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PARAMETRIC DESIGN AND THERMAL-ENERGY OPTIMIZATION OF PREFABRICATED WALL PANELS FROM LOCAL RAW MATERIALS FOR THE HOT-DRY CLIMATE OF UZBEKISTAN

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Abstract. The building envelope of residential stock in Uzbekistan is still dominated by fired clay brick masonry, whose thermal transmittance is several times higher than modern energy-efficiency targets, while the hot-dry continental climate of the Bukhara region imposes high summer cooling and winter heating loads. This thesis presents a computational framework for the design of prefabricated sandwich wall panels made of locally available raw materials (cotton-stalk arbolite, expanded perlite, basalt fibre) and optimized for the local climate. The framework links mixture design (Taguchi/RSM), parametric modelling in Rhinoceros/Grasshopper, dynamic thermal simulation with Ladybug Tools (Honeybee/EnergyPlus) and multi-objective evolutionary optimization in Wallacei. A preliminary steady-state calculation according to ISO 6946 shows that the proposed panel configurations reduce the thermal transmittance of the external wall by 48–65% compared with a 380 mm brick wall, while keeping a heavy internal layer that provides thermal inertia against the large diurnal temperature swing.

Keywords: prefabricated wall panel; arbolite; local raw materials; hot-dry climate; parametric design; Ladybug Tools; multi-objective optimization; thermal transmittance.

Annotatsiya. O‘zbekistonda turar joy binolarining tashqi devorlari hanuzgacha asosan pishgan g‘ishtdan quriladi va ularning issiqlik o‘tkazuvchanligi zamonaviy energiya samaradorligi talablaridan ancha yuqori. Tezisda Buxoro viloyatining quruq-issiq iqlimi uchun mahalliy xom ashyodan (g‘o‘zapoya asosidagi arbolit, ko‘pchitilgan perlit, bazalt tola) tayyorlanadigan prefabrik devor panellarini parametrik loyihalash va optimallashtirishning kompyuter metodikasi taklif etiladi. Metodika tarkibni optimallashtirish (Taguchi/RSM), Rhinoceros/Grasshopper muhitida parametrik modellash, Ladybug Tools (Honeybee/EnergyPlus) yordamida issiqlik simulyatsiyasi va Wallacei orqali ko‘p maqsadli optimallashtirishni birlashtiradi. ISO 6946 bo‘yicha dastlabki hisob panellar devorning issiqlik o‘tkazuvchanligini 380 mm g‘isht devorga nisbatan 48–65% ga kamaytirishini ko‘rsatdi.

Kalit so‘zlar: prefabrik devor paneli; arbolit; mahalliy xom ashyo; quruq-issiq iqlim; parametrik loyihalash; Ladybug Tools; ko‘p maqsadli optimallashtirish.

Аннотация. Наружные стены жилых зданий Узбекистана по-прежнему возводятся преимущественно из керамического кирпича, теплопередача которого значительно превышает современные требования энергоэффективности. В тезисах предложена расчётная методика параметрического проектирования и оптимизации сборных стеновых панелей из местного сырья (арболит на основе стеблей хлопчатника, вспученный перлит, базальтовое волокно) для сухого жаркого климата Бухарской области. Методика объединяет подбор состава (Тагучи/RSM), параметрическое моделирование в Rhinoceros/Grasshopper, динамическое тепловое моделирование в Ladybug Tools (Honeybee/EnergyPlus) и многокритериальную оптимизацию в Wallacei. Предварительный расчёт по ISO 6946 показал снижение

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коэффициента теплопередачи стены на 48–65% по сравнению с кирпичной стеной толщиной 380 мм.

Ключевые слова: сборная стеновая панель; арболит; местное сырьё; сухой жаркий климат; параметрическое проектирование; Ladybug Tools; многокритериальная оптимизация.

Introduction

Energy efficiency of the building sector has become a national priority in Uzbekistan: the country relies heavily on fossil fuels, and recent studies show that wider use of energy-efficient materials can substantially cut heating and cooling consumption across its climate zones [1]. Nevertheless, carbon-intensive fired brick and concrete still dominate the construction market, and the potential of local agricultural by-products and mineral raw materials for wall production remains largely untapped [2].

Prefabrication offers controlled quality, short construction time and lower material waste, but conventional precast systems often perform poorly in thermal terms if the envelope is not designed for the specific climate [3, 4]. Simulation studies of prefabricated housing in hot-arid regions report cooling-demand reductions of 30–43% when the base concrete-block wall is replaced by low-conductivity assemblies, with the best results obtained by materials of very low thermal conductivity rather than by latent-heat or moisture-buffering solutions [3]. Bio-based fibrous cores such as compressed straw have also been validated experimentally as efficient, low-carbon wall packages [5, 6].

At the same time, parametric design environments coupled with validated physics engines make it possible to explore thousands of envelope alternatives early in design [7, 8]. However, such performance-driven workflows have not yet been applied to prefabricated panels made from Uzbek raw materials under the hot-dry continental climate of Bukhara, which combines summer peaks above 40 °C, cold winters and large diurnal temperature swings. This gap defines the relevance of the present research.

Aim and objectives

The aim of the research is to develop and validate a parametric design and optimization workflow for prefabricated sandwich wall panels made from local raw materials, ensuring minimum thermal transmittance, sufficient thermal inertia, low embodied carbon and acceptable production cost for the hot-dry climate of Uzbekistan. The objectives are: (i) to select and characterize local raw materials and optimize the composition of the insulating core; (ii) to build a parametric model of the panel; (iii) to evaluate the thermal and energy performance of panel variants in a reference residential building; (iv) to identify Pareto-optimal panel configurations and formulate design recommendations.

Materials and methods

The proposed workflow consists of five interconnected stages (Fig. 1). In the material stage, cotton-stalk arbolite (a cement-bonded composite in which local cotton stalks replace wood chips [2]), expanded perlite and basalt fibre reinforcement are investigated; Taguchi orthogonal arrays and Response Surface Methodology (RSM) are used to optimize the mixture for thermal conductivity, density and compressive strength. In the modelling stage, the panel cross-section (facing layers, core thickness, insulation position, connecting ribs) is described parametrically in Rhinoceros 7/Grasshopper. Each variant is then assigned to a reference residential building and simulated with Ladybug and Honeybee using the EnergyPlus engine and a typical-year weather file of Bukhara [7]. Finally, the Wallacei evolutionary engine searches for Pareto-optimal solutions with respect to U-value, cooling and heating demand, embodied CO_2-eq (streamlined LCA) and cost [8]; selected solutions are verified by laboratory tests.

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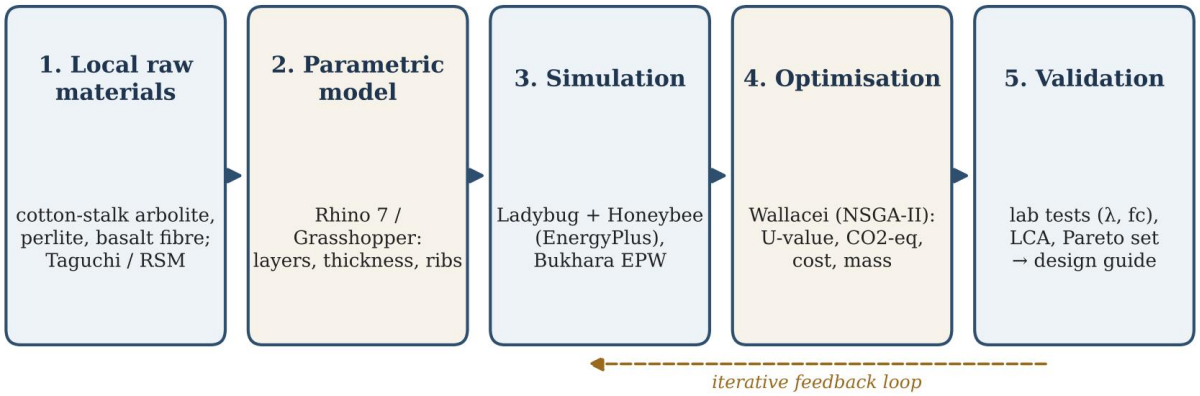


Fig. 1. Research workflow for parametric design and optimization of prefabricated wall panels
Source: developed by the author.

Results and discussion

As a first step, the thermal resistance of the reference walls and three panel configurations was calculated under steady-state conditions according to ISO 6946 [9], with internal and external surface resistances Rsi = 0.13 and Rse = 0.04 m²·K/W. Design thermal conductivities correspond to operating condition A (dry zone) of the national building heat-engineering norms [10]; for cotton-stalk arbolite a target value λ = 0.12 W/(m·K) at a density of about 550 kg/m³ was assumed, to be confirmed experimentally. Results are given in Table 1.

Table 1. Preliminary thermal performance of external wall options (steady state, ISO 6946)

Wall option	Layers (outside → inside), mm	Thickness, mm	R, m²·K/W	U, W/(m²·K)	Mass, kg/m²	ΔU vs W1
W1 – fired brick (reference)	plaster 20 + clay brick 380 + plaster 20	420	0.77	1.31	756	—
W2 – AAC block D500	plaster 20 + AAC 300 + plaster 20	340	2.37	0.42	222	–68%
P1 – sandwich panel	concrete 50 + arbolite 150 + concrete 40	240	1.47	0.68	308	–48%
P2 – sandwich panel	concrete 50 + arbolite 200 + concrete 40	290	1.88	0.53	335	–59%
P3 – hybrid panel	concrete 50 + arbolite 150 + perlite 50 + concrete 40	290	2.18	0.46	320	–65%

Note: λ, W/(m·K): cement-sand plaster 0.76; clay brick masonry 0.70; reinforced concrete 1.92 [10]; AAC D500 0.14; arbolite 0.12 (target); expanded perlite board 0.07. Thermal bridges at panel ribs and joints are not included and will be assessed in 2D/3D analysis. Source: calculated by the author.

Even the simplest panel (P1), only 240 mm thick, reduces the U-value by about 48% relative to the 380 mm brick wall, while configurations P2 and P3 achieve reductions of 59% and 65%. The AAC wall shows a comparable U-value, but it is a site-laid masonry with low surface mass (222 kg/m²). The sandwich panels keep a dense internal concrete layer, which increases the heat storage capacity on the

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room side; in the hot-dry climate with large day–night amplitudes this is expected to damp indoor temperature peaks and allow night-time cooling — an effect that steady-state calculation cannot capture and that will be quantified by dynamic Honeybee/EnergyPlus simulation. These results confirm that the decisive design variables are core thickness, core conductivity and the position of the heavy layer, which are exactly the parameters exposed to the optimization algorithm.

Conclusion

1. A five-stage computational framework combining mixture optimization, parametric modelling, dynamic energy simulation and multi-objective optimization is proposed for prefabricated wall panels made of local Uzbek raw materials.

2. Preliminary ISO 6946 calculations show that sandwich panels with a cotton-stalk arbolite core reduce the thermal transmittance of external walls by 48–65% compared with traditional 380 mm brick walls, at 31–43% lower wall thickness and less than half the surface mass.

3. Further work includes laboratory determination of arbolite properties, 2D thermal-bridge analysis of joints, dynamic simulation of a reference building in Bukhara, LCA-based embodied-carbon assessment and derivation of Pareto-optimal design recommendations for prefabrication plants in Uzbekistan.

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