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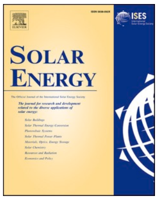

Pixelization approach for façade integrated coloured photovoltaics-with architectural proposals in city context of Trondheim, Norway

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ABSTRACT

Façade integrated photovoltaics (FIPV) is an emerging and essential way to utilize solar energy in built environment. However, there is limited architectural study of FIPV, especially addressing the topic of colour performance. This study developed a theoretical method with pixelated colour design for integrating opaque coloured photovoltaics on building facades. The city of Trondheim in Norway was taken as a case study. Two main façade prototypes for FIPV were derived from Trondheim's urban context. Typical hues for the two façade prototypes were selected from Trondheim's urban colour palette, and colour harmony strategies were applied as design guidelines to generate NCS colour combinations for FIPV. Then a series of pixelated FIPV designs was proposed.

The aesthetic performance of the proposed pixelated FIPV designs was tested through an online survey among architects, urban designers and laypersons from different countries. A 5-level semantic differential scaling was employed for aesthetic evaluation. The results demonstrated that the FIPV concept was widely supported by participants, while the proposed pixelated FIPV designs were aesthetically preferred and considered as coherent with urban context by the majority of participants.

Besides, the energy production efficiencies of proposed designs were calculated. Pixelated coloured FIPV facades showed promising energy production efficiency (theoretically about 85–93% of black PV facades). The overall façade lightness demonstrated a much stronger influence on efficiency than hue.

This study presented a promising pixelization method for FIPV design, through which a balanced FIPV performance including pleasing façade aesthetic quality, satisfied urban integration, and high energy production efficiency could be achieved.

1. Introduction

Building integrated photovoltaics (BIPV) is a promising method to harvest the most abundant renewable energy -solar energy - in the built environment and can strongly support the growing demand for nearly zero energy buildings (Debbarma et al., 2017; Ferrara et al., 2017; Jelle and Breivik, 2012; Peng et al., 2011). In the past, roof areas were often used for implementing photovoltaics. However, due to limited roof areas, there is increasing demand to integrate photovoltaics into building facades (Atmaja, 2013; Brito et al., 2017; Chen et al., 2019; Evola et al., 2014; Knera et al., 2015). Real case studies have shown that BIPV can be an attractive and sustainable solution for building façade retrofit projects (Di Gregorio et al., 2014; Frontini et al., 2016; Saretta et al., 2019). At high latitudes, such as Norway, the relatively low solar elevation also makes façade integration more feasible.

In the opinion of architects and city planners, the dark colour is the most serious hinder for applying photovoltaics on building facades. An international survey investigating the barriers of solar thermal and photovoltaics showed that architects require flexible colour choice when selecting such systems in their design (Farkas et al., 2010). The colours of façades play an essential role in influencing people's perception of the urban environment and generating perceived city images (Jalali et al., 2013; Lynch, 1960). The dark blue and black colours of traditional commercial photovoltaics do not match the façade colours in most cities. A black facade can be accepted as a single case, even in city centres, but it is not suitable for general use. Fortunately, current technological methods enable the production of novel opaque PV with nearly unlimited choice of colours. For instance, the KromatixTM technology

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employs multi-layered interference filters to give PV products a desired colour that may vary with view angles (Jolissaint et al., 2017). Other practical technologies apply coloured anti-reflective coatings on solar cells(Ding et al., 2018; Selj et al., 2011), utilize special solar filters or mineral coatings, etc. (Eder et al., 2019).

Even though the number of colours and colour nuances of FIPV can be much larger in near future, there is a lack of systematic architectural methods to support colour design of facade integrated photovoltaics (FIPV) and create harmonious colour facade design, especially in urban context. Scholars have raised awareness of absence of knowledge in colour design in cities and urban developments (Booker and Angelo, 2018). Furthermore, colour preferences from architectural perspective and energy perspective are usually contradictory. For instance, the lightness of FIPV has been found as the most important factors influencing the energy production of opaque coloured photovoltaics, lower lightness levels are preferred for electricity generation (Røyset et al., 2020). This is opposite with the preference of façade colour from the aesthetic perspective. Li et al. (2020) investigated the two-colour harmony of building facades with psychological tests, in which 43 participants were asked to evaluate the harmony degree of 308 different colour combinations of one building project in Taipei city. The experimental results showed that people prefer facades with a primary colour in high lightness level, and a greater lightness difference between primary colour and the supplementary colour is also preferred.

This study examined the possibility of using the pixelization method to provide architectural solutions with satisfying aesthetic performance and high energy efficiency. Pixelization or pixelating is not a recently emerging praxis, the concept is based on the organization of the whole, where the parts that act upon one another make each other visible (different colour, texture or specularity) by networking and the whole is more than the sum of its entities (Balik, 2010). As an architectural language, pixelization designs can be found in many real projects. The relationship between façade elements (like bricks or modular panels) and the overall façade is analogous as the divisionism strokes to the whole Neo-Impressionism paintings. Through pixelization design, architects can create desired façade images with smooth transitions in colour by carefully organizing the façade elements in different colours. Although the praxis of pixelization is not new to architects, to the authors' knowledge, the pixelization method for façades was not a subject for scientific studies so far. In this study, a systematic pixelization method applying colour harmony strategies was presented. This 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. The Norwegian colour standard, NCS colour system, was employed in this study and colour harmony strategies have been used as guidance, a series of detailed FIPV design proposals were developed in different urban context scenarios in Trondheim city.

2. Research aim and questions

2.1. Research aim

This study aimed to develop a practical architectural design method to promote the integration of opaque coloured photovoltaics into building facades. From the architectural perspective, the purpose of the method was to provide architects a high level of freedom in choice of colours (including hue, lightness and chromaticness) when selecting colours for FIPV design. On the other hand, efficient energy production also needed to be taken into consideration. Additionally, the aesthetic preferences of both architects/urban planners and laypersons needed to be considered. Here the definition of laypersons was people without professional education or working experience in architecture, urban planning, or design disciplines.

2.2. Research questions

(1) How to develop pixelated FIPV designs in the context of Trondheim city?
(2) Can the proposed pixelization method provide FIPV designs harmoniously integrated into the urban context and provide aesthetically preferred façades? *(hypothesis one: pixelization design can provide aesthetically preferred façades, hypothesis two: pixelization method can provide FIPV designs that are harmoniously integrated into the urban context)*
(3) What is the energy production performance of pixelated FIPV designs?

These three research questions will be re-mentioned and answered in the following paragraphs.

3. Theoretical background

To develop an architectural method for façade integrated PV (FIPV) in the urban context, theories about environmental aesthetics and colour harmony can serve as the theoretical foundation, and tools like colour palettes of urban environments can be employed as a direct design reference.

3.1. Environmental aesthetics in the built environment

The basic theoretical background of this study is environmental aesthetics, which is an interdisciplinary field that emerged in the late 20th century. Environmental aesthetics focuses on the aesthetic appreciation of both natural and human environments, and explores the human-environment interaction (Carlson, 2010). The aesthetic preference has roots in human evolution process. According to Appleton (1975), modern human's experience of aesthetic satisfaction is a response to the qualities in the surroundings with real or symbolic meaning for survival, people prefer an environment that can provide both safe feeling and the capability to observe and understand surroundings, and people's aesthetic preference is developed during the evolutionary process. Similarly, Kaplan (1987) also claimed that people have the demand to notice, understand, evaluate and behave in an environment that could be supportive or harmful to their survival. Kaplan categorized people's preference of environmental perception into two levels: understanding and exploration. Each level can be further divided into immediate and predicted perception scenarios, making in total four scenarios: Coherence, Legibility, Complexity and Mystery. Besides the inherited impact from evolution, people's aesthetic preference is also influenced by cultural background, individual experience, interests and abilities (Appleton, 1975; Küller, 1991). In the built environment, many studies have found that aesthetic differences exist between architects/designers and laypersons. The difference can be explained by the different knowledge structure and aesthetic experience of observers (Devlin, 1990; Devlin and Nasar, 1989; Gifford et al., 2002). Although aesthetic preference distinctions do exist between different groups, Nasar (2000) has summarized six positive qualities for people's common preference in the built environment, including 'order', 'moderate complexity', 'report of natural elements', 'good maintenance, good hygiene', 'openness' and 'historical significance'. Nasar's positive qualities in built environments can be a fundamental reference for this theoretical study.

3.2. Colour harmony theories

Colour plays an essential role in people's aesthetic perception. For centuries, researchers have tried to encode the rules or principles of optimal colour combinations for aesthetic perception. The concept of colour harmony has been discussed by scientists and artists, and different traditional colour harmony theories were proposed. Johann

Fig. 1. Colourful historical warehouses in the traditional city center of Trondheim, many of them are used as apartments today (by author).

Wolfgang von Goethe believed that people desire to see the opposite colour of one given colour, the law of colour harmony lies in the relationship: yellow needs violet, blue needs orange, and purple needs green (von Goethe, 1810). Similarly, Johannes Itten (1974) also paid special attention to colour contrast, he developed a 12-colour wheel based on primary colours, secondary colours and tertiary colours. If two colours lie on the opposite position of this colour wheel, their combination can be harmonious. Chevreul (1855) claimed that both analogy and contrast can contribute to the colour harmony. The harmony of analogy includes colours in the same or neighbourhood hues but with slightly different lightness, colours in the same saturation but with neighbourhood hues, and colour combinations with one dominating colour. While the harmony of contrast includes colours in the same hue but with large different lightness, colours in the neighbourhood hues but with different saturation, colour combinations of Complementary hues. In the book ‘A Grammar of Colour’, Munsell (1969) described a colour harmony theory based on the balance of lightness, chroma and hue. A sense of comfort or colour harmony can be achieved if the overall impression of colours is balanced on middle grey. Area ratio also needs to be considered for harmony: small areas of high chroma colours need to be balanced by large areas of low chroma colours. These traditional colour harmony theories are mostly based on observation and lack of experimental support, although many of them are still popular for colour communication today.

In the contemporary age, the exploration of colour harmony continues. Westland et al. (2013) 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). Colour combination studies with observers participating experiments have shown that colour pairs with similarity in hue or chroma, difference in lightness are evaluated more harmonious (Schloss and Palmer, 2011; Szabó et al., 2010). Similarly, the experimental result from Hård and Sivik (2001) indicated that the colour pictures with similarity or constancy in hue are more aesthetically preferred. Anders Hård and his team developed a novel colour ordering and notation system- NCS (the Natural Colour System) in 1960s, this colour system does not require users to have any knowledge of physical or physiological attributes of colour stimuli (Hård et al., 1996). In 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 (NCS, 2019a). The NCS colour system has become the national standard in Sweden, Norway, etc, and is the system that is employed in this study.

Although theories of colour harmony are diverse and it is difficult to form a universal law, many recent researchers agree that colour harmony is related strongly with the emotion of pleasantness, a set of colours producing a pleasing effect can be defined as colour harmony (Burchett, 1991; Granville, 1987; Judd and Wyszecki, 1975; Ou and Luo, 2006). Key attributes of colour combinations like order and balance can contribute to colour harmony (Burchett, 1991; Li et al., 2020; Ou and Luo, 2006), which are in accordance with Narsar’s positive qualities of aesthetic preference in the built environment.

3.3. Colour design strategies in urban context

Colour is one of the key aspects of the image of the city (Lynch, 1960). For architects and urban planners, it is necessary to consider the specificity of the place and the need of good design tools to prevent prejudicial operations when making colour selection for colour designs (Zennaro, 2017). Colour plan or colour palette strategies have been tested in many cities and they are practical tools to generate façade colour design fitting the surrounding urban context while strengthen the local identity simultaneously. For instance, to support the restoration of the historical center of Turin city, Brino (2009) investigated popular colours of main streets and squares in Turin, and a colour plan with around 80 hues was developed, imitating the local building materials like marble, granite, terracotta and bricks. Brino’s concept was followed by other cities in Italy and France, nearly 50 colour plans are generated since 1978. Similarly, Sibillano (2011) developed a colour fan with 117 colours to determine the colours and materials of every single building in Zurich, detailed colour attributes like saturation and brightness are also included. A colour plan of the entire city presenting the colour and material profiles of Zurich is generated. Lenclos (2009) presented a ‘Geography of Colours’ strategy to support harmonious architectural design with local identity. For a particular site, sample fragments were taken from local buildings and sites, their perceived colours were later translated into painted colour plates and then grouped into series of palettes.

Systematic colour palettes have also been developed as fundamental supporting tools for colour design in Trondheim. Angelo and Booker registered the nominal colours of Trondheim city with the help of NCS index and NCS colour scanners (to find the nearest Standard NCS notations). The nominal colour, or inherent colour, means the colour of an object observed under the standardised viewing conditions, a prerequisite for the NCS colour samples to coincide with their specifications. For practical operation reasons, the nominal colours of building facades

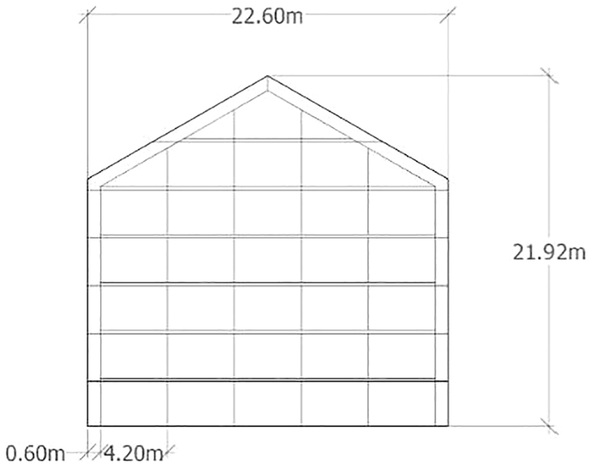


Fig. 2. Façade prototype for multi-story buildings.

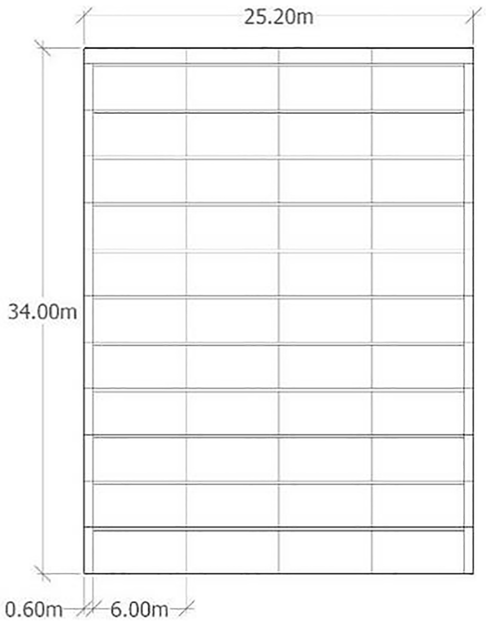


Fig. 3. Façade prototype for high-rise buildings.

can be determined by visual comparison with NCS samples places directly towards the facade surface (Anter, 2002). Based on this registration, involving around 200 buildings in the city and lasting over 4-years' time, a colour palette of the city has been developed (Angelo and Booker, 2018). This colour palette of Trondheim is now used by the municipality as a guide to select main hues of different buildings and to develop colour designs for a single building facade or a street frontage.

In summary, in this study, Nasar's positive qualities including '**order**', '**moderate complexity**' and **historical significance** were employed as a theoretical environmental aesthetic foundation. Contemporary colour harmony hue concepts (Monochromatic hue, analogous hues, complementary and split-complementary hues) together with colour harmony principles suggested in NCS system (colours with same/similar hue, chromaticness or lightness) were employed as colour harmony principles. The Trondheim city was taken as the case city in this research, therefore, with respect to local historic and cultural identity, the colour palette of Trondheim, developed by Angelo and Booker, was used here as a direct colour database for colour selection of FIPV in Trondheim context.

4. Methodology

4.1. Case study city of Trondheim

With more than 170,000 inhabitants, Trondheim is the third largest city in Norway (Hernández-Palacio, 2017), the city also possess a rich history in urban development, evidence shows that its urban functions already begun at the beginning of the 11th century (Petersén et al., 2015). Nowadays, it is a dynamic city where history and modern development meet. Most of the traditional buildings are located in the city center, many of them are built of wood and have colorfully painted facades. The historical warehouses situated alongside the Nidelva river (Fig. 1) stand out as iconic and unique array of coloured volumes. These warehouses' history date back to the 17th century, when they had key

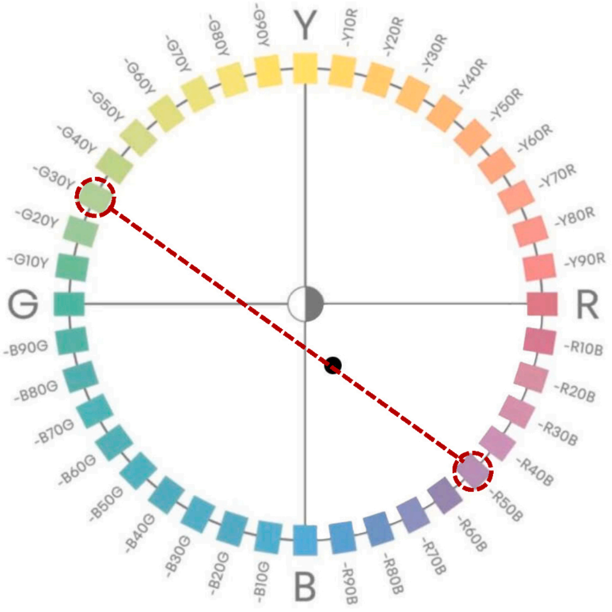


Fig. 5. Complementary hues in NCS circle.

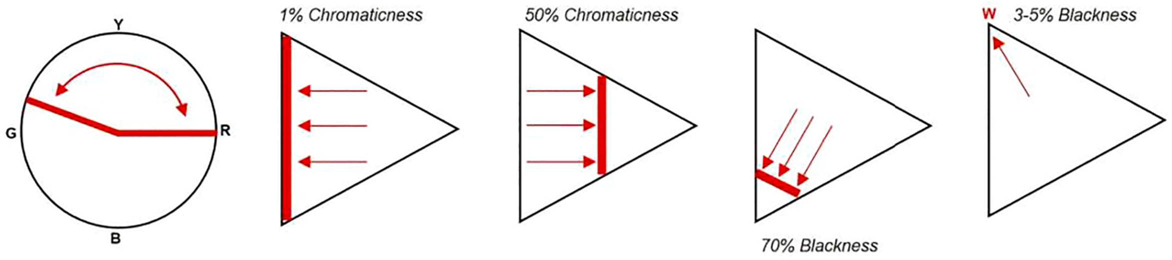


Fig. 4. Trondheim's colour design general rules in NCS diagrams, adapted from Angelo and Booker (From left to right: 1. Typical hue range; 2. Minimum chromaticness >1%; 3. Maximum chromaticness 50%; 4. Maximum Blackness 70%; 5. Blackness >3–5% (Angelo and Booker, 2016).

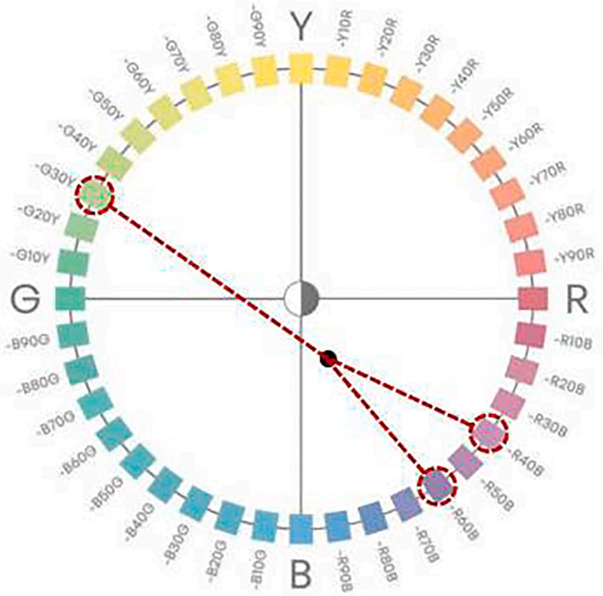


Fig. 6. Split complementary hues in NCS circle.

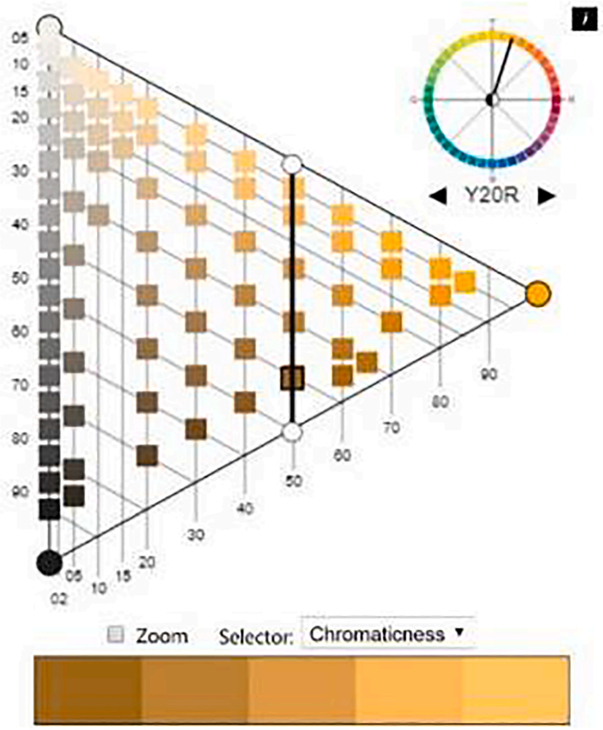


Fig. 7. Y20R NCS colour set with the same chromaticness = 50.

roles in the port trading activities of Trondheim. Although most of the warehouses are repeatedly burned by fire, they are often rebuilt again and again following similar construction principles (Grytli, 2013). They are very much appreciated by the city residents as the most important urban tissue giving identity for the city, besides the medieval cathedral Nidarosdomen. Generally, the age of buildings decreases with the distance from the city.

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 (Arkivsenteret, 2020; Kittang et al., 2018; Kittang and Bye, 2019; Lobaccaro et al., 2017), thus two facade typologies have been chosen for the present FIPV design study. One façade prototype geometry was generated with respect of the traditional warehouses in Trondheim center; most of these colourful warehouses are 5–8 stories buildings with pitch roofs, which are also common in other historical Norwegian cities. A facade prototype with a height to width ratio ≈1 was proposed to represent a multi-story building, the façade dimension is 22.6 m in width, 21.92 m of total height with a 2-floor-height pitch roof (Fig. 2). The second facade prototype represented a typical high-rise apartment block located outside the traditional city center. Having large facade areas, these buildings are well suited for FIPV. A facade dimension of 25.2 * 34.0 m was proposed by following the work of Lobaccaro who studied the geometry of buildings in Trondheim in connection with the evaluation of their

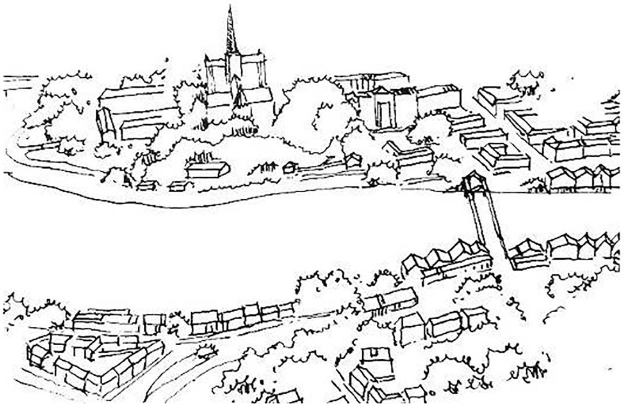


Fig. 8. Urban context of Trondheim's center with wooden warehouses.

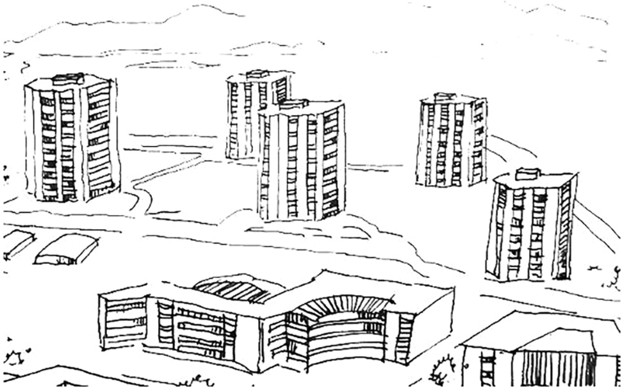


Fig. 9. Urban context of Trondheim's suburb area with high-rises.

Table 1
Hues for monochromatic colour design collected from the Trondheim colour guide.

Urban context	Typical existing façade	hues for monochromatic colour design	NCS nuance (chromaticness and blackness)
Sensitive center	multi-story wooden façades	Y20R, Y30R, Y40R, Y70R, Y80R, Y90R, G30Y, G50Y, R80B, R90B, B	General nuance rules by Angelo and Booker + Same chromaticness
Less sensitive areas	brick façades	Y20R, Y30R, Y70R, Y80R	General rules proposed by Angelo and Booker + Same chromaticness
	Large rendered façades	Y20R, Y30R, Y70R, Y80R, G30Y, G50Y, R90B, B	General rules proposed by Angelo and Booker + Same chromaticness

Table 2
Hues for analogous colour design collected from the Trondheim colour guide.

Urban context	Typical existing façade	hues for analogous color design	NCS nuance (chromaticness and blackness)
Sensitive center	multi-story wooden façades	Y20R + Y30R + Y40R + Y70R + Y80R + Y90R G30Y + G50Y R80B + R90B + B	General rules proposed by Angelo and Booker + Same chromaticness
Less sensitive areas	brick façades	Y20R + Y30R Y70R + Y80R	General rules proposed by Angelo and Booker + Same chromaticness
	Large rendered façades	Y20R + Y30R + Y70R + Y80R G30Y + G50Y R90B + B	General rules proposed by Angelo and Booker + Same chromaticness

potential for solar radiation harvesting. In his study, the building geometry (25 * 33 * 20 m) for high-rise was used as a reference (Lobaccaro et al., 2017). The proposed façade represented a high-rise apartment or office with 11 floors, each floor can be divided into 4 apartments/offices (Fig. 3).

4.2. *Colour design strategies in Trondheim context*

Colour design strategies were developed here at two levels: **the urban level** and **the building level**. In the urban level, holistic colour information of Trondheim context was considered by employing Trondheim's colour palette as guiding reference to respect local history and strengthen the identical image of Trondheim. At the building design level contemporary colour harmony concepts are employed to generate colour combinations for FIPV facades.

(a) Colour design strategies at the urban level

The colour palette developed by Angelo and Booker (2018) listed the typical colours used in Trondheim and also presented the typical colours relation to surface texture and building types. For example, the chromatic façade colours on timber cladding façades were identified to hues between NCS G30Y–Y90R, with medium levels of chromaticness, blackness and whiteness. While buildings with facades of stone, and larger building volumes of rendering, typically have hues between NCS Y10 –Y90R, and in nuances of 10–50% blackness and 2–20% chromaticness (Angelo and Booker, 2016). The general rules proposed by Angelo and Booker for colour guidelines are employed here as a direct reference for the study (Fig. 4). The rules refer to NCS including:

(i) typical hues in Trondheim are in the range from reddish hues to greenish hues, bluish hues are very rare and violet ones are not existing,
(ii) minimum chromaticness should be 1%,
(iii) maximum chromaticness is 50%,
(iv) maximum blackness is 70% and
(v) Blackness should never be less than 3–5%.

Thus, the following two strategies were employed at the urban level, which provided a basic NCS hue sample pool and served as guidelines in nuances aspect: 1. NCS hues for FIPV design were selected from the Trondheim's colour palette; 2. Following the NCS nuances guidance developed by Angelo and Booker.

(b) Colour design strategies at the building level

At the building level, 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 (Femenias et al., 2017; Munari Probst and Roecker, 2019).

Therefore, in addition to colour strategies at the urban level, contemporary colour harmony concepts were synthesized together as colour strategies at the building level, including monochromatic NCS hue (a single hue on NCS colour circle), analogous NCS hues (neighborhood hues on NCS colour circle), complementary and split-complementary NCS hue concepts, and NCS colours with the same/similar chromaticness.

In the NCS colour circles, complementary hues can be paired by drawing straight lines across the intersection point with approximate position c = 20 and the hue = R75B, e.g. Fig. 5 (NCS, 2019b). Split-complementary hues are one hue and the two hues on either side of its complementary colour (Fig. 6). For a given NCS hue, colour sets in constant chromaticness show smooth transition and could provide rich colour choice for FIPV design when chromaticness value is set less than 50% (Fig. 7).

The following colour harmony strategies, together with the same chromaticness strategy were employed to serve FIPV colour design in building level:

(1) Monochromatic colour harmony strategy (colours in the same hue)
(2) Analogous colour harmony strategy (colours in similar hues)
(3) Complementary and Split complementary colour harmony strategy
(4) Colour combination with the same chromaticness

4.3. *NCS colours sets for FIPV design in Trondheim*

Following the colour strategies in urban and building level, groups of NCS colours were selected with consideration of parameters of **hue and chromaticness**. The creation of harmonious NCS colour sets can be utilized directly in pixelization colour design of FIPV.

The main areas of facades' FIPV employed monochromatic colour harmony and analogous colour harmony strategies, which could provide order and harmonious colour transition in dominant areas of FIPV façades. According to Munari Probst and Roecker (2015), urban sensitive levels have strong impact on the integration requirement of solar energy systems, urban centers with higher sensitivity need more integrated solution than less sensitive suburb areas.

For sensitive urban contexts like Trondheim's traditional central area (Fig. 8), the typical hues of Trondheim's wooden building facades in central context were used as hue sample pool. For façade designs (e.g.

Table 3
Hues for split complementary colour design collected from the Trondheim colour guide.

Urban context	Typical existing façade	hues for split complementary color design (main facade)	hues for split complementary colour design (decoration area)	NCS nuance (chromaticness and blackness)
Sensitive center	multi-story wooden façades	Y20R + Y30R + Y40R Y70R + Y80R + Y90R G30Y + G50Y	*R90B + B + B10G + B20G* *B30G + B40G + B50G + B60G* *R40B + R50B + R60B + R70B*	General rules proposed by Angelo and Booker+/Same chromaticness
Less sensitive areas	brick façades	Y20R + Y30R Y70R + Y80R	*R90B + B + B10G* *B30G + B40G + B50G*	General rules proposed by Angelo and Booker + Same chromaticness
	large rendered façades	Y20R + Y30R Y70R + Y80R	*R90B + B + B10G* *B30G + B40G + B50G*	General rules proposed by Angelo and Booker + Same chromaticness

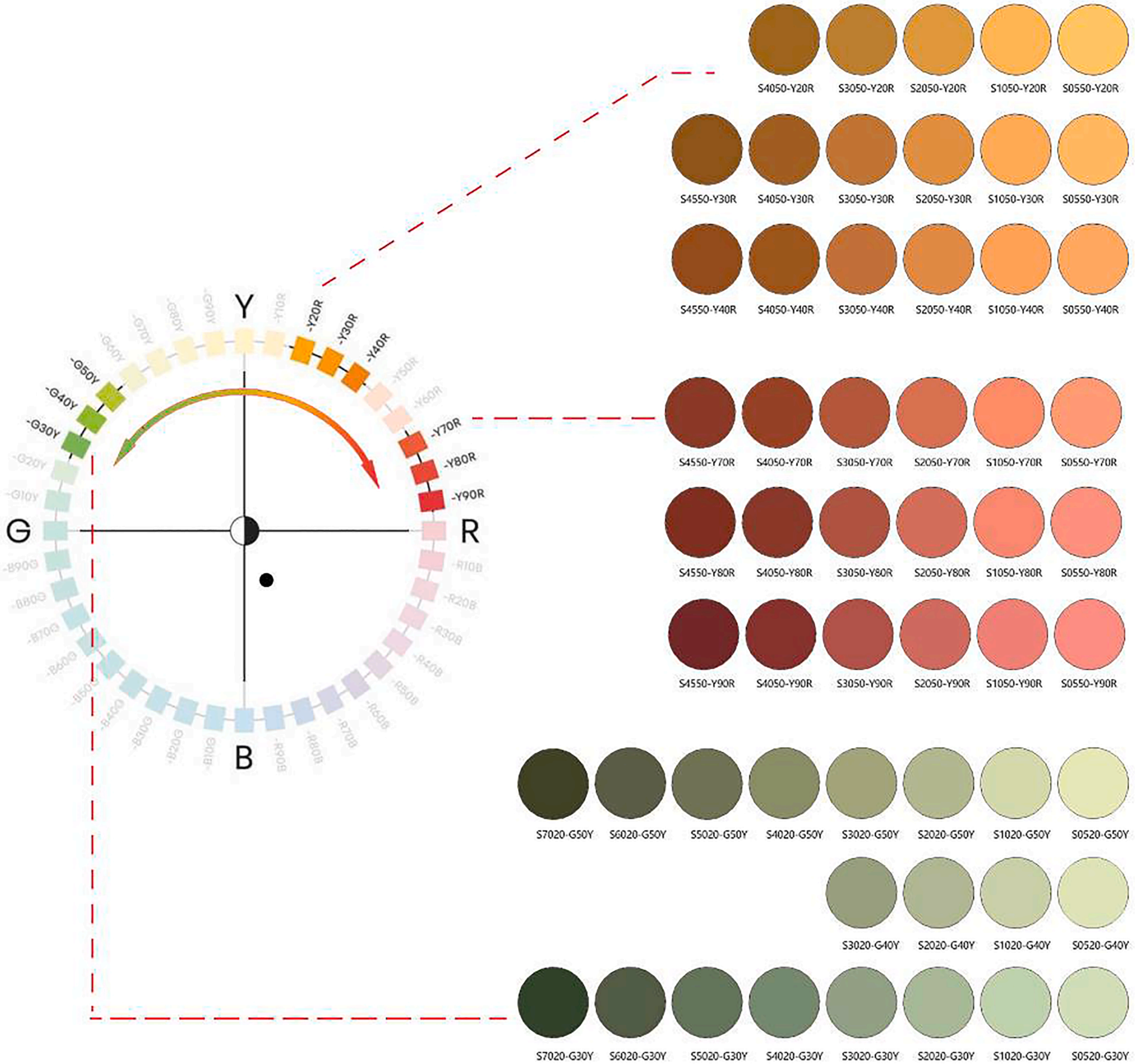


Fig. 10. Typical NCS colours for monotonous and analogous colour harmony design in wooden context.

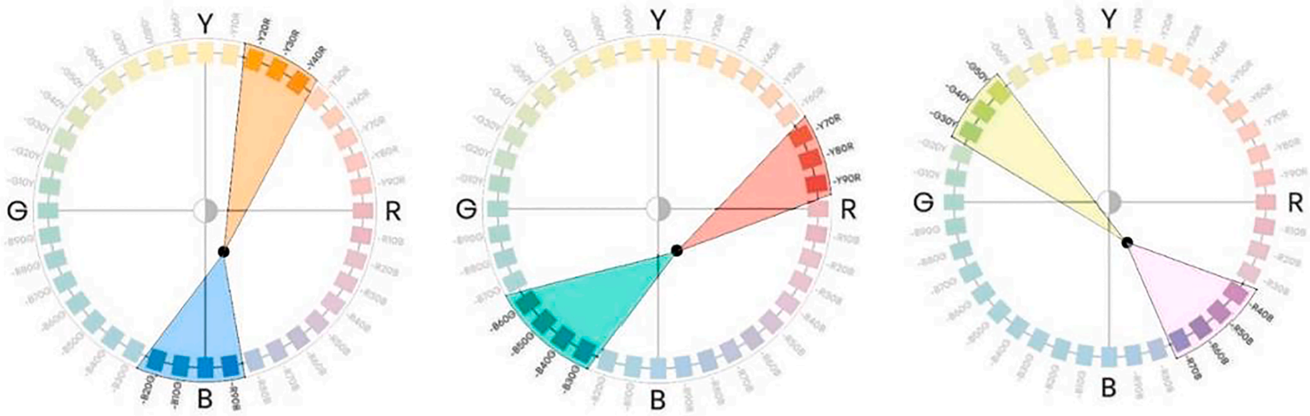


Fig. 11. Hue sets: Y20R- Y40R and R90B-B20G, Y70R-Y90R and B30G-B60G, G30Y-G50Y and R40B- R70B.

Fig. 12. Selected NCS colour combinations for FIPV design, Hues: Y20R- Y40R and R90B-B20G, Chromaticness: 50%

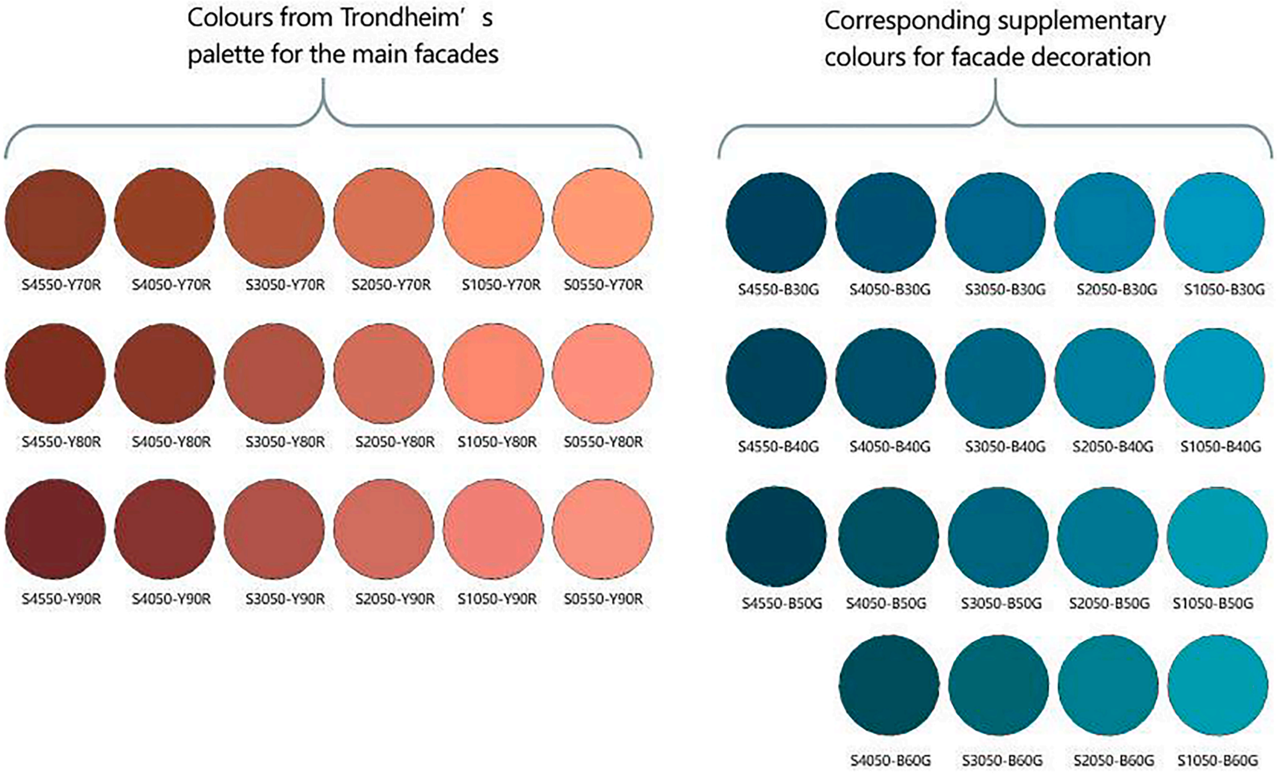


Fig. 13. Selected NCS colour combinations for FIPV design, Hues: Y70R- Y90R and B30G-B60G, Chromaticness: 50%

new high-rises) in relative less sensitive urban context outside city center (Fig. 9), the typical hues derived from brick or rendered facades were used as hue reference (Tables 1 and 2). Complementary and split-complementary colour harmony strategies were also applied in design proposals especially for decoration on FIPV facades. Hues for primary façade areas are grouped for different contexts (wooden, brick and large rendered facades), the corresponding complementary and split-complementary hues can be used in window frames, balcony areas

Fig. 14. Selected NCS split complementary colours for FIPV design, Hues: G50Y-G30Y and B30G-B60G, Chromaticness: 20%

etc. as supplementary hues. To provide more colour choice for architects and create preferred moderate complexity for aesthetic performance (Nasar, 2000), supplementary hues can be outside of Trondheim's colour palette (Table 3).

Chromaticness is a key parameter of NCS nuance influencing the aesthetic performance of FIPV. In both sensitive and less sensitive urban contexts, the chosen chromaticness levels for FIPV designs considered the general colour design rules proposed by Angelo and Booker (2018), who also warn against greying trend of current Norwegian architecture design with low chromaticness (Booker and Angelo, 2018, 2016). Therefore, relatively high chromaticness levels are applied (NCS colours) for FIPV design proposals. For instance, in the following FIPV design proposals in sensitive contexts, 50% chromaticness was chosen for yellowish and reddish hues, and 20% chromaticness was chosen for greenish hues (see Fig. 5), while the most common yellowish and reddish NCS colours in current Trondheim contexts varies between 30% or 40% chromaticness (e.g. S 3030-Y30R), and typical greenish NCS colours have around 10% chromaticness (e.g. S3010-G50Y). Bluish colours are rare exceptions in Trondheim's context. Therefore, they were not discussed as a colour for main facades in following FIPV design proposals.

4.3.1. *NCS colour sets for FIPV in sensitive contexts*

Selected NCS colour sets for FIPV in a sensitive context were demonstrated in the diagrams below. Fig. 10 showed the colour sets for monotonous and analogous colour design of FIPV in main façade areas.

Complementary and split-complementary colour harmony strategy could improve the 'moderate complexity' of FIPV facades and create pleasant visual attractiveness. Figs. 11–14 showed hue and colour combinations for FIPV with consideration of using Complementary and split-complementary colours as supplementary façade decoration colours.

Corresponding complementary and split complementary colours could be applied for window frames, balconies and other decoration

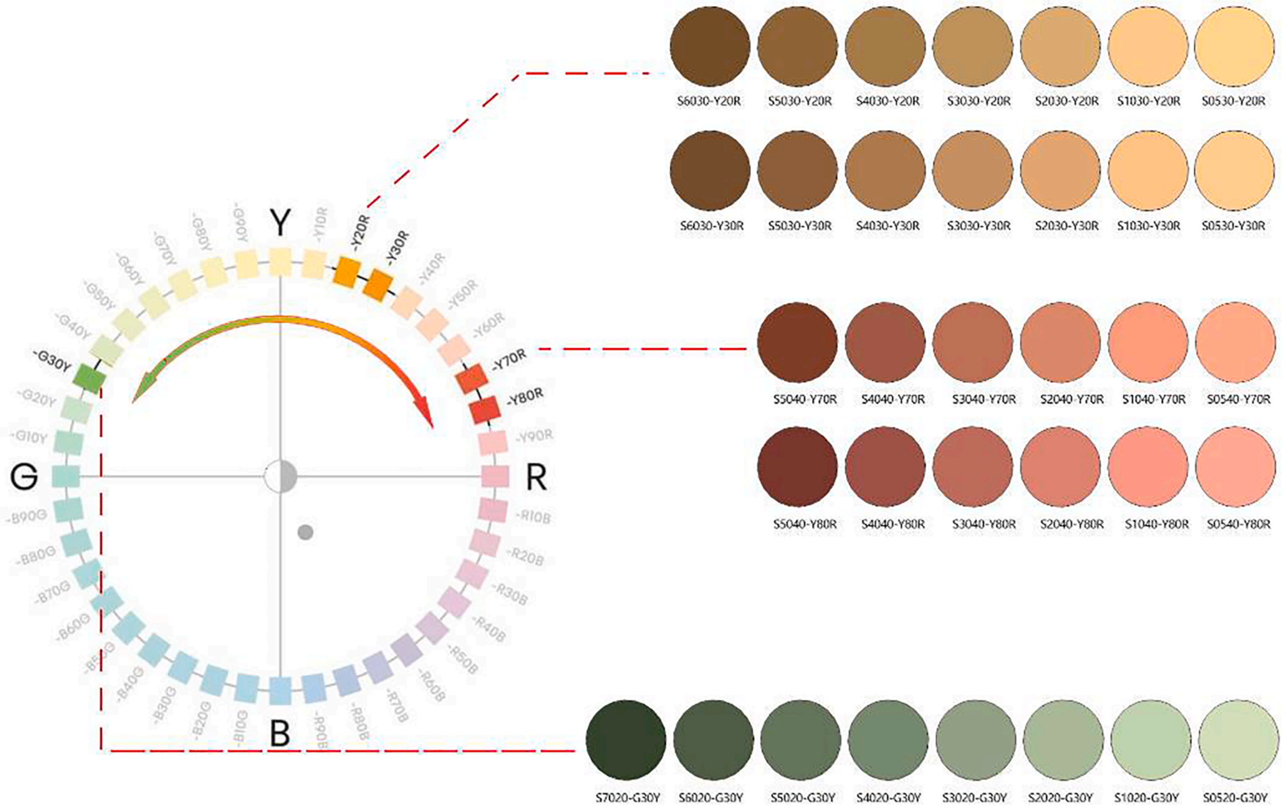


Fig. 15. Typical NCS colours for monotonous and analogous colour harmony design in brick and large rendered context.

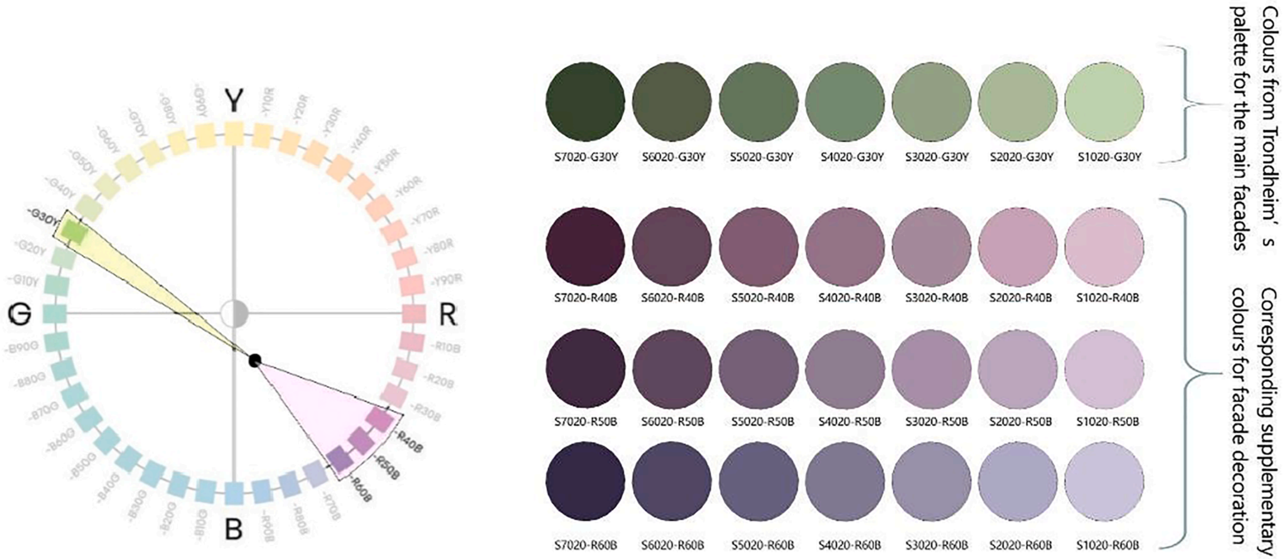


Fig. 16. NCS complementary and split complementary hues: G30Y and R40B-R60B (left) and colours with chromaticness of 20% (right).

areas of building facades as supplementary colours. These complementary NCS colours may be outside Trondheim's colour palette and can enrich the colour choices for architects.

4.3.2. NCS colours for FIPV in less sensitive context of Trondheim.

The colour palette of Trondheim showed that the general chromaticness level in less sensitive areas is lower than in traditional center areas. Figs. 15–18 demonstrated the selected NCS colours set for FIPV in less sensitive context.

4.4. Online aesthetic survey method

To examine the proposed theoretical pixelization method, an online international survey was designed to test hypothesis in research question 2. In the survey, the city of Trondheim in Norway was taken as a case study and two main façade prototypes (multi-story and high-rise building) are derived from Trondheim's urban context for FIPV designs. The semantic differential scale, a widely used rating method to measure attitudes or the meaning of concepts (Osgood et al., 1957) was employed in this survey to allow quantitative analysis of participants'

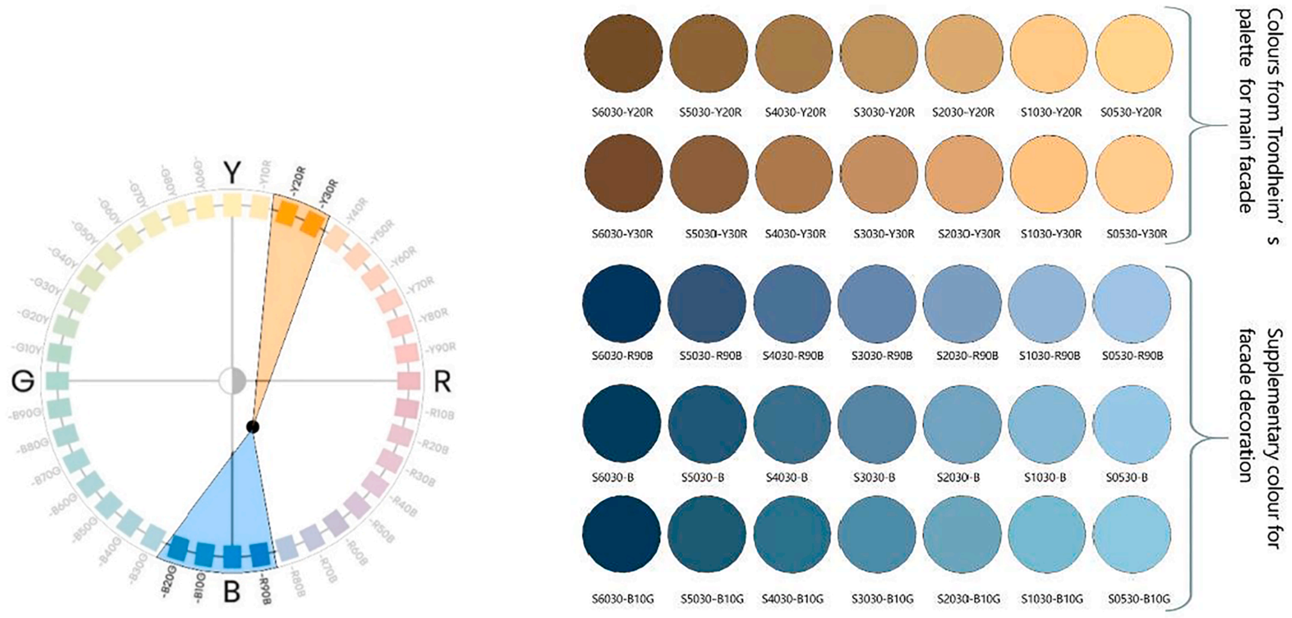


Fig. 17. NCS complementary and split complementary hues: Y20R, Y30R and R90B-B10G (left) and colours with Chromaticness of 30% (right).

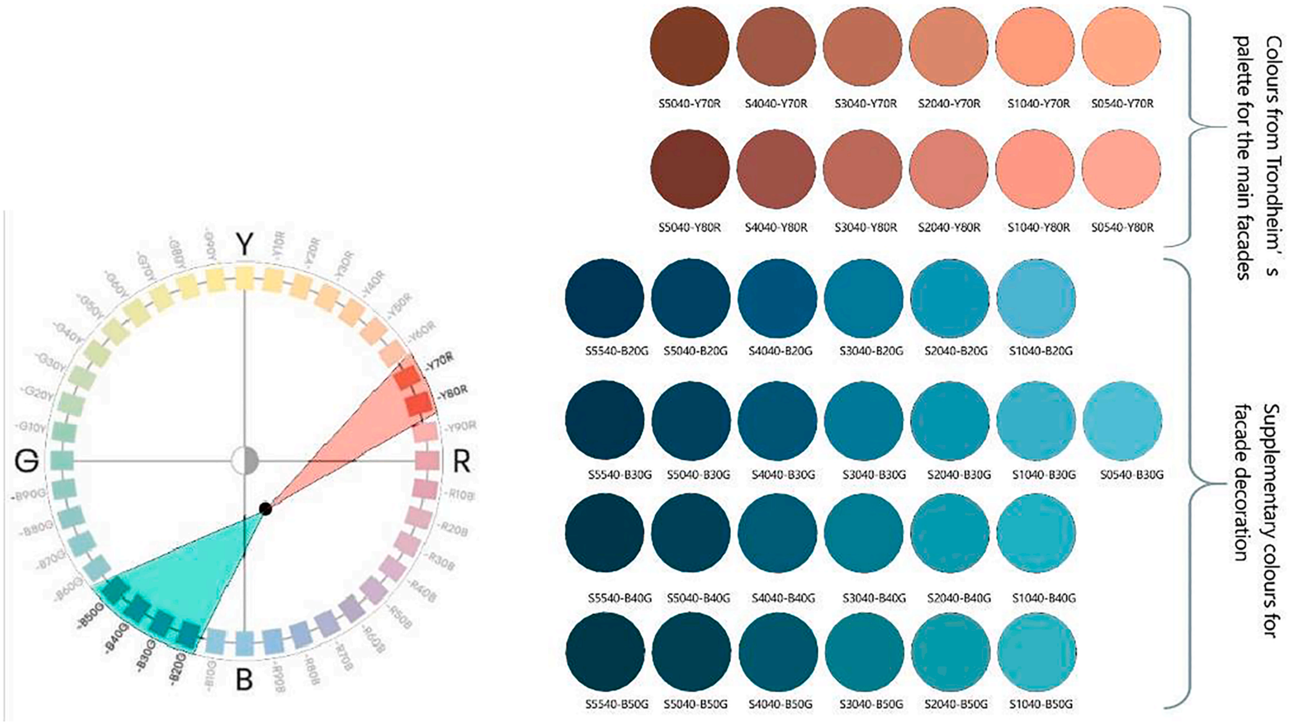


Fig. 18. NCS Complementary and split complementary hues: Y70R, Y80R and B20G-B50G (left) and colours with Chromaticness of 40%

subjective preferences. In the first part of the survey, the basic data about participants like gender, age, professional background, and also their general attitudes towards FIPV were collected. In the second part, participants were asked to evaluate aesthetics of the derived two façade prototypes (without a context) and their corresponding pixelization FIPV designs. Participants were asked to rate their preference on the 5-level semantic differential scale. In the third part, pixelization design proposals for real buildings in the urban context of Trondheim were presented Participants were asked to evaluate the integration levels of pixelization FIPV design proposals on the same 5-levels semantic differential scale.

5. Pixelization design and proposals of FIPV in Trondheim

The first research question *'How to develop pixelated FIPV designs in the context of Trondheim city?'* will be answered in this section. With selected NCS colour sets for different urban contexts, architects can play with colour design for the FIPV to express their design styles or individual artistic ideas.

5.1. Pixelization design

It is interesting to notice that many realized architecture projects

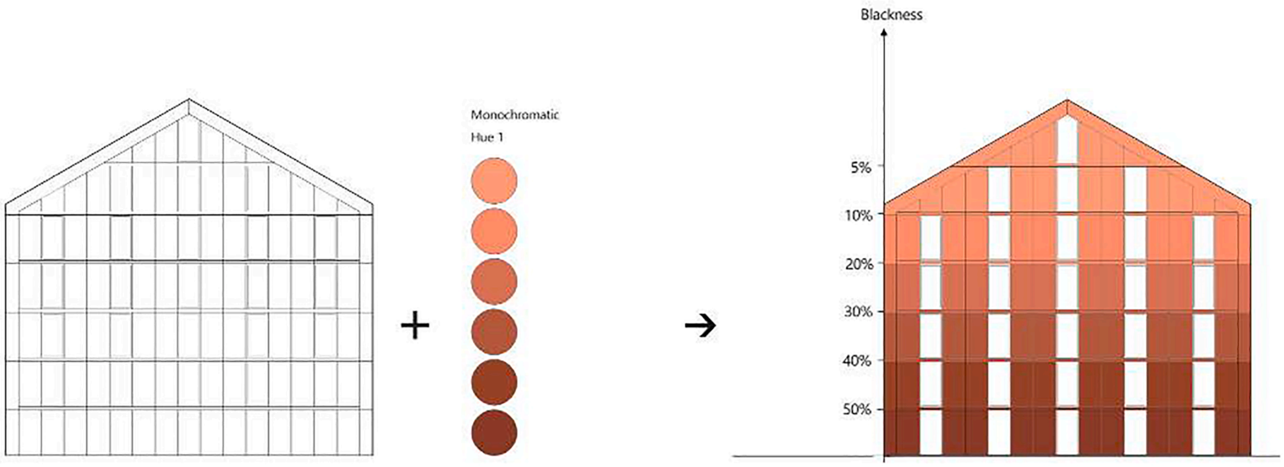


Fig. 19. Diagram of pixelization method for applying monotonous NCS colours in main façade areas.

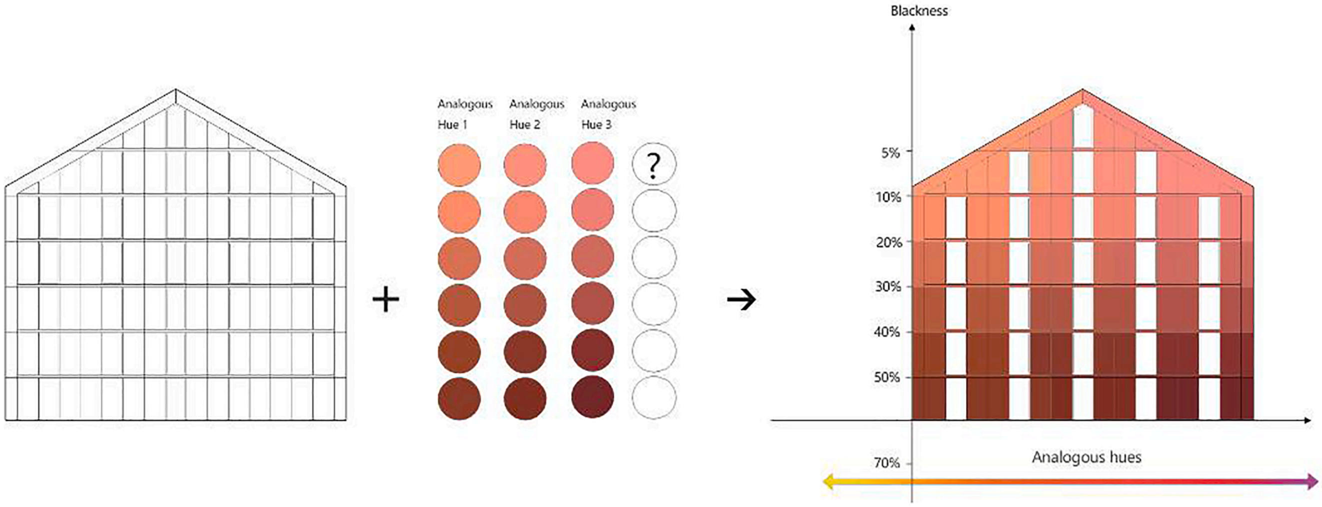


Fig. 20. Diagram of pixelization method for applying analogous NCS colours in main façade areas.

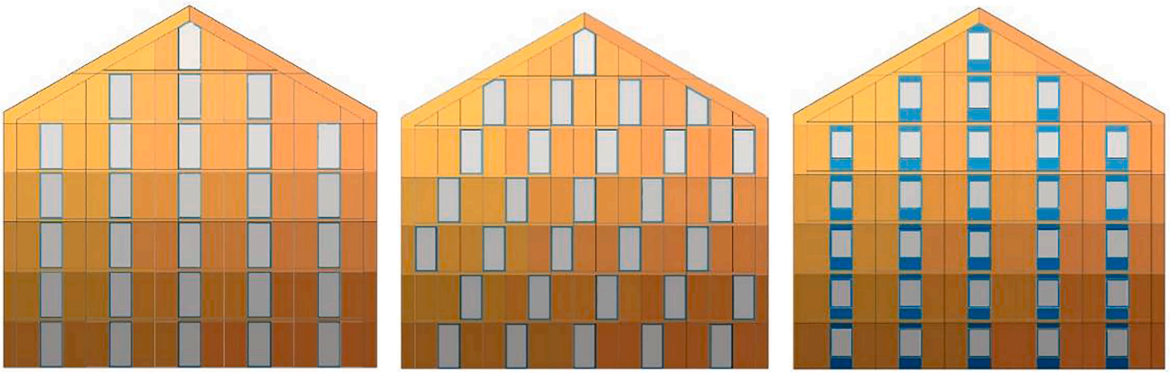


Fig. 21. Split complementary colour harmony design proposals (Hue Y20R, Y30R, Y40R and B with chromaticness = 50).

with pixelization design share a common architectural expression of gradually reducing the blackness level of facades from facades bottom to the top (brandt + simon architekten, 2019; dRMM, 2019a, 2019b; Reiulf Ramstad Architects, 2019). In this study, a pixelization method that aims to generate harmonious colour combinations was presented. It utilized the colours according to an order, created moderate complexity for FIPV design and respected the historical significance/local identity. To create a harmonious colour performance of FIPV facades, this pixelization method organized colours on facades in orders and variations, with focused on both ***hue*** and ***nuance*** (blackness and chromaticness) (Figs. 19 and 20).

For the main facades area, the FIPV panels with selected NCS colours were suggested to be arranged in an order, the transit in hues and nuances aimed to provide clear order and moderate complexity in facades

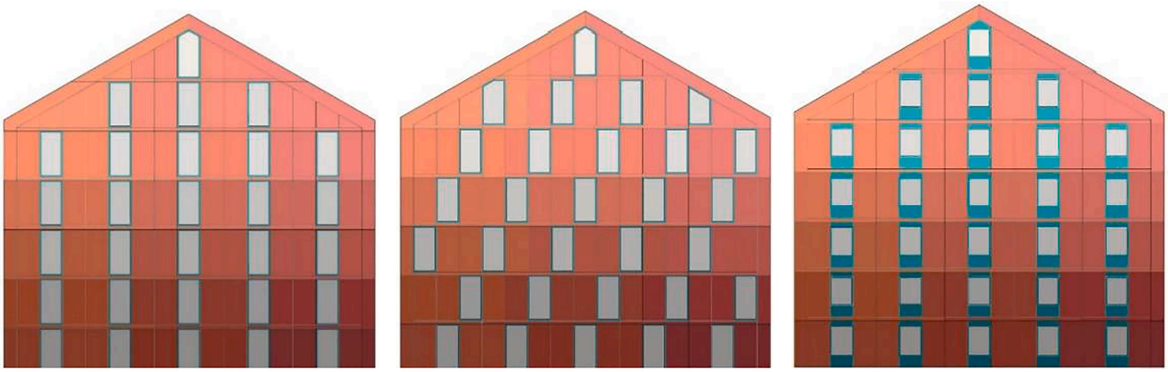


Fig. 22. Split complementary colour harmony design proposals (hue Y70R, Y80R, Y90R and B40G with chromaticness = 50).

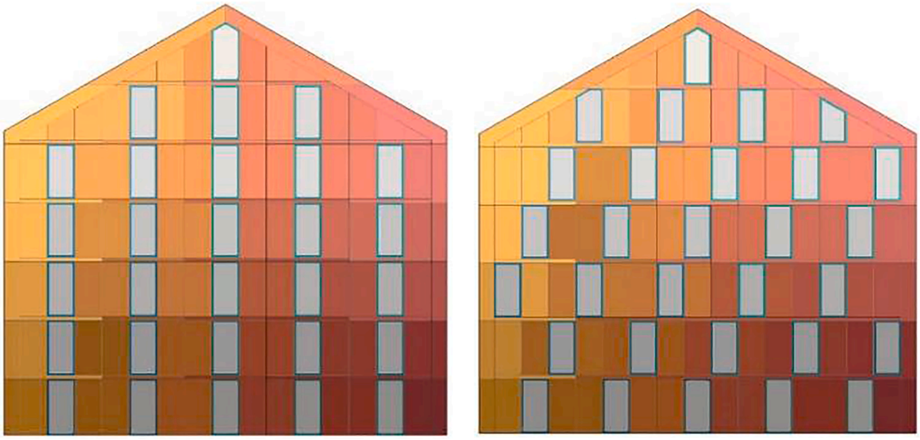


Fig. 23. Colour harmony design proposals (hue Y20R to Y90R, B and B40G with chromaticness = 50).

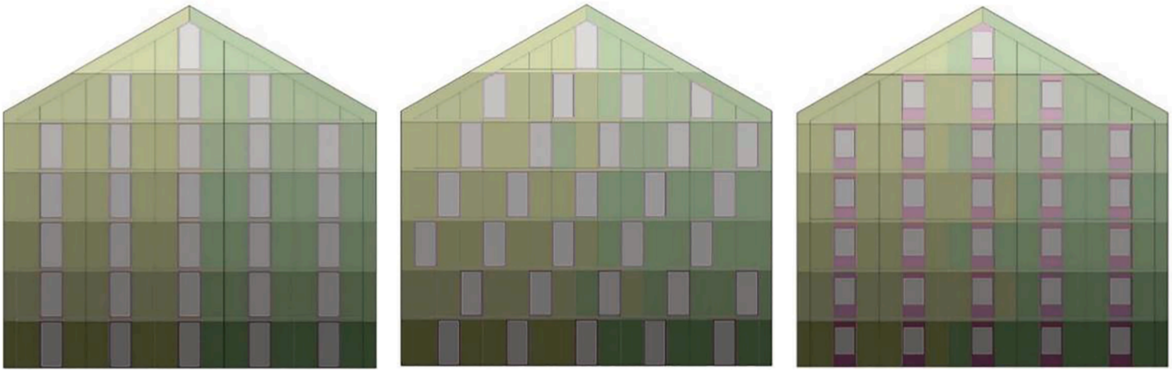


Fig. 24. Split complementary colour harmony design proposals (hue G50Y, G30Y, R40B with chromaticness = 20).

while the selected NCS colour sets based on local context can promise a color coherence with historical significance/ local identity:

(1) Horizontally, colours are in the same hue (monotonous hue) or transit gradually among analogous hues.
(2) Vertically, colours transit gradually in blackness level, from highest blackness on the lowest floor and lowest blackness on the top.
(3) The same facades share equal or close chromaticness level(s).

For supplementary façade areas like decoration elements, usages of Complementary or split-complementary colours were encouraged, which can give architects rich choices of colour design.

5.2. IPixelization design proposals in different contextual scenarios

Detailed pixelization proposals were categorized into two scenarios in Trondheim: *FIPV proposals in a sensitive urban context* and *FIPV proposals in a less sensitive urban context.*

5.2.1. Pixelization design proposals for multi-story houses in Trondheim's sensitive context

For multi-story building façade proposals in a sensitive context with colourful wooden houses, the colours of FIPV need to respect the identity of traditional urban image. Reddish, yellowish and greenish colours are common in Trondheim's traditional warehouses, these NCS colours could be used with monochromatic and analogous harmony strategies

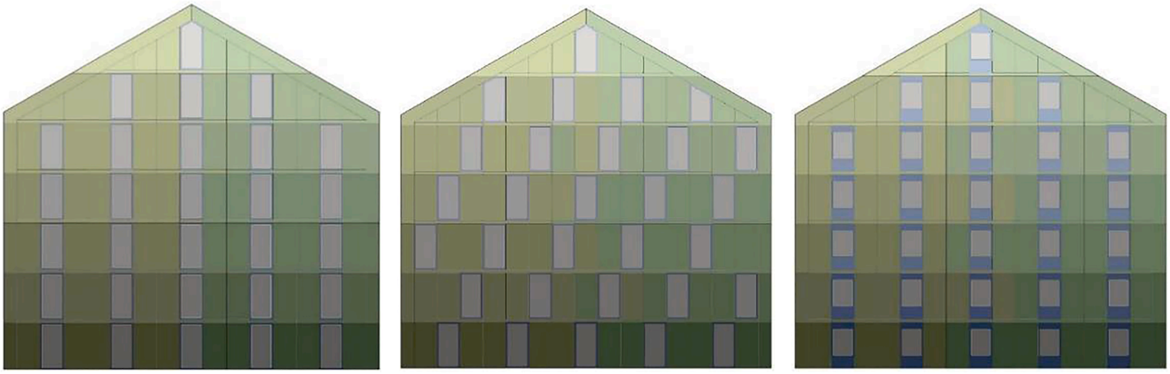


Fig. 25. Split complementary colour harmony design proposals (hue G50Y, G30Y, R70B with chromaticness = 20).

Fig. 26. Selected renovation building by Nidelva River (inside the red dash frame). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 27. Renovation proposal 1 with FIPV in hues of Y70R + Y80R + Y90R (chromaticness = 50).

for main FIPV facades. Fig. 21 showed pixelated FIPV proposals with typical yellowish hues: Y20R, Y 30R and Y40R. Three types of window-arrays were presented in design proposals to demonstrate some typical modern façade styles (large windows in an ordered array, large windows in random array, small windows). Windows of façade prototypes were shown with the neutral grey colour which represents a reflection of overcast, grey sky during long periods of the year. The frequency of clear sky in Trondheim is only 20–30%. Also, for an observer standing in a short distance from the façade, the blackness level of the reflected sky on the window glass decreases with the height since the brightest area of the sky (zenith) is reflected from the top windows. Similarly, Fig. 22 showed pixelated FIPV proposals with typical reddish hues: Y70R, Y 80R and Y90R.

Fig. 23 showed slightly different proposals with combination of hues in Y20R, Y30R, Y40R, Y70R, Y80R and Y90R. It was interesting to see the effect of combing all these neighbouring hues with the same chromaticeness (C = 50) in the FIPV design: even though there was a small gap that interrupts the continuity of analogous hue range (Y50R, Y60R were missing since they are not in Trondheim's colour palette, see Fig. 13), the façade colours still showed a relatively smooth transition.

Fig. 28. Renovation proposal 2 with FIPV in hues of Y70R + Y80R + Y90R + B40G (chromaticness = 50).

Fig. 29. Selected renovation building by Nidelva river (inside the red dash frame). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 30. Renovation proposal 1 with FIPV in hue G30Y + G50Y (chromaticness = 20).

Green colours are the most beneficial ones regarding energy production, a recent study showed that for PV of equal lightness, green photovoltaics has a theoretical potential to obtain higher energy efficiency than reddish and yellowish ones (Røyset et al., 2020). Figs. 24 and 25 demonstrated the FIPV proposals in greenish hues (G30Y and G 50Y)

The above-proposed design strategies of FIPV could be applied in a real building. In the following subchapters, a series of FIPV application cases were proposed.

FIPV proposal for multi-story house case1. A reddish historical warehouse (Fig. 26) was selected as an application case, the façade geometry and its window design were slightly modified to fit the modular design of FIPV. Two proposals were presented, one with pixelated FIPV in a combination of analogous reddish NCS colours (in hues of Y70R, Y80R, Y90R, chromaticness = 50%), the other with pixelated FIPV in a combination of reddish NCS colours and also corresponding split-Complementary bluish NCS colours around windows as decoration design (Figs. 27 and 28).

Fig. 31. Renovation proposal 2 with FIPV in hue G30Y + G50Y + R40B (chromaticness = 20).

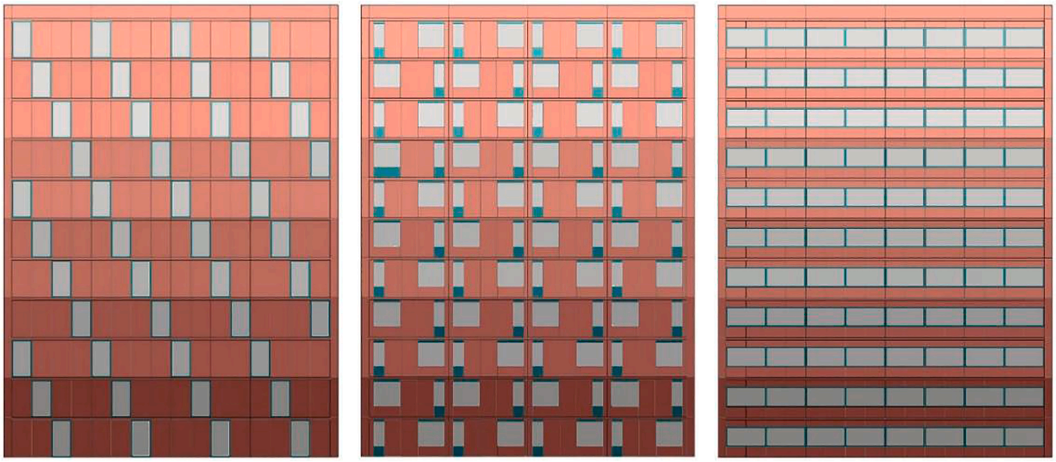


Fig. 32. Split complementary colour harmony design proposals (hue Y80R and B40G with chromaticness = 40).

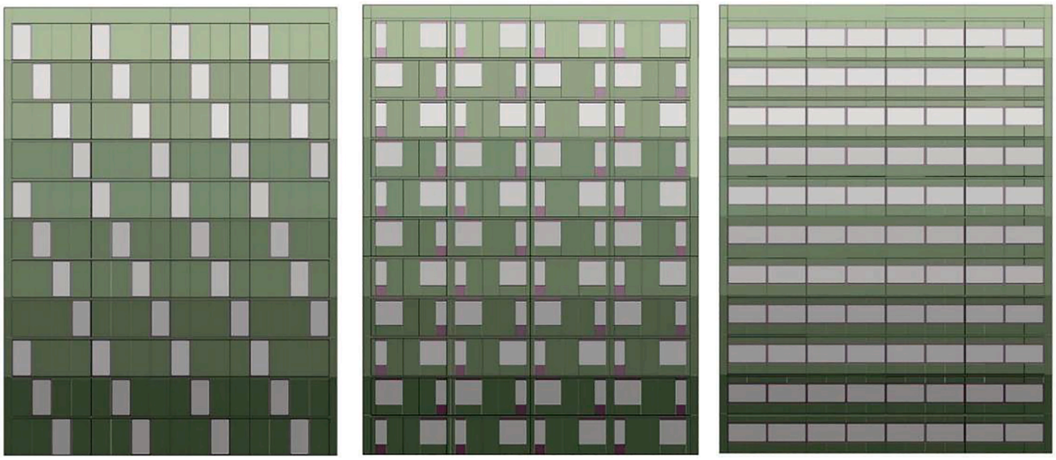


Fig. 33. Split complementary colour harmony design proposals (hue G30Y and R40B with chromaticness = 20).

FIPV proposal for multi-story house case2. Similarly, an existing greenish warehouse alongside Nidelva river was chosen as application case 2 (Fig. 29). Two proposals with analogous greenish NCS colours (in hues of G30Y, G50Y, chromaticness = 50%) were presented. One with only analogous colour FIPV, and a white colour for window frames (the other warehouses on this side of the river have white windows), Fig. 30, the other also employed split-complementary NCS colours in window frame areas, Fig. 31.

5.2.2. Pixelization design proposals for a high-rise in less sensitive urban context

Typical NCS colours in Trondheim's brick/rendered context were used as references in less sensitive urban context. Figs. 32–34 presented design proposals for façade prototype geometry of high-rise buildings in

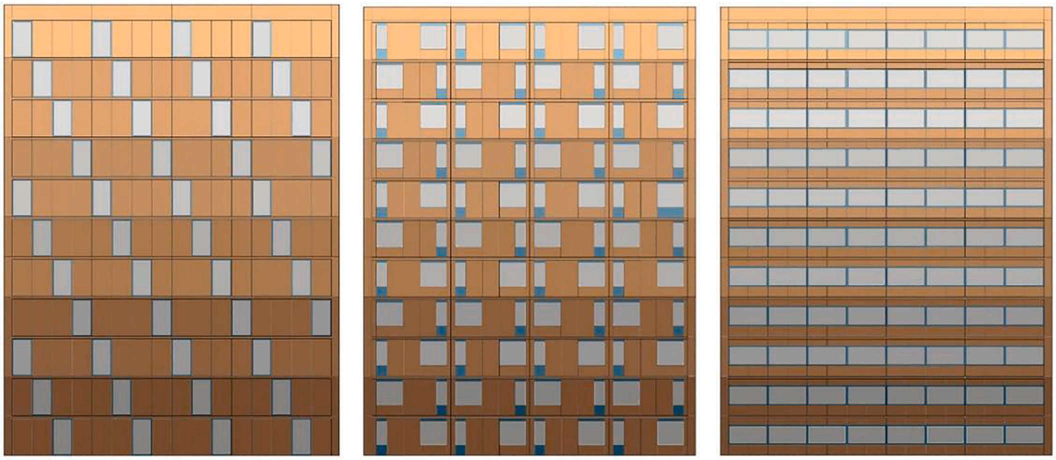


Fig. 34. Split complementary colour harmony design proposal 25 (hue Y30R and B with chromaticness = 30).

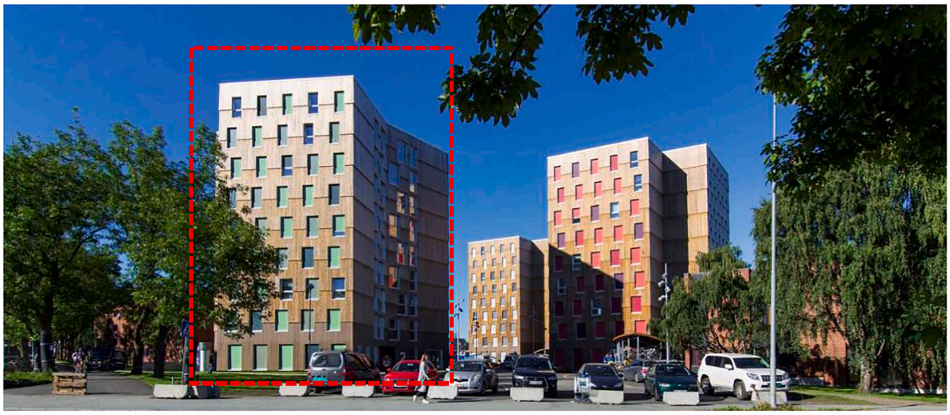


Fig. 35. Moholt student apartment tower in Trondheim.
Source: www.archdaily.com.

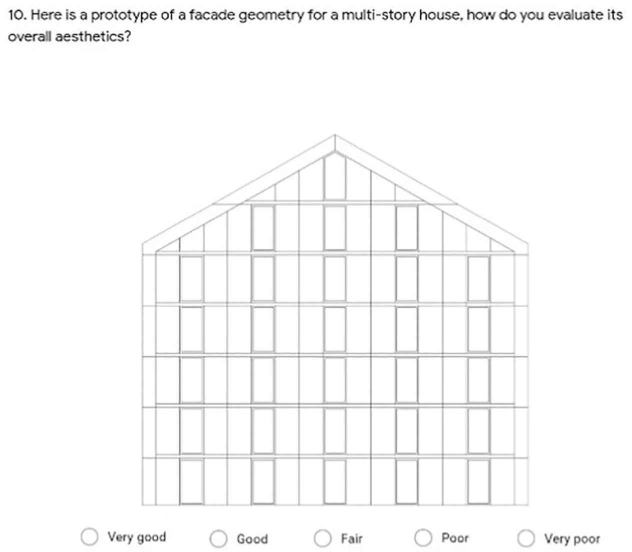
Fig. 36. FIPV renovation design proposal with monochromatic NCS colours in hue Y30R, chromaticness = 30%.

reddish, greenish and yellowish hues:

FIPV design proposal of high-rise project 1. A high-rise apartment in the Moholt district, Trondheim (Fig. 35) was chosen as FIPV application case, the existing building facades were wooden claddings with yellowish colours. A set of typical NCS yellowish colours (hue Y30R, chromaticness = 30%) were applied in the FIPV renovation design for the apartment's facades. (SEE Fig. 36)

To answer research question 1 in brief, in this study, pixelization design for FIPV is developed through the following steps:

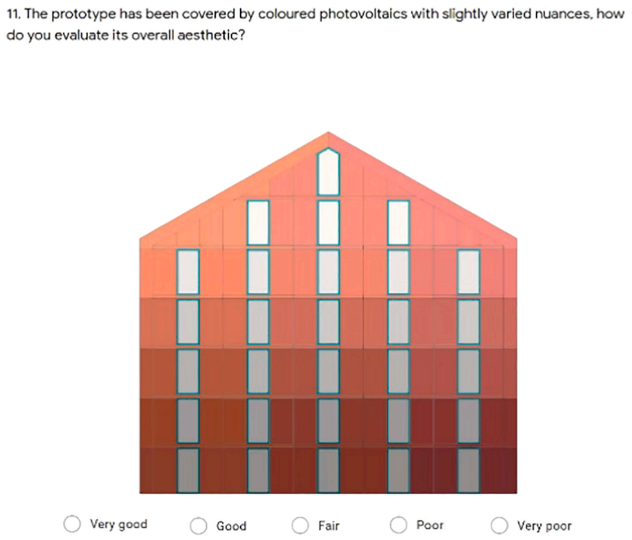
(1) Colour strategies at the urban and the building levels were proposed based on environmental aesthetic theories and colour harmony concepts.
(2) Typical building façade geometries were derived from local urban contexts.
(3) NCS colour sets for FIPV designs were selected according to proposed colour strategies and local colour palettes.
(4) Pixelization designs for FIPV were generated through organizing selected NCS colours on facades in orders and variations, with focus on both hue and nuance.



10. Here is a prototype of a facade geometry for a multi-story house, how do you evaluate its overall aesthetics?

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

Fig. 37. Preference evaluation of multi-story facade prototype.



11. The prototype has been covered by coloured photovoltaics with slightly varied nuances, how do you evaluate its overall aesthetic?

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

Fig. 38. Preference evaluation of pixelated FIPVs design for multi-story facade prototype.

6. Online aesthetic survey

To examine the proposed theoretical pixelization method in this study and to answer the research question 2: “*Can the proposed pixelization method provide FIPV designs harmoniously integrated into the urban context and provide aesthetically preferred façades?*”, an online international aesthetic survey was carried out. This anonymous survey was designed mainly to collect subjective aesthetic preference of people for proposed pixelated FIPV designs. People of all ages, genders and all backgrounds (e.g. architecture/urban design/fine art or layperson) are 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. Questions in the first part are listed below:

Question 1 – What do you think about application of PVs on building roofs and facades? (very supportive, supportive, neutral, against, very against)
Question 2 – How do you evaluate your knowledge and/or experience with photovoltaics? (rich, good, some, little, no experience)
Question 3 – Are you an architect/ designer /urban planner /fine artist/ or a student of those professions? (Yes, no)
Question 4 – What is your country of origin?
Question 5 – In which country have you lived in the last two years?
Question 6- What is your gender?
Question 7 – And your age? (less than 30; 30–50; more than 50)
Question 8 – Have you been to Trondheim city center in the last ten years? (Yes, No)
Question 9 – What is your email address (optional)

The second part of this survey was designed to examine the proposed theoretical pixelization method. In this part, 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 buildings in Trondheim, on a 5-level semantic differential scale rating from “*Very good*”, “*Good*”, “*Fair*”, “*Poor*” to “*Very Poor*” (Fig. 37-*Question 10:Here is a prototype of a facade geometry for a multi-story house, how do you evaluate its overall aesthetics?*). Then a pixelated FIPV design for the multi-story façade prototype with NCS colours in analogous hues of Y70R, Y80R, Y90R was presented and evaluated with the same 5-level semantic differential scale (Fig. 38-*Question 11: The prototype has been covered by coloured photovoltaics with slightly varied nuances, how do you evaluate its overall aesthetic?*).

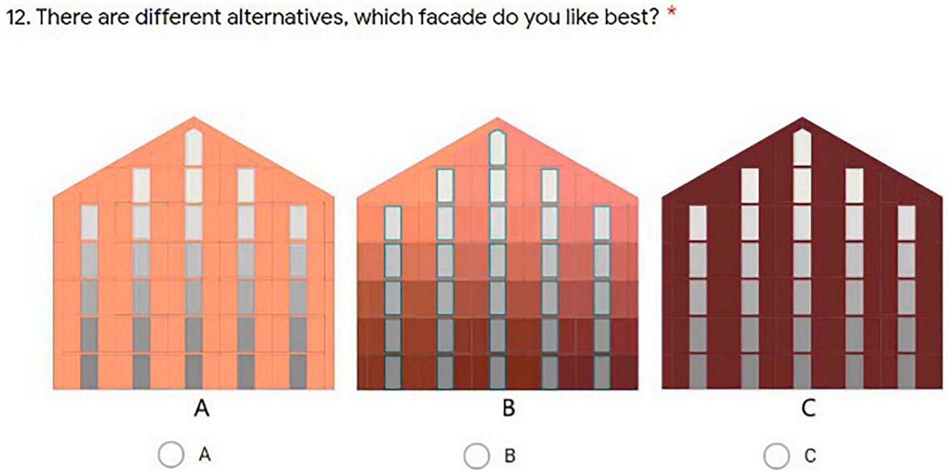
In addition, the aesthetic performance of the pixelated FIPV design for multi-story façade prototype was compared with two non-pixelated FIPV designs (in hue Y70R and Y90 R respectively) by asking participants to choose their most preferred one among them(Fig. 39-Question 12).

Three similar questions for the high-rise building typology were following, participants were asked to evaluate the aesthetic of high-rise facade prototype, aesthetic of pixelated FIPV design for high-rise prototype with NCS colours in hue Y30R, and to choose the most preferred design among pixelated and non-pixelated FIPV designs (Fig. 40-Question 15). It was expected that the pixelated FIPV designs will be more preferred than the original multi-story/high-rise prototypes and also the non-pixelated designs according to the theoretical hypothesis that pixelization design with colour harmony strategies and moderate complexity can provide aesthetically pleasing effects.

In the third part of the survey, the hypothesis for research question 2: “*pixelization method can provide FIPV designs that are harmoniously integrated into the urban context*” was tested with aesthetic evaluation of a series of pixelization design proposals for real buildings in Trondheim’s urban context, the same 5- levels semantic differential scaling as in the second part was employed. Participants were asked to evaluate the environmental context integration levels of pixelization FIPV design proposals for real multi-story buildings and high-rise case in Trondheim (Fig. 41-Question 16, Fig. 43-Question 18, and Fig. 44-Question 20).

Besides, the aesthetic performance of presented pixelization FIPV designs for real buildings were also evaluated (e.g. Fig. 42-Question 17) to further test the hypothesis in research question 2 “*pixelization design can provide aesthetically preferred façades?*” with real building cases. In the final session of the survey, participants can leave their comments as additional feedback. To avoid number preference bias, the numerical rating was not given in the survey but was assigned when the data was analysed (e.g. 1 = Very poor to 5 = Very good). The concept of pixelization was not mentioned throughout the survey text to avoid any potential preconceived judgment.

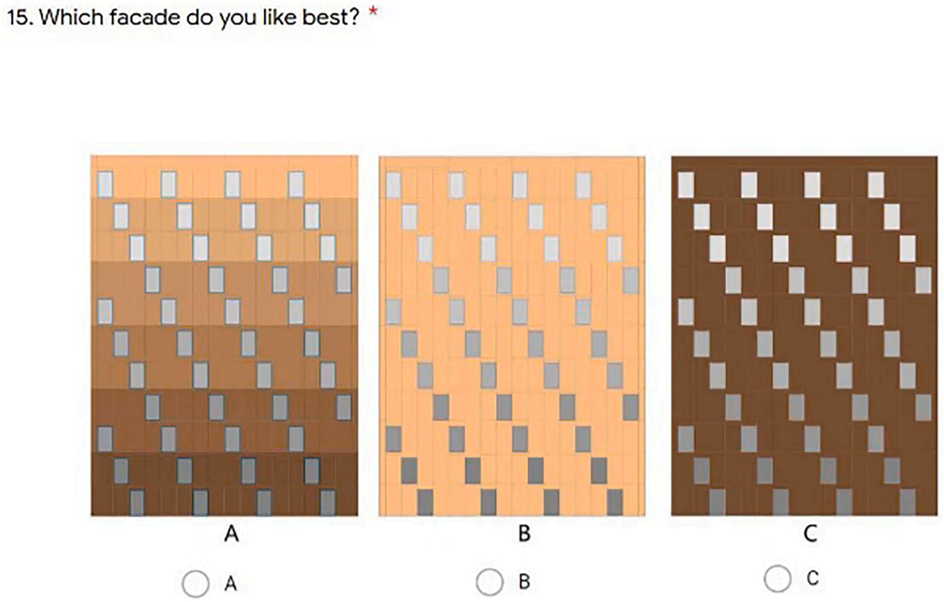
Before sending out the formal survey invitation, a trail test was conducted inside the Light and Colour Center research group in



12. There are different alternatives, which facade do you like best? *

○ A ○ B ○ C

Fig. 39. Preference evaluation of pixelization and non-pixelization design, multi-story designs.



15. Which facade do you like best? *

○ A ○ B ○ C

Fig. 40. Preference evaluation of pixelization and non-pixelization design, high-rise design.

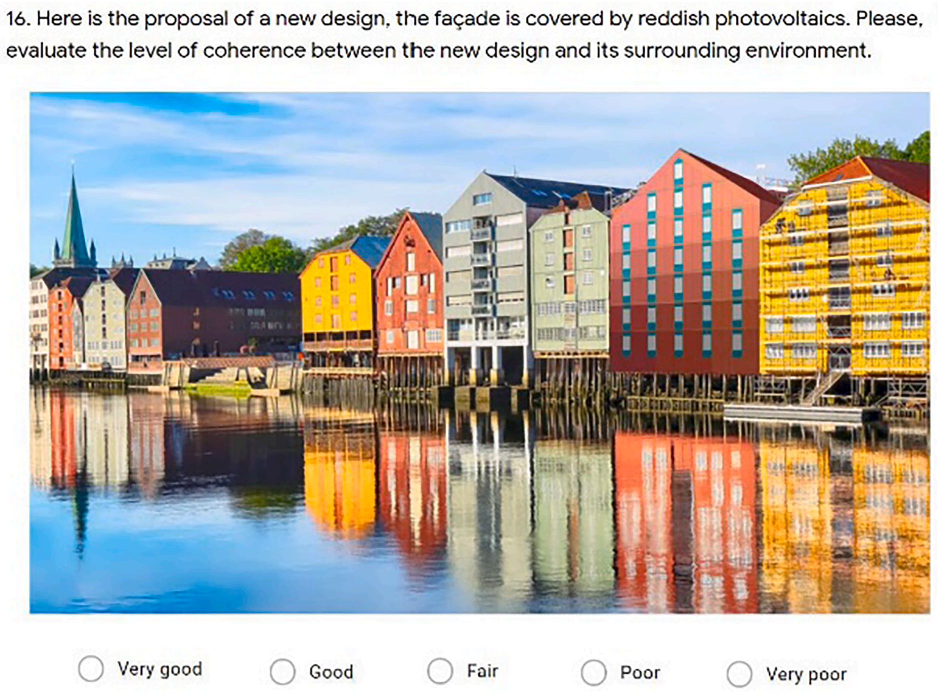
Norwegian University of Science and Technology to make sure the survey could be easily assessed and conducted, and all photos and text in the online survey can be loaded smoothly. After that, the survey invitation link was sent out through emails, announcements on university website, posts on social media like Facebook and WeChat to invite people from all backgrounds.

In total 309 participants living in various countries (including Norway, Denmark, China, Poland, Netherlands, Italy, Australia, USA, Japan, Brasilia, etc.) took part in this survey, 42% of participants were 'experts' with education (master or above level) or working experience in architecture, urban design or fine arts fields, while the rest were 'laypersons' without related backgrounds (Fig. 45).

IBM SPSS (version 27) and Microsoft Excel were used to analyse the survey 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 urban context. Results are found from the analysis:

(1) There is a clear supportive attitude towards the application of FIPV, in total 81% of participants choose to support or very support this concept (Fig. 46).
(2) For two façade-prototypes, the pixelated FIPV designs were more preferred than non-pixelated FIPV designs when they have the same or similar hues (Fig. 47).
(3) Participants showed a general preference towards the aesthetic qualities of presented pixelated FIPV designs.
(4) The presented pixelated FIPV designs were perceived well integrated into urban contexts by the majority of participants (more than 50%).

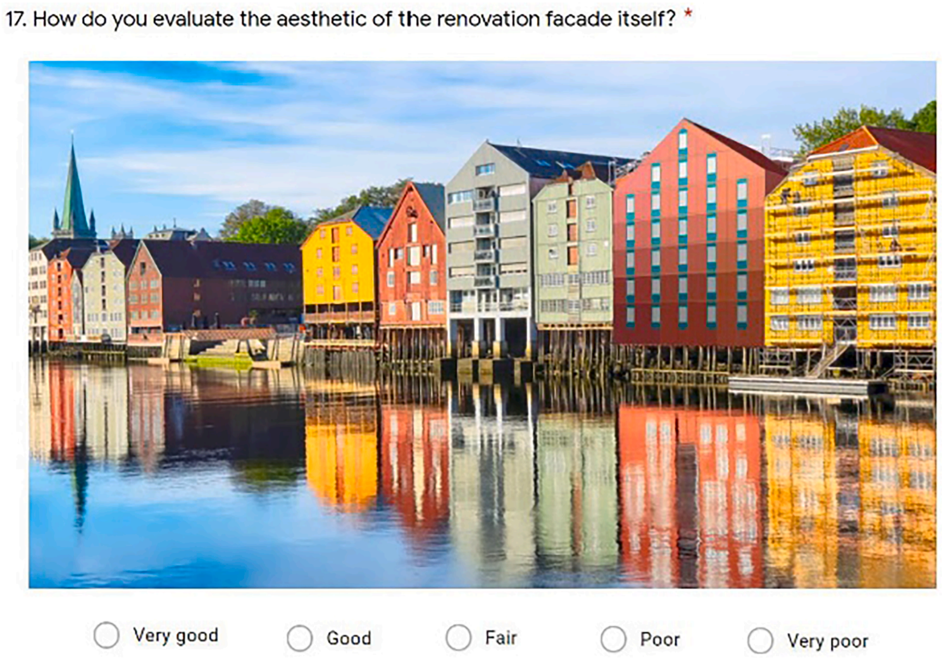
For multi-story and high-rise prototypes, the mean values of rated aesthetic qualities were increased when pixelated FIPV designs were applied (Tables 4 and 5). Besides, comparing with non-pixelated FIPV designs in the same or similar hues, pixelated FIPV designs were most preferred by participants (Fig. 47). This indicated that pixelated FIPV designs can potentially promote the façades' aesthetic qualities and have aesthetical advantages compared to non-pixelated FIPV design when using PV in the same or similar hues.



16. Here is the proposal of a new design, the façade is covered by reddish photovoltaics. Please, evaluate the level of coherence between the new design and its surrounding environment.

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

Fig. 41. Contextual integration evaluation of pixelization façade design, reddish multi-story house in Trondheim.



17. How do you evaluate the aesthetic of the renovation facade itself? *

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

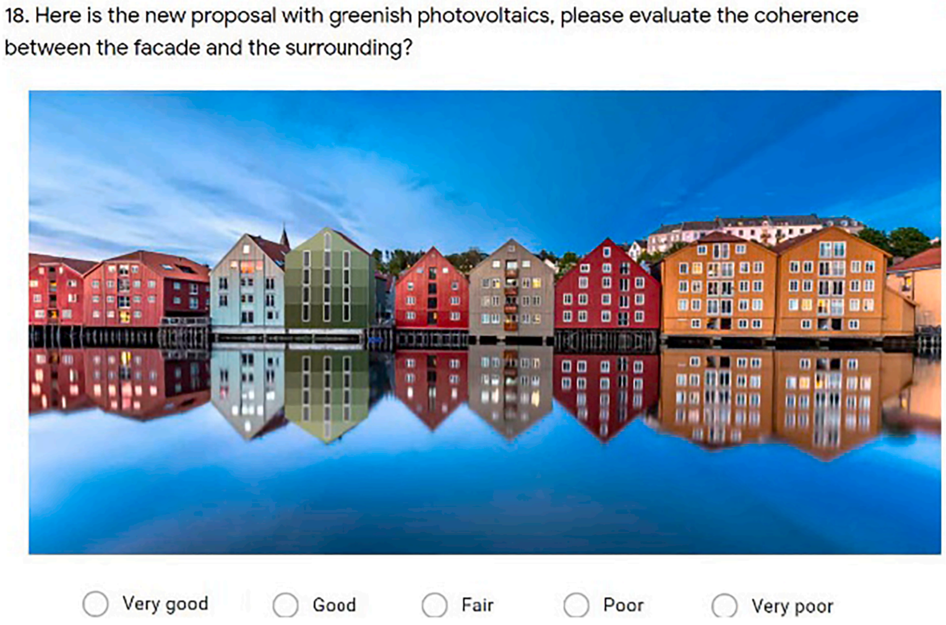
Fig. 42. Preference evaluation of pixelization façade reddish multi-story house in Trondheim.

For pixelated FIPV façade proposals for 3 building projects in Trondheim, rating results from both the architects/urban designers group and layperson group shared the same trend: Mean values of rated aesthetic quality levels and contextual coherence levels were in the ranges of 3.36–4.15 and 3.45–4.28 respectively (Figs. 48 and 49).

The results supported the hypothesis in research question 2: pixelization method can provide FIPV designs that are harmoniously integrated into the urban context and with aesthetically pleasing façades. In addition, laypersons tended to rate the presented pixelated FIPV proposals with 'higher scores' in both aesthetic quality evaluation and contextual coherence evaluation. Mean values from laypersons were higher than (or at least equal to) the mean values from architects/urban designers, a potential reason for this phenomenon could be that architects/urban designers with professional aesthetic training may have higher standards than laypersons in architectural evaluation.

7. Theoretical energy performance simulation of proposed FIPV design

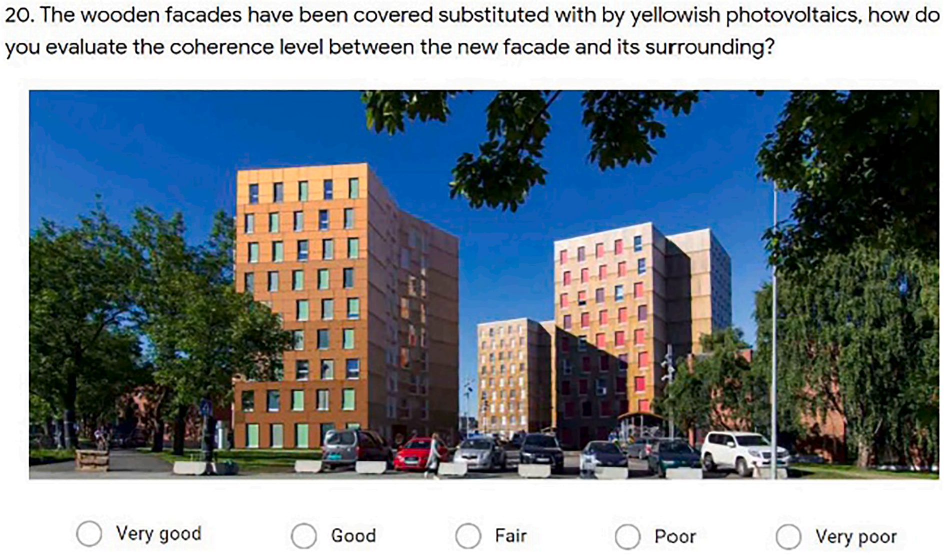
The energy production performance of a series of proposed pixelated



18. Here is the new proposal with greenish photovoltaics, please evaluate the coherence between the facade and the surrounding?

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

Fig. 43. Contextual integration evaluation of pixelization façade design, greenish multi-story house in Trondheim.



20. The wooden facades have been covered substituted with by yellowish photovoltaics, how do you evaluate the coherence level between the new facade and its surrounding?

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

Fig. 44. Contextual integration evaluation of pixelization façade design, high-rise building in Trondheim.

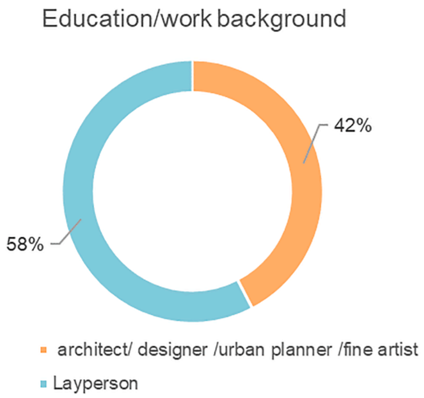


Fig. 45. Backgrounds of participants.

façade designs was calculated. This included 4 multi-story façade designs presented in Section 5.2.1 (Fig. 50 top) and 3 high-rise façade designs presented in section 5.2.2 (Fig. 50 bottom). To compare the energy production performance between pixelated design proposals and non-pixelated single colour facades, pixelated façade designs (Fig. 39B, Fig. 40A) and non-pixelated façade designs (Fig. 39A, Fig. 39C, Fig. 40B, Fig. 40C) used in the online survey were also simulated for energy production performance.

The estimated energy production efficiency was based on a recently developed model (Røyset et al., 2020). Firstly, model reflectance spectra was created to have the same CIELAB XYZ (CIE, 2004) colour coordinates as the façade pixels. The spectra were designed to have three flat-top reflectance bands with reflectance amplitude Rb, Rg, Rr, in the blue, green, and red spectral regions respectively. The spectral ranges were 420–490 nm, 490–575 nm, and 575–690 nm. Outside these spectral regions, a constant reflectance of 5% was assumed in order to also take unwanted spectral reflectance into account. For the colour

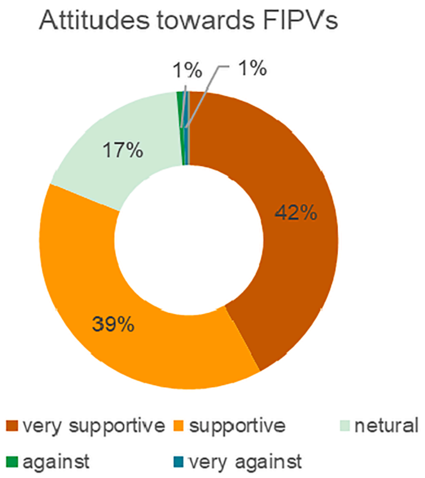


Fig. 46. Participants' attitudes towards FIPV.

calculation, the 2° observer and D65 illuminant was employed. The energy generation was then modelled by calculating the photovoltaic short circuit photocurrent density J_{SC} as Eq. (1) (Nelson, 2003):

$$J_{sc} = \int_{300\ \mathrm{nm}}^{1200\ \mathrm{nm}} \frac{q\lambda}{hc}(1-R(\lambda))I(\lambda)IQE(\lambda)d\lambda \tag{1}$$

where q is the electron charge, λ is the wavelength, hc/λ is the photon energy, R(λ) is the spectral reflectance, I(λ) is the irradiance spectrum, and IQE(λ) is the internal quantum efficiency of the solar cell. As displayed by Eq. (1), the energy generation is reduced by increasing reflectance. The spectral dependence on J_{SC} is nearly constant in the visible spectral range. For each colour, the relative efficiencies were calculated as $E = 1 - P = J_{SC}/J_{SC0}$ where P is the relative efficiency loss caused by reflectance, J_{SC} is the calculated photovoltaic current, and J_{SC0} is the generated current in the case of zero reflectance. The calculated relative efficiency numbers thereby indicate the theoretical potential of efficiencies for coloured PV relative to a perfectly absorbing (zero-reflecting) PV.

For each façade, a relative efficiency by area-weighting the contribution from each pixel was calculated. Similarly, a façade averaged CIELAB Y lightness was calculated to investigate the influence of lightness. Previous research by the authors has shown that lightness is the main determining factor of efficiency (Røyset et al., 2020). Therefore, a colour performance index CPI = Y/P was proposed, as a figure of merit to illustrate how energy efficient lightness Y can be achieved with a minimal efficiency loss P. In addition to a strong dependence on lightness, a weaker dependence on hue was identified, with green-yellow colours as the most energy-efficient, caused by the high eye sensitivity

Table 4
Paired Samples T-test Statistics for Aesthetic Qualities of Multi-story prototype/FIPV design.

Pair 1	Mean	N	Std. Deviation	Std. Error Mean
Aesthetic quality of multi-story house prototype	**3.278**	309	0.8414	0.0479
Aesthetic quality of Pixelated FIPV design for multi-story house prototype	**3.638**	309	0.8890	0.0506

Table 5
Paired Samples T-test Statistics for Aesthetic Qualities of High-rise prototype/FIPV design.

Pair 2	Mean	N	Std. Deviation	Std. Error Mean
Aesthetic quality of high-rise prototype	**3.411**	309	0.8194	0.0466
Aesthetic quality of Pixelated FIPV design for high-rise prototype	**3.492**	309	0.9245	0.0526

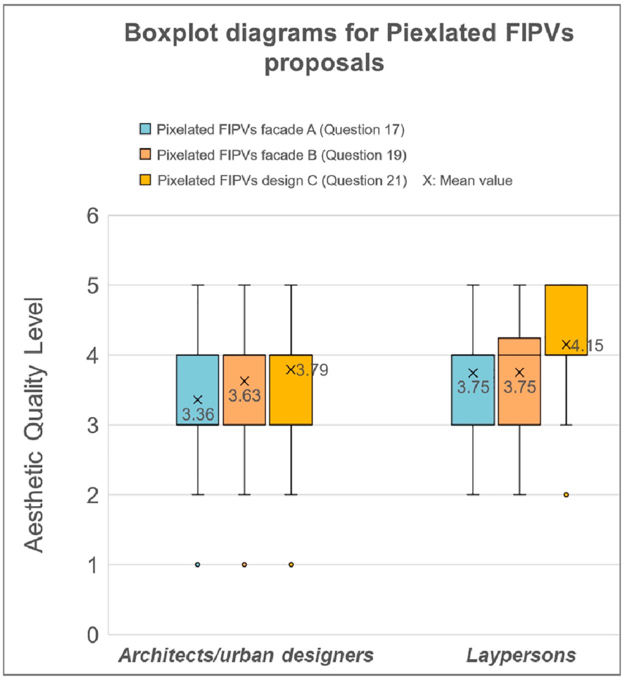


Fig. 48. The aesthetic evaluation result of pixelated FIPV proposals.

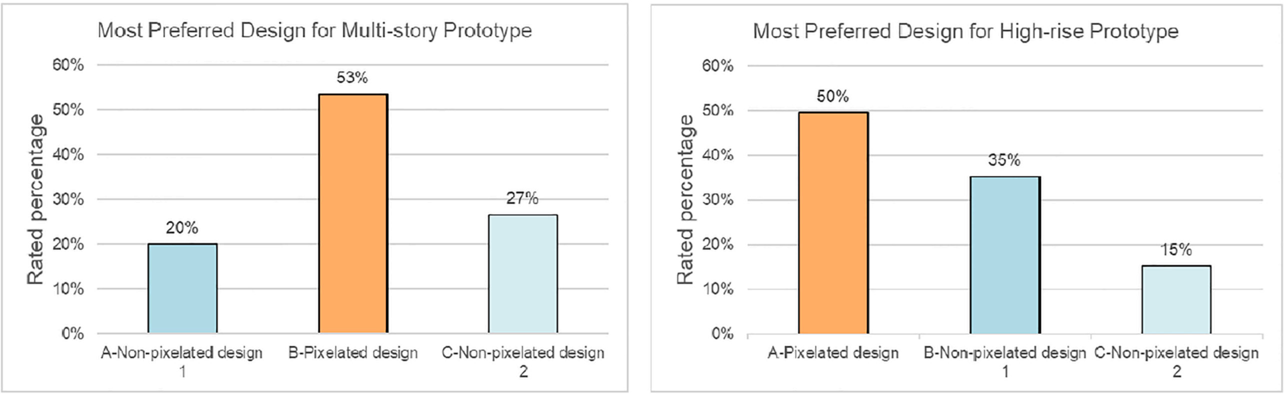


Fig. 47. Aesthetic performance, Pixelization design VS non-pixelated designs for two building prototypes.

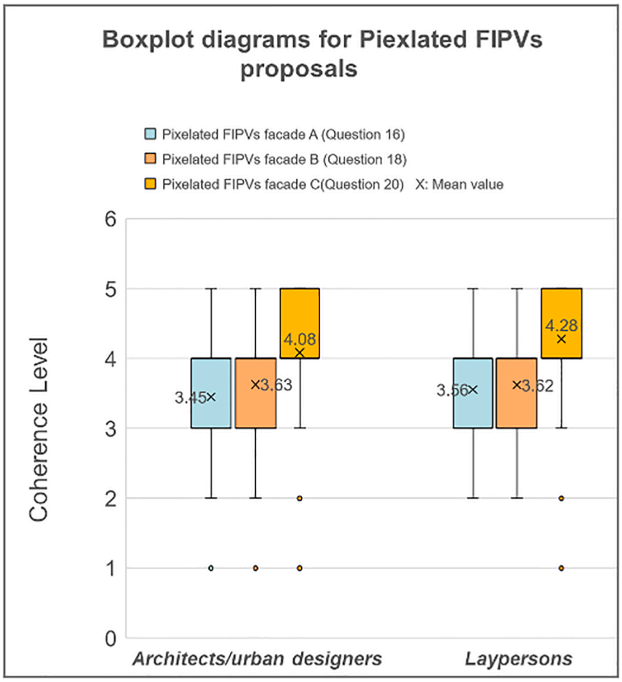


Fig. 49. The contextual coherence evaluation result of pixelated FIPV proposals.

in this spectral region.

To compare the energy production efficiency among different façade proposals, the efficiency of a representative non-pixelated black PV façade with spectrally flat 5% reflectance and 95% relative efficiency was also included. The calculated relative efficiency, lightness Y, and colour performance index CPI are given in Table 6.

Table 6 showed that the relative efficiencies of all the pixelated multi-story and high-rise facades range from 80.1 to 88.3%, while the black PV has a theoretical efficiency of 95%. This demonstrated that the presented facades with attractive pixelated coloured FIPV has a theoretical potential to achieve about 85–93% of the energy production efficiency relative to a representative black PV façade. Compared with dark and light non-pixelated façade designs (Fig. 39A, Fig. 39C, Fig. 40B, Fig. 40C), pixelated façade designs (Fig. 39B, Fig. 40A) have medium overall façade lightness Y values and medium relative efficiencies.

The difference in efficiency of the high-rise 1–3 facades can be

Table 6
Calculated relative efficiency, Lightness Y, and colour performance index CPI for selected façades designs.

Façade	Relative efficiency	Lightness CIE Y	Colour Performance Index CPI
Black PV reference	95.0%	0.05	2.11
Multi-story 1 (Y20R-Y40R)	80.1%	0.36	2.14
Multi-story 2 (Y70R-Y90R)	83.5%	0.25	1.82
Multi-story 3 (G50Y, G30Y)	86.0%	0.28	2.45
Multi-story4 (Y20R-Y40R, Y70R-Y90R)	81.8%	0.31	1.99
High-rise 1 (Y80R, Pixelated)	83.1%	0.27	1.89
High-rise 2 (G30Y, Pixelated)	88.3%	0.22	2.48
High-rise 3 (Y30R, Pixelated)	83.6%	0.30	2.15
Fig. 39A (Non-pixelated)	75.3%	0.41	1.85
Fig. 39B (Pixelated)	83.5%	0.25	1.82
Fig. 39C (Non-pixelated)	92.1%	0.09	1.71
Fig. 40A (Pixelated)	83.6%	0.30	2.15
Fig. 40B (Non-pixelated)	69.9%	0.60	2.20
Fig. 40C (Non-pixelated)	92.4%	0.10	2.04

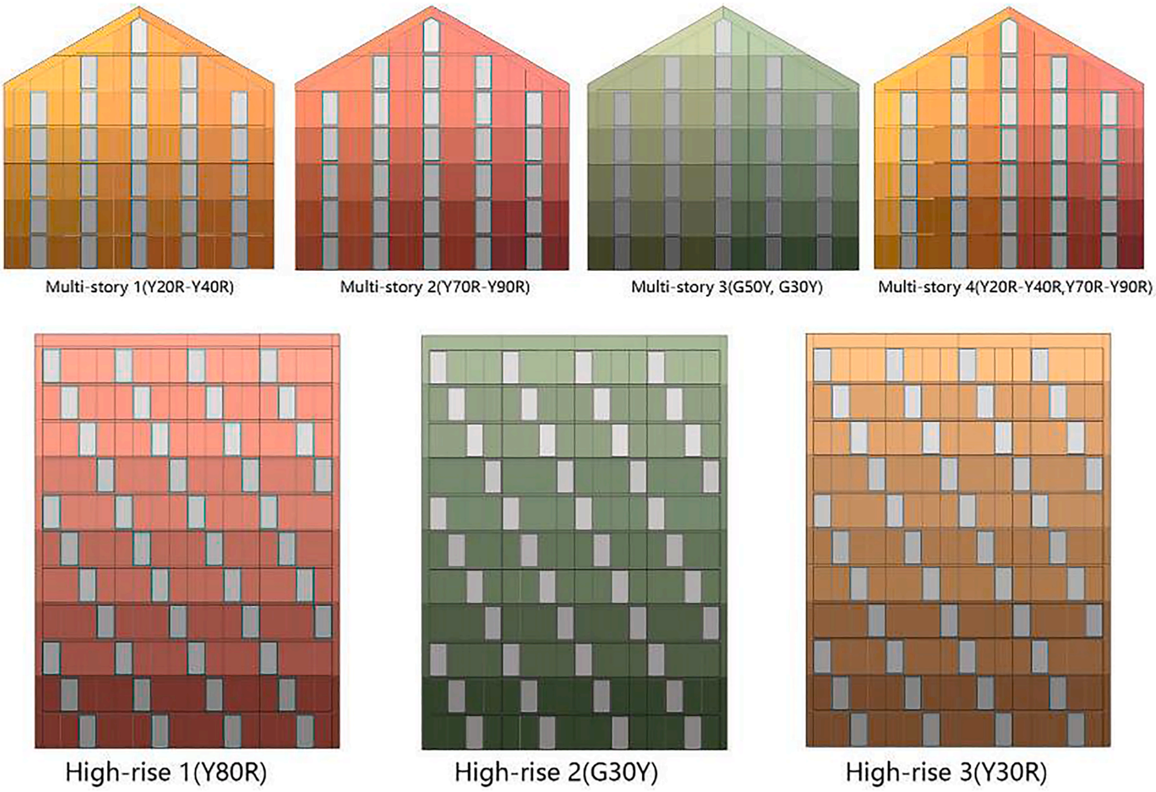


Fig. 50. Selected multi-story facades (top) and high-rise facades (bottom) for energy simulation.

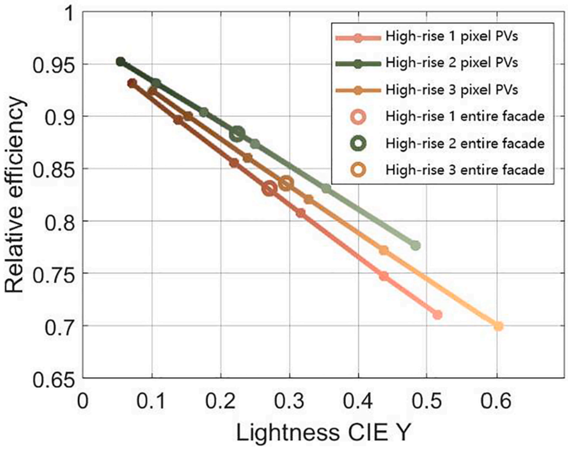


Fig. 51. Relative energy production efficiency of high-rise façade proposals.

explained by observing the differences in lightness and hue. Fig. 45 displayed the relation between efficiency and CIELAB Y lightness for the colours of pixel façade PV modules in the high-rise 1–3 facades. It can be clearly seen that there is a large variation in lightness, and a large variation in the efficiency of individual pixel PV modules. It also illustrated that for a given lightness the PV modules with green hue (high-rise 2 with hue G30Y) are more efficient than the yellowish pixel PV of high-rise 3 and the reddish pixel PV of high-rise 1. Overall, the Fig. 51 showed that lightness has a much stronger influence on efficiency than hue. The colour performance indices (CPI) in Table 6 were therefore useful in identifying the contribution from other factors than lightness.

A similar analysis of the Multi-story 1–4 facades gave similar results. Multi-story 1 has the lowest efficiency, mainly because it is the lightest façade. The green Multi-story 3 has the highest efficiency due to optimum hue and a low lightness. An additional effect of the Multi-story facades was that there is more than one hue on the façade. This has not a strong influence on the results. For the research question 3, what is the energy production performance of pixelated FIPV designs? The theoretical simulation showed that pixelated coloured FIPV facades may have promising energy production efficiency (theoretically about 85–93% of a black PV reference facades). In the meantime, aesthetically preferred pixelated FIPV façade designs demonstrated an intermediate level of energy production efficiency when comparing with dark and light non-pixelated FIPV designs respectively, in same or neighbourhood hues.

8. Discussion and conclusion

This study presented a novel method to promote FIPV in the built environment, with promising potential to create high-quality aesthetic facade designs harmoniously integrated with local urban context. Narsar's environmental theory serves as the fundamental theoretical background, and contemporary colour harmony concepts were integrated together with local colour contextual identity. Special focus of this study was on colour aspects from the architectural perspective.

Specularity (glossiness) of FIPV has not been discussed in this study, it could be an important issue to be further studied for FIPV colour design. Other studies by the author has found that the surface property including gloss level can have impacts on the measured colour angular sensitivity of opaque colour PV(Xiang et al., 2021). Some PVs (e.g. Gloss level $>$ 70 GU) with high gloss surface demonstrate goniochromism phenomena while some matt PVs with low gloss surface (eg. Gloss level $<$ 10 GU) show stable colour performance. How the specularity of the module influence the perceived colour performance of FIPV could be an interesting topic and also can be important for architects to take into design consideration.

One factor that was not included in this aesthetic study is the influence of distance on the perceived colours of FIPV. A series of studies has shown that perceived colours from a distance (e.g. 30 m or 50 m) may vary from the nominal colours of façades (Anter, 2002; Sochocka and Anter, 2017). This phenomenon may also affect the aesthetic performance of designed FIPV in the urban context. The online survey in this study has limitations with respect to evaluating the specularity and distance impact. To further explore the impact of specularity and viewing distance on colour design of FIPV, evaluation experiments with real PV on facades or scaled physical models in urban contexts under different natural illumination conditions could be the future steps.

Another interesting aspect that could be investigated in future research is the economic impact of the proposed pixelization method for FIPV in the life cycle perspective. The economic impact of pixelated FIPV could be compared with typical dark or blue PVs and also traditional façade cladding materials like ceramic panels, aluminium plates or marble materials etc. Practical economic data of coloured PVs could be collected when more products are commercialized in the future markets.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solener.2021.06.079.

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