INNOVATIVE PUBLICATION
Journal of Effective Learning and Sustainable Innovation
Vol.4 №10 (2026). OCTOBER
innovativepublication.uz

UDC 69.05:692.23:621.311.243:004.94

IMPROVING ORGANISATIONAL AND TECHNOLOGICAL SOLUTIONS FOR THE DESIGN AND INSTALLATION OF ENERGY-EFFICIENT FACADE SYSTEMS AND SOLAR PHOTOVOLTAIC POWER PLANTS IN BUILDINGS USING BIM AND ENERGY AUDIT RESULTS

Nurmatov Ravshan Qahhor o‘g‘li
(Chief Power Engineer, Tashkent University of Architecture and Civil Engineering, Tashkent, Uzbekistan)
E-mail: nurmatovravshan1@gmail.com
Qodirov Sardor Sobir o‘g‘li
(Assistant, Department of Construction of Buildings and Structures, Tashkent University of Architecture and Civil Engineering, Tashkent, Uzbekistan)
E-mail: sardorqodirov110599@gmail.com

Abstract. Linking facade and photovoltaic installation works to diagnostic findings is a pressing task in the energy-efficient retrofit of existing buildings. This paper proposes a methodological approach that links thermographic diagnostics, energy calculations, and building information modelling (BIM) for planning such retrofits. The study combines a focused review of selected publications and technical documents with conceptual framework development. It defines procedures for verifying temperature anomalies through supplementary inspections, linking verified data to BIM elements, and translating these data into work quantities, labour requirements, and prerequisites for commencing activities. The methodological outputs comprise a diagnostic interpretation framework, a coordination table for facade and photovoltaic system installation, and a three-scenario evaluation plan. Reductions in building energy demand, photovoltaic electricity generation, and construction management outcomes are assessed separately. No building-specific thermographic measurements or completed BIM experiment are reported; the practical effectiveness of the method requires independent empirical validation. The proposed approach can be used in preparing method statements and work schedules for energy-efficient retrofit projects.
Keywords: energy audit, thermography, thermal bridge, BIM, 4D planning, facade system, solar photovoltaic system, installation sequence, labour requirements, quality control.

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SAMARADOR FASAD TIZIMLARI VA QUYOSH FOTOELEKTR STANSIYALARINI BIM TEXNOLOGIYALARI YORDAMIDA LOYIHALASH HAMDA ULARNI O‘RNATISHNING TASHKILIY VA TEXNOLOGIK YECHIMLARINI TAKOMILLASHTIRISH

Nurmatov Ravshan Qahhor o‘g‘li
(bosh energetik, Toshkent arxitektura-qurilish universiteti, Toshkent, O‘zbekiston)
E-mail: nurmatovravshan1@gmail.com
Qodirov Sardor Sobir o‘g‘li
(«Bino va inshootlar qurilishi» kafedrasi assistenti, Toshkent arxitektura-qurilish universiteti, Toshkent, O‘zbekiston)
E-mail: sardorqodirov110599@gmail.com

Annotatsiya. Mavjud binolarni energiya samarador modernizatsiya qilishda fasad va fotoelektr tizimlarini o‘rnatish ishlarini diagnostika natijalari bilan bog‘lash dolzarb vazifa hisoblanadi. Maqolada termografik diagnostika, energetik hisoblash va qurilish jarayonlarini BIM asosida rejalashtirishni bog‘lovchi uslubiy yondashuv taklif etiladi. Ish tanlangan adabiyotlar va texnik hujjatlar tahliliga hamda konseptual model ishlab chiqishga asoslangan. Harorat anomaliyalarini qo‘shimcha tekshiruv orqali tasdiqlash, tekshirilgan ma’lumotlarni BIM elementlariga biriktirish va ularni ish hajmi, mehnat sarfi hamda operatsiyalarni boshlash shartlariga aylantirish tartibi ishlab chiqilgan. Metodik natijalar diagnostik talqin sxemasi, fasad va fotoelektr tizimlari montajini muvofiqlashtirish jadvali hamda uch variantli baholash rejasidan iborat. Energiya talabining kamayishi, fotoelektr tizimining elektr ishlab chiqarishi va ishlarni tashkil etish samarasi alohida baholanadi. Muayyan obyekt bo‘yicha termografik o‘lchovlar yoki bajarilgan BIM tajribasi natijalari keltirilmagan; usulning amaliy samarasi mustaqil tajribaviy tekshiruvni talab qiladi. Taklif etilgan yondashuvdan energiya samarador rekonstruksiya loyihalari uchun texnologik kartalar va ish jadvallarini ishlab chiqishda foydalanish mumkin.

Kalit so‘zlar: energiya auditi, termografiya, issiqlik ko‘prigi, BIM, 4D rejalashtirish, fasad tizimi, quyosh fotoelektr tizimi, montaj ketma-ketligi, mehnat sarfi, sifat nazorati.

СОВЕРШЕНСТВОВАНИЕ ОРГАНИЗАЦИОННЫХ И ТЕХНОЛОГИЧЕСКИХ РЕШЕНИЙ ПРОЕКТИРОВАНИЯ И МОНТАЖА ЭНЕРГОЭФФЕКТИВНЫХ ФАСАДНЫХ СИСТЕМ И СОЛНЕЧНЫХ ФОТОЭЛЕКТРИЧЕСКИХ СТАНЦИЙ В ЗДАНИЯХ С ПРИМЕНЕНИЕМ ТЕХНОЛОГИЙ BIM НА ОСНОВЕ РЕЗУЛЬТАТОВ ЭНЕРГОАУДИТА

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Нурматов Равшан Каххор угли
(главный энергетик, Ташкентский архитектурно-строительный университет, Ташкент, Узбекистан)
E-mail: nurmatovravshan1@gmail.com
Кодиров Сардор Собир угли
(ассистент кафедры «Строительство зданий и сооружений», Ташкентский архитектурно-строительный университет, Ташкент, Узбекистан)
E-mail: sardorqodirov110599@gmail.com

Аннотация. Увязка монтажа фасадных и фотоэлектрических систем с результатами диагностики является актуальной задачей энергоэффективной модернизации существующих зданий. В статье предложен методический подход, связывающий термографическую диагностику, энергетические расчёты и планирование строительных процессов на основе BIM. Работа основана на анализе выбранных публикаций и технических документов, а также разработке концептуальной модели. Определён порядок подтверждения температурных аномалий дополнительными обследованиями, привязки проверенных данных к элементам BIM и их преобразования в объёмы работ, трудозатраты и условия начала операций. Методические результаты включают схему интерпретации диагностических данных, таблицу координации монтажа фасадных и фотоэлектрических систем и план оценки трёх вариантов организации работ. Снижение потребности здания в энергии, выработка электроэнергии фотоэлектрической системой и организационный эффект оцениваются раздельно. Результаты термографических измерений или выполненного BIM-эксперимента на конкретном объекте не представлены; практическая эффективность метода требует независимой экспериментальной проверки. Предложенный подход может использоваться при разработке технологических карт и календарных графиков проектов энергоэффективной реконструкции.

Ключевые слова: энергоаудит, термография, тепловой мост, BIM, 4D-планирование, фасадная система, солнечная фотоэлектрическая система, последовательность монтажа, трудозатраты, контроль качества.

Introduction

Energy-efficient retrofitting requires attention to both the design performance of building components and the quality of their installation. Insulation thickness alone does not describe the condition of an existing facade: discontinuities, junction details, moisture, and workmanship defects can affect its thermal behaviour. When facade

refurbishment and solar photovoltaic (PV) installation are undertaken within the same project, access, fixing locations, cable routes, and inspection requirements must also be coordinated.

The aim of this study is to develop a methodological framework that connects verified energy audit and supplementary inspection findings with facade and PV design decisions, installation sequencing, and quality control in a common BIM information structure. The research question is how diagnostic status can be translated into specific activities, labour requirements, and conditions for releasing subsequent work.

The working hypothesis is that accounting for verified defects and activity dependencies may improve the accuracy of labour and duration estimates and reduce rework under equivalent design and quality requirements. This is a hypothesis for future testing. The present paper reports conceptual and methodological outputs rather than measured improvements on a construction site.

Literature review

ISO 6781-1:2023 establishes the scope and general procedures of infrared thermographic services for detecting thermal, air, and moisture irregularities in buildings, including requirements concerning equipment, personnel, and reporting [1]. Its publicly accessible description supports the use of thermography as a structured diagnostic service. In this paper, supplementary measurements are proposed to test the suspected causes of observed anomalies; detailed inspection conditions must be specified for each investigation.

Aïssani et al. investigated workmanship defects in insulation and proposed analytical models for effective thermal conductivity that account for defect type and size [2]. Their work supports including installation quality in the thermal assessment of a facade. It does not establish that the area of a coloured region in a thermogram is equal to the physical area of a defect.

Nusen et al. combined BIM with a multi-objective genetic algorithm for renovation planning and scheduling [3]. Their study addresses schedule, cost, and resource coordination. Consequently, producing a 4D animation or linking model elements to dates is insufficient, on its own, to substantiate a claim of methodological novelty.

PVWatts V8 provides a separate basis for estimating PV output from system specifications and weather data [4]. The selected sources address diagnostics, insulation performance, scheduling, and PV modelling. This paper proposes a connection between these functions through verified defect records and activity release conditions. The review is focused and non-systematic; it does not establish that comparable integration methods are absent from the wider literature.

Research methodology

Study design and scope

The study consists of a focused literature review, development of a proposed BIM data structure, formulation of activity dependencies, and design of a comparative validation protocol. No site measurements, calibrated building energy model, or implemented 4D simulation were available for this study. All workflows and tables below are proposed methodological tools. The illustrative installation sequence assumes an externally insulated facade with a reinforced render finish and a building-associated PV system; it must be adapted for other facade types and project conditions.

Diagnostic evidence and BIM records

Each inspected facade section is assigned a unique identifier. Its record contains links to the thermogram and visible-light photograph; inspection date and environmental conditions; anomaly location and geometry; diagnostic status and supporting evidence; confirmed defects and corrective activities; measured work quantities and units; the basis of labour estimates; and predecessor activities, waiting periods, and acceptance criteria.

The inspection record should state facade orientation, indoor and outdoor air temperatures, operating conditions, recent solar exposure, wind, surface condition, camera settings, and assumptions concerning emissivity and reflected radiation. Compared areas must be assessed for differences in materials and exposure. An anomaly is initially recorded as unverified, and its status is updated when supplementary evidence confirms, rejects, or leaves the suspected cause unresolved. Unverified observations must not be treated as confirmed repair quantities.

Thermogram geometry must be checked against measured building dimensions and the corresponding BIM element. A window-perimeter anomaly, for example, is linked to the relevant junction; the sealing quantity is determined in linear metres from verified model geometry and on-site measurement. Contact temperatures, moisture measurements, junction inspection, and pressure-difference testing are selected according to the suspected cause. Table 1 summarises the proposed interpretation logic.

Table 1. Proposed interpretation of thermographic observations

Thermographic observation	Possible cause	Verification method	BIM and work-plan entry after verification
A cold strip along a structural element on the internal surface under heating conditions	A thermal bridge or discontinuity in the insulation	Review of junction details, contact temperature measurements, and local thermal calculations where needed	Junction geometry, additional work quantities, and an inspection point
Localised cooling around a window perimeter under heating conditions	Air leakage or a thermal bridge at the junction	Testing under a pressure difference, airflow observation, and junction inspection	Operations for opening, preparing, sealing, and inspecting the joint for acceptance
A localised patch with an uneven temperature distribution	Moisture, differences in materials, or other surface effects	Moisture measurement, visible-light photography, and repeat thermography	Moisture source, corrective activity, and release condition for subsequent work
Repeating anomalies aligned with cladding or fixing points	Heat transfer through fixings or characteristics of the assembly	Comparison with connection details and fixing locations, supported by calculations	Fixing type, number, and parameters to be included in thermal calculations

Work quantities and activity release conditions

For each confirmed defect, the proposed record links the affected element to a defined repair operation and its measured quantity. Estimated labour is obtained by multiplying the work quantity by an appropriate unit labour requirement and summing across operations. Each rate must have an identified source, such as an applicable estimating norm or a site productivity record. Access restrictions and preparatory tasks are listed explicitly to avoid omitting or counting the same work twice.

An activity can commence only when its predecessors are complete, required waiting periods have elapsed, the work area and resources are available, and the relevant inspection has been accepted. In the 4D model, a failed or unresolved inspection keeps the dependent activity unreleased. The model records the inspection evidence and responsible acceptance role; a colour change in an animation alone is not evidence of acceptance.

Energy and PV assessment boundaries

The building energy model requires checks of wall layers, thermal zones, glazing, orientation, and operating schedules. Retrofit and baseline cases must use comparable weather and occupancy assumptions. Model geometry alone does not verify the thermal inputs. Reductions in heating and cooling demand should be reported separately from delivered energy consumption, with the conversion assumptions stated.

PVWatts inputs include location or weather file, nameplate capacity, array and module type, tilt, azimuth, and losses [4]. With hourly output enabled, the API reports AC output in watts; energy in kWh is obtained by multiplying average interval power by the interval duration in hours and dividing by 1000. The suitability of available weather data for the study location must be checked. PV generation, on-site use, and export are separate quantities; self-consumption requires time-aligned load and generation data. PV generation must not be presented as a reduction in the building's underlying energy demand.

Comparative validation protocol

Three schedules are proposed for comparison. Scenario A uses conventional planning for a fixed retrofit design. Scenario B uses a 4D BIM schedule for the same design, scope, and input information. Scenario C incorporates verified diagnostic status, any justified preparatory tasks, and explicit inspection release conditions into the 4D schedule. The design, quality requirements, resource assumptions, and weather and access constraints must be recorded for all three scenarios.

The B–A comparison is intended to examine the effect of BIM coordination. The C–B comparison examines the additional diagnostic workflow. If diagnostics reveal extra necessary work, the changed scope must be reported: a difference in total duration alone cannot then be attributed to planning quality. Comparable work packages should be assessed separately, alongside total project outcomes and the cost of additional diagnosis.

Future validation should compare predicted and observed duration and labour on work areas not used to establish the model or productivity rates. Duration error can be

expressed as the absolute difference between predicted and observed time, with relative error reported only where observed duration is non-zero. Idle time, rework hours, and defects should be recorded using consistent definitions and inspection intensity. Audit, inspection, and BIM preparation costs belong in the total cost comparison. These checks are proposed and have not yet been performed.

Analysis and results

Methodological outputs

The outputs of this study are the diagnostic interpretation framework in Table 1, the element-level information structure, and the installation coordination procedure in Table 2. Together, they provide a traceable path from an observed anomaly to a verified defect, a measured work quantity, a scheduled activity, and an acceptance record. This traceability is a feature of the proposed framework, not a measured improvement in project performance.

Table 2. Proposed coordination of facade and PV installation

Operation	Prerequisite for commencement	Checks in the BIM and 4D model
Facade substrate preparation	Inspection completed and work quantities determined	Work area, scaffolding, access routes, and crew availability
Rectification of confirmed defects	Cause established and repair method specified	Repair quantities, materials, and acceptance criteria
Preparation of facade cable penetrations and fixing locations	PV cable routes and connection details approved	Potential reopening of finishes and clashes with other services
Insulation installation and junction treatment	Substrate accepted and suitable conditions established	Activity sequence, labour allocation, and inspection before concealment
Reinforcement and finishing	Previous layer accepted and specified waiting period completed	Dependencies between layers and readiness of the work area
Installation of PV supports, modules, and cables	Supporting substrate and anchorage design approved; work area released	Lifting equipment, delivery routes, exclusion zones, and interference with facade works

Operation	Prerequisite for commencement	Checks in the BIM and 4D model
Testing and final inspection	Relevant installation works completed	As-built records, outstanding defects, test results, and acceptance status

Table 2 identifies dependencies to be checked, rather than imposing a universal sequence. PV anchors or cable penetrations that affect waterproofing or insulation may need to be installed before facade finishing. Other PV activities may proceed in parallel where access, lifting operations, work zones, and safety conditions allow. The project-specific sequence must reflect these interfaces.

Interpretation and limitations

The proposed framework separates three questions: whether facade measures reduce energy demand, how much electricity the PV system generates, and whether the construction workflow improves delivery. A successful energy calculation does not validate the schedule; an accepted schedule does not establish the thermal quality of the completed facade. Each claim requires its own evidence.

The comparison protocol also exposes a potential bias. More intensive inspections may initially identify more defects, so a higher recorded defect count does not necessarily indicate poorer workmanship. Future assessment should distinguish defects detected before concealment, unresolved defects at handover, and defects discovered after completion, using comparable inspection procedures.

No numerical saving, reduction in labour, or shortening of project duration can be reported from the available material. No building-specific thermograms, construction logs, calibrated energy results, or comparative schedule outputs were supplied. The proposed contribution is therefore a framework and a testable evaluation plan. Establishing novelty and practical advantage requires a broader review and independent implementation data.

Conclusion and recommendations

This study proposes a method for integrating verified energy audit findings with BIM-based planning of facade and PV installation. Its methodological contribution is the explicit linkage between diagnostic status, corrective work quantities, labour assumptions, activity dependencies, and inspection release conditions. The two tables define how this linkage can be recorded and applied in a project workflow.

For implementation, the recommended sequence is to verify suspected defects, register

evidence against BIM elements, quantify the necessary operations, assign supported labour rates, and define acceptance conditions before scheduling dependent work. Energy demand and PV electricity generation should be evaluated within separate and clearly stated accounting boundaries.

The next research stage should test the three scheduling scenarios on comparable work packages and validate predictions on independent areas. Changes in scope, resource availability, inspection effort, and preparation costs must be documented. Until these tests are completed, the method should be presented as a proposed approach rather than a proven source of energy savings or construction efficiency gains.

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