JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

COMPARATIVE EVALUATION OF RESIDENTIAL BUILDING DESIGN ALTERNATIVES BASED ON CONSTRUCTION COST, MATERIAL EFFICIENCY, FUNCTIONAL PERFORMANCE, AND AESTHETIC QUALITY: A LITERATURE REVIEW

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Abstract : Choosing between alternative designs for a residential building is a multi-criteria problem. A scheme that is cheapest to build may use more material, perform poorly in operation, or fail to satisfy users visually. This review synthesises nine studies on life cycle assessment (LCA), construction materials, prefabrication, space efficiency, multi-criteria decision analysis (MCDA), green rating systems and sustainable design. It examines what each says about four evaluation criteria: construction cost, material efficiency, functional performance and aesthetic quality. The literature shows that (i) embodied impacts form a larger share of life cycle burdens as buildings become more efficient in use, (ii) differences between structural or material alternatives are often small once the whole life cycle is considered, (iii) cost, environmental and functional criteria can be combined through MCDA but results depend heavily on criteria weights, and (iv) aesthetic quality is the least developed criterion, with almost no quantitative comparison of elevations. These gaps motivate the present research, which compares alternative designs of a hypothetical residential building with identical functional requirements.

IndexTerms - RESIDENTIAL BUILDINGS, DESIGN ALTERNATIVES, CONSTRUCTION COST, MATERIAL EFFICIENCY, LIFE CYCLE ASSESSMENT, SPACE EFFICIENCY, MULTI-CRITERIA ANALYSIS, AESTHETICS
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I. INTRODUCTION

Housing demand rises with population, and the construction sector is a major consumer of energy and materials. Dani et al. note that the global construction industry accounts for about 40% of primary energy use and one third of global carbon emissions [3]. Motuziene et al. add that residential buildings are among the largest energy consumers in the European Union and that single-family houses are responsible for 60% of residential CO2 emissions in the EU [2]. Decisions made at the design stage fix most of a building's material demand, cost and performance for decades, so early comparison of alternatives is among the most valuable activities in a project.

A design alternative can be judged on many dimensions. This review organises the literature under the four criteria used in the present research:

- Construction cost: initial and life cycle cost of the alternative.
- Material efficiency: quantity, embodied energy and carbon of materials, and waste.
- Functional performance: space utilisation, thermal and operational performance, and quality of the living environment.
- Aesthetic quality: visual and architectural quality of the design, particularly the elevation.

The review draws on the following sources: Zhu et al. on prefabrication in China [1]; Motuziene et al. on envelope alternatives for an energy-efficient house [2]; Dani et al. on timber and steel houses in New Zealand [3]; Ilgin and Aslantamer on space efficiency [4]; Khan and Niazi on sustainable material selection [5]; Cabeza et al. on LCA and life cycle energy analysis (LCEA) of buildings [6]; Janjua et al. on residential LCA [7]; Mazur et al. on housing environment quality [8]; Lu et al. on green rating systems and waste [9]; and Almashaqbeh on sustainable versus traditional interior design [10]. The final section identifies the research gap.

II. LIFE CYCLE PERSPECTIVES ON RESIDENTIAL DESIGN

2.1 The LCA, LCEA and LCCA frameworks

Life cycle assessment evaluates environmental burdens across a building's life, usually from material production through construction, use, maintenance and end of life. Cabeza et al. reviewed LCA, LCEA and life cycle cost analysis (LCCA) studies of buildings, construction products and construction systems [6]. Their central observations are structural. Most studies examine "exemplary" low-energy buildings, very few examine traditional buildings of the type found in most cities,

most are urban, and the geographic distribution of studies is uneven. They also found only one LCCA of a whole building, which shows how thin the evidence is on cost over the life cycle [6].

Janjua et al. screened about 807 refereed articles on residential buildings published between 2009 and 2019 [7]. They found that building materials, embodied energy and operating energy contribute chiefly to environmental and socio-economic objectives, and that the carbon footprint is the most common indicator. They argue that reliance on a single indicator risks trade-offs between environmental, social and economic objectives going unnoticed. They also found that most studies use only an approximate service life and neglect the quality of materials, although a method that reflects the durability of individual components would give more realistic results. Social LCA, they conclude, still needs a methodological breakthrough before it can be applied routinely [7].

Two lessons follow for a design comparison. First, results are sensitive to system boundary and service life. Dani et al. used 90 years for New Zealand houses, Motuziene et al. used 100 years, and Zhu et al. used 50 years for Chinese buildings, so absolute figures cannot be compared across studies [1][2][3]. Second, comparison is most defensible between alternatives analysed within one consistent boundary, which Motuziene et al. make explicit when they state that comparing alternatives within a study is acceptable even though comparison across studies is not [2].

2.2 Embodied versus operational impacts

A recurring theme is that the balance between embodied and operational burdens shifts as buildings become more efficient. Motuziene et al. studied an 81 m2 single- family house in Lithuania built to passive house requirements and found that embodied primary energy was 35 to 40% of life cycle primary energy, "a few times" higher than for standard buildings. They attribute this to lower operational demand combined with more material and more sophisticated technical systems [2]. The authors conclude that material selection deserves special attention in energy-efficient houses, although operational energy still matters most overall [2].

Dani et al. reach a complementary conclusion for conventional New Zealand houses with a 90-year life. Operational energy (module B6) contributed 57.67% of life cycle carbon in the timber house and 49.53% in the steel house, and production (A1 to A3) was the second largest contributor at 15.98% and 27.49% respectively [3]. Zhu et al., studying two prefabricated apartment buildings in Chengdu and Shenzhen, report life cycle energy intensities of 21.6 and 25.5 GJ/m2, with

embodied phases of about 6.1 and 5.0 GJ/m2 [1]. Operational demand differed greatly between the two (15.5 and 20.5 GJ/m2), mainly because of cooling in the hot Shenzhen climate [1]. Together these studies show that the relative importance of material efficiency depends on climate, building efficiency and assumed life.

III. CONSTRUCTION COST

Cost appears in the reviewed literature in three forms: initial construction cost, life cycle cost, and cost as a weighted criterion in decision making.

Motuziene et al. computed life cycle cost per square metre for three alternative envelopes: masonry, log and timber frame. The alternatives differed by only up to 3%, and the masonry house was the cheapest to construct (about 343 EUR/m2 for production and construction, against 375 for the log house and 360 for the timber frame house). Technical systems accounted for 54 to 56% of the embodied life cycle expenses, because they are expensive and need replacing more often [2]. The implication is that the envelope material is not always the dominant cost lever; services and replacement cycles can be.

Zhu et al. treat cost indirectly, noting that precast facades and semi-precast slabs reduce formwork and labour demand and improve on-site efficiency, but their quantitative focus is energy [1]. Dani et al. explicitly leave cost out and focus on carbon, which they acknowledge limits the decision value of their comparison [3]. Khan and Niazi's survey of 647 professionals, discussed below, rank initial cost (29.5%) and long-term savings (27.8%) among the highest- priority sub-criteria, which suggests that practitioners treat cost as decisive even when LCA studies do not [5].

The interior design study by Almashaqbeh is useful because it frames the same cost question for finishes. Using expert interviews and case studies, it argues that sustainable options often cost more initially but can lower operating cost and extend material lifespan, so that life cycle cost, not first cost, should drive selection [10]. Lu et al. similarly note that green buildings normally incur higher upfront costs because of more sustainable materials or services, which must be recovered through improved performance [9].

IV. MATERIAL EFFICIENCY

4.1 Material quantities and embodied energy

Material efficiency in the literature is mostly expressed as embodied energy or carbon per unit floor area, rather than as material quantity per unit of function. Zhu et al. found that steel and concrete dominated both quantity and embodied energy in their precast projects, and that

prefabricated and traditional buildings used similar amounts of principal materials [1]. Their hybrid LCA gave embodied energy intensities of 6.11 GJ/m2 (Project A) and 5.04 GJ/m2 (Project B), about 11 to 13% higher than a process-based model because the hybrid approach captures upstream supply-chain energy. They conclude that the embodied saving from prefabrication is "less evident" than often assumed, because factory production adds connectors and reinforcement and substitutes energy-intensive concrete for brick [1]. Their conclusions also rest on only two cases, and they say so.

Motuziene et al. found that the walls, roof and floor of the building envelope make the major impact on embodied flows. The masonry alternative had the highest embodied primary energy, 29% above the log house and 21% above the timber frame house, driven largely by the roof construction, and nearly twice the ozone layer depletion because of finishes such as plywood flooring and ceramic tiles [2].

4.2 Material substitution: timber versus steel

Dani et al. compared a 107 m2 light timber house with a 146 m2 light steel house, both in Auckland and both with a 90-year life. Total life cycle carbon was 13.72 kg CO2e/m2/year for timber and 15.41 for steel, a difference of 12.3%. Production-stage carbon was about 50% lower for timber (2.31 against 4.66). But steel earned a larger recycling credit (module D: -1.53 against -0.74) because of its higher recyclability, which narrowed the gap [3]. Their conclusion is that the difference is small enough that light steel can substitute for timber during a timber shortage. Two cautions apply: the houses differ in floor area and occupancy (three versus five occupants), and all timber was assumed to come from non-sustainable forestry, which raises the timber result [3].

4.3 Waste and green rating systems

Material efficiency also covers waste. Lu et al. compared LEED, China's Green Building Evaluation Label and Hong Kong's BEAM Plus, and found that these systems do not greatly promote superior construction waste management performance despite having waste-related credits. The interviewees attributed this to the design of the rating systems, developers' biases and a lack of incentives, and judged legal and economic incentives to be more decisive drivers [9]. Zhu et al. likewise point to waste reduction as a benefit of factory production, though they do not quantify it [1]. Dani et al. suggest that light steel generated less construction waste than timber, which explained its slightly lower construction- stage carbon [3].

4.4 Criteria for selecting sustainable materials

Khan and Niazi surveyed 647 architects, builders, environmental specialists and others, mainly in Afghanistan, and used EFA, ANOVA, regression, ranking and sensitivity analysis to examine material selection for residential projects [5]. They report that low carbon footprint (27.0%) and recyclability (26.5%) ranked highest within environmental compatibility, that thermal performance ($F = 15.72$) and durability (regression beta = 0.60) were highly significant, and that material availability had the highest sensitivity factor score (0.85). Recycled steel and low-emission concrete were prioritised over bamboo because of local availability and cost [5]. Aesthetic value and cultural relevance ranked lowest.

This study is valuable for its breadth of criteria, but it should be read critically. The ANOVA table reports 57 within-group degrees of freedom, which implies about 60 observations rather than 647, and some p-values do not follow monotonically from the F-values (for example $F = 12.63$ with $p = 0.034$, against $F = 12.37$ with $p = 0.0002$) [5]. The authors also acknowledge that the sample is limited geographically and by occupation [5]. Its rankings are best treated as indicative of professional opinion rather than as verified performance data.

V. FUNCTIONAL PERFORMANCE

Functional performance covers three related aspects: space utilisation, thermal and energy performance, and the overall quality of the living environment.

5.1 Space utilisation

Ilgin and Aslantamer analysed 166 tall buildings from the CTBUH database (27 residential, 44 office, 31 hotel and 64 mixed-use) and found average space efficiencies, defined as usable area as a share of gross floor area, of 76% for residential, 71% for office, 81% for hotel and 71% for mixed-use towers. The core-to-GFA ratios were 19%, 26%, 16% and 26% respectively [4]. Central cores were dominant (93% of residential cases) and prismatic forms were most common in residential towers (56%). Central core planning and simple prismatic geometry were identified as the most important design measures for efficiency, whereas twisted and free forms tended to lose usable area [4]. The authors also note that residential efficiency varies because circulation, amenities, balconies and larger apartments reduce the leasable share [4].

The relevance to a low- or mid-rise residential scheme is partial. The data concern tall towers, so the specific percentages should not be transferred directly, but the underlying principle, that circulation and service cores and complex geometry consume floor area, applies at

any height. It is also a reminder that efficiency is a ratio that can be computed objectively for any design alternative.

5.2 Thermal and operational performance

Zhu et al. simulated four scenarios in DesignBuilder: a prefabricated building, a traditional building built to local energy ordinance, a brick-concrete building, and a baseline meeting the minimum design standard. The brick-concrete scenario used 10.2% (Shenzhen) and 19.6% (Chengdu) more heating and cooling energy than the baseline, whereas the prefabricated and code-compliant traditional buildings were close to each other and to the baseline [1]. The annual operational energy for the Chengdu case was about 314 MJ/m2 for the prefabricated building, against 309.5 MJ/m2 for the traditional code-compliant one and 336.5 MJ/m2 for the brick-concrete one [1]. In the mild Chengdu cooling season the brick-concrete building actually used less energy, because its lower airtightness allowed more natural ventilation, which shows how occupant behaviour and assumptions can reverse expected results [1].

Motuziene et al. fixed the heat transfer coefficients of the three envelopes to be equal, so that differences arose from embodied rather than operational energy [2]. This is an important methodological device for design comparison: if functional equivalence is enforced (same floor area, same U-values, same services), the alternatives can be compared fairly on the remaining criteria. Dani et al. found that operational energy use was almost identical between the timber and steel houses (difference of about 1%), although their occupancy assumptions differed [3].

5.3 Quality of the housing environment

Mazur et al. reviewed five assessment systems for housing quality in temperate climates: Building for Life 12, Home Quality Mark, Housing Quality Indicators, the Systeme d'Evaluation de Logements, and NF Habitat HQE. From these they derived 13 categories of quality factors that together describe a good housing environment, combining energy efficiency and thermal comfort with the needs of residents [8]. They argue that designing for quality is difficult to evaluate and that multi-criteria assessment systems help designers and investors by making the criteria explicit [8]. This provides a structured vocabulary for the "functional performance" criterion that goes beyond energy alone.

VI. AESTHETIC QUALITY

Aesthetic quality is the weakest criterion in the evidence base. In the reviewed studies it appears in three ways.

First, as a low-weight criterion. In Khan and Niazi's rankings, visual appeal (17.5%), design flexibility (16.9%) and compatibility with cultural context (15.6%) were all rated of low importance, below durability, cost and environmental compatibility, and aesthetic value ($p = 0.052$) and cultural relevance ($p = 0.073$) were not significant at the 5% level in their ANOVA [5]. The authors still describe them as relevant secondary criteria.

Second, as a design constraint on efficiency. Ilgin and Aslantamer show that expressive forms (twisted, free- form, tapered) are common in contemporary towers but generally reduce space efficiency, and they describe a trade-off between architectural expression and functional performance [4]. This is among the few studies that quantify what a visual or formal decision costs in functional terms.

Third, as an element of the user experience. Almashaqbeh concludes that sustainable interior design can balance aesthetics, functionality and sustainability, using qualitative expert interviews and case studies rather than numerical scoring [10]. Mazur et al. include perceived quality and environment in their housing quality categories [8].

None of the reviewed sources provides a reproducible method to compare the aesthetic quality of alternative building elevations. Evaluations are qualitative, depend on expert judgement, or are reduced to a single weight in a larger model. This gap matters directly for the present research, whose fourth objective is to evaluate and compare the aesthetic quality of proposed residential elevations.

VII. MULTI-CRITERIA EVALUATION OF ALTERNATIVES

Because no alternative wins on every criterion, a method is needed to combine them. Motuziene et al. propose an algorithm that links energy simulation, LCA, LCC and MCDA. They used the Analytic Hierarchy Process (AHP), with weights from 30 expert scientists and a consistency ratio below 0.1, and the COPRAS method to rank the alternatives. The derived weights were life cycle cost 0.489, non-renewable primary energy 0.329, global warming 0.119 and ozone layer depletion 0.064. The log house ranked first (utility degree 100%), followed by the timber frame (98.45%) and masonry (94.38%) alternatives [2]. When all weights were set equal, the order did not change but the gaps widened (100%, 97.5%, 90%), showing that the ranking was robust but its magnitude was weight-dependent [2]. The authors caution that the differences between alternatives are modest and sensitive to assumptions such as identical lifetimes, and that the omitted items (appliances, furniture, cooling) affect accuracy [2].

Khan and Niazi apply a statistical framework rather than a decision algorithm, and their sensitivity analysis ranks criteria rather than alternatives [5]. Mazur et al. use multi-criteria comparison of rating systems rather than of designs [8]. Cabeza et al. and Janjua et al. both stress the need for broader indicator sets so that environmental, economic and social trade-offs are visible [6][7].

Taken together, the literature supports a design- comparison approach with four features: equal functional requirements, a consistent system boundary, multiple criteria with explicit weights, and a sensitivity test on the weights.

VIII. SYNTHESIS AND RESEARCH GAP

The reviewed studies agree on several points. Operational energy generally dominates life cycle burdens, but embodied impacts rise in importance as buildings become more efficient [2][3]. Differences between structural and material alternatives tend to be small in total life cycle terms, so there is little case for assuming that one system is always superior [1][2][3]. Cost, environmental and functional criteria conflict, and no alternative is best on all of them [2]. Service life and data quality strongly influence results [3][7].

They also leave important gaps:

- Few comparisons of cost and material quantity at the design stage. Most studies use LCA inventories or surveys rather than bills of quantities for alternative layouts of the same functional programme. Cabeza et al. found just one whole- building LCCA [6].
- Space utilisation is studied mainly for tall buildings, with little evidence for typical low- and mid-rise residential schemes [4].
- Aesthetic quality lacks a quantitative method, and is mostly treated qualitatively or as a minor weight [4][5][8][10].
- Context. The studies come from China, Lithuania, New Zealand, Afghanistan and Europe, and none uses Indian cost data or Indian residential typologies. The reviewed sources do not discuss Indian conditions, so applying the findings there needs care.
- Integration. No study combines cost, material quantity, functional performance and aesthetics for alternatives of a single residential building in one framework.

The present research addresses these gaps by developing alternative designs for a hypothetical residential building with the same functional requirements, estimating material quantities and construction cost for each, evaluating space utilisation and functional performance, assessing the elevations' aesthetic quality, and analysing

the trade-offs among the four criteria. The multi-criteria structure of Motuziene et al. [2], the space efficiency metrics of Ilgin and Aslantamer [4] and the housing quality categories of Mazur et al. [8] provide the methodological basis.

IX. CONCLUSION

The literature establishes that residential design alternatives should be compared on several criteria simultaneously, that a consistent boundary and equal functional requirements are preconditions for a fair comparison, and that small differences between alternatives require sensitivity testing. It also shows that cost and material efficiency are well represented, functional performance is partly represented, and aesthetic quality remains underdeveloped. A comparative study that quantifies cost and material quantities, measures space utilisation, evaluates elevation quality in a structured way, and analyses the trade-offs between them would add a useful, integrated contribution.

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