different ingredient proportions, as seen in *Figure 5*. It is important to stir the substance evenly to avoid lumps until it becomes clear *(Neelam, et al., 2018)*. The procedure held out to cook bioplastic is pictured step by step in *Figure 6*.

Bioplastic was poured in the cork frames initially covering it with thin layer, waiting for 1-2 minutes for it to harden and seal the base from gaps and then pour the necessary thickness of bioplastic.

Ratio changes in the recipe result in different material properties. By changing the mentioned ratio between ingredients, we observed bioplastic turning brittle if too little glycerine was used, or sticky if too much. Bioplastic has inner structure depending on the way of stirring, pouring or blowing air in it.

We observed that gelatine-based bioplastic is moisture sensitive, which explains its ability to reabsorb water when exposed to a humid environment. When dehydrated, under any recipe, bioplastics tend to shrink, towards its geometric centre, causing spatial deformations. The inverse process occurs during re-hydration, where bioplastic swells again. During this process, it takes 1,5-2 hours for tile to get to its initial form. It can be repeated multiple times without major changes in infill structure. However, each geometry produced is unique and dependent on many factors, especially in our case study, where the frame-material has no shrinkage during the bioplastic dehydration process. Re-hydration of one deformed tile is shown in *Figure 7*.

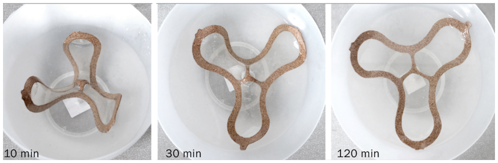


Figure 7
Re-hydration process

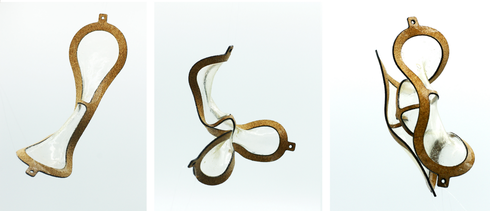


Figure 8
Tile geometry after dehydration

The material behaviour of bio-plastic can be programmable by changing the recipe and types of used bioplastics *(El-Gewely, at al., 2018)*. Thus, we chose to investigate its intelligence and deploy the material in the design project.

The relationship between bioplastic infill and cork frame resulted in three-dimensional deformation, when dehydrated. As a result, the frame bends following the tensions caused by shrinking infill material. After careful observation, we have distinguished a pattern of how each tile variation tends to deform. However, no further investigations were carried to analyse the conditions that cause one or another type of deformation. *Figure 8.* showcases one example of each geometry pattern, as it dehydrated.

Light carriers.

Joints were designed and fabricated using 3D printing *[3]*, making final details highly precise. Its role as "Light-carrier" became a design defining condition, since the LED has to be placed in it, as pictured in *Figure 9*. Joint geometry resulted in 3 different variations using parametric design tools. This allowed connecting two, three or four tiles together with one joint. Two pieces for each joint variation were 3D printed from semi-translucent PLA (polylactic acid). Filament choice provided with the desired level of translucency and light qualities. Components were assembled in free form using steel screws to ensure stiff fixture. Tiles were connected placing them in between two joint pieces.

Step 2. Implementing Sensorics

This design step is the one dealing with the significance of a person role when it interacts with the lighting installation. It was accomplished by using two ultrasonic sensors (HC-SR04) that detect objects by using ultrasound, Arduino micro-controller *[2]* and set of LEDs. The sensory assembly is pictured in Figure 10.

Through time difference between triggering each sensor that is placed at a certain distance from each other, an individual walking speed was captured with Arduino micro-controller. It was then used as a time module to control the LEDs in lighting objects, to light up and lead the passer-by in the speed of the prior one. The interaction was triggered every time when someone would pass by the installation.

An individual walking speed was chosen as a parameter to characterize passers-by relation with urban darkness due to the ability to capture it immediately on a selected site and respond in a form of light. It helped to receive interaction with a minimal delay. Therefore, the interaction with the cyber-physical system can be described as two-phase, involving two different individuals. In phase one the first passer-by is treated as an input source, in order to collect necessary information - walking speed. In phase two the following passer-by is challenged to

Figure 9
Joint detail drawing and assembly

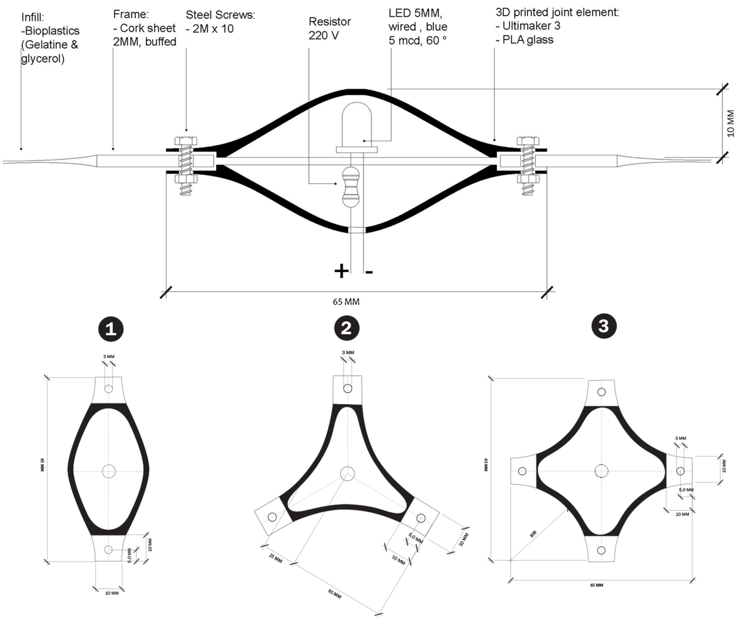
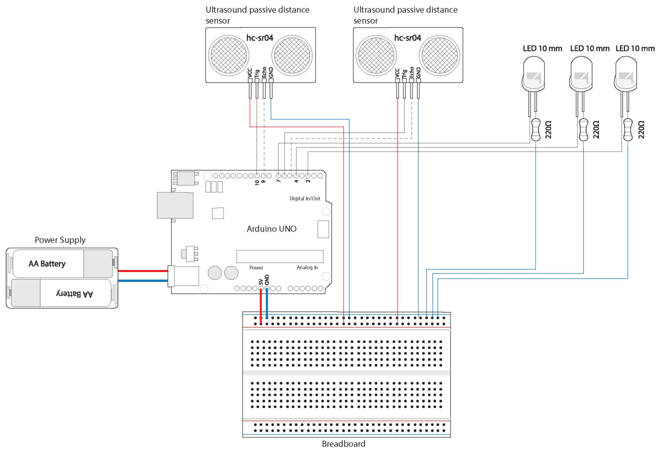


Figure 10
Sensory assembly



follow someone else's behaviour in space, by following the prior passers-by walking speed.

Figure 11. is a snapshot of the on site experiment process, held out in TU Berlin, as a small installation.

Figure 11
Installation on site

Experimentation results.

Experiments with materials, fabrication technology and digital communication systems have exposed our work to new urban lighting opportunities, that address not only physical but also emotional needs for urban lighting of cities and citizens.

In some cases, installation on site received additional attention from passers-by, making them stop or ask questions giving not completely precise input data. The distraction might have occurred because of installation visual look or uncommon lighting patterns. Therefore, in order to have precise data, some of the data that have abnormal walking features, like stopping, should be excluded.

However, it provided us with a set of walking speeds that could eventually become a database for different walking rhythms and could be used to define or characterize different areas in the city in terms of anxiety level or time of occupancy.

The modularity of the tiles and joints created a number of assembly possibilities, making the project easy to transform and adjust, off and on-site. However, the assembly was not flexible enough due to the design and number of connection points. This should be further investigated. Module scalability allowed easy fabrication, transport and manufacturing. The size of installation was limited to three lighting objects, covering the distance of only 3-4 meters due to the time needed for tiles to dehydrate.

Use of biodegradable materials like bioplastics and cork answers a necessity for environmentally friendly solutions in urban design. Bioplastic cooking can be made in lab-like as well as home-like environments, meaning, it does not require specific equipment. Some bioplastic tiles broke during the pealing process from the surface when it was not covered with soap detergent or oil. We also observed that if kept in water for more than 12 hours bioplastic tends to easily break or dissolve. That raised questions on its longevity and possible applications in outdoor conditions.

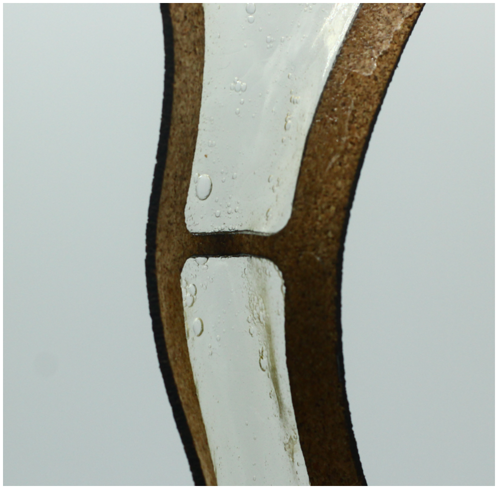


Figure 12
Inner infill structure

The quality of light was not analysed in this project. However, different light reflections on the ground were created, when going through semi-translucent bioplastic infill that has inner structure. *Figure 12.* depicts the effect of light on the material, making also visible its' inner structure.

CONCLUSION AND PROSPECTS

In this paper, we presented the design and fabrication process of a lightweight modular responsive lighting installation that links material behaviour, human perception of light and sensory interaction in an urban space. Material behaviour has shown us many of the unused possibilities of lighting furniture design. It makes us question the current urban lighting rules and trends.

A more sensitive approach to urban lighting was introduced, instead of providing a constant functional light, mediating it through human presence and perception. The main objective of this project was to expand urban lighting modularity and materiality characteristics and include perception into the interaction process, by triggering a subject's emotional state.

Despite the various advantages that bioplastics might have, like the reduction of CO_2 emissions, decreased dependency on fossil fuels, less toxic waste and enhanced properties, there is still a long way until they will be able to substitute petrochemical rivals in terms of manufacturing and practical use in urban design. On the other hand, cork is commonly used and has a long history of applications as a sustainable material.

Despite mentioned experiment results and observations, there is a lot of further investigations that need to be done, in order to clearly define how uses of material behaviour programming -as a part of the design- could redefine the city's relationship with urban darkness and foster biodiversity.

Multiple new hypotheses emerged during the project process leading to new research or experimentations. In order to better understand the subtle human relation with light and how the perception of individual passers-by towards the space and sense of safety changed with this installation, a further qualitative study made with survey should be done.

In order to test the effect of the prototype on an urban scale and to collect data, a greater number of lighting objects needs to be produced and applied in the city. Instead of walking pace, different sorts of data, like a heartbeat or mobile data could be used to define the way lighting objects are triggered.

Possible project prospect could be creating an application, with mapped personal routes and walking speeds that would be used to personalize urban lighting patterns.

Our installation bridges mind and body by including physical activity and mental processes, leading to a complete experience of the urban environment and its' inherent values. After all, urban equipment is a key to bring humankind closer to having a healthy relationship with the environment they live in.

Acknowledgment

We wish to thank Professor Raoul Bunschoten, CHORA Conscious City, chair of the department for Sustainable Urban Planning and Design, Institute of Architecture, Technical University of Berlin for supporting the research conducted. Research was co-funded by the European Union, H2020, EIT Digital 2019, Action Line 'Digital Cities', activity number 19053.

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