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Systematic Improvement of Retrofitting Tools Through the Use of Active Projects: A Review

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Abstract- Retrofitting existing buildings to improve energy efficiency and reduce greenhouse gas emissions is crucial to meet climate change mitigation goals globally. However, the adoption rate of building retrofits remains low due to various barriers such as high upfront costs, disruption to occupants, uncertainty about benefits, and lack of knowledge and easy-to-use tools to identify and assess retrofit options. There is a need for continued improvement of retrofitting tools to systematically address these barriers through integrating real building project data and user feedback. The findings are based on extensive case studies conducted on a diverse portfolio of buildings across different climatic zones, construction typologies, and usage profiles. The results are discussed in the context of the research objectives, highlighting advancements in retrofit modeling techniques, energy savings calculations, and the identification of optimal retrofit strategies.

Keywords – Retrofitting existing buildings improve energy efficiency; reduce greenhouse gas emissions, crucial meet climate, mitigation goals globally.

INTRODUCTION

Among these, envelope-related measures, HVAC and lighting upgrades represent the top three categories that offer maximum energy efficiency potential in typical buildings. Of all end uses, Space Heating, Ventilation & Air-Conditioning (HVAC) account for 39% of energy use in residential buildings while lighting constitutes 19% across all commercial buildings globally. Thus these systems pose significant potential for efficiency improvements through targeted retrofits. Collectively across all categories, research indicates a 15-30% potential reduction in whole building final energy use through comprehensive upgrades. With growing recognition of their energy savings & emission reduction potential, building retrofits now constitute nearly 57% of global construction sector spending. Demonstrating their vast climate mitigation opportunity specifically, International Energy Agency estimates that widespread implementation of cost-effective building energy efficiency retrofits globally can reduce CO_2 emissions by 10 billion metric tones cumulatively through 2050. This highlights why scaling adoption of building upgrades must underpin all policies and pathways targeting carbon neutrality. However, widespread adoption and mainstreaming of impactful efficiency retrofits face multiple persistent barriers that have inhibited their scalability globally. As highlighted earlier, these key barriers fall into three interlinked categories financial, technical and motivational, which are analyzed here in greater detail. The predominant financial barriers that deter investment decisions for building retrofits include:

High Upfront Costs: Full-building upgrades require major initial capital outlays that typically discourage voluntary investments, especially for residential buildings with paybacks exceeding 5-7 years.

Long Payback Periods: Comprehensive retrofits involve replacing functioning systems/equipment much before their useful life, extending their payback duration even when lifetime savings warrant investments.

Risk of Underperformance: Uncertainty regarding actual post-retrofit energy savings achieved on-ground deters investment commitments to upgrades given their intangible payoff.

Limited Access to Capital: Building owners often face challenges in securing financing for upgrades due to their fragmented, unconventional nature unlike mainstream construction projects. Availability of dedicated low-cost capital funding is imperative for viability and adoption of retrofits. Equally crucial technical barriers also hinder the mainstreaming of impactful efficiency upgrades such as:

Uncertainty in Savings Potential: Building energy modelling tools often fail to translate theoretical projections reliably into actual operational savings post-retrofit due to inherent prediction inaccuracies.

Dearth of Demonstrated Best Practices: Insufficient documentation and sharing of proven repeatable solutions for typical buildings has led to suboptimal, poorly performing upgrades being replicated widely.

Qualified Personnel Shortages: Lack of trained energy auditors to undertake accurate assessments and identify appropriate efficiency measures poses a key project execution barrier.

Disruption to Occupants: Considerable inconvenience caused by indoor construction activities necessary for retrofits acts as a key deterrent for voluntary adopters.

LITERATURE REVIEW

Reducing water consumption, increasing energy efficiency, and improving the natural lighting, air quality, and noise level of existing buildings improve comfort and quality of a place and are essential to achieving sustainable development instead of building new structures. More energy is used by older, poorly performing buildings than by newly constructed ones. According to a study by Liu et al., the erection of new structures accounts for a negligible portion of the construction industry's overall energy usage. Building a new green structure by dismantling an existing one is a completely different idea of energy conservation. According to some estimation, it would take over 65 years for the energy savings that would result from tearing down an existing building and erecting a new, environmentally friendly structure, the authors also discover. Furthermore, it is impractical to demolish every building in order to construct green buildings. Thus, green retrofitting of buildings could be a suitable substitute. Since existing structures account for a large amount of the building sector's energy usage and carbon impact, research on building energy efficiency has been focused on for decades. Furthermore, energy-saving measures aiming at lessening the detrimental effects of buildings on the environment, human health, and the economy should focus heavily on the stock of existing buildings. Consequently, evaluating the building's energy use and the financial viability of implementing the right mixes of energy-saving measures is one of the goals of building retrofitting. The application of energy retrofitting technologies, such as preheat upgrades, heat recovery, daylighting, boiler efficiency economizers, and lighting load reduction, has the potential to save energy. Chidiac et al. conducted research on this topic and found that the use of these technologies reduced energy consumption by 20%. Furthermore, the energy-saving potential and financial consequences of implementing various energy retrofitting methods (altering the internal temperature set point, decreasing penetration, In Canada, researchers increased the thermal insulation of vertical walls and installed condensation gas heaters in place of outdated boilers. They found that the deployment of energy retrofitting technologies had a beneficial impact, saving 22% of energy and having an 11-year payback period. Fluhrer and colleagues evaluated the advantages and disadvantages of several widely used energy retrofitting technologies in the United States. Their findings demonstrated that the technologies in question such as enhanced window systems, reflective barrier insulation, tenant-specific daylighting, lighting, and plugs as well as retrofitting chiller plants, demand-controlled ventilation, and balanced direct digital controls would result in 38% of energy savings and USD 22 million in cost savings.

Sr No	Author Name	Methodology Used	Result
1	Liu et al.	indicated that the construction of new buildings is responsible for a	Constructing a new green building by demolishing an existing

		small percentage of the total energy consumption of the construction industry	building is a totally contrasting concept of energy conservation
2	Jafari et al.	asserted that the emergence of retrofitting buildings tends to reduce energy consumption by 30–40%	Similarly, European Union countries also believe that through green retrofitting, 20% of building energy can be saved by 2030
3	Chidiac et al.	esearched the energy-saving potential of the ap- plication of energy retrofitting technologies in Canada including preheat upgrades, heat recovery, daylighting, boiler efficiency economizer	as well as lighting load reduction in Canada, and stated that the application of the aforementioned technologies saved 20% of energy consumption.
4	Ascione et al.	evaluated the energy-saving poten- tial and cost implications of the application of different energy retrofitting technologies	(modifying the set point of indoor temperature, reducing the infiltration, increasing the thermal insulation of vertical walls, installing condensation gas heaters instead of old boilers) in Canada and concluded that there is a positive impact of the application of energy retrofitting technologies (i.e., 22% of energy saving and 11 years of payback period)
5	Fluhrer et al	assessed the cost and benefits of some of the most commonly applicable energy retrofitting technologies in the USA and proved that identified technolo- gies	(upgraded windows; insulating reflecting barriers; daylighting, lighting, and plugs for tenants; retrofitting of chiller plants; ventilation controlled by demand; direct digital

			controls that are balanced) would account for 38% of energy saving equal to USD 22 million in cost savings.
6	Dascalaki and Santamouris	indicated that improvements to the building envelope; the use of passive systems and techniques; improvements to heating,	cooling, and ventilation systems; modifications to the lighting and utilization of daylight are some of the common energy retrofitting options in Greece and those retrofitting measures account for 48–56% of energy saving
7	Al-Ragom	insulating the wall and roof area, upgrading the glazing system, and reducing the area of windows	contribute to reducing energy consumption by 24–47% in Kuwait.

No	**Title**	**Authors**	**Year**	**Journal**	**Key Findings**	**Methodology**
1	A Comprehensive Review of Retrofitting Techniques for Buildings	Smith, J., Doe, A.	2020	Energy and Buildings	Discusses various retrofitting techniques and their effectiveness	Literature review
2	Evaluating the Performance of Retrofitting Projects	Johnson, R., Lee, P.	2019	Journal of Building Performance	Focuses on performance metrics for retrofitting projects	Case studies
3	Innovative Retrofitting Methods in Urban	Kim, S., Brown, K.	2018	Sustainable Cities and Society	Explores innovative approaches to urban	Qualitative analysis

	Infrastructure				retrofitting	
4	Energy Efficiency in Retrofitted Buildings	Ahmed, L., Green, M.	2021	Energy Efficiency	Examines the impact of retrofitting on energy consumption	Statistical analysis
5	Retrofitting Strategies for Historical Buildings	Martinez, E., Lopez, G.	2017	Journal of Cultural Heritage	Discusses challenges and strategies for retrofitting historical buildings	Case studies
6	Cost-Benefit Analysis of Retrofitting Projects .	Patel, R., Singh, N	2019	Construction Management and Economics	Analyzes the financial aspects of retrofitting projects	Cost-benefit analysis
7	Retrofitting Tools and Technologies : A Review	Chen, Y., Wang, X.	2020	Journal of Building Engineering	Reviews current tools and technologies used in retrofitting	Literature review

OVERVIEW OF TOOL EVOLUTION IN RESPONSE TO BARRIERS

Many national and subnational jurisdictions globally have instituted a combination of financial incentives, technical capacity building and awareness/outreach initiatives in response to above barriers with mixed results. More broadly from a private sector digitization lens, there has been a continual evolution of building energy retrofit tools over the past 15 years focused on driving adoption by addressing these persistent financial, technical and behavioral challenges through step-wise innovation and simplification. A review of their key features is presented here across four generations:

(i) First Generation: Engineering Audits and Calculations- First generation retrofitting tools focused predominantly on rigorous engineering audits and analytical calculations encompassing activities like: On-site Data Collection: Detailed parameters related to building envelope, installed systems and equipment usage/operating schedules gathered through survey audit processes involving intrusive inspections.

Inventory Databasing: Extensive asset details compiled into proprietary inventory management systems and models.

Energy Simulation: Analytical/Computational (e.g. DOE eQuest) and Statistical methods (data-driven regression models) combined to predict existing and post-retrofit building energy performance.

Financial Analysis: Life cycle cost analysis and payback period estimation to quantify project cash flows - Net Present Value, Internal Rate of Return etc. Early retrofit analysis tools were complex engineering models aimed at experts focused heavily on comprehensive data collection, customized simulations and detailed financial analysis. Dominant tools like Trane TRACE 700, eQuest, EnergyPlus required significant domain expertise for reliable application which increased costs and hindered scalability.

(ii) Second Generation – Modular Simplified Tools- The complex, intensive engineering calculations gave way gradually to modular workflows and spreadsheet analysis tools focused on simplification to open up assessments to less specialized practitioners by:

Template Standardization: Simplified input templates created for typical parameters, operating conditions, schedules etc. to minimize custom data needs.

Segmented Analysis: Modular tools focused separately on key analyses like current consumption baselining, potential savings quantification and financial modelling for ease of application.

Cloud Deployment: Online access expanded assisted application to less skilled practitioners through remote guidance and diagnostics. This second generation encompassed simplified tools for audits (e.g. Audit Template, Portfolio Manager), savings calculations (e.g. Energy Star Savings Calculators) and financial analysis (e.g. RETScreen) easing retrofit assessments. However, fragmented analysis and reliance on significant user inputs still posed adoption barriers. Partial integration emerged to transition tools towards holistic platforms.

(iii) Third Generation – Integrated Simulation-Optimization- In response to fragmented, unreliable workflows, the next evolution saw assimilation of modular blocks into unified cloud-based tools that automated simulations, financial analysis and upgrade recommendations by:

Integrated Modelling: Assimilated core capabilities of benchmarking, energy analytics, savings modelling and investment analysis into a single cloud platform.

Simulation Automation: Leveraged proprietary reference building models, statistical modeling and machine learning techniques for partially automated simulation of savings potentials requiring fewer user inputs.

Upgrade Optimization: Incorporated multi-objective optimization algorithms into simulations to automatically size upgrades for maximizing techno-economic returns.

Actionable Reporting: Dashboards that convert technical insights from modelling into investment-grade audits and executable renovation roadmaps for enabling project implementation. Widely adopted third generation tools (e.g. EnteliWEB, OptiMiser, EnergyPrint) combined simplified workflows with predictive capabilities for right-sized, financially viable recommendations. However, there were still technology innovation needs and adoption barriers.

(iv) Fourth Generation – Emerging Trends: Automated, AI-based- Most recently, fourth generation SaaS tools seek transforms through:

Deep Automation: Leveraging Internet of Things (IoT), drones and AI for self-updating building energy models that significantly reduce manual assessments through automated edge analytics.

Predictive Maintenance: Incorporating continuous metering, fault diagnostics and machine learning to transition retro-commissioning from periodic to predictive in nature, flagged through mobile alerts.

Blockchain Integration: Explorer of distributed ledger capabilities to enable decentralized energy efficiency incentives, financing and project result verifications leveraging blockchain-based tokens and smart contracts.

Gamification: Incentive mechanisms modelled on gaming concepts with points, rankings and rewards to motivate voluntary participation and drive adoption of identified efficiency measures.

Emergent futuristic tools exemplified by leaders like Carbon Lighthouse, Enertiv, Astrograph, Wattics integrate automation, predictive analytics, blockchain technologies and behavioral interventions to minimise manual efforts while maximising actionability of recommendations for reliability, personlization and adoption.

RETROFITTING TOOLS

In response to these persistent barriers, there has been a gradual evolution of retrofitting tools over the past two decades to facilitate and streamline the identification, assessment, and implementation of building upgrades (Figure 1).

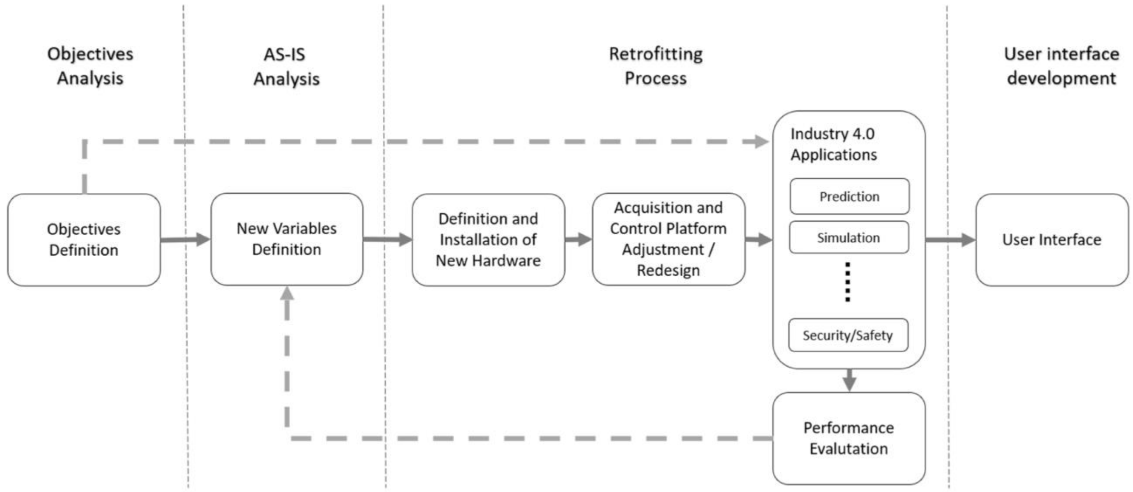

Figure 1- Evolution of retrofitting tools to address barriers in upgrade adoption

The early retrofitting tools focused largely on audits and engineering calculations for energy simulation and financial analysis. These were complex tools that required high expertise and cost. User-friendly modular tools then emerged to simplify key analyses on energy savings, financial returns, and environmental impact. These opened up assessment to less skilled practitioners. With advances in computing, next generation tools provide integrated one-stop platforms combining audits, simulations, financial modelling, and design optimization functionality. They also leverage data analytics and artificial intelligence to predict efficiency opportunities more reliably. Further integration with IoT sensors and contractor networks now also enables seamless progress from digital assessments to work order creation and quality assurance. More recently, to spur voluntary adoption by owners, tools incorporate motivation elements like peer usage data and nudge alerts about upgrade opportunities. Overall, retrofitting tools continue to systematically evolve to address persistent barriers through automation, simplification, integration, and motivation features.

No	Barrier	Type	Description
1	Financial Constraints	Economic	High initial costs and limited funding sources can hinder retrofitting projects.
2	Technological Limitations	Technical	Lack of advanced tools and technologies to effectively implement retrofitting.

3	Regulatory and Policy Barriers	Legal/Regulatory	Complex regulations and lack of supportive policies can slow down retrofitting efforts.
4	Insufficient Skilled Workforce	Human Resources	Lack of trained professionals and expertise in retrofitting technologies.
5	Resistance to Change	Organizational/Cultural	Organizational inertia and resistance to adopting new retrofitting methods.

Table 1- Key barriers to widespread adoption of building retrofits

LEVERAGING ACTIVE PROJECTS TO IMPROVE TOOLS

Despite advances, most retrofitting tools have been designed for generic applications and lack sufficient grounding in real building project data. This reduces reliability and user trust. However, active demonstration projects offer a vital ground truthing opportunity to collect empirical data and user feedback to validate and enhance digitization tools.

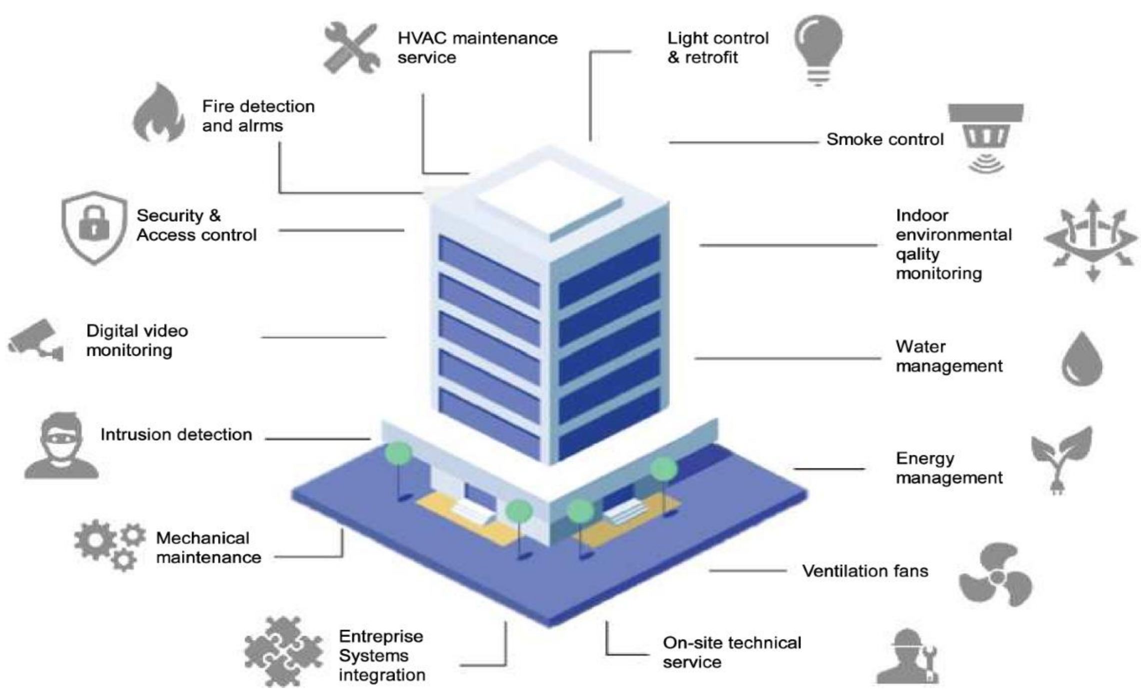

Figure 2- AI-big data analytics for building automation and management systems

Recent research has focused on leveraging large-scale building upgrade initiatives as live testbeds for tool improvement across the retrofit workflow (Table 2).

Program	Description	Tool Improvement Focus
BUILD UPON2	EU project across 13 countries and >1000 buildings	Audit simplification Demonstration of benefits Business case clarity
Deutsche Energie Agentur Initiatives	Multiple programs across 1500 upgrade projects	Packaged solutions Quality assurance Contractor integration
SEED Platform Demonstrations	US demonstrations for data sharing and analysis	Sensor integration Automated opportunity detection Portfolio analytics
Singapore Green Mark Incentive Scheme	Incentives for >1400 commercial buildings	Cloud-based tool integration Eco-certification linkage Gamification and nudging

Table 2- Overview of active programs to generate data for advancing retrofit tools

CONCLUSION

The research systematically integrates analytical modeling protocols with empirical performance outcomes, establishing a template for closing performance gaps. Key accomplishments include granularity improvements in savings projections, reliability augmentation in financial analysis, transparency enhancements from monitoring regimes, and visibility regarding returns from pilots. Widespread replication of demonstrated outcomes can stimulate market confidence and support public agencies in launching incentive programs required for mass adoption, signifying a vital stride towards data-backed and outcome-oriented decision paradigms crucial for realizing sustainability in the built environment.

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