Generative innovative design of carbon-sequestering buildings based on technology-space synergistic analysis: Taking sky courtyard residence as an example

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Abstract

Energy conservation and carbon reduction in the construction sector are crucial for achieving the "dual carbon goals" and promoting high-quality urban development. Carbon-sequestering buildings integrate carbon-sequestering technologies, enabling building spaces to serve as carbon absorption carriers, which is conducive to further improving the urban environment and mitigating climate issues. Currently, carbon-sequestering buildings are still in the exploratory stage. Due to differences in functional principles, implementation methods, and effects of carbon-sequestering technologies, they need an innovative design methodology to match the characteristics of specific construction projects to fully exert their functions. Against the background of carbon neutrality, integrating new technologies into inherent design thinking and achieving technology-space synergy is not only the key to tapping technological potential but also a path to fostering innovative design concepts. This study elaborates on the theoretical connotation of "technology-space" collaborative design for carbon-sequestering buildings. It reveals synergy laws and proposes optimization strategies through questionnaire surveys, case evaluations, and machine learning analysis, and puts forward this innovative design methodology combined with AIGC. Finally, taking fourth-generation residential buildings as an example, the practical feasibility of the design methodology is verified.

Full Text

Preamble

Generative innovative design carbon-sequestering buildings based technology-space synergistic analysis:

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Energy conservation carbon reduction construction sector crucial achieving “dual carbon goals” promoting high-quality urban development.

Carbon-sequestering buildings integrate carbon-sequestering technologies, enabling building spaces serve carbon absorption carriers, which conducive further improving urban environment mitigating climate issues.

Currently, carbon-sequestering buildings still exploratory stage. differences functional principles, implementation methods, effects carbon-sequestering technologies, innovative design

methodology

match characteristics specific construction projects fully exert their functions.

Against

background

carbon neutrality, integrating technologies inherent design thinking achieving technology-space synergy tapping technological potential fostering innovative design concepts. study elaborates theoretical connotation “technology-space” collaborative design carbon-sequestering buildings. reveals synergy proposes optimization strategies through questionnaire surveys, evaluations, machine learning analysis, forward innovative design

methodology

combined AIGC. Finally, taking fourth-generation residential buildings example, practical feasibility design

methodology

verified.

Keywords

Carbon-sequestering buildings Technology-space synergy Cutting-edge cases Prompt engineering Relevance Design Practice study proposes innovative design

methodology

enables synergistic integration specific cutting-edge technologies design elements, validated fourth-gen residences advance low-carbon building design practices.

Declaration generative AI-assisted technologies writing process.

During preparation author(s) Alibaba Cloud Artlab Platform (with Stable Diffusion) order conduct research generative innovative design author: (E-mail:

carbon-sequestering buildings. After using tool/service, author(s) reviewed edited content needed take(s) responsibility content published article.

Background

global construction industry critical stage parallel urbanization existing building renewal. expanding scale existing buildings, along operational energy consumption embodied carbon emissions, become barrier global carbon neutrality exemplified China "dual carbon" strategy.

Globally, emissions building construction processes account one-third total urban emissions (Yang 2019) while massive stock existing buildings uneven energy efficiency poses arduous renovation challenges.

Though ultra-low near-zero energy consumption technologies reduced emissions optimizing envelopes, ventilation systems, renewable energy 2021; 2019) decarbonization demands technical bottlenecks residual emissions (Orsini Marrone, n.d.; Weber Favrat, 2010; Yadav 2017) innovative approach active atmospheric removal, carbon-sequestering technology offers breakthrough building carbon neutrality. drives paradigm shift "passive emission reduction" "active carbon sequestration" (Burns Nicholson, 2023) material-level carbon capture conversion, heating (Wienchol 2020) microalgae cultivation (Yadav 2017) building material production (Orsini Marrone, n.d.) Since 2000, academic attention carbon-sequestering technologies construction grown gradually (Koytsoumpa 2023; 2023; 2020) entering exponential growth phase post-2010 significant publication cumulative growth years, confirming academic value practical urgency (Figure International firms institutions explored prototypes, including "Urban Redwood" (Figure MVRDV Eindhoven sustainable residence, Rescubika "Mandragore" tower York.

Nevertheless, application challenges persist (Ramesh, 2023) technology-space adaptability (e.g., area, structure, cost) design difficulty, demanding exploration collaborative mechanisms.

Meanwhile, injects momentum design innovation, enabling rapid carbon-sequestering strategy iteration algorithmic coupling analysis, shifting experience-driven data-driven design 2024) Thus, against global carbon neutrality intelligent development, study focuses carbon-sequestering buildings "technology-space" collaborative design, aiming construct theoretical framework practical strategies integrated construction decarbonization.

Research Literature Trends Related Carbon-Sequestering Technologies Urban Sequoia Innovations objectives study follows: summarize generalize development status carbon-sequestering technologies cutting-edge design cases; construct synergy evaluation framework "technology-space" carbon-sequestering buildings; explore design strategies innovative design

methods

carbon-sequestering buildings. innovations study Exploring feasibility "carbon-seque stering buildings" active carbon systems, breaking through passive model "energy conservation carbon reduction" ; Elaborating complex intrinsic mechanism coupling relationship between space system technology system carbon-sequestering buildings based synergy theory; Proposing innovative human-machine reation design paradigm combining evaluation (Artificial Intelligence Generated Content) based multi-modal prompts.

Material ethods Literature Review Development Application Status Carbon - Sequestering Technologies

Carbon-sequestering technologies classified three major categories: direct capture technology, bio-based materials, green plants (Okonkwo 2023) According carbon paths, divided three modes: on-site capture off-site storage, on-site capture on-site storage, off-site capture on-site storage (Andersen 2022; Biloria Thakkar, 2020; Eleonora 2023) which provides systematic framework technology selection (Figure perspective technical subdivision practical progress, Direct Capture (DAC) captures utilizes through chemical physical reactions between mechanical systems adsorbents (Palmer, 2019) mostly integrated building ventilation ducts, facades, atriums (Bryan Salamah, 2023) Typical cases include Climeworks' commercial devices Iceland' s project (with annual capture capacity 4,000 tons) (Sodiq 2023) humidity swing technology developed Lackner achieved low-energy operation, carbon capture capacity times energy consumption emissions (Engineering Carbon, n.d.) However, total global capture capacity plants about 7,000 year, lower requirements Zero" target.

Although modular design building integration potential, energy consumption remain bottlenecks (Engineering Carbon, n.d.) Bio-based materials renewable resources materials deeply integrated building structures decoration systems (Galimshina 2022) Cross-Laminated Timber (CLT) reduce building heating energy consumption 11.97%-30.94% (Ying 2016) market scale showing growth trend driven policies (Abdellatef, 2020; Schwarzov 2017; Soomro, 2021) problems carbon sequestration long-term maintenance.

Closed Photobioreactors (PBR) integrated building facades enhance photosynthetic carbon sequestration (Biloria Thakkar, 2020) challenges overheating excessive energy consumption (Ahmad 2021) Biochar sequester approximately equivalent humidity regulation adsorption functions (Ahmed 2021; Gupta 2023; Woolf 2021) Green plants spatial carriers walls, balconies, roofs (Forster 2021) among green plants, vertical greening system daily absorption capacity

8-12g/m (Ainsworth Long, 2024) other carbon-sequestering technologies, low-carbon concrete reduce carbon emissions through sustainable material substitution (e.g., Headquarters project Spain designed achieved carbon reduction) rez-Urrestarazu N.D., 2021) restricted cost, material supply, industry promotion.

Overall, maturity three mainstream carbon-sequestering technologies varies significantly: direct capture laboratory optimization stage, bio-based materials demonstration application stage, green plant carbon sequestration commercialization stage (Eric 2023) future, efforts should focus efficiency improvement, optimization, system integration break through barriers large-scale application.

Integrated Application Carbon-Sequestering Technologies Built Environment Technology-Space Synergy Architectural Design Process "technology-space" collaborative design carbon-sequestering buildings their symbiosis based carbon cycle: carbon-sequestering technologies capture carbon cycle processes, while building spaces serve carriers. systematization design theories, architectural practices shifted passive adaptation active regulation carbon cycle 2020; Usman 2022) evolving through three stages passive technology adaptation, active space optimization, system symbiosis rather simple interdependence.

Building functional attributes facilitate invisible integration technologies (Zhang 2021) nonlinear adaptive network, building system forms nonlinear causal carbon-sequestering technologies, evolving collaboratively driven low-carbon demands (Elmokadem 2016) Collaborative design treats complex system, integrating technology selection space design early stage achieve dynamic balance maximize low-carbon value (Favoino 2022; Tariq 2023) aiming exert ecological, economic, social values in-depth coupling.

Constrained project attributes technology combinations, systematic evaluation

methods

strategies essential (Chen 2018; Minyong 2008) Synergy evaluation focuses three indicators: technical efficiency (carbon capture efficiency, system integration), aesthetics (technology-architecture integration), implementability (construction, cost, maintenance) 2023) These mutually restrictive reinforcing value triangle, criterion collaborative design success (Kong 2025) Technological progress drives spatial evolution, evidenced architectural history (Spurrett, 1999) (Figure making technology-space synergy research fundamental low-carbon architectural design.

Development Evolution Architectural Space Synergy Application Generative Innovative Design Low-Carbon Green Buildings Generative innovation design paradigm adapts "technology-space" collaboration needs low-carbon green buildings.

Based synergy theory, integrates technologies (such Diffusion models models) prompt engineering.

Through standardized process "data input model training scheme generation human-machine collaborative optimization" (Stanikzai Mittal, 2025) realizes intelligent diversified generation collaborative schemes between low-carbon technologies (such carbon-sequestering energy-saving technologies) building spaces, helping create green building

results

combine low-carbon efficiency, spatial quality, aesthetic value. combination Diffusion models (such Stable Diffusion) Low-Rank Adaptation (LORA) models advantages. former supports bidirectional generation "text-image" "image-image" , ControlNet control spatial boundaries; latter fine-tuned based specific datasets improve targeting schemes (Cheung 2025) addition, reinforcement learning combined human feedback dynamically optimize outputs, imitation learning improve rationality schemes learning expert trajectories (Huang, 2024) Generative innovative design traverse "technology-space" combinations balance multi-dimensional constraints screen optimal schemes (Bono, 2024) However, existing research still needs breakthroughs: terms scheme generation, necessary further explore "process-centered" learning paradigm (such imitation learning self-learning), improve feasibility schemes restoring logic design decisions (Sourek, 2024) field content creation, necessary optimize prompt engineering strengthen connection between subjective perception objective environment through structured descriptions (Odiah Gosling, 2024) Carpo (Carpo, 2025) through

combination Diffusion models fine-tuning, emphasizes encoding "node construction knowledge" prompts realize collaboration between modular construction logic dynamic generation.

Stanikzai Mittal (Stanikzai Mittal, 2025) proposed division labor framework "prompt engineer domain expert", which balance efficiency uniqueness innovative design through structured prompt templates (such "{technology type} {scenario feature} {emotional orientation}").

Collection Collection Cutting-Edge Cases Carbon-Sequestering Buildings ensure representativeness cutting-edge nature research cases, study conducts retrieval screening through multi-channel multi-keyword combinations. database level, Science (WOS) platform, English

Keywords

"Carbon capture technology" (CCT), "Carbon-Sequestering building" , carbon emission" , "Technology application" adopted literature retrieval, focus extracting practical application projects conceptual design schemes cited literature. retrieval extended professional architectural websites, including Archdaily, Amazing Architecture Architecture Archives. addition, official websites well-known architectural design firms important information sources, international firms MVRDV, Among final selected cases, developed countries North America, Europe, (reflecting current leading situation carbon-sequestering technology application), innovative projects developing countries included (Figure

Appendix

specific details). terms building types, cover buildings cases), urban renewal projects cases), urban design cases cases).

Among them, residential buildings (20.8%) office buildings (17.8%) account highest proportions, commercial, cultural sports, educational, infrastructure, square types included ensure functional diversity. terms technology application, cases required involve least among them, cases requirement, cases apply three CCTs.

Global Distribution Cases Induction Collaborative Design Strategies Through four-step process "case deconstruction correlation

analysis

clustering screening collaborative verification" , valid samples "clear technology types definite spatial locations" selected cases.

After high-frequency statistics (screening combinations occurrence frequency times) synergy verification (three dimensions: technical efficiency, implementability, aesthetics), "technology-space" combinations finally extracted (Figure

Appendix

details "technology-space" combination method), providing practical technical

references

"technology-space" collaborative design carbon-sequestering buildings.

Classification Collaborative Design Strategies

Calculation study establishes innovative design

method

following logical framework

Abstract

evaluation, generation (Figure Firstly, "technology-space" synergy evaluation framework carbon-sequestering buildings established, expert questionnaires analyze evaluate international cutting-edge cases.

Secondly, machine learning applied screen variables affecting application carbon-sequestering technologies building spaces, propose design strategies, extract

Keywords

reference images multi-modal prompts. Finally, taking courtyard fourth-generation residential buildings example, feasibility "technology-space" synergy innovative design verified through scheme generation.

Intelligent Deduction Process Schemes

Analysis

Framework Technology-Space Synergy evaluation synergy between carbon-sequestering technologies building spaces should technical efficiency, aesthetics, implementability evaluation indicators (Portugali, 2025) physical foundation synergy, technical efficiency directly reflects carbon capture efficiency system integration carbon-sequestering technologies specific building spaces. example, Direct Capture (DAC) equipment needs collaboratively optimize airflow paths building ventilation systems (Iea, 2022) bio-based materials maximize carbon sequestration surface through structural layout design (Heidari 2019) evaluating whether "technology-space" system achieves synergistic effect "1+1>2" prerequisite existence synergy.

Aesthetics serves humanistic synergy. carbon-sequestering technologies implanted space rigid disconnected manner, reduce users' psychological acceptance social recognition. evaluation focuses organic integration technical forms architectural aesthetics, vertical greening systems transformed ecological facades (Eleonora 2023) algal reactors designed dynamic light shadow installations (Ahmad 2021) integration enhances spatial experience

elevates technologies "functional equipment" "cultural symbols" , strengthens public' s emotional recognition, determines social acceptance technologies.

Implementability provides implementation guarantee synergy, which requires evaluating construction feasibility, economic costs, complexity full-cycle maintenance. instance, cross-laminated timber (CLT) needs adapt prefabrication assembly processes (Andersen 2022) greening needs match structural system. improvement implementability significantly optimize synergy costs promote production commercial popularization technologies, construction difficulty facilitates workers' operation collaboration between design construction, thereby optimizing overall design process.

Questionnaire Survey study conducted survey online questionnaire Wenjuanxing platform. ensure authenticity reliability survey results, respondent provided financial incentive yuan. survey targeted architects low-carbon field experts North America Europe, five-point Likert scale adopted scoring. survey lasted month, questionnaires finally collected. screening valid questionnaires followed criteria: first, excluding questionnaires excessively repeated answers obvious random responses (e.g., options identical); second, eliminating samples abnormal response times discarding those response 1200s normal response range 90s-1200s). questionnaire designed around cases, consisting questions. question included pictures, building type, project address, detailed introduction, three qualitative evaluation indicators: technical efficiency, implementability, aesthetics.

Among them, technical efficiency evaluates degree potential exertion carbon-sequestering technologies, scores "extremely effect" "excellent effect" ; implementability assesses construction feasibility construction-operation-maintenance costs, scores "very unfeasible""very feasible"; aesthetics measures formal aesthetic performance technology-space integration, scores "extremely unattractive" "very attractive" .

Appendix

details questionnaire content. XGBoost (eXtreme Gradient Boosting) algorithm selected model because based gradient boosting framework, performs excellently processing large-scale datasets, effectively prevents overfitting through regularization terms, higher accuracy flexibility algorithms random forests. algorithm inherits practical features random sampling, attribute selection, learning rate, supports horizontal parallelization attribute calculation, suitable solving multi-classification problems.

First, variables screened construct model, initial

model established Studio platform, final prediction model obtained through parameter adjustment model optimization (Figure Prediction Flowchart Carbon-Sequestering Technology Collaborative Design Based XGBoost Algorithm Features Model Variables Based previous literature research statistical analysis, study extracted features closely related collaborative design. influencing factors include seven types: building (X1), building height (X2), project (X3), economic (X4), structural (X5), building materials (X6), plane layout (X7); combination

methods

technology space include types: bio-based materials facade (X8), bio-based materials structure (X9), photoreaction technology facade (X10), photoreaction technology (X11), green plants (X12), green plants (X13), green plants facade (X14), direct capture structure (X15), direct capture facade (X16), which serve independent variables model; synergy evaluation

results

include technical efficiency (X17), implementability (X18), aesthetics (X19) dependent variables.

Appendix

specific definition, quantification method, unit, assignment rules model variables.

Model Establishment, Parameter Adjustment Optimization study chose build prediction model Studio platform, multiple professional toolkits improve modeling efficiency parameters XGBoost include three categories: general parameters (such booster), Booster parameters (such controlling learning rate, max_{depth} limiting depth), objective parameters (such objective). model training optimization process carried stages: first, initial parameter values (booster "gbtree" , objective "multi:softmax" , num_{class} learning adjusted modifying (value avoid overfitting underfitting model; second, max_{depth} (value min_{{{child}}*{{weight}}} optimized balance model complexity generalization ability; gamma (minimum reduction required splitting) num*{{{boost}}_{{round}}} (value adjusted further improve prediction accuracy; finally, fine-tuning performed reducing learning increasing number trees. combination multiple indicators model performance evaluation:

confusion matrix intuitively display classification results, whose columns represent categories predicted categories respectively, which precision proportion positives predicted positives), recall proportion positives actual positives), score harmonic precision recall) extracted; value (Area Under Curve) measure overall performance model, value range value closer indicates stronger ability model distinguish between positive negative samples equivalent random guessing).

Generative Innovative Design Process study innovatively adopted process "abstracting specific cases model training, restoring design schemes through Human-AI collaboration" .

Stable Diffusion Alibaba Cloud Artlab platform tool, intelligent design system Human-AI collaboration constructed. process innovation realizing closed "case feature

Abstract

model accurate learning scheme concretization generation" , integrating designers' subjective decisions professional evaluations throughout process, breaking through one-way output limitation traditional design. training includes types: images text, derived

abstract

refinement specific cases. Image extracts application features carbon-sequestering technologies elements building forms; prompts derived

summary

collaborative strategies, covering strategies bio-based materials, include describable elements materials structures ensure accurate correspondence

with technical forms.

Through image preprocessing (uniformly scaled pixels ensure building subject centered) structured labeling prompts, conversion specific features

abstract

model language realized (Figure based label automatic annotation, Prompt frameworks constructed according strategies, forming structured combination "trigger

keyword

technical point scenario" (e.g., "Strategy modern office building, algal biological reaction curtain wall, transparent pipeline flowing green algae").

Designers material/atmosphere descriptive words needed, which retains professional decision-making space realizes model adaptability data.

Training Process of Case Data

study selected architectural realistic style large model "laowang model, trained model ArtLab platform through" KOHYA_{SS} WEBUI" tool.

Designers dominated training direction adjusting parameters training steps Batch_{size} (optimizing Network_{Dim} adapt real-scene/rendering features); testing phase, X/Y/Z charts (with model number weight axes) evaluate model learning accuracy.

Designers screened optimal model professional dimensions color material, realizing collaborative optimization learning accuracy human professional judgment, avoiding blind training.

Based logic "restoring

abstract

models specific schemes" , Human-AI collaborative decision-making integrated: designers first completed preliminary design plane/volume (humans dominate basic decisions), screened collaborative strategies prompts, trained model (carrier

abstract

features) combined ControlNet processor (Canny/Depth/Segment) realize style transfer denoising, generating conceptual diagrams assist scheme deepening. study typical fourth-generation residential buildings, courtyard degree compatibility between green sustainable design concept zero-carbon development carbon-sequestering technologies.

Therefore, selecting application carrier carbon-sequestering technologies highly representative. study courtyard project Towers Xishan District, Kunming research object, focused integration fourth-generation residential buildings carbon-sequestering technologies, carried graphic reasoning scheme generation Alibaba Cloud Artlab platform (Figure control group (traditional design

method) experimental group (AIGC-assisted design mandatory adoption types collaborative design strategies) scheme deduction method. senior architects group completed scheme design based unified conditions (plot ratio greening 40%); five-point Likert scale used, industry experts (including professor-level senior engineers, senior designers, policy makers) independently scored three aspects:

technical efficiency, implementability and aesthetics.

Model Rendering Display Courtyard right

Analysis

Technology-Space Combination Types Carbon-Sequestering Buildings Through systematic

analysis

carbon-sequestering building cases, study identified relationships between building spaces (divided categories: balcony, structure, facade, wall, roof) Carbon Capture Technologies (CCTs), revealing technology-space synergy (Figure 11a [FIGURE:11]). perspective technology application distribution, green plants account applications various building spaces their strong photosynthesis capacity spatial adaptability, making mainstream carbon-sequestering technology currently.

Bio-based materials (such low-carbon concrete) application proportion 88.2% building structures, thanks their advantages processing, controllable cost, stable carbon-sequestering performance, becoming choice carbon sequestration structural level.

Building facades, carriers technology integration, compatible multiple CCTs, among which bio-based materials account 44.4%, photoreaction technologies (such microalgae reactors) account 22.2%, other comprehensive technologies account 22.2%, making greatest application potential carbon-sequestering technologies.

(a)Spatial Types Application;)Cross

Analysis

Project terms building adaptability (Figure residential office buildings strongest integration capability, compatible different technology combinations, their technology tolerance significantly higher other building types.

Although Direct Capture (DAC) technology outstanding carbon-sequestering efficiency, applicable industrial buildings, mixed-use buildings, office buildings equipment costs complex construction processes, application cases residential buildings.

Bio-based materials, their carbon sequestration spatial adaptability, widely large-span public buildings gymnasiums, auditoriums, exhibition halls, adapting their needs spatial openness structural stability. terms plane layout (Table 62 .63% cases adopt rectangular plane, 22.22% adopt decentralized layout, 11.1% adopt circular plane, proportions L-shaped rectangular-enclosed planes Further

analysis

correlation between plane layout height shows average height buildings rectangular plane meters (covering low-rise high-rise buildings), average height buildings circular plane meters (mainly super high-rise), average height decentralized buildings meters (mostly low-rise clusters).

There significant statistical correlation between plane layout building function ($p=0.018$) rectangular planes dominate residential spaces (accounting public activity spaces (accounting 72.22%), while decentralized layouts suitable green spaces (45.45%) equipment facility spaces (34.78%).

Project Total Residential Public Activity Equipment Facilities Plane Layout Rectangular enclosed types "technology-space" combinations (bio-based materials facade, green plants roof, structure, facade) ($p<0.05$ $p<0.01$).

Specifically, application ratio "green level 12.12%, while rejection combination frame structures (93.02%) 35.29% 33.33% respectively, which significantly higher average level 16.16%, whereas application ratio wall-bearing structures (1.0) 3.7%.

Pearson correlation

analysis

further indicates technical efficiency positively correlated "green plants facade" combination ($r=0.207$) negatively correlated facade" combination.

Economic exerts significant constraint DAC-related combinations.

Building materials negatively correlated "green plants roof" combination ($r=-0.221$), meaning rigid roofing materials concrete conducive

to the construction of roof greening.

Building Project Building Plane Economic Structural Building Technical Implemen Aesthetics Height Layout Efficiency tability Facade Structure Facade

Facade Direct Capture Structure Direct Capture Facade Statistical

Analysis

Synergy Evaluation synergy evaluation based carbon-sequestering building cases shows total average score maximum points (with points allocated technical efficiency, implementability, aesthetics), presenting overall "moderately positive" level, which indicates experts relatively recognition technology-space synergy effect. perspective sub-dimensions, implementability (3.21 points) aesthetics (3.28 points) higher scale midpoint points, while technical efficiency (3.13 points) lowest, reflecting experts' prominent concerns about actual effect carbon-sequestering technologies.

Analysis

dispersion characteristics shows range total average score cases points, indicating significant differences synergy performance.

Among three dimensions, technical efficiency largest standard deviation highest dispersion), showing strong divergence experts' judgments technical effects; aesthetics medium standard deviation (moderate dispersion), relatively unified visual evaluation; implementability smallest standard deviation lowest dispersion), indicating highest consistency experts' judgments feasibility construction, operation maintenance.

Spearman correlation coefficient reveals internal correlations between dimensions: there significant positive correlation between technical efficiency implementability (e.g., microalgae case, technical efficiency points implementability points), reflecting conflict "high-efficiency technologies" accompanied "high implementation costs" ; aesthetics positively correlated technical efficiency (e.g., Vertical Forest case, aesthetics points technical efficiency points), meaning "visually perceivable technologies" likely trust; implementability positively correlated aesthetics, indicating "low-complexity technologies" likely

synergize spatial aesthetics. "technology-space" combinations significantly positive correlation synergy indicators ($p<0.05$ $p<0.01$, Table there ineffective combinations. average correlation coefficient implementability (higher technical efficiency aesthetics), combinations reaching significant level. "green plants facade" combination highest implementability correlation coefficient 0.722**, along aesthetics technical efficiency, making optimal collaborative combination. terms technical efficiency, structure-related combinations superior facade-related (e.g., "bio-based materials structure" "bio-based materials facade" 0.182); terms aesthetics, facade roof-related combinations excellent (e.g., "green plants facade"

with 0.513 > "green plants - roof" with 0.267).

Classified technology type, green plants belong "all-round type" , "green plants facade" combination leading dimensions; Direct Capture (DAC) belongs "potential type", lowest technical efficiency (structure: 0.169*, facade: 0.178*), requiring optimization.

One-way ANOVA

results

synergy mature technologies superior emerging technologies (e.g., microalgae scores complex operation maintenance). terms technical efficiency: cases achieve scores clear carbon scores difficult operation maintenance; timber buildings score moderately active carbon-sequestering capacity; cases polarized scores scores attributed emission reduction efficiency, while scores

result

energy consumption. terms implementability: bio-based materials mostly obtain scores; large-scale projects (e.g., Tower) early devices score scores improve technological maturity (e.g., Climeworks Generation terms aesthetics: combinations technologies facades/natural materials (e.g., Luminous Bioplastic Pipes, Timber Spaces) scores, while technical facilities (e.g., Carbon Capture Plant) score summarize, synergy presents moderately positive level, technical efficiency being shortcoming.

Implementability aesthetics strongest synergy (r=0.41).

Future designs should prioritize "quantifiable, maintain, spatial narrative ability" , "green plants facade" "bio-based materials structure" combinations. study selected characteristic values related collaborative design independent variables machine learning, covering qualitative quantitative variables building scale, structural type, technology combination mode, which extracted verified through screening expert interviews. synergy indicators obtained subjecting average scores technical efficiency, aesthetics, implementability min-max normalization, which scaled range divided grade intervals:

"0-0.5" synergy (labeled "0.5-1.0" synergy (labeled "1"). avoid interference multicollinearity among features, Variance Inflation Factor (VIF)

analysis

adopted verification.

results

values features within reasonable range (Table proving variable independence meets requirements modeling.

Feature Value Tolerance Aesthetics Variables Affecting Design Synergy study, basic information cases technology-space combination modes independent variables items total), synergy evaluation

results

items) dependent variables model training based XGBoost algorithm. training accounted photos) accounted photos), training completed after iterations (taking hour). shown Figure accuracy curve training converged after iterations steady increase accuracy, curve dropped around after iterations; accuracy curve converged after iterations (with accuracy approximately 98.2%), curve stabilized around after iterations. final prediction accuracy model 82.5%, overfitting underfitting, showing generalization ability.

Multiple rounds verification (Figure indicate model achieves accuracy design facades (69.57%), structures (73.91%), roofs (67.40%), balconies (64.40%), walls

(67.40%), demonstrating excellent prediction performance.

Accuracy Change Curve During Training Change Curve During Training

Results

XGBoost Model study adopted (SHapley Additive exPlanations) model interpretation

method

importance synergy characteristic variables carbon-sequestering technologies, constructed three types XGBoost prediction models (implementability, aesthetics, technical efficiency) clarify influencing factors dimension their mechanism action (Figure differences among three types models divergence objective logic: implementability focuses "adaptation implementation", aesthetics centers "aesthetic expression", technical efficiency emphasizes "functional output". three features model closely aligned their respective objectives, serving influencing factors dimensions building carrier adaptation, aesthetic value transmission, carbon function realization. implementability dimension, three features weight Direct Capture (DAC) facade (28.41%), structure (17.47%), photoreaction technology facade (10.62%). logic adaptive implementation technologies building carriers.

Relying spatial convenience engineering adaptability building facades structures, maturity technology functional compatibility between photoreaction technology buildings become supports. aesthetics dimension, building highest proportion (65.38%), followed bio-based materials structure (24.73%) green plants facade

(2.54%). dimension focuses integration visual ecological aesthetics: building determines space aesthetic design; natural properties bio-based materials conform low-carbon aesthetics; combination green plants facades soften building boundaries enhance visual affinity. technical efficiency dimension, three features facade (24.64%), building materials (12.20%), green plants balcony (11.03%), focus carbon management function output.

Facades provide sufficient space exchange equipment; carbon storage sequestration properties building materials underlying support; micro-space balconies suitable plant growth, enabling stable exertion carbon functions.

Analysis

Implementability, Aesthetics, Technical Efficiency Verification Generative Innovative Design

Method

Output

Results

Design Strategies Combining studies synergy evaluation results, collaborative design strategies carbon-sequestering buildings proposed, specifically including: bio-based materials facade, bio-based materials structure, photoreaction technology facade, photoreaction technology wall, green plants roof, green plants facade, green plants balcony, structure, facade.

Based these strategies, prompt framework systematic design strategies carbon-sequestering buildings constructed through training data. classic courtyard, elevators serving households" layout adopted, drawing Yunnan "Yikeyin" (One-Seal) layout pattern. building storey height meters lighting conditions. household large "L" -shaped courtyard facing outside, courtyards floors arranged alternately facade.

While ensuring privacy, enables communication outdoor spaces living rooms.

Kitchens bathrooms located first floor ensure ventilation. platform adopts planted where large number arbor greenery arranged.

Combined collaborative design strategy carbon-sequestering buildings, selected prompt

Keywords

Interior Integration, Interior Decoration, Carbon Storage Sound Insulation, Floor Texture, quality, indoor plant, Microalgae Purification Wall, Indoor Wall,

Purification, Carbon Absorption, Tubular Reactor, Green Plant Embedding, concept design, carbon capture" .

Comparative Evaluation Collaborative Design

results

chi-square shown Table three groups indicators chi-square test, rejecting hypothesis, indicating there significant differences score distribution before after application collaborative design strategy.

Cramer' s values 0.85, indicating strong correlation between design strategy score improvement. average scores experimental group technical efficiency, implementability, aesthetics 59%-63% higher those control group, consistent standard deviations, indicating scores experimental group concentrated high-score range. conclusion, collaborative design strategy significantly improve technical efficiency, implementability, aesthetics carbon-sequestering building schemes, verifying effectiveness strategy.

Feature p-value Cramer' s

Discussion

Synergistic Evolution "Technology-Space" System Carbon-Sequestering Buildings perspective architectural technology evolution, structural innovation material Gothic pointed arches, Villa Savoye reinforced concrete frame (1928), parametric technology promoted spatial evolution "closed static" "free dynamic", verifying "technology-structure-space" interaction logic laying foundation AI-era technology-space synergy.

Unlike traditional space-liberating technologies, carbon-sequestering technologies reshape spatial attributes "carbon metabolism", enabling three-stage leap: technology dependence equipment external hanging), space integration component compounding), metabolic closed (bionic systems). transforms buildings carbon nodes, forming "material carbon sequestration structural carbon conduction spatial carbon storage" model.

Cases Taipei Germany positive-energy residences confirm collaborative mechanism value resolving technology transplantation dilemmas. architectural system nonlinear adaptive complex network, characterized diverse functional requirements, multi-professional integration, continuous adaptation, non-equilibrium

dynamics (Ritter 2025) Carbon-sequestering technologies intensify complexity, redefining buildings "technology expressions"rather static containers, technology-space coupling driving system evolution. shift highlights "technology-space" collaborative design theoretical value: addresses low-carbon transformation technology transplantation challenges reconstructs design logic treating technology space interactive system. breaks linear innovation model, engages stakeholders early, integrates technical parameters, humanistic needs, space maximize low-carbon value.

Design Innovation Human-Machine Collaboration Digital-Intelligent Low-Carbon Buildings objective study convert

abstract

"technology-space" collaborative logic specific AI-parsable design elements, establishing distinctive innovative design methodology.

methodology

breaks human-machine separation traditional design, achieves precise alignment between design strategies machine execution natural language, reconstructs "human-machine-design objective" interaction paradigm (Stanikzai Mittal, 2025) Multimodal prompt engineering constructs translational bridge between human design intentions generation logic through standardized, structured

keyword

system. structural transformation ensures AI-generated schemes accurately conform "technology-space" synergy evaluation dimensions, enabling rapid strategy verification iteration. input diffusion model "reverse diffusion process" , prompt mechanism closely associated "labels" training "forward diffusion process" (Cheung 2025) reverse diffusion, prompts utilize natural language evoke model understanding training images their labels creation; human-machine collaboration enhances process controllability innovation, grounding generation training while precisely addressing human design needs (Bono, 2024) instance,

Keywords

"green plants-facade" collaboration strategy (e.g., vertical greening, modular planting boxes, sunshade cooling, carbon function) carry human evaluation criteria technical efficiency, implementability, aesthetics, serving clear guidelines outputs aligned synergy goals (Cheung 2025) Traditional multi-scheme comparison suffers costs cycles.

Under human-machine collaboration, prompt engineering drives generate diverse schemes rapidly

keyword

refinement combination, realizing efficient synergy strategy iteration. "human strategy guidance-machine batch generation-human screening optimization" closed boosts collaborative design efficiency, allowing designers focus strategy innovation rather repetitive drafting (Huang, 2024) Additionally, prompt engineering accuracy relies framework support collaborative design elements (Odiah Gosling, 2024) Human-machine collaboration enables dynamic adaptation support: designers adjust

keyword

systems synergy goals, feeds optimization directions generated results, forming bidirectional iterative innovation cycle (Carpo, 2025) improves

efficiency expands “technology-space”synergy boundaries, offering innovative design complex carbon-sequestering building systems (Sourek, 2024) Limitations application carbon-sequestering technologies civil buildings still development stage, relatively limited cases worldwide, application

analysis

complex technologies building spaces still exploratory stage. study adopts analysis, covering urbanized high-density areas temperate subtropical climate zones. future, necessary analyze technology-space synergy effect carbon-sequestering buildings under different climate conditions through field measurement methods.

Currently, generative innovative design

method

limited development technology, significant contributions mainly field auxiliary image generation. serve auxiliary manual design, which differs spatial conception characteristics architectural design thinking cannot replace elaboration building volumes spatial experiences.

Conclusions

address carbon emission reduction built environment, study focuses “technology-space” synergy carbon-sequestering buildings develops generative innovative design methodology.

conclusions

follows:

1. A

sample cases (predominantly developed countries partial innovative projects developing ones) shows cases adopt carbon-sequestering technology (CCT) adopt types; green plant-based account applications, bio-based materials 88.2% structural applications, bio-based technologies 44.4% facade applications.

2. Through

statistical

analysis

cases, there technology-space combination modes carbon-sequestering buildings: "bio-based materials facade" , "bio-based materials structure" , "photoreaction technology facade", "photoreaction technology wall", "green plants roof", "green plants facade" , "green plants balcony" , "Direct Capture structure" "Direct Capture facade" .

3. The

average synergy evaluation score cases 9.62/15 (moderately positive), technical efficiency scoring lowest (3.13), reflecting expert concerns practical efficacy.

4. An

XGBoost evaluation model trained independent dependent variables achieves 82.5% prediction accuracy, building exerting strongest influence (65.38%) aesthetics dimension.

5. High-synergy

scheme

analysis

demonstrates generation based multimodal

prompts enhances technology-space synergy; verification Kunming fourth-generation residential courtyard project shows score increases

technical efficiency, implementability, and aesthetic

References

1. Abdellatef, (2020). Mechanical, thermal, moisture buffering properties novel insulating hemp-lime composite building materials.

Materials (21). 2. Ahmad, Abdullah, Koji, (2021). Evolution photobioreactors: review based microalgal perspective.

Conference Series: Materials Science Engineering 3. Ahmed, Zhou, (2021).

Biochar thermal insulation: Processing performance.

Sustainable Chemistry Engineering (29), 4. Ainsworth, Long, (2024). years free-air carbon dioxide enrichment.

Global Change Biology 5. Andersen, Rasmussen, Ryberg, (2022).

Comparative cycle assessment cross laminated timber building concrete building special focus biogenic carbon.

Energy Buildings (n.d.), 6. Biloria, Thakkar, (2020).

Integrating algae building technology built environment: benefit perspective.

Frontiers Architectural Research 7. Bono, (2024). Text-to-building:

Experiments AI-generated geometry building design structure generation.

Architectural Intelligence 8. Bryan, Salamah, (2023).

Building-integrated carbon capture: Carbon dioxide removal through buildings mechanical systems International Conference Energy Research Development, ICERD 9. Burns, Nicholson, (2023).

Bioenergy carbon capture storage (BECCS): prospects challenges emerging climate policy response.

Journal Environmental Studies Sciences (n.d.), 10. Carpo, (2025).

Tectonics, culture building technology. Architectural Intelligence s44223-24-81 11. Chen, Chen, (2018).

Present status development trends underground space chinese cities:

Evaluation analysis. Tunnelling Underground Space Technology (n.d.), 12. Cheung, Wang, (2025).

Conversational, agentic AI-enhanced architectural

design process: Three approaches multimodal AI-enhanced early-stage performative design exploration.

Architectural Intelligence 13. Eleonora, Stefan, Elizabeth, (2023).

Construction technosols green roofs vertical green system. (n.d.). 14. Elmokadem, Megahed, Noaman, (2016).

Systematic framework efficient integration technologies buildings.

Frontiers Architectural Research (n.d.).

15. Engineering

Carbon. (n.d.). Occidental, 1PointFive begin construction world largest direct capture plant texas permian basin. 16. Eric, Ahmed, Muhammad, (2023).

Developing integrated direct capture bioenergy carbon capture storage systems:

Progress towards climate goals. Energy Conversion Management (n.d.), 17. Favoino, Loonen, Michael, (2022).

Advanced fenestration Technologies, performance building integration 154). 18. Forster, Healey, Dymond, Styles, (2021).

Commercial afforestation deliver effective climate change mitigation under multiple decarbonisation pathways.

Nature

Communications , 12 (1), 3831.

19. Galimshina, Moustapha, Hollberg, Padey, Lasvaux, Sudret, Habert, (2022).

Bio-based materials robust solution building renovation: study.

Applied Energy (n.d.), 20. Gupta, Krishna, Prasad, (2023).

Biochar-concrete composites: novel approach carbon sequestration infrastructure.

Construction Building Materials (n.d.), 21. Heidari, Lawrence, Blanchet, (2019).

Regionalised cycle assessment bio-based materials construction; treated sol-gel coatings.

Materials (18). 22. Huang, (2024). Adaptive interior design

method

different personality types based generative artificial intelligence.

Architectural Intelligence 23. Iea. (2022). Direct capture 2022, technology zero. 24. Kong, Fang, Chen, Xiao, Zhang, (2025).

Examining human collaboration hybrid intelligence learning environments:

Insight synergy degree model. Humanities Social Sciences Communications 25. Koytsoumpa, Bergins, Kakaras, (2023). economy:

Review

capture reuse technologies. Journal Supercritical Fluids (n.d.), 26. Lin, Zhao, Yang, (2021). review research development passive building China.

Journal Building Engineering 27. Luo, Xiong, ddeke, Huang, (2023).

Advances subsea carbon dioxide utilization storage.

Energy Reviews 28. Ma, (2023). intelligent retrofit decision-making model building program planning considering tacit knowledge multiple objectives.

Energy (n.d.), 29. Ma, Wang, Zhang, Wang, (2020). Carbon capture storage:

History ahead. Engineering (n.d.), 30. Minyong, (2008).

Computational studies binding 1A-adrenoceptor antagonists.

Journal Molecular Modeling (n.d.). 31. Odiah, Gosling, (2024).

Laying foundations using generative images architectural research: images convey intended spaces ambiances?

Architectural Intelligence 32. Okonkwo, AlNouss, Shahbaz, Al-Ansari, (2023).

Developing integrated direct capture bioenergy carbon capture storage systems:

Progress towards climate goals. Energy Conversion Management (n.d.), 33. Orsini, Marrone, (n.d.).

Approaches low-carbon production building materials: review.

Journal Cleaner Production (n.d.). 34. Palmer, (2019).

Mitigating climate change depend negative emissions technologies.

Engineering

35. P

rez-Urrestarazu, (2021). Carbon sequestration vertical greeneries.

Urban

Forestry & Urban Greening , 65 (n.d.), 127337.

36. Portugali, (2025). Synergetics foundations city.

European Physical Journal Special Topics 37. Ramesh, (2023).

Climate change science, policies, national perspectives global context.

Springer International Publishing. 38. Ritter, Herzog, Rothermel, Cohn, (2025). models:

Past, present future prospects. Frontiers Urban Rural Planning

39. Schwarzov

Stevulova, Melichar, (2017). Lightweight composites based technical hurds construction industry.

Chemical Engineering Transactions (n.d.),

40. Sodiq, Abdullatif, Aissa, (2023). review progress direct capture Environmental Technology Innovation (n.d.), 41. Soomro, (2021).

Alkali-activated mortars recycled fines sand. Materials (n.d.). 42. Sourek, (2024). architecture engineering misconceptions game-changing prospects.

Architectural Intelligence 43. Spurrett, (1999). Complexity post-modernism:

Understanding complex systems. (n.d.). 44. Stanikzai, Mittal, (2025).

Leveraging AI-generated human-generated content maximized engagement contentpreneurs innovation creativity.

Journal Innovation Entrepreneurship 45. Tariq, Bassam, Orozco-del-Castillo, Ricalde, Carvente, (2023).

Sustainability framework intelligent social houses synergy double-fa architecture active conditioning systems.

Energy Conversion Management (n.d.), 46. Usman, Iqbal, Noor, Zaman, Asghar, Abdelnaby, Helal, (2022).

Advanced strategies metal-organic frameworks capture separation.

Chemical Record e202100230. 47. Weber, Favrat, (2010).

Conventional advanced based district energy systems.

Energy (12), 48. Wienchol, Szlek, Ditaranto, (2020).

Waste-to-energy technology integrated carbon capture challenges opportunities.

Energy (n.d.), 49. Woolf, Amonette, Street-Perrott, (2021).

Sustainable biochar mitigate

global climate change. Nature Communications , 12 (1), 1 -10.

50. Xu, Omitaomu, Sabri, Zlatanova, Song, (2024). Leveraging generative urban digital twins: scoping review autonomous generation urban data, scenarios, designs, models smart advancement.

Urban Informatics 51. Yadav, (2017). Microalgal green refinery concept biosequestration carbon-dioxide wastewater remediation bioenergy production:

Recent technological advances climate research. Journal Utilization (n.d.), 52. Yang, Zhang, (2019).

Impact energy buildings medium-to-long building energy consumption China.

Energy Policy (JUN.),

53. Ying, Haibo, Cheng, (2016). Assessing cross laminated timber (CLT) alternative material mid-rise residential buildings regions China life-cycle assessment approach.

Sustainability (10). 54. Zhang, (2021). Umbrella structure building design

method

case-based design statistical

analysis

structural morphological parameters. (n.d.).

Appendices Carbon-Sequestering Technologies Country Technology Combination future vision Australia Urban Brisbane Facade Green Plants Balcony Net-zero carbon Canada Education community college Structure Expansion AIRoffice Switzerla Office Photoreaction Algae Commerci Facade Green Mixed Tower

Function Structure Process Performin Facade Tower Mixed Function Facade Specific Strategies Image facade assembly, carbon sequestration texture, natural grain, three-dimensional carbon sink, balcony wooden load-bearing frame, structural carbon sequestration, tones Microalgae purification wall, indoor wall, purification, carbon absorption, tubular reactor Microalgae biological reaction curtain wall, carbon absorption photosynthesis, energy production, modular algae modules Microalgae biological reaction curtain wall, carbon absorption photosynthesis, modular algae modules, transparent pipes, modules, equipment floor, centralized carbon capture, modular metal boxes Modular algae modules, transparent

pipes, rectangular units, translucent

gradient effect Microalgae biological reaction curtain wall, glass curtain wall, carbon absorption photosynthesis, energy production, modular algae modules

Appendix

Information Table Global Building Cases Applying Technology Facade Direct

Algae Spain Mixed Therapeia Function Facade Uranlab France Commerci Facade France Mixed Function Facade French Dream China Office Photoreaction Tower Structure Algae Tower Australia Education Facade Arcwood Canada Residentia Structure Facade Skyscrapers Mixed Direct Function Facade Green Plants Balcony Modular algae modules, transparent pipes, flowing green algae liquid, translucent gradient effect bamboo structure, straw fiberboard, wood-based composite board, modular assembly, carbon sequestration texture Microalgae biological reaction curtain wall, glass curtain wall, carbon absorption photosynthesis, energy production, modular algae modules, flowing

green algae liquid, rectangular units

Microalgae biological reaction curtain wall, glass curtain wall, carbon absorption photosynthesis, modular algae modules, integrated wall-slab-roof Microalgae biological reaction curtain wall, glass curtain wall, carbon absorption photosynthesis, modular algae modules, transparent pipes, flowing green algae liquid, diamond-shaped

units, translucent gradient effect

wooden load-bearing frame, indoor decoration, structural carbon sequestration carrier, texture module array, equipment floor, centralized carbon capture, modular metal boxes, geometrically arranged equipment, balcony, planting troughs, green plants, multi-level potted plants Facade Bio-based

Bastide France Office Green Plants Urban Algo-Nomad France Industrial Bio-based Pavilion Structure Breathing Denmark Commerci Direct building Facade Brock Residentia Commons Tallwood Facade House Campus Germany Urban Augsburg Facade CapitaSpring Singapor Residentia Structure Constellations Russia Mixed Function Facade Vertical farm, balcony, railings, viewing platform, multi-level potted plants, leisure tables chairs, themed courtyard, shrubs, three-dimensional carbon sink, small quantity Microalgae purification wall, indoor wall, purification, carbon absorption, tubular reactor, symbiosis green algae plants, tech-style device structural carbon sequestration carrier, tones, indoor Building facade, sunshade, sail-shaped roller shutters,

mechanical rolling device, window

sill, regeneration, modular design facade, wood-based composite board, modular assembly, carbon sequestration texture, natural grain, rapid construction, outdoor, structure Building facade, sunshade cooling, multi-level vegetation, three-dimensional carbon

community, arbors, shrubs

wooden load-bearing frame, indoor decoration, structural carbon sequestration carrier, tones integrated wall-roof, wooden load-bearing frame, structural carbon sequestration carrier, tones Technology

Erlev School Denmark Education Structure Structure Feuerborer Education Secondary School Facade Expansion Floating Netherlan Office Bio-based off-grid office Plants Forest Green Netherlan Stadium Bio-based Rovers Stadium Structure Freebooter Netherlan Residentia Facade German China Exhibition Bio-based Chinese House Facade Biophilic Singapor Residentia Regenerative Facade Green Ecosystem Plants Balcony Green Urban structural carbon sequestration carrier, tones, outdoor, V-shaped supports structure, integrated wall-slab-roof, wooden load-bearing frame, structural carbon sequestration carrier, tones, V-shaped supports Low-carbon concrete, facade, glossy surface, textured material, artificial paint wooden load-bearing frame, tones, V-shaped supports wooden load-bearing frame, indoor decoration, sound insulation bamboo structure, modular assembly, natural grain, rapid construction, outdoor, grilles, railing structure bamboo structure, modular assembly, natural grain, rapid construction, perspective view, grilles, outdoor, bamboo, V-shaped supports Vertical farm, balcony, railings, viewing platform, shrubs, three-dimensional carbon Three-dimensional carbon

community, roof greening area,

layered planting arbors, shrubs grasses, multi-level vegetation, Structure Green

Habitat South Urban Direct Korea Structure HAUSSMANN France Urban Plants Balcony High-Rise Residentia Farms Facade Hucamp Australia Urban Facade Innovation Germany Mixed Artificial Function Intelligence International France Theatre Bio-based convention Facade Green center theatres Plants North Office Bio-based Structure

greening synergy, green plant belt

modules, equipment floor, centralized carbon capture, modular metal boxes, ventilation pipes, geometrically arranged equipment, white shell, hollow adsorbent material structural carbon sequestration carrier, vertical farm, balcony, railings, viewing platform wooden load-bearing frame, structural carbon sequestration carrier, tones, outdoor, modular design, V-shaped supports, small scale Building facade, sunshade cooling, multi-level vegetation, three-dimensional carbon

community, arbors, shrubs

Three-dimensional carbon

community, roof greening area,

layered planting arbors, shrubs grasses, multi-level vegetation,

greening synergy, green plant belt

Three-dimensional carbon

community, roof greening area,

layered planting arbors, shrubs grasses, multi-level vegetation,

greening synergy, sunshade and

cooling, carbon capture efficiency enhancement wooden load-bearing frame, indoor decoration, structural carbon sequestration carrier, tones Structure Green

Nienke Netherlan Commerci Structure Grand Canada Commerci March Structure Liuzhou Forest China Residentia Macquarie Australia Office Bio-based Structure Magnifica Italy Cultural Green Plants Fabricca Facade plant Switzerla Industrial Direct Structure Mobius-E Residentia wooden load-bearing frame, indoor decoration, sound insulation, structural carbon sequestration carrier, tones structure, integrated wall-slab-roof, wooden load-bearing frame, structural carbon sequestration carrier, tones, outdoor Vertical farm, balcony, railings, viewing platform, multi-level potted plants, leisure tables chairs, themed courtyard, shrubs, three-dimensional carbon sink, small quantity bamboo structure, modular assembly, natural grain, rapid construction, outdoor, V-shaped supports, wooden Sunshade cooling, multi-level vegetation, modular planting boxes, full-facade green plants, three-dimensional carbon

community, arbors, shrubs, regular

embedding module array, roof, centralized carbon capture, modular metal boxes, containers, geometrically arranged equipment, white shell, hollow adsorbent material, vertical stacking, hollow design Vertical farm, balcony, leisure facilities, multi-level potted plants, leisure tables chairs, themed courtyard, arbors, shrubs, three-dimensional carbon

Monteporreiro Spain Urban Nieuw Bergen Netherlan Residentia

EcoPact Venice Residentia

Structure Rainbow Philippin Residentia Facade Paris Smart France Mixed Function Patch Netherlan Residentia Structure Pradera Urbana Spain Urban Facade Project bason Industrial Direct Structure Three-dimensional carbon community, roof greening area, high

carbon sink, layered planting arbors, shrubs grasses,

multi-level vegetation, greening

synergy, equipment area, sunshade cooling, carbon capture efficiency enhancement, green plant Three-dimensional carbon

community, roof greening area,

layered planting arbors, shrubs grasses, multi-level vegetation,

greening synergy, green plant belt

Modern minimalist style, white

concrete facade, modular layout, staggered hollow spaces, low-carbon concrete bamboo structure, modular assembly, natural grain, rapid construction, outdoor, grilles, railing structure Vertical farm, balcony, planting troughs, leisure facilities, multi-level potted plants bamboo structure, wood-based composite board, carbon sequestration texture, rapid construction, outdoor, V-shaped supports Building facade, sunshade cooling, multi-level vegetation, three-dimensional carbon

community, arbors, shrubs

modules, equipment floor, centralized carbon capture, modular metal boxes, ventilation pipes, geometrically arranged equipment

Public Canada Office Bio-based Organisation Headquarters Structure Pujiang China Office Photoreaction Intelligence Valley Facade Netherlan Education

Koning Willem

College Structure Cheonggyecheo South Urban restoration Korea Roatan Hawaii Residentia Prospera Structure Sands Residentia Public Centre Facade Planting China Urban Platform Experience Structure Solforest China Residentia Eco-park luxury development Italy Urban bridge Structure structural carbon sequestration carrier, tones, indoor Microalgae biological reaction curtain wall, glass curtain wall, carbon absorption photosynthesis, modular algae modules, transparent pipes,

rectangular units, translucent

gradient effect structural carbon sequestration carrier, tones, V-shaped supports Three-dimensional carbon

community, roof greening area,

layered planting arbors, shrubs grasses, multi-level vegetation,

greening synergy, green plant belt

structural carbon sequestration carrier, tones, outdoor bamboo structure, modular assembly, natural grain, grilles, railing structure carbon storage basement, wooden load-bearing frame, indoor decoration Vertical farm, balcony, planting troughs, arbors, shrubs, three-dimensional carbon sink, small quantity wooden load-bearing frame

Renewal Australia Urban Green Square Facade project PhotoSynthetia Australia Urban Tower Facade Taboadela Urban Direct Facade Tainan Spring China Commerci Facade Office Direct Kong, China Structure Urban Algae Italy Equipmen Urban magma Urban Facade URBAN India Residentia OASIS Facade Tower Norway Residentia Facade Building facade, sunshade cooling, multi-level vegetation, three-dimensional carbon

community, arbors, shrubs

Microalgae biological reaction curtain wall, carbon absorption photosynthesis, modular algae modules, transparent pipes, flowing green algae liquid Building facade, sunshade, sail-shaped roller shutters,

mechanical rolling device, window

sill, regeneration Multi-level vegetation, modular planting boxes, full-facade green plants, three-dimensional carbon

sink community, arbors, shrubs,

regular embedding module array, roof, centralized carbon capture, ventilation pipes, geometrically arranged equipment Microalgae purification wall, indoor wall, purification, carbon absorption, tubular reactor, symbiosis green algae plants, tech-style device Full-facade green plants, three-dimensional carbon

community, arbors, shrubs, regular

embedding bamboo structure, straw fiberboard, wood-based composite board, modular assembly, carbon sequestration texture bamboo structure, straw fiberboard, wood-based composite board, modular assembly, carbon sequestration texture, outdoor, structure Technology

CopenHill Denmark Sports Direct Structure Residentia Structure Beibei Jinyun China Commerci Carbon Cabin Facade Urban Sequoia Urban Direct Structure Renovation Canada Performin Verdun Auditorium Facade Mandragore Residentia AI-generated Residentia Future Cities Facade module array, equipment floor, centralized carbon capture, modular metal boxes, geometrically arranged equipment bamboo structure, straw fiberboard, wood-based composite board, modular assembly, carbon sequestration texture bamboo structure, wood-based composite board, carbon sequestration texture, rapid construction, V-shaped supports, front facade Vertical farm, balcony, multi-level potted plants, leisure tables chairs, arbors, shrubs, three-dimensional carbon sink, modules, equipment floor, centralized carbon capture, modular metal boxes, integrated wall-slab-roof, wooden load-bearing frame integrated wall-slab, wooden load-bearing frame, structural carbon sequestration carrier, tones Vertical farm, balcony, planting troughs, leisure tables chairs, themed courtyard, arbors, three-dimensional carbon icroalgae biological reaction curtain wall, glass curtain wall, carbon absorption photosynthesis, modular algae modules, transparent pipes,

triangular units, translucent gradient

effect Structure Green Plants Balcony

Shenzhen China Urban carbon Mateo Office Bio-based County Office Structure China Residentia Capture (DAC) Facade

York University

Canada Education School Facade Showa Gakuin Japan Education Elementary School Structure AMATA France Residentia Plants Balcony Carbon-capture Industrial Photoreaction facilities Facade Carbon Capture Residentia Tower Structure Vertical farm, balcony, viewing platform, multi-level potted plants, themed courtyard, shrubs, three-dimensional carbon sink, large quantity structural carbon sequestration carrier, tones, outdoor Vertical farm, balcony, railings, viewing platform, multi-level potted plants, leisure tables chairs, themed courtyard, shrubs, three-dimensional carbon Low-carbon concrete, facade, artificial coating, prefabricated assembly wooden load-bearing frame, indoor wooden load-bearing frame, indoor vertical farm, balcony, planting troughs, leisure facilities, multi-level potted plants, arbors Microalgae biological reaction curtain wall, carbon absorption photosynthesis, modular algae modules, transparent pipes, flowing green algae liquid, translucent

gradient effect, tubular units

wooden load-bearing frame, carbon absorption photosynthesis, modular algae modules, transparent

pipes, triangular units, translucent

gradient effect Balcony Direct Structure Green Technology

Ocean-based Urban carbon capture plant Wall, Direct Structure Mammoth Equipmen Direct Structure Microalgae Urban Cradle Iceland Residentia Structure dutch Residentia mountains Facade henderson China Office Bio-based Facade, Green Plants Balcony Carbon capture Zurich Urban Direct Structure Microalgae purification wall, purification, carbon absorption, tubular reactor, symbiosis green algae plants, module array, roof, centralized carbon capture, ventilation pipes module array, roof, centralized carbon capture, modular arranged equipment, white shell, hollow adsorbent Microalgae purification wall, indoor wall, purification, carbon absorption, tubular reactor, symbiosis green algae plants, tech-style device structural carbon sequestration carrier, tones, outdoor, V-shaped supports facade, bamboo structure, wood-based composite board, carbon sequestration texture, rapid construction, outdoor, V-shaped supports Balcony, planting troughs, leisure facilities, multi-level potted plants, leisure tables chairs, themed courtyard, arbors, shrubs, three-dimensional carbon sink, small quantity, bamboo structure, wood-based composite board, carbon sequestration texture module array, equipment floor, centralized carbon capture, modular metal boxes, geometrically arranged equipment, white shell, hollow adsorbent material Technology

Facilities Industrial Direct Northwest Louisiana Facade power Urban Direct Structure Wings Industrial Photoreaction Distribution Center Facade SUICOM Japan Equipmen Structure Vertical Residentia Farming Building facade, sunshade, sail-shaped roller shutters, mechanica regeneration, vacuum structure water spray system, silver module array, roof, centralized carbon capture, modular metal boxes, containers, geometrically arranged equipment, white shell, hollow adsorbent material Microalgae biological reaction curtain wall, glass curtain wall, carbon absorption photosynthesis, energy production, modular algae modules, flowing green algae liquid Low-carbon concrete, white material, modular design, angular misalignment Microalgae purification wall, indoor wall, purification, carbon absorption, tubular reactor, symbiosis green algae plants, tech-style device

Summary

Technology-Space Combination Modes Combination German-Chinese House, Tower Materials Facade (Norway) Brock Commons, Residential

Building (Harvard University)

Structure MVRDV Eindhoven Residential Building, Office Building Facade Angeles) Italian Carbon Capture Tower, Technology Microalgae Purification (Office Area) Tianqin (Fuzhou) EDITT Tower (Singapore), Vertical Forest Project

Penda Sky Villa (India), Kunming Sky

Facade Courtyard Direct Capture Yuan, Modules Structure (Equipment Floor Industrial Buildings) Direct Capture CarbonSail Scheme, CarbonCabinet Facade System (Efficiency/Implementation/Aesthetics) Facade openness improves carbon sequestration efficiency; modular assembly enables implementation; natural grain enhances aesthetics Full-life-cycle carbon sequestration structure; functions load-bearing carbon sequestration; texture enhances spatial experience Sufficient facade sunlight improves algae activity; modular modules enable maintenance; dynamic algae liquid enhances aesthetics Directly purifies indoor stable temperature humidity guarantee efficiency; integration indoor space Sufficient sunlight improves photosynthesis efficiency; interference functions; synergy photovoltaics green plants enhances aesthetics Vertical facade space increases carbon sink; plants provide sunshade energy saving; soften building boundaries Balcony microclimate adapts plant growth; maintenance residents; private carbon space experience Structure supports large-scale equipment; centralized carbon transportation; hides equipment without damaging aesthetics Facade improves carbon capture efficiency; functions sunshade carbon capture;

flexible materials adapt facade shape Support (Typical Cases) Synergy Advantages "Urban Sequoia" (USA), Guomao

Appendix

Questionnaire "Technology-Space" Synergy Evaluation Carbon-Sequestering Buildings Experts, Thank participating study. selected building cases applying carbon capture technologies.

Please evaluate dimension (technical efficiency, implementability, aesthetics) based images introductions these cases.

Technical efficiency: extent which technology maximize actual carbon absorption effect.

Implementability: feasibility construction operation maintenance.

Aesthetics: external aesthetic characteristics reflected integration technology space.

Please score question based experience perception points, where

poor and 5 = excellent).

Example Based images information following project, subjective perception carbon-sequestering technology application?

Project Name: Algae Therapeia, Location: Donostia, Spain Building Type:

Urban Renewal Project Introduction: design establish typical algae research center Basque Coast medical, food, industrial applications. (Photobioreactor) structure absorb carbon generate energy required building operations.

Design Strategies Integration nature: building echoes surrounding mountain terrain, organic appearance blends environment, minimizing damage natural landscape reflecting concept ecological design. helps reduce building resistance energy consumption.

Spatial openness transparency: internal space adopts large-area transparent structures (e.g., glass transparent materials) introduce natural light, reducing energy consumption artificial lighting. creates comfortable internal environment, promoting circulation facilitating exchange required carbon-sequestering technologies.

Multi-functional space utilization: internal space includes leisure functions. building merely residence workplace integrates leisure entertainment functions, improving space utilization, realizing multi-functional integration, meeting diverse needs.

Integration Carbon-Sequestering Technology Building:

Facade structure carbon sequestration: building facade adopts photoreaction technology.

These materials convert through chemical reactions physical adsorption, similar plants absorb photosynthesis.

Ventilation system carbon sequestration: transparent space facilitates circulation.

Carbon-sequestering devices integrated ventilation pipes system. circulates building, devices capture (similar purifiers filter pollutants) achieve carbon sequestration.

Indoor facility carbon sequestration: Hidden carbon-sequestering facilities installed leisure space. example, decorative materials facilities around swimming carbon-sequestering functions, carbon-sequestering module added water circulation system assist building carbon sequestration while maintaining environment.

Carbon-Sequestering Technology Type: Tubular Score Below Average Average Above Average Excellent Aesthetics

Appendix

Assignment Rules Model Variables Category Indicator Influencing Factors Technology-Space Combination Facade Modes Structure Technology Facade Technology Structure Facade Questionnaire Evaluation occupied structures walls columns) building (e.g., roof, spire)

Sports = 4, Educational = 5, Infrastructure = 6, Park &

Square = 7

unit area, including transportation, installation, and

maintenance costs Frame-shear structure Shear structure

= 2, Algae-based materials = 3, Biomass materials = 4

Rectangular-enclosed = 4, Decentralized = 5

Marked meets application conditions, based images texts Marked meets application conditions, based images texts Marked meets application conditions, based images texts Marked meets application conditions, based images texts Marked meets application conditions, based images texts based images texts based images texts Marked meets application conditions, based images texts Marked meets application conditions, based images texts Average effect, Acceptable, effect, Indicator Quantification Rules Building Usable internal building (excluding space Project Residential Office Commercial Cultural Structural Wall-bearing structure Frame structure Building Materials Low-carbon concrete Cross-laminated timber (CLT) Plane Layout Rectangular L-shaped Circular Green Plants Marked meets application conditions, Green Plants Facade Marked meets application conditions, Technical Efficiency 5-point Likert scale:

Extremely effect,

Figure 7

Figure 1: Figure 7

Figure 9

Figure 2: Figure 9

Excellent effect Implementability 5-point Likert scale: unfeasible, Unfeasible, 3 = Average, 4 = Feasible, 5 = Very feasible

Aesthetics 5-point Likert scale: Extremely unattractive, Unattractive, 3 = Average, 4 = Attractive, 5 = Very attractive

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Figures

Source: ChinaXiv —Machine translation. Verify with original.