Chapter 9

Low-Cost Digital Twins for Rural Built Environment:
Pathways to CO2 Mitigation and Healthier Indoor Environments

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ABSTRACT

Rural interiors often rely on solid fuels and habit-based ventilation rather than on measured needs. Under such conditions, carbon dioxide and fine particulates rise to levels that burden health and cognition. This chapter develops a frugal digital-twin methodology for villages, connecting an open-data GIS-to-BIM geometric backbone, or an AI method where data are absent, with a calibrated mesh of low-cost indoor sensors and a feedback layer that converts readings into timed natural-ventilation purges, which are gated against outdoor pollution episodes. The approach begins as a digital shadow and prays toward two-way control when budgets and governance permit. It is anchored in accepted guidance for indoor environmental quality and positions biophilic additions as complements to ventilation rather than substitutes unless integrated into active botanical filters.

INTRODUCTION

Indoor air quality in rural settlements remains an overlooked aspect of environmental practice, even as urban policies for ambient air quality become stricter and

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more effective technologies emerge in cities. For instance, low-cost sensor networks integrated with building information models have been shown to be valuable in urban settings (D'Uva & Bolognesi, 2024). However, such data-driven methods are rare in small towns and hamlets, where rules of thumb still manage indoor environments: windows are opened based on habit or comfort rather than measured needs; stoves and space heaters are operated according to custom and expense rather than exposure levels. This approach inevitably leads to consequences that significantly worsen air quality. Carbon dioxide and humidity build up in sealed rooms during winter evenings, and particulate matter from combustion remains long after a meal or heating cycle. Moreover, environmental factors like wind and heat inversion can affect air quality and introduce avoidable pollution. In such contexts, understandable and straightforward techniques connecting measurement to action are more valuable than complex infrastructure villages cannot afford, maintain, or trust.

This chapter aims to develop a digital twin (DT) methodology that villages can build and maintain. The method is designed to be energy-efficient and affordable regarding capital cost. It begins with a geometric backbone created from open data, expressed as a continuous NURBS surface with extruded building stock. It allows the entire settlement to be visualised immediately, from the breezeways between houses to the orientations of individual rooms. The NURBS entities are then upgraded to BIM systems for more precise analysis and more efficient forecast measures. The system incorporates a network of calibrated, low-cost sensors that stream indoor carbon dioxide, temperature, humidity, and, where resources permit, fine particulate data. It culminates in a feedback layer that converts those readings into simple, timely actions, such as a short cross-breeze purge when the outdoor air is clean. In selected rooms, the real-time sensor data can activate a low-torque actuator that opens a window for a precise duration, thereby transforming a one-way digital shadow into a two-way DT.

The argument for using a high-technology solution like DT is based on four premises. The first is that indoor carbon dioxide levels serve as a reliable indicator of ventilation adequacy when interpreted in relation to outdoor baselines and occupancy patterns. The second is that outdoor particulate conditions fluctuate hourly and cannot be reliably deduced from intuition alone; the environment must be analysed before opening windows. The third is that translating measurements into action is effective only if residents understand what they see. Additionally, local technicians should be able to maintain the system without excessive cost and effort. A fourth consideration involves humidity mitigation, which can reach levels that promote mould growth and masonry deterioration, especially during winter. These premises explain why this chapter emphasises alignment with accepted guidance on indoor environmental quality, considers communication and governance as important as sensors and regulations; and views the DT as a narrative thread that links territory,

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