

Color differences between Urban Digital Twin and the real city.

Optimisations and compensations

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ABSTRACT

With the rapid development of science and technology, urban digital twins have gradually become an essential tool for city planning and management, integrating real-time data such as traffic and energy consumption, and transforming our cities into smarter and more responsive environments. By creating virtual digital twin cities, urban management operations can be monitored and optimised in a more efficient and accurate manner, opening up new scenarios also projected towards the evolution of new development models for a better quality of life.

On the basis of these premises and above all considering color as a key element in the visual perception of a city, the aim of this contribution is to verify whether in digital twins cities retain their color peculiarities and what the methodological criteria of reliability might be for a new way of managing color, considering the new technologies available.

Referring to some examples of digital twins of cities published on the web and in particular referring to the Helsinki project, the essay aims to investigate whether and to what extent there are color differences between the virtual and the real vision of the city and what can be, on the basis of the results collected, possible optimisations or compensations to consider the Urban Digital Twin as a documental source also in color management both in the field of urban design and redevelopment and in the survey of the state of places.

KEYWORDS Urban Digital Twin, color management, digital urban colors, Color Validity Index

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1. Introduction

Digital twin cities (Urban Digital Twins) represent one of the most advanced technologies for urban management and planning. These models integrate not only three-dimensional representations of buildings and infrastructure, but also real-time data streams such as traffic, environmental monitoring and energy consumption (Mazzetto, 2024). Through the use of technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI), Urban Digital Twins offer comprehensive control and optimised city management, making cities increasingly intelligent and responsive to modern needs (Ogunsakin, Mehandjiev, & Marin, 2023).

The use of Urban Digital Twins is successfully spreading not only in Italy, but all over the world. In Italy, for example, Bologna has implemented this technology to protect cultural heritage, manage tourism and develop smart city applications. Similarly, cities such as Berlin, Helsinki, Shanghai and Tokyo are experimenting with various models of Digital Twins for different purposes, including managing urban resources and responding to environmental and climate emergencies.

However, an often-overlooked aspect of these models is the accurate handling of color, which is fundamental to the visual perception and architectural identity of a city. This study aims to investigate whether digital representations maintain the color fidelity of real cities and whether color can be considered a geospatial datum accurately represented in Digital Twins. Through the analysis of some examples of Urban Digital Twins, with a special focus on the city of Helsinki, investigations will be carried out on samples of buildings in order to propose a methodology that can also be applied in other urban contexts.

2. Urban Digital Twins: the case of Helsinki

With the advancement of technology, urban digital twins have emerged as key tools for city management and planning, offering unprecedented opportunities to optimise urban services and improve quality of life. These models not only represent buildings and infrastructure in 3D, but also integrate data from IoT devices, enabling real-time monitoring of aspects such as traffic, environment and energy consumption. Globally, cities such as Singapore and Dubai have demonstrated the effectiveness of Digital Twins in improving urban safety and sustainability (Fig.1), using scenario simulation and managing resources more efficiently (World Economic Forum, 2023).

However, one of the most complex and often overlooked aspects of these models is accurate color management.



Fig. 1. Examples of Digital Twins cities.

Color fidelity is crucial for the visual perception and architectural identity of cities, as it directly influences the aesthetic appearance of buildings, the legibility of urban spaces and the psychological well-being of citizens. Previous studies have shown that color reproduction in urban digital twins is affected by numerous challenges, including variability in daylight conditions, reflectivity of building materials and wear and tear over time (Wurm et al., 2024). For example, variations in brightness during the day can alter color perception, while the ageing of building materials can introduce discrepancies between the real and virtual worlds (Zhang & Liu, 2023). In Italy, the use of digital twins is growing, with cities such as Bologna exploiting their potential for cultural heritage protection and tourism management. In addition, companies such as CGR SpA (Compagnia Generale Ripresearee) are using photogrammetry and remote sensing with multispectral sensors to improve the color accuracy of urban representations. This approach has proven its value in complex urban management, emphasising the importance of integrating color data into virtual models.

Despite technological advances, the application of color management techniques to open urban spaces remains a significant challenge. This study aims to help fill this gap by introducing a methodology based on the Chromatic Validity Index (CVI) to assess and improve color fidelity in urban digital twins. With a special focus on the Digital Twin in Helsinki, five representative buildings were chosen to perform a color sampling of the main elements (Fig. 2).

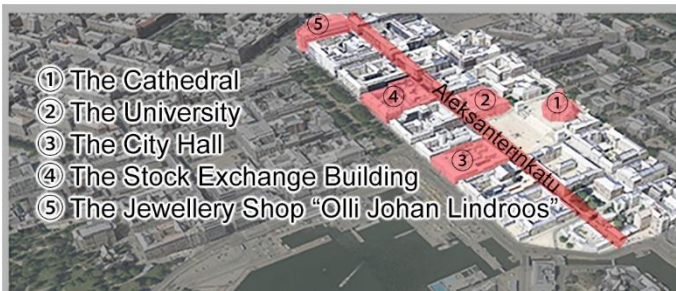


Fig. 2. Digital Twin in Helsinki. Highlighted are the five buildings chosen as champions. (<https://kartta.hel.fi/3d/mesh/> accessed on 30 September 2024).

Through a detailed analysis of the virtual color representation and a comparison with real scenarios, this paper analyses the current state of color fidelity and proposes optimisation strategies to improve the overall visual perception of urban spaces. Finally, a new methodological approach for analysing and documenting color in digital twins is presented, contributing to more precise and integrated color management in urban design and redevelopment (Parraga, Troscianko, & Tolhurst, 2002).

3. Objectives and survey methodology

Helsinki is an example of excellence in the use of urban digital twins due to its accessibility and advanced technological application. The city is a pioneer in heritage protection, urban planning and intelligent transport. The publicly accessible Helsinki Digital Twin offers interactive features that simplify urban analysis for researchers. For example, the Urban Data model integrates unique identifiers (GMLID, RATU and VTJ-PRT) for advanced data flow management and provides details such as height, material and year of construction for each building.

The choice of Helsinki as the object of study is relevant both for its scientific value and for the practical applications it offers. This study analyses color fidelity in digital urban models, focusing on discrepancies between virtual and real scenarios and proposing strategies to improve color management in Digital Twins. As it was not possible to carry out direct surveys, façade colors were analysed using Google Earth, keeping the methodology unchanged to ensure consistency of results. However, it is hoped that future analyses can be refined with field surveys.

The specific objectives of the research include assessing the current state of color management in the Helsinki Digital Twin, identifying color differences between the virtual and real city and proposing strategies to improve color fidelity in digital models.

The case study focuses on the Aleksanterinkatu district in central Helsinki and five main buildings: the Cathedral, City Hall, University, Stock Exchange Building and Olli Johan Lindroos Jewellers. Color samples were selected uniformly on the main façade areas (walls, roofs, window frames and doors) to ensure representativeness of the data. The color data of the façades were extracted using Adobe Photoshop, with RGB values collected from both the digital model and real images. Color differences (ΔE) were calculated to classify deviations, while the Color Validity Index (CVI) (Chen et al., 2018) measured overall fidelity. Optimisation strategies include color calibration, light simulation and implementation of automatic correction algorithms. In this study, the main focus is on hue, as it is a key element for visual perception and architectural identity. Variations in brightness and saturation, although recorded, are considered secondary due to their dependence on external environmental factors such as natural lighting and dirt accumulation. Hue, on the other hand, offers a more stable and relevant indication for our purposes.

4. Workflow

1. *Virtual model data collection and pre-processing.* We acquired color data from the Digital Twin 3D of the buildings located along Aleksanterinkatu Street using the Helsinki City Urban Model. These data provide a detailed virtual representation, which is essential for later comparison with real data.

2. *Collecting and analysing the color of the real model.* Using color extraction software such as Adobe Photoshop, we sampled the colors of the building facades, including areas such as walls, roofs, window frames and doors. For each sample, RGB values were recorded, ensuring accurate and consistent color analysis.

3. *Comparison of virtual and real scenes.* The color samples of the virtual model were compared with the real images extracted from Google Earth. This comparison made it possible to identify and analyse any color discrepancies between the digital models and the real buildings, helping to assess the color fidelity of the Helsinki Digital Twin.

5. Analysis of color data and differences. Comparative tables

Color data was analysed on the selected samples for each building from both the Digital Twin in Helsinki and Google Earth to which was added an analysis of the calculated color differences as follows (Schanda, 2007). First, the RGB color space was converted to XYZ according to the following formula:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \cdot \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}$$

The XYZ values were converted to CIELAB, a color space that better reflects human perception of brightness, chrominance and hue. The transformation formula is as follows:

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500 \left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right) \right)$$

$$b^* = 200 \left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right) \right)$$

Finally, the converted CIELAB values are used to calculate the color difference, referring to the following formula:

$$\Delta E_{ab}^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2}$$

Finally, a comparative table of the results of the color data analysis of the samples taken from both the Digital Twin in Helsinki and Google Earth was drawn up for each selected building, a description of which follows (Figs. 3 and 4). Based on the ΔE value obtained, one can classify the type of color deviation, indicating whether it is a shift towards lighter, darker, warmer or cooler tones.

The Cathedral. The virtual façades show lower brightness, predominance of green and higher saturation than in reality. Specific differences: walls $\Delta E = 17.11$ (less brightness, green tendency); roof $\Delta E = 70.87$ (low brightness, reduced saturation); door $\Delta E = 58.33$ (red-brown tendency); window $\Delta E = 13.12$ (slight yellow tendency).

The Town Hall. The virtual model is darker and colder. Specific differences: wall $\Delta E = 46.41$ (cold and dark shade); roof $\Delta E = 26.00$ (slight cold shift); door $\Delta E = 190.75$ (marked shift towards light and cold shades); window $\Delta E = 7.87$ (good fidelity).

University. Good color fidelity with exceptions. Specific differences: wall $\Delta E = 2.18$ (high fidelity); roof $\Delta E = 20.70$ (slightly lighter and colder); door $\Delta E = 21.16$ (lighter and less saturated); window $\Delta E = 22.23$ (colder and darker); column $\Delta E = 13.28$ (slight darkening).

The Stock Exchange Building. Moderate discrepancies with lighter and less saturated tones. Specific differences: wall 1 $\Delta E = 23.17$; wall 2 $\Delta E = 20.13$ (both less deep and warm); roof $\Delta E = 55.89$ (lighter); door $\Delta E = 23.75$ (colder and desaturated); window $\Delta E = 27.61$ (lighter).

Olli Johan Lindroos' Jewellery. Marked differences, with generally lighter and less warm tones. Specific differences: wall 1 $\Delta E = 22.74$ (less saturated); wall 2 $\Delta E = 72.98$ (significant loss of warm shades); roof $\Delta E = 102.69$ (light and cold); door $\Delta E = 36.12$ (less intense); window $\Delta E = 55.69$ (less warm and less authentic). For a clear visualisation of the treated color deviations, see Figure 5.

6. Evaluation of the effectiveness of color management using the Color Validity Index (CVI)

The Color Validity Index (CVI) is used to measure the degree of color fidelity between the virtual model and the real scene. The formula for calculating the CVI value is as follows:

$$CVI = \frac{\sum \Delta E}{n}$$

The lower the CVI value, the higher the color fidelity. The color validity index was calculated for each selected building on the basis of a number of samples, as follows:

The Cathedral: $\sum \Delta E = 17.11 + 70.87 + 58.33 + 13.12 = 159.43$; number of samples = 4; CVI = 39.86.

The Town Hall: $\sum \Delta E = 46.41 + 26.00 + 190.75 + 7.87 = 271.03$; number of samples = 4; CVI = 67.76.

The University: $\sum \Delta E = 2.18 + 20.70 + 21.16 + 22.23 + 13.28 = 79.55$; number of samples = 5; CVI = 15.91.

The Stock Exchange Building: $\sum \Delta E = 23.17 + 20.13 + 55.89 + 27.61 + 11.59 = 138.39$; number of samples = 5; CVI = 27.68.

Olli Johan Lindroos' Jewellery: $\sum \Delta E = 22,74 + 72,98 + 102,69 + 36,12 + 55,69 = 290,22$; number of samples = 5; CVI = 58,04.

Evaluation of the results. The results show that the University has the best color fidelity with a CVI of 15.91, while City Hall and Jewellery show significant deviations (CVIs of 67.76 and 58.04). These results underline the need for specific optimisation strategies to improve color accuracy in virtual models (Fig. 6).

The Cathedral					The City Hall								
Helsinki Digital Twin Information		Helsinki Digital Twin (H.D.T. Virtual Model)		Google Earth (G.E. Mod. Reale)	Photo (G.E.)		Helsinki Digital Twin Information		Helsinki Digital Twin (H.D.T. Virtual Model)		Google Earth (G.E. Mod. Reale)	Photo (G.E.)	
Building Information: Building height: 58.89 m; lower elevation: 13.44 m; VTJ-PRT: 103027179C; RATU: 211; GMLID: BID_4d58c091-9185-42fd-a8be-78f1f6eb891f.					Building Information : Building height: 32.7 m; Lower elevation: 1.9 m; VTJ-PRT:103027184J; RATU: 216; GMLID: BID_29d5c8c9-a6e1-439b-ad4e-ccab20d9f9e								
Sample		RGB (Virtual Model)	RGB (Real Model)	(ΔE)	Type of Chromatic Deviation	Sample		RGB (Virtual Model)	RGB (Real Model)	(ΔE)	Type of Chromatic Deviation		
Wall H.D.T.	Wall G.E.	194 201 205	247 247 245	17.11	Slight shift towards lighter and more neutral tones.	Wall H.D.T.	Wall G.E.	197 200 205	214 229 237	46.41	Shift towards lighter and cooler tones.		
Roof H.D.T.	Roof G.E.	188 203 203	125 185 176	70.87	Marked shift towards darker and cooler tones.	Roof H.D.T.	Roof G.E.	238 239 237	214 229 237	26.00	Moderate shift towards slightly darker tones.		
Door H.D.T.	Door G.E.	188 171 150	96 65 38	58.33	Significant shift towards darker and warmer tones.	Door H.D.T.	Door G.E.	176 176 175	99 63 42	190.75	Significant shift towards much darker and warmer tones.		
Window H.D.T.	Window G.E.	209 210 208	247 247 245	13.12	Slight shift towards lighter and more neutral tones.	Window H.D.T.	Window G.E.	201 199 204	196 198 198	7.87	Minimal shift towards slightly darker and neutral tones.		
NOTE: 1.VTJ-PRT: Permanent building identifier. 2. RATU: Used as the unique "building ID". 3. GMLID: Unique identifier in GML format (Geography Markup Language), used to distinguish individual geographic objects within a GML dataset.													

The University					The Stock Exchange Building								
Helsinki Digital Twin Information		Helsinki Digital Twin (H.D.T. Virtual Model)		Google Earth (G.E. Mod. Reale)	Photo (G.E.)		Helsinki Digital Twin Information		Helsinki Digital Twin (H.D.T. Virtual Model)		Google Earth (G.E. Mod. Reale)	Photo (G.E.)	
Building Information: Building height: 29.38 m; Lower elevation: 4.31 m; VTJ-PRT : 103036766M; RATU: 328; GMLID : BID_3a9b6d01-301d-421b-9b85-f8b4d7165e8e. Coordinates: East: 25497267.22 – North: 6672955.49 – N2000: 27.82					Building Information: Building height: 30.74 m; Lower elevation: 1.91 m; VTJ-PRT : 1030367814; RATU: 340; GMLID : BID_3da327ac-519e-49e3-afec-9f086c2b12ee								
Sample		RGB (Virtual Model)	RGB (Real Model)	(ΔE)	Type of Chromatic Deviation	Sample		RGB (Virtual Model)	RGB (Real Model)	(ΔE)	Type of Chromatic Deviation		
Wall H.D.T.	Wall G.E.	204 200 185	207 199 187	2.18	Minimal shift, almost imperceptible.	Wall1 H.D.T.	Wall1 G.E.	190 169 165	155 110 104	23.17	Shift towards darker and warmer tones.		
Roof H.D.T.	Roof G.E.	238 239 237	183 201 226	20.70	Moderate shift towards cooler and slightly darker tones.	Wall2 H.D.T.	Wall2 G.E.	180 172 162	176 141 109	20.13	Shift towards darker and slightly warmer tones.		
Door H.D.T.	Door G.E.	154 146 136	91 98 90	21.16	Shift towards darker and cooler tones.	Roof H.D.T.	Roof G.E.	213 213 216	69 70 87	55.89	Significant shift towards much darker and cooler tones.		
Window H.D.T.	Window G.E.	176 176 175	112 123 134	22.23	Moderate shift towards cooler and darker tones.	Door H.D.T.	Door G.E.	114 91 82	136 83 47	23.75	Shift towards warmer and slightly lighter tones.		
Column H.D.T.	Column G.E.	188 189 188	225 226 225	13.28	Shift towards lighter and neutral tones.	Window H.D.T.	Window G.E.	105 93 93	74 40 23	27.61	Shift towards darker and warmer tones.		
NOTE: 1.VTJ-PRT: Permanent identifier of the building. 2.RATU: Used uniquely as the "building ID". 3.GMLID: Unique identifier in GML (Geography Markup Language) format, used to distinguish individual geographic features within a GML dataset.													

Fig.3 - Comparative tables of virtual and real color and color difference data for the Helsinki Cathedral, City Hall, University and Stock Exchange Building.

The Jewellery Shop “Olli Johan Lindroos”

























					
Helsinki Digital Twin Information	Helsinki Digital Twin (H.D.T. Virtual Model)	Google Earth (G.E. Mod. Reale)	Photo (G.E.)		
Building Information: Building height: 56.23 m; Lower elevation: 4.27 m; VTJ-PRT ¹ : 1030367471; RATU ² : 313; GMLID ³ : BID_7f0175c2-6ea2-4ae0-95e8-98151cb612f3					
Sample		RGB (Virtual Model)	RGB (Real Model)	(ΔE)	Type of Chromatic Deviation
Wall1 H.D.T.	Wall1 G.E.	139 117 113	155 111 98	22.74	Moderate shift towards warmer and slightly darker tones.
					
Wall2 H.D.T.	Wall2 G.E.	209 210 208	188 171 150	72.98	Significant shift towards much darker and warmer tones.
					
Roof H.D.T.	Roof G.E.	194 201 205	125 153 146	102.69	Strong shift towards much darker and cooler tones.
					
Door H.D.T.	Door G.E.	88 81 90	115 81 66	36.12	Shift towards slightly lighter and warmer tones.
					
Window H.D.T.	Window G.E.	181 171 170	161 145 125	55.69	Significant shift towards darker and warmer tones.
					
NOTE: 1.VTJ-PRT: Permanent identifier of the building 2. RATU: Used uniquely as the "building ID". 3.GMLID: Unique identifier in GML (Geography Markup Language) format, used to distinguish individual geographic features within a GML dataset.					

Fig.4 - Comparative table of virtual and real color and color difference data from the ‘Olli Johan Lindroos’ Jewellery Shop in Helsinki.

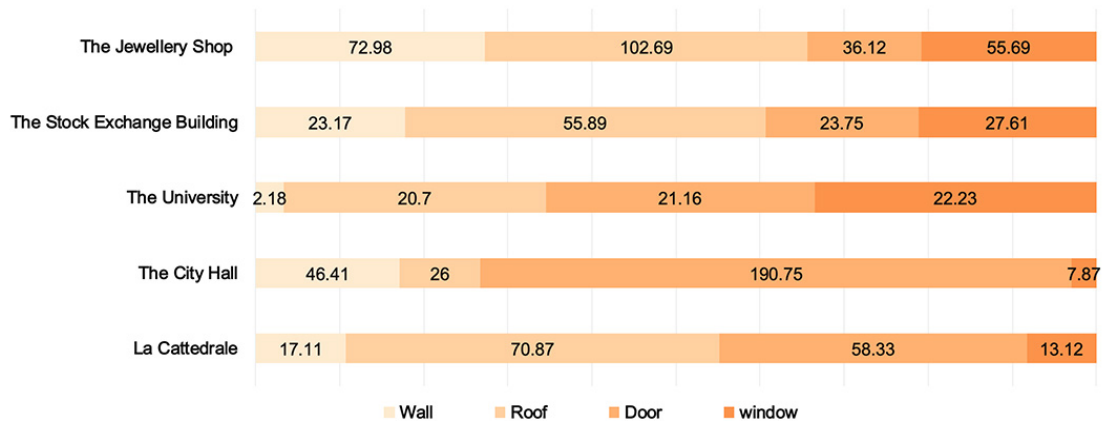


Fig.5 -Chromatic deviations (ΔE) for architectural elements. The graph illustrates the color deviations (ΔE) between the virtual model and reality for five buildings. The bars indicate the different architectural elements, with higher values representing significant color deviations.

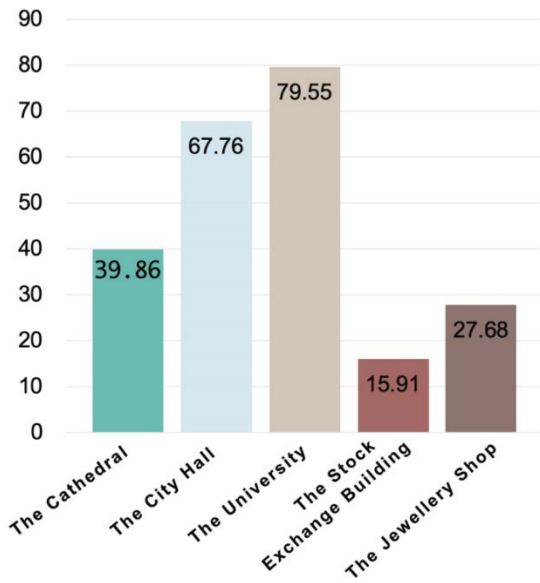


Fig.6 - Histogram representing the Color Validity Index (CVI) of the analysed buildings in the city of Helsinki. The lower CVI value indicates higher color fidelity.

7. Optimisation strategies

Optimisation of areas with high ΔE . For areas with ΔE greater than 50 (e.g. cathedral roof, town hall door), optimisation of reflectance and material texture mapping is required to reduce color differences.

Color Space Alignment. To precisely align RGB hues between the virtual and real models, color management software such as ColorMunki or Spyder can be used for consistent color calibration.

Improved light simulation. The lighting parameters in the virtual model must be adjusted to reflect real conditions. The use of a full spectrum render can improve color fidelity compared to ambient lighting.

Introduction of color correction algorithms. Algorithms such as gamma correction, color temperature adjustment and brightness balancing can automatically compensate for color differences.

Real-time CVI Monitoring System. To maintain high color fidelity, a continuous CVI monitoring system is useful, which periodically detects and corrects discrepancies between the virtual model and reality.

The implementation of these strategies can significantly improve the color validity of digital twins, ensuring a more accurate match and a better visual experience in the urban context.

Figure 7 shows the example of the City Hall where after the application of the strategies, the CVI dropped to 4.82, an improvement of 92.83%, demonstrating a true color match.

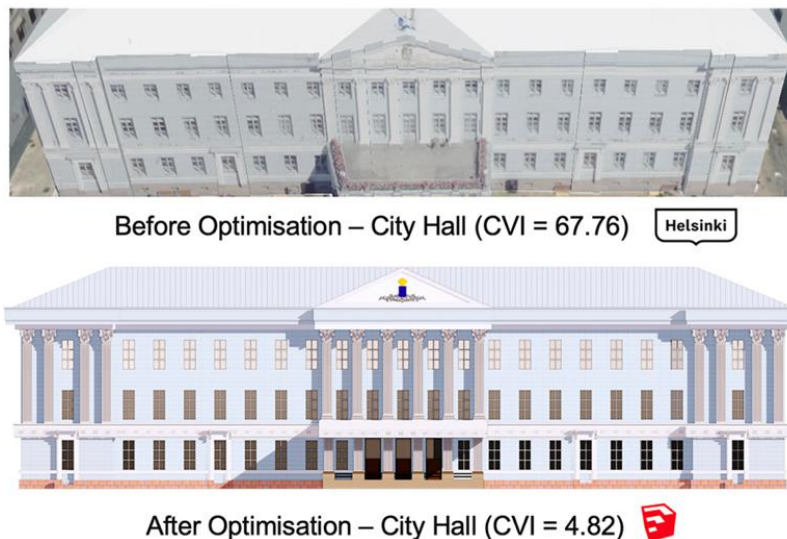


Fig.7 - The City Hall before and after optimisation

8. Conclusions

The present study explored color management in digital urban twins, focusing on the case of Helsinki. Through a comparison of the color data from the Digital Twin and those obtained from Google Earth, critical issues affecting

the quality of the digital representation emerged, especially in terms of brightness and saturation. However, the investigation showed that effective color control is possible by using advanced color analysis software and calculating color differences (ΔE) with the Chromatic Validity Index (CVI). This approach made it possible to

accurately measure the color fidelity between the virtual model and the real scene and to propose targeted optimisation strategies.

The results of this study support the use of Urban Digital Twins as valuable tools not only for color management, but also for urban design and redevelopment. With proper color control, Digital Twins can improve the documentation and preservation of the visual identity of cities. To further increase color fidelity, the integration of Level of Detail (LOD) is recommended, including accurate color data on building façades and roofs, obtained through field surveys with advanced digital technologies.

Finally, future research could extend these strategies to other urban contexts, with the aim of confirming the validity of the results and promoting the adoption of digital twins as fundamental tools for integrated urban management, including color aspects for visually coherent and sustainable cities.

9. Conflict of interest declaration

The authors declare no conflict of interest including financial, personal or other relationship with other people and organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, this work.

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The images in Figure 1 are taken from: https://www.vopoint.com/algorithms_14.html
https://www3.weforum.org/docs/WEF_Digital_Twin_Cities_2023.pdf (Accessed: 2 April 2025).

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12. Short biography of the authors

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