Aesthetic evaluation of facade integrated coloured photovoltaics designs – an international online survey

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Façade Integrated Photovoltaics (FIPV) is a promising way to utilize solar energy and to reduce GHG emission in the built environment. However, to the authors knowledge, the colour design of façade integrated photovoltaics has not been studied scientifically yet. The authors developed a theoretical pixelization design method for generation of colour designs for façades with integrated photovoltaics, in which local urban NCS colour palette and colour harmony strategies are used. The city of Trondheim in Norway acts as a backdrop for the study, and two main façade prototypes (multi-story and high-rise building) are derived from the Trondheim's urban context. To test the method, an online international survey has been carried out. In the first part of the anonymous survey, participants' general attitudes towards FIPV, and their basic information was collected. In the second part, participants were asked to evaluate the aesthetics of two façade prototypes having a pixelization FIPV design, on a 5-step semantic differential scale. Besides, participants were asked to choose the most preferred one among pixelization and non-pixelization façade designs. In the third part, the urban integration levels of pixelization design proposals for real buildings were evaluated with the same 5- levels semantic differential scale. Nearly half of the total 309 participants were 'experts' with education or working experience in architecture, urban design, or fine arts fields, while the remaining participants were 'laypersons' i.e. without related backgrounds. The survey results show a general preference for the aesthetic qualities of presented pixelated FIPV designs. Also, the presented pixelated FIPV designs are perceived well integrated into urban contexts by the majority of participants. In addition, laypersons tend to rate the presented pixelated FIPV proposals with higher scores in both, aesthetic quality evaluation and contextual coherence evaluation.

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Introduction

Buildings are the largest energy consumption sector which account for one-third of the global energy usage and greenhouse gas (GHG) emission [1]. Façade integrated photovoltaics (FIPV) is a strategy to harvest renewable solar energy on-site leading to the reduction of GHG emission. Most of the precedent studies are focusing on technical aspects like energy productivity [2]. However, many of the new FIPV are not appreciated by people cause of the traditional black or dark blue with low lightness coloured PV panels exposed on building facades. There is urgent need to develop architectural methods to promote the application of FIPVs in urban context. The authors developed a novel theoretical pixelization design method for generation of colour designs for façades with integrated photovoltaics. Pixelization design can be found in artistic works like Neo-Impressionism paintings. Architects can also use this concept as architectural language to create desired façade images. This pixelization method utilized orders of colours, allows moderate complexity for FIPV design and enables even covering of facades of existing buildings in accord with the historical significance and local identity.

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Case study of Trondheim city

Trondheim city in Norway acts as a backdrop of the pixelization study and online survey. Trondheim is the third largest city in Norway and nowadays it is a city where history and modern development meet. In the traditional central area, a large number of historical buildings (see Figure 1) situated alongside the Nidelva river with colourful wooden facades are very much appreciated by the citizens as the most important urban tissue representing the identity of the city. Figure 2 shows the colour palette of Trondheim city [3]. Generally, the age of buildings decreases with the distance from the city.

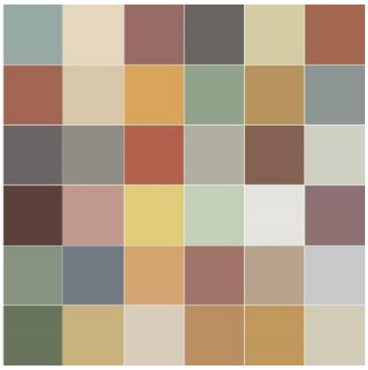


Figure 1 (left): Colourful historical warehouses in the traditional city center of Trondheim.
Figure 2 (right): Colour palette of Trondheim [3].

In building typology aspect, the typical building typologies of Trondheim has been investigated based on materials from Trondheim's archive, literature of local urban heritage and contemporary urban morphology [4-5], and two facade typologies have derived for FIPV design with pixelization method. One façade prototype geometry was generated with respect of the traditional warehouses in Trondheim center (Figure 3). The second facade prototype represented a typical high-rise apartment block located outside the traditional city center (Figure 5).

In colour design aspect, colour harmony concepts together with the colour palette of Trondheim context [3] have been used as guidance. Colour harmony is one of the key criteria for aesthetic preference and the colours of integrated photovoltaics should be in harmony with the rest of the building [6]. Westland *et al.* [7] summarized four common schemes of colour harmony theories represented in many art and design textbooks with reference to hue circles: Monochromatic harmony (colours in the same or similar hues), analogous harmony (colours in similar hues), complementary colour harmony (opposite colours on a hue circle) and split-complementary harmony (one colour and the two colours on either side of its complementary colour). In the Norwegian colour standard NCS systems, it is suggested that compositions of colours with similarity in one or more of colour attributes (e.g. hue, chromaticness, nuance, blackness etc.) also tend to be more highly appreciated (more harmonious) than others [8]. In this study, the following colour harmony strategies, together with the same chromaticness strategy were employed to serve FIPV colour design.

- Monochromatic colour harmony strategy
- Analogous colour harmony strategy
- Complementary and Split complementary colour harmony strategy
- Colour combination with the same chromaticness

A series of colour combination sets (Figures 4 and 6) were developed for detailed FIPV design proposals [9], which were tested in the online survey.

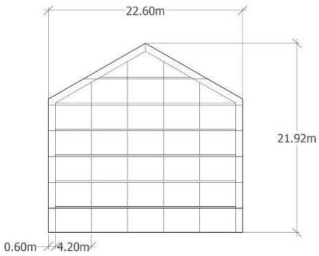


Figure 3 (left): Façade prototype for multi-story buildings.
Figure 4 (right): Colour sets for FIPV colour design, for multi-story buildings in sensitive city center in Trondheim.

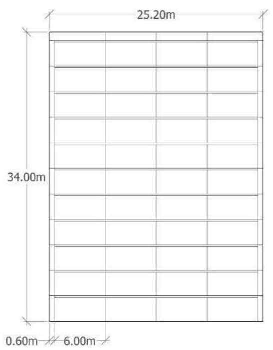


Figure 5 (left): Façade prototype for high-rise buildings.
Figure 6 (right): Colour sets for FIPV colour design, for high-rise buildings outside traditional city center of Trondheim.

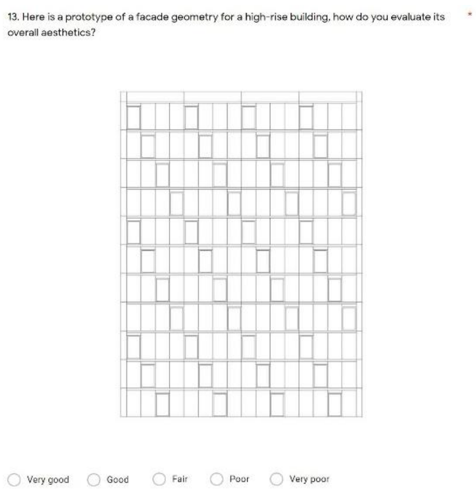
Online survey and results

To examine the proposed theoretical pixelization method in this study and to test the research hypothesis:

1. *pixelization design can provide aesthetically preferred façades*
2. *pixelization method can provide FIPV designs that are harmoniously integrated into the urban co eligible for the study.*

This online survey consisted of three main parts and was developed based on the online survey platform Google Form. In the first part, participants' general attitudes towards FIPV and the basic information like gender, ages, professional background were collected.

In the second part of this survey, the hypothesis that pixelization design can provide aesthetically preferred façades was tested through a series of questions with façade prototype photos: firstly, participants were invited to evaluate the overall aesthetic of derived façade prototype (without colours) of multi-story and high-rise buildings in Trondheim, on a 5-level semantic differential scale rating from "Very good", "Good", "Fair", "Poor" to "Very Poor" (e.g. Figure 7-Question 13: Here is a prototype of a facade geometry for a high-rise building, how do you evaluate its overall aesthetics?). Then pixelated FIPV designs for the corresponding building prototype with NCS colours in monotonous hues of Y30R was presented and evaluated with the same 5-level semantic differential scale (e.g., Figure 8-Question 14: The prototype has been covered by coloured photovoltaics with slightly varied nuances, how do you evaluate its overall aesthetic now?).



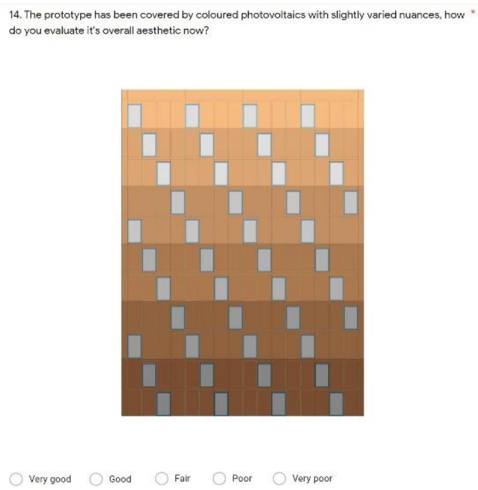


Figure 7 (left): Preference evaluation of high-rise facade prototype.
Figure 8 (right): Preference evaluation of pixelated FIPVs design for high-rise facade prototype.

In addition, the participants were asked to choose their most preferred ones among the pixelated FIPV designs and non-pixelated FIPV designs (Figure 9-question 15). In the third part, participants were asked to evaluate both the context coherence/integration performance and façade aesthetic performance of pixelization design proposals for real buildings in Trondheim, using the same 5-levels semantic differential scaling. (e.g., Figures 10-12).

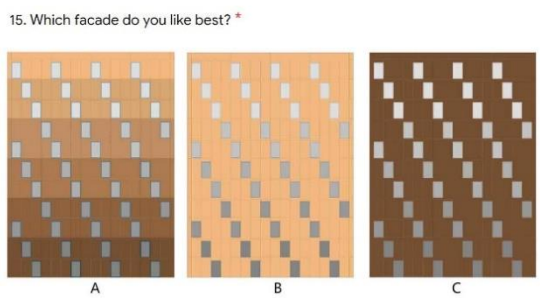


Figure 9 (left): Preference evaluation of pixelization and non-pixelization design, high-rise design.
Figure 10 (right): Selected traditional wooden warehouse for FIPV design.

Figure 11 (left): Contextual integration evaluation.
Figure 12 (right): Preference evaluation of FIPV design.

In total 309 participants participated in this survey, among them around 58% participants were 'laypersons' without education or working experience in architecture, urban design or fine arts related backgrounds. Microsoft Excel were used to analyse the data. 5-scale numerical rating was applied for corresponding aesthetic quality levels/contextual coherence levels: 1=Very poor, 2=Poor, 3=Fair, 4=Good, 5=Very good. A mean value above 3 can be viewed as the design is generally preferred by participants or that it is coherent with the surrounding context.

Results were found from the analysis:

1. For two façade-prototypes, the pixelated FIPV designs were more preferred than non-pixelated FIPV designs when they have the same or similar hues (Figure 13).
2. The presented pixelated FIPV designs were perceived well integrated into urban contexts
3. Participants showed a general aesthetic preference towards the pixelated FIPV designs.
4. Visiting experience with the city center in the past ten years was not an influential parameter of context integration and façade aesthetic evaluation (Figures 14-15).
5. Both genders share similar trend in context integration and aesthetic evaluation (Figure 16).
6. Both the context integration and façade aesthetic performance of FIPV design proposals were more preferred by layperson group, compared with expert group (e.g. Figure 17).

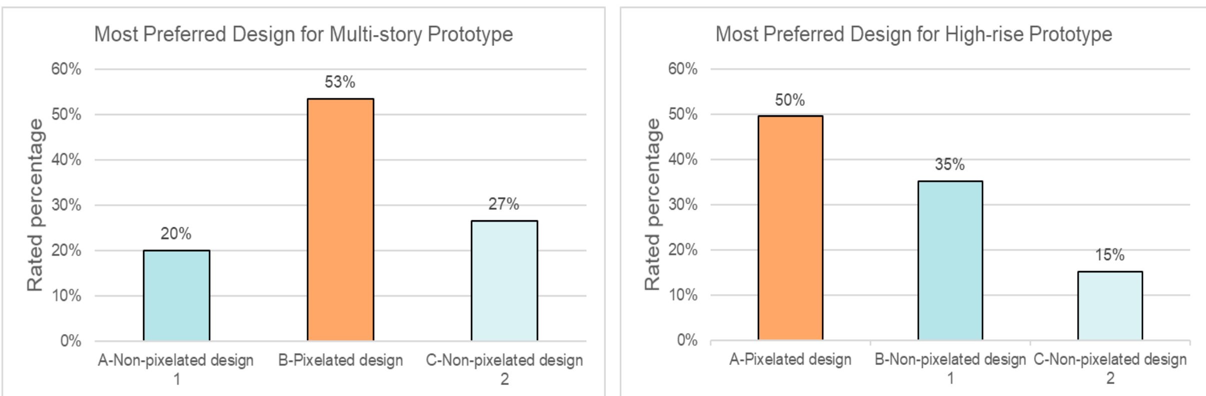
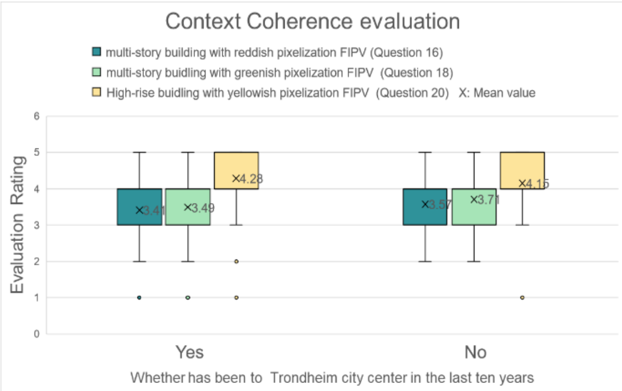


Figure 13: Aesthetic performance, Pixelization design VS non-pixelated designs for two building prototypes.



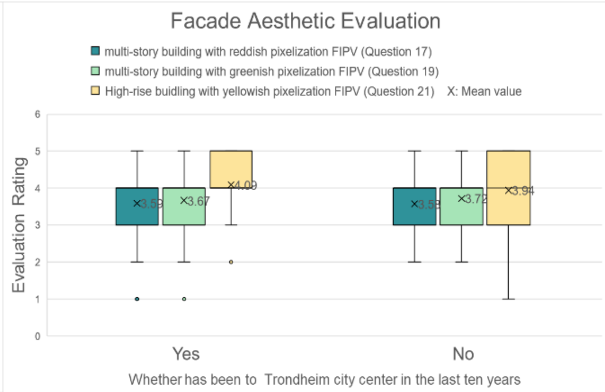
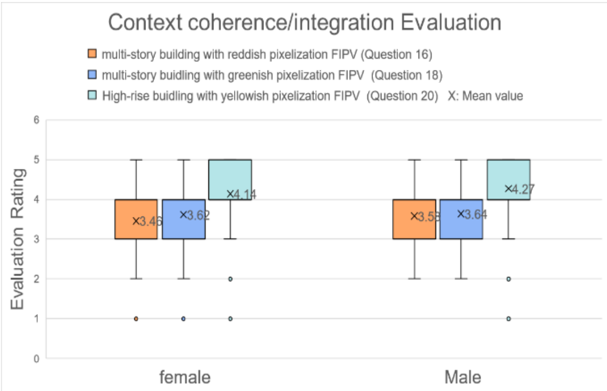


Figure 14 (left): Context coherence evaluation analysis.
Figure 15 (right): Façade aesthetic performance analysis.



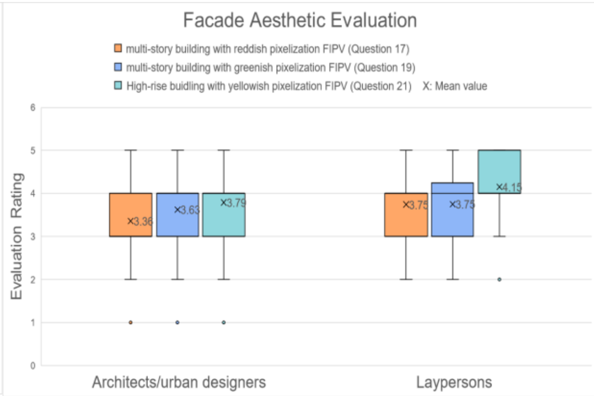


Figure 16 (left): Context coherence evaluation analysis.
Figure 17 (right): Façade aesthetic performance analysis.

Discussion and conclusions

The survey result provided evidence to support the two hypotheses: 1. pixelization design can provide aesthetically preferred façades, 2. pixelization method can provide FIPV designs that are harmoniously integrated into the urban context. Also, the survey result showed that, laypersons tend to rate the presented pixelated FIPV proposals with higher scores in both, aesthetic quality evaluation and contextual coherence evaluation. A potential reason for this phenomenon could be that the expert group with professional aesthetic training, have higher expectations. Online aesthetic survey is an efficiency way to collect subjective feedbacks from a large number of participants, however online photos cannot demonstrate all visual properties of photovoltaics materials (e.g., gloss and texture). Further research could be using (scaled) physical models to test the pixelization method.

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