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# 3E Multi Decision-making model for Energy-efficient Retrofit Framework (ERF) on Existing Buildings: A Case Study in Shanghai

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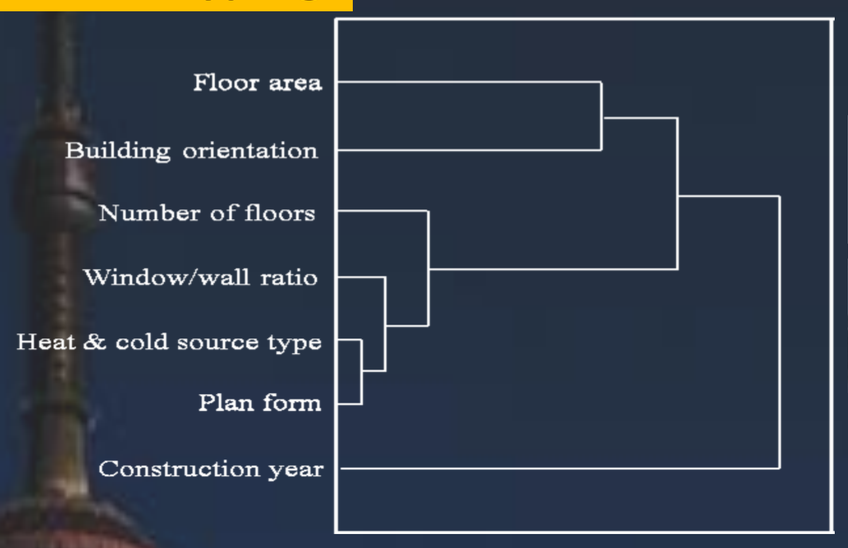
## 1. Abstract

Low-rise office buildings in Shanghai, which account for over 50% of existing office stocks, are old and energy inefficient. Hence, this research develops an energy-efficient retrofit framework founded on a multi-objective decision-making model with consideration to energy, environmental and economic (3E) concerns. IES-VE software evaluated the 3E impacts of 12 specific retrofit measures; while a simplified LCC assessment and annual $CO_2$ savings provided the optimum retrofit package.

## 2. Prototyping



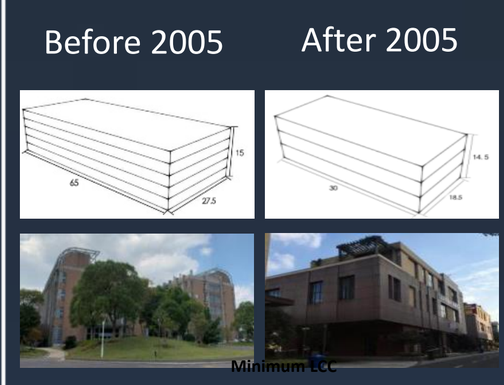
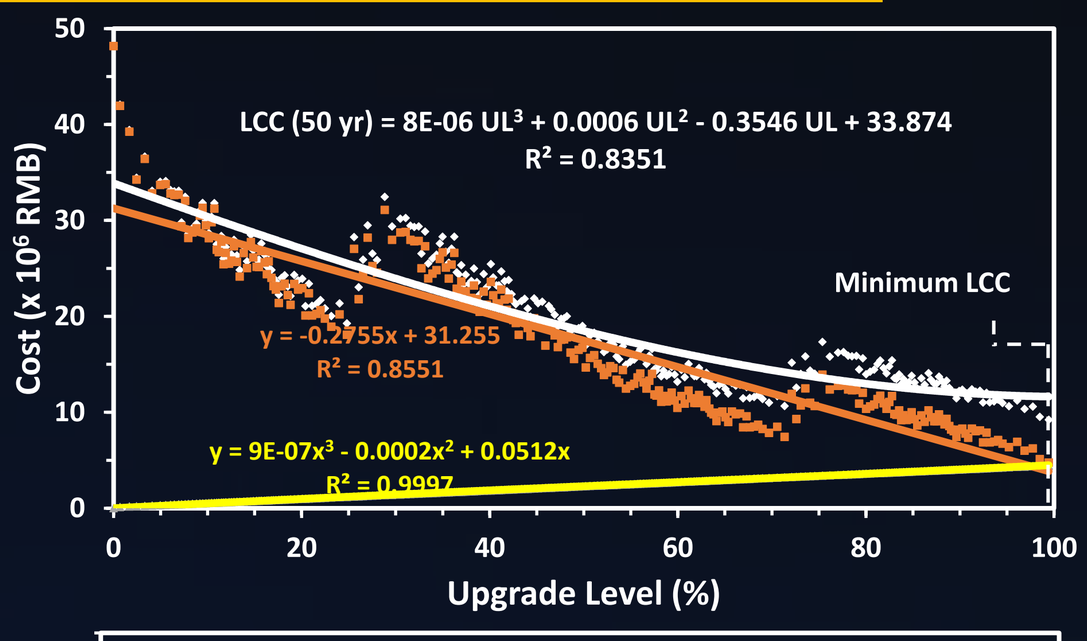




Fig. 1. Cluster analysis of the impact of building characteristics on its energy consumption, prototypical and typological buildings before and after 2005, as defined by cluster and correlation analysis.

## 3. 50 years life-cycle cost (LCC) analysis



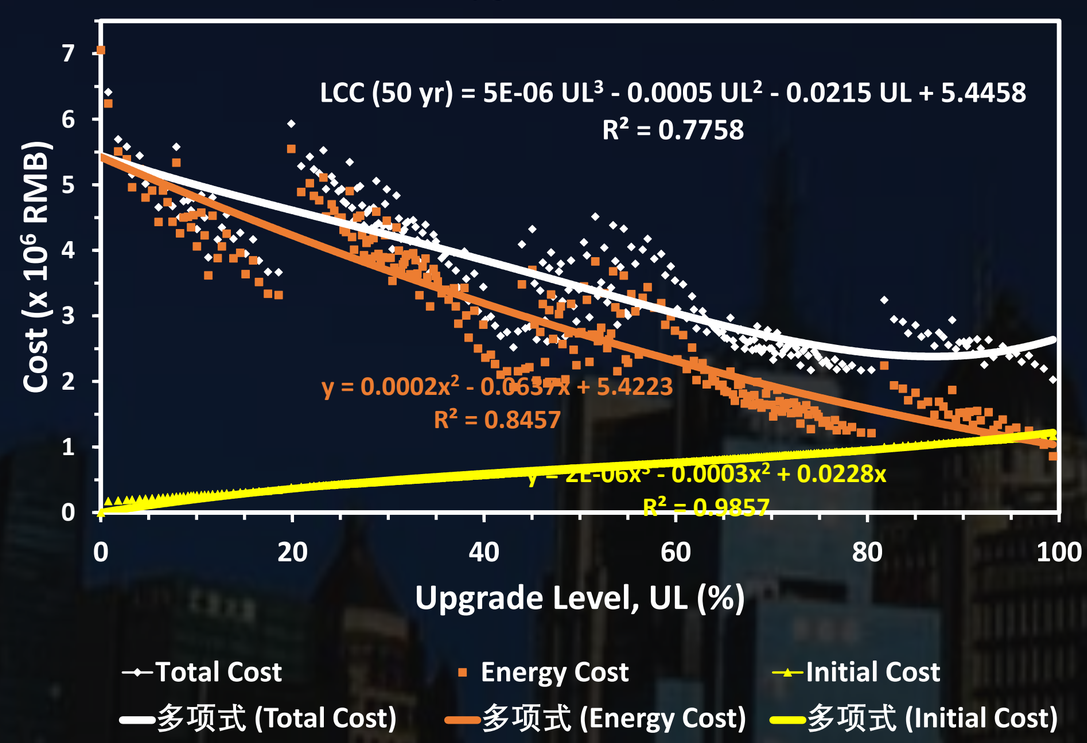




Fig. 2. Optimal retrofit strategy (upgrade level) in terms of the minimum LCC (TC) evaluation for buildings built (a) before, and (b) after 2005

## 4. Results

| Group | Activity | Specific Retrofit Measures | Optimal retrofit strategy at minimum LCC for buildings built | |
|---|---|---|---|---|
| | | | Before 2005 | After 2005 |
| **Original** | None | original model, based on 1980 or 2005 building codes in China | | |
| **Energy Conserving Behaviors** | 1. Occupancy regimes | Occupancy period: 9 am - 5 pm | ✓ | ✓ |
| | 2. Comfort requirements | Reduce the set indoor temperature range by 1 °C | | ✓ |
| **Equipment /Lighting System** | 3. Natural ventilation | reduce ventilation rate from 8.3 L/s/person to 8 L/s/person | ✓ | ✓ |
| | 4. Upgrade lighting | increase lighting efficiency to 9 W/m² | ✓ | |
| | 5. Upgrade HVAC | improve energy-efficiency of system | ✓ | ✓ |
| **Building Envelope** | 6. Insulate ceilings | add 20mm XPS insulation material | ✓ | |
| | 7. Insulate walls | add 160mm XPS insulation material | ✓ | ✓ |
| | 8. Insulate cool roofs | add 150mm XPS insulation material | ✓ | ✓ |
| | 9. Upgrade windows | replace windows with energy-efficient ones (6low-E+12air+6+12air+6low-E) | ✓ | |
| | 10. Air-tightness | change air-tightness infiltration to Na = 0.6 ach | ✓ | ✓ |
| **Renewable energy** | 11. Install solar PV system | PV panel system | ✓ | ✓ |
| | 12. Install geothermal system | heat pump for heating and cooling load | ✓ | ✓ |
| **Initial investment cost (million RMB)** | | | 4.2 | 1.0 |
| **Energy reduction (%)** | | | 89 | 74 |
| **Annual $CO_2$ saved (Gg)** | | | 0.9970 | 0.1062 |
| **LCC (million RMB)** | | | 12.4 | 2.4 |

## 5. Validation

Empirical and comparative validation indicate an 82% reduction in building energy use intensity at minimum LCC. This indicates a 90% match in the result when compared with the predicted 74% reduction. Overall, the proposed 3E multi-objective decision-making framework for establishing the optimal retrofit solution for low-rise buildings in Shanghai is reliable and can provide guidance for building stakeholders in the selection of suitable retrofit strategies in building projects.

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