Delivering smart city system through experimental smart building concept. Design case of Nordhavn Community Centre, Denmark

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Abstract. It is an undisputed fact that the development of a city requires more energy to accommodate the needs of the city’s population. Greater energy consumption due to growing cities is a concern for scholars as well as governments all over the world. In the European Union, Denmark’s renewable energy policy provides tax exemptions for passive air conditioning and renewable energy sources to foster public participation. To meet its energy provision objectives under this condition, cities need instruments to reduce energy consumption. The building of a community centre in Nordhavn (Denmark) was chosen as such an instrument due to its flexibility and possible exposure to solar radiation as an endless source of energy. An experimental design for the building envelope was developed to test its thermal performance when including a thermal storage wall. Design research was conducted using 3D modelling. Testing was done on a simulation of the building made with the Ecotect software application to provide comparable results for thermal performance supported by qualitative-descriptive methods. It was concluded that including a thermal storage wall in the building model corresponds well with the objectives of the design. Based on the result of the test, in the context of, the thermal storage wall is capable of contributing to passive air conditioning.

1. Introduction
The advance and rapid changes in the modern built environment have made city development into a more demanding job for city planners, local government and related stakeholders. Not only in the practical realm; the smart city discourse is also evolving in theoretical frameworks. Although it is a relatively new concept, many scholars have defined the smart city in different areas and from different points of view. They generally agree that smart cities are created to facilitate urban dwellers’s needs in a more efficient manner. Calvillo et al. [1] further explain that the smart city is a medium to optimize urban resource allocation, particularly in energy provision, transportation and waste control. Another perspective can be seen from the use of ICT to connect certain urban services with indicators observed by users. Baron [2] states that the use of ICT has captivated the younger generations in modern society to engage with the smart city system, since almost all city systems are in their grip. These conditions, in fact, did not occur suddenly, according to Darwish [3]. The over-use of natural resources caused by conventional economic development has increased awareness of many scholars in terms of how to tackle this problem without compromising the needs of future generations. From this point of view, it can be seen that there is an ultimate goal in the utilization of smart city systems, starting from managing resources and simplifying monitoring processes to ensuring the needs of future generations.
As an urban area gradually expands, alterations in land-use in nearby territory – rural, hinterland, and water ecosystem – are evident. A variety of public amenities, easy access to vital transportation and proximity of workplaces persuade more people to migrate to locations with a higher standard of living. The socio-economic and political aspects embedded in a city make its development inevitable. Some people, especially low incomers, are forced to make a trade-off between their good quality of life in the hinterland and living and working in a city with the promise of a better subsistence. It is widely known that more than 50 per cent of the world’s population now lives in cities [4]. This massive number is projected to rise further in the following decades. Since natural resources are limited, the demands of public needs cannot be ignored, so urban management is certainly becoming a necessity. Some cities already encounter severe urban problems due to overcapacity. For example, the mega-region Jakarta and its satellite cities (together called Jabodetabek) is occupied by 31 million people\(^1\) in a total area of 6283.34 km\(^2\). Jabodetabek faces challenging problems in transportation due to traffic congestion, among others [5]. Such problems do not merely occur in developing countries; the developed world faces similar problems, yet with a different emphasis. Taking Denmark as an example, [6] points out the necessity of maintaining energy resources.

"The history of green Denmark lies in the oil crisis 1973-1974; Denmark was dependent on imported energy, and the pollution caused by fossil fuels was largely recognized. The need for more environmental policy raised and ever since renewable energy and energy efficiency have been the cornerstones of the Danish energy framework. In 2015, 49% of Denmark’s energy production came from crude oil and 23% from renewable energy. E.g. 67% of total production of electricity came from renewable energy sources. Over the next 10 years, the share of electricity production from renewables is expected to increase to around 82%.” [p. 6]

One of the solutions in Denmark is a energy policy providing tax exemptions for passive air conditioning and renewable energy sources to foster public participation. Responding to the Intergovernmental Panel on Climate Change (IPCC) in 2010, stating that the building sector contributes 32% and 19% to global energy use and GHG emissions respectively, it is no wonder that the Danish Government introduced an energy efficient building policy as a foundation for achieving the ultimate goal of reducing energy use and mitigating GHG emissions.

The aim of this paper is to present an experimental design for the building envelope of a community centre in Nordhavn (Denmark) in view of investigating whether it can used for reducing energy use by passive air conditioning. The design was developed based on analyses of the physical conditions of the location, microclimate conditions, building mass orientation, wind directions, landscaping and a thermal storage wall system. The configuration of the building mass, which reflects Nordhavn’s morphology, was attained by optimizing sunray exposure in winter, minimizing sunray exposure in summer, optimizing air circulation. To achieve optimum sunray exposure, normally, the longest side of the building is orientated to face south. However, this may lead to over-radiation in summer. Hence it was decided that the appropriate orientation is having the shortest side of the building face the south (in accordance with the solar path direction). In view of the wind, which is very useful in summer for cooling, the building mass was configured in a U-shape, so that more surface will be exposed to the wind. However, wind exposure should be avoided during the winter, which was done by arranging vegetation in the surroundings of the building envelope. Thermal testing of the design model was done, although only for a sector (the thermal storage wall area).

\(^1\)Obtained from BadanPengelolaTransportasiJabodetabek website (http://bptj.dephub.go.id/?p=1274 , reported on 27 Sept 2017)

\(^2\) Calculated from Central Bureau of Statistics (2017)
2. Methodology

2.1. Building model
A building model was designed for a location in Nordhavn, Denmark. Before examining the properties of the building envelope, a description of the location and a brief explanation and analysis of its physical conditions are provided.

2.1.1 Physical conditions
Copenhagen is the capital of Denmark, located in Northern Europe, close to Norway, Sweden and Germany. Copenhagen is part of the region of Oresund (Zealand, Lolland-Falster and Bornholm in Denmark and Scania in Sweden), which has 10 districts and where Nordhavn is one of the cities around Copenhagen.

The images above illustrate the current condition of Nordhavn for several physical aspects. According to figure 1, most of the built-up area is on the west side because the eastern side functions as an industrial area with a port and water activities. Thus, the city structure is varied in size and distribution. The location for the building model is at a fisherman settlement on the north side. Figure 2 shows the condition of the urban space. From this picture it can be seen that the urban structure is geometric with repetitive masses and spaces, which enables dynamic development. The distribution of green areas can be seen in figure 3. Most of these areas are designated as protected territory. On the other side, the pattern of urban space development is dominated by vertical and horizontal lines that cross each other and define the direction of the city’s structure as shown in figure 4. As a result of the larger development of the west side, traffic circulation also mainly occurs on that side, with crowded meeting points, both for motor vehicles and other means of transportation. Nodes and traffic circulation can be seen in figure 5. Meanwhile, the types of transportation are depicted in figure 6. Public transportation is quite varied, i.e. there are public buses, fast boats and in the future also water taxies.
2.1.2 Location and microclimate
The location of the building model is situated nearby a fisherman village and a new residential area. As for the microclimate aspect, Denmark has a temperate climate with temperatures ranging from –15 to 35 °C with most precipitation in the winter season, in the form of rain, fog and snow (Lohnert et al. [7]). For the region of Nordhavn, the winter season is from October to April with average temperature at 3.8 °C, followed by the spring season from May to June with an average temperature of 14.5 °C, while in the summer time the average temperature increases a little to around 15.1 °C. It decreases to 2 °C in the autumn [windfinder.com, 2014]. Apart from considering temperature, wind distribution also has to be taken into account. According to the Norwegian meteorological institute NRK [8], the wind mostly comes from a direction between west and northwest (11%). The second most prevailing wind directions are south and southwest (9% and 8%, respectively). Winds are considerably strong in the southern area of Nordhavn.

2.1.3 Building mass orientation
Because the designated location is situated in the northern hemisphere (latitude 55.71 and longitude 12.6), generally, the sun’s position in relation to the site is in the south. The specific sun positions at the location
were further examined using the Ecotect 2011 software application, considering critical days in summer (June 21) and winter (December 21). The result of the Ecotect analysis was as follows:

![Figure 10a](image1.png)  
**Figure 10a** Position of the sun on December 21 at 09.00 (figure 10a), 12.00 (figure 10b) and 15.00 (figure 10c).

From the data, it can be found that the location of the sun at 09.00 = 138°, at 12.00 = 173° and at 15.00 = 218°. The analysis of the sun’s position in winter is important for determining the orientation as well as the form of the building mass in relation to the use of a thermal storage wall system. This system works by capturing sunlight and passing it into the building. According to Branz [9] the optimal angle for the design of a thermal storage wall on the south is between 30° to the right and 30° to the left. This is also consistent with the result of the azimuth position at 150° and 210° from the analysis of the position of the sun. It shows that at an angle of 30° to the right and to the left represents the time when the sun is at its daily peak (around 12.00).

2.1.4 Wind

The wind tends to blow from the northwest, south and east, causing the southern part of the proposed site to get more wind (see figure 11). Figure 11 shows the wind rose projected on top of the site and the resulting wind patterns.

2.1.4 Landscape

Vegetation in the surroundings of the proposed site can act as protection against the weather (sun and wind). This depends on plant type, plant size, leaf splits, and growth conditions [7]. Which can be adapted to the design objectives. In summer, evergreen plants are able to provide total protection and produce cool areas around the building to make it more comfortable in summer, while molt type plants may serve as heat triggering agents around the building to conserve heat during winter. A similar idea has also been put forward by Pelsmaker in [10], in which she presents several scenarios for winter and summer and provides an overview of the positioning of plants around a building. Lochner et al. [7] further classifies different kinds of trees according to their ability to produce shadows in the winter time, as shown in figure 12.
The varying shading percentage (15-80%) indicates the trees’ capabilities to produce shadow. The plum tree is the plant that produces the most shadow (80%), while honey locust produces the least (15%). The calculations also depend on the height, extension and thickness of the plant branches.

2.1.6 Thermal Wall Storage
A thermal storage wall is a way of achieving passive air conditioning that utilizes the microclimate (sunshine, wind, and air). Wilson [11] explains that a heat storage wall, better known as thermal storage wall, is an indoor air conditioning technology that consists of glazing, air between glazing, and wall mass, ventilation, and extended roof (overhang). He describes the general workings of a thermal storage wall as follows: the glazing side receives heat from the sun, which is absorbed by dark-coloured masses (dark surfaces are able to absorb heat better); hot air enters into the room through an air inlet; cold air moves out of the room through vented wall mass, while conduction of air movement (direct) occurs on unvented wall mass.

There are two types of thermal storage walls: thermal storage walls with perforation (vented) and without perforation (unvented). Each type has advantages and disadvantages. According to Wilson [11], a vented thermal storage wall is more appropriate for rooms that are used in the morning and afternoon, because the indoor temperature is higher during the daytime and cooler at night. Thus, the resulting temperature is more varied than with an unvented thermal storage wall. An unvented thermal storage wall works based on the conduction properties of the system. Because there is no perforation in the system, the

**Figure 11a**

**Figure 11b**

**Figures 11.** Wind orientation on the proposed site. Figure 11a demonstrates the wind distribution, while figure 11b shows the main directions of wind.

**Figure 12.** Types of plants/trees with varying ability to produce sunlight in winter [7]
temperature conditions are more stable. Thus, an unvented thermal storage wall is more appropriate for residential buildings.

The effect of a thermal storage wall also differs during the summer and the winter. In summer, Wilson [11] suggests, when the indoor temperature is too high, ventilation vents on the upper side of the wall mass should be closed, while vents on the lower side and in the glazing should remain open. To get cool air into the building, he suggests placing a window on the north side of the building, so there is an indoor breeze and indoor heat build-up can be reduced. Siliski [12] recommends the use of plants on the north side of the building to cool the air in summer. Siliski [12] also adds some benefits of ventilation during the night and on rainy days by adjusting the ventilation to the needs of the users. For the building model a vented thermal wall system was chosen, considering the static building purpose (community centre). It is incorporated in the building model by adding heat storage material in the form of brick/concrete partitions, so the heat can be absorbed during the day and released during the night. The vented thermal storage wall is equipped with ventilation on the north side. However, because of its location in the northern hemisphere, in summer the sun is higher and tends to cause excessive heat through the glazing. On the other hand, the benefits of a thermal storage wall are highly desirable in winter. When the sun warms the glazing on the outside, the air between the glazing and the wall mass expands and flows into the room through the upper and lower ventilation vents. During the night, all the ventilation vents, both inside and outside, should be closed to prevent warm air from going out of the room.

2.2 Synthesis of Building Mass Concept

The building mass concept of the building model was derived from the observations and analyses of its physical conditions in chapter 3. It contains among others: a building mass system that optimizes passive heating (in winter), minimizes passive heating (summer), optimizes wind cooling and air circulation, and reflects the morphology of Nordhavn city.

![Figure 13a Sun rays in winter](image)

![Figure 13b Sun rays in summer](image)

![Figure 13c Wind](image)
The configuration of the building changed during the design process. To maximize the utilization of sunlight in winter, the long side of a building mass should be oriented to the south. Thus, the surface area of the building will be exposed to more sunlight. However, the sun’s radiation may become excessive in summer, in which case the shortest sides of the building model face should south. Responding to the prevailing wind directions in view of wind cooling is useful in summer, therefore a U-shaped building mass configuration was considered. However, wind cooling should be avoided in winter due to the thermal discomfort caused by cold winds. A solution can be found in arranging vegetation around the building correspondingly.

In addition, the building mass configuration was also investigated in relation to the air circulation between the building components. The initial building mass configuration was designed with reference to the basic morphological form of Nordhavn city. The basic form was then transformed in response to the microclimate in an effort to obtain thermal comfort by utilizing sun, wind and vegetation. The resulting building mass configuration is shown in figure 14.

Based on consideration of heat radiation exposure in summer and in winter, the sides of the mass were given an angle of 225º (figure 14, second from left). Considering that heat radiation is very useful in winter, the long sides of the building mass were designed to face south. This is in line with the building’s orientation to take maximum advantage of thermal storage wall system. Meanwhile, to reduce heat build-up in the building mass in the summer, evergreen vegetation is planted nearby the building envelope. The configuration of the building mass with an opening at the top enables the wind to reach all parts of the building (figure 14, third from left). The wind will also spread to the north side, whereas it potentially dominates the south side. From the above considerations, the initial configuration of the building mass was obtained (figure 14, fourth from the left), which was the basis for the next building mass shape.
3. Result and discussion
In a design test, the effectiveness of the building mass orientation and shape was determined. In this case, the design test focused on the sun’s effect on the building in relation to the thermal storage wall system used in the design.

Testing was done for the peak of winter (December 21) in order to know the solar path, which can be used in deciding where to locate the thermal storage wall system. The testing procedure was based on the latitude and longitude of the location, which was simulated with the help of the Ecotect software application. From the test it was found that the most significant time of day is 10.30, since at that moment most points of the building are exposed to sunlight. At these points, the thermal storage wall will be located. After ensuring that the building receives the highest possible amount of heat radiation, the test was continued by examining the thermal performance of the building envelope, more specifically the thermal storage wall, which was done by comparing the thermal performance of the building envelope with and without thermal storage wall in an Ecotect simulation.
Figure 17. Result of building model in Ecotect software with thermal storage wall (left figure) and without thermal storage wall (right figure).

The test was done to observe the amount of solar heat absorbed by the building envelope. Figure 17 shows the condition of the building envelope both with and without thermal storage wall for comparison. The yellow colour in the result is indicates the highest level of heat absorption, while the blue colour represents the lowest level. The red color represents a fair amount of heat absorption, while the color changing to violet and blue indicates that there is little solar heat penetration. The result shows that if a thermal storage wall is installed, solar heat can still penetrate into the building envelope, as can be seen from the red color. It is suspected that this condition is also influenced by the building envelope containing glass elements.

The test showed that the position and orientation of the thermal storage wall in the model can contribute to the passive heating of the building. This is shown by the decrease of the violet area in the building envelope, which is due to heat radiation being absorbed by the thermal storage wall. With this system, heat that has been captured in the storage wall can be released to the interior.

In this study, the test was not intended to provide specific temperature values but only to examine to which degree the thermal storage wall is efficient in relation to its orientation and position. To provide specific temperature values many influencing factors need to be assessed, such as air tightness, hourly air circulation and heating system, whereas in this simulation these factors could not be included due to the limited information and author’s knowledge.

Figure 18 shows the angle of the sun when it is at its highest position (at 12:00) on December 21st. From these measurements it can be seen that the angle between the position of the sun and the horizontal plane is 15°.

Figure 18. Sun position in winter

Similar to the calculation of the winter altitude, calculation of the summer altitude was also undertaken using Ecotect. The difference between both tests was the testing time. In summer, the critical day is June 21st. Therefore, the summer altitude calculation was done for that day.
According to the result, the angle is 60º at 12.00 a.m. (highest angle). From both calculations it can be clearly seen that the altitude angles change along the year. The data above were then used to examine the result of application of the thermal storage wall in building envelope for the whole model. From figure 20 it was found that in summer, the sides of the building are more exposed to sunlight. In winter, the sides of the building envelope in the south and the west are mostly exposed to sunlight, as marked by the red areas.

In a temperate climate, the effort to increase temperature is more demanding to decrease temperature. Therefore, the thermal storage wall in the building model is able to contribute to the passive air conditioning of the building.

4. Conclusion
Testing was conducted on a sector (i.e. the thermal storage wall area) of an experimental design for the envelope of a community centre in Nordhavn (Denmark). It was concluded that the location of the thermal storage wall in the building is appropriate for the objective of the design, i.e. to contribute to the passive air conditioning of the building. In summer, the building envelope could be over-exposed to heat radiation. However, the vegetation in the surroundings of the building envelope was not taken into account in the test due to the limitations of the author’s hardware. The building envelope is also exposed
to heat radiation in winter, particularly from south to west. Based on the test result, the thermal storage wall system is capable of contributing to passive air conditioning of the building. In a wider context, the system can also contribute to a smart city system with respect to energy use reduction.

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