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INITIATING THE CONCEPTUALISATION OF HUMAN-DATA INTERACTIONS IN REGENERATIVE BUILDING PRODUCTION

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Abstract

Regeneration, which aims at climate positivity, is not yet considered in building production research, let alone implemented in praxis (except isolated cases). In this paper, we start investigating its potential in building production, especially focusing on the relevant human-data interactions (HDI) around building processes. We therefore review the recent literature on regeneration and HDI within urban planning, architectural design, and business model innovation, and use the phenomena construction methodology to conceptualize basic HDI dimensions in regenerative building production. Our results show that HDI can be crucial for transforming building production processes and management, as well as upskilling labor, towards regeneration.

Introduction

The mainstream construction industry is degrading ecosystems, resources, and human living conditions – e.g., generating ca. 40% of the global CO_2 emissions (WEF, 2024), and ca. 40% of EU's total waste (Eurostat, 2024). A critical part of this impact originates in building production (Erlandsson, 2021) – i.e., the on-site building processes and associated value and material flows, stakeholders, social contexts, and management practices.

To amend this impact, emission-free building sites, re- and up-cycling, climate declarations, lifecycle analysis, sustainable investments (EU 2021), and the buildings' energy performance (EP 2023), have been embraced in construction management. However, current building production work, while legitimizing some sustainable and circular initiatives, mostly fails to change entrenched norms and practices because it is still prioritizing short-term cost reduction and profit maximization over long-term resource efficiency (Kifokeris and Koch, 2024; Oyefusi et al. 2024). For sustainability, circularity and resource-efficiency to become widespread in building production, practices, skills, needs, and value flows should be approached with an emphasis on long-lasting net positive impact. Such an approach can be guided by the concept of regeneration (Morseletto, 2022). While sustainability aims at meeting present needs without compromising the future, and circularity focuses on material and component recycling and reuse, regeneration surpasses them by going beyond negative impact mitigation and actively focusing on repairing damage, improving well-being, restoring ecosystems, and a net positive impact (Hahn and Tampe, 2021). It involves humans as key ecosystem contributors engaging and collaborating holistically (Mang et al., 2016).

Regenerative strategies focus on resource efficiency and environmental improvement (Bocken and Geradts, 2022). On top of circular practices like material and component reuse (Cianchi et al., 2023), regeneration aims at promoting well-being and reversing environmental degradation (Naeem et al. 2022). Examples from the food and agricultural industries have shown that regenerative business models and policies strive for equitable stakeholder partnerships (Konietzko et al., 2023) and require collaboration and interdisciplinarity for long-term resource security (Bocken and Geradts, 2022).

Regenerative design and ecologically balanced spaces (De Wolf & Bocken 2024) have been explored to foster the building occupants' well-being (Sadat et al. 2024) – which has led to a few regenerative cases, like carbon-absorbing buildings and self-healing materials (Churkina et al. 2020). In this exploration, the interaction of digital technologies with humans has been exemplified as critical (De Wolf and Bocken, 2024). However, beyond isolated examples, regeneration has not been adopted in building production praxis, and the implications of relevant human-data interactions (HDI), have not been examined.

In this paper, we therefore initiate the investigation on how HDI can contribute to transforming building production towards regeneration. To achieve that, we review the recent literature on the nexus of regeneration and HDI within the built environment and use the phenomena construction methodology to conceptualize basic HDI dimensions in regenerative building production. We frame this effort using a working theory of HDI, as it is conceived by the HDI Committee of EC3.

Theoretical framework: HDI in the Built Environment

HDI for the built environment focuses on "understanding the interactions between actors and data throughout the lifecycle of built assets […] to improve the outcomes (e.g., economic, environmental, and societal) and value of data and interactions for both involved and affected parties" (Kassem and Kifokeris, 2025). In this context, three principles are central (Li et al., 2024):

1. Legibility: Data and analytic algorithms should be both transparent and comprehensible to users.
2. Agency: Opting-in or -out of data collection and processing, engaging with data collection, storage, and use, and understanding and modifying data and the inferences drawn from it, should be supported.
3. Negotiability: Decisions should be re-evaluated as contexts change.

A built asset can refer to an individual building or infrastructural component, system, or space, an entire building or infrastructural asset, and even whole districts and cities (Kassem and Kifokeris, 2025). Given such a wide span, data could be generated from multiple sources, including the Internet of Things (IoT), Building Information Modelling (BIM), Virtual and Augmented Reality (VR and AR), Artificial Intelligence (AI) and Machine Learning (ML), Distributed Ledger Technologies (DLT) like blockchain (Li et al., 2023), Production Automation and Robotics, and other in-use/operational management systems (e.g., smart buildings and cities) (Kassem and Kifokeris, 2025). Data states can include primary data (i.e., available for use without requiring further transformation) and derivative data (i.e., data transformed to enable certain decisions or make the data consumable and valuable) (Kassem and Kifokeris, 2025).

Another key point within the definition given above is that HDI pervades different phases of a built asset's lifecycle. One can then investigate how such a manifestation develops from one lifecycle phase to the next in an incremental way (Calvetti et al., 2023) or focus on a specific phase. Considering production, Calvetti et al. (2024) have shown the implications of HDI for electronic performance monitoring in construction sites, where they postulated that producing, consuming, regulating and utilizing the relevant data flows and interactions is mainly a managerial issue embedded in the on-site environment.

Research method

To address its stated research question, this paper situates the insights gained from a targeted literature review within the aforementioned theoretical framework and then utilizes that to develop a conceptual schema.

The literature review concerns the recent scholarship on regeneration and HDI within the built environment – which mostly focuses on design, digital twins (DTs) and urban planning, since building production has scarcely been researched in relation to both regeneration and HDI. The review was conducted via the iterative concept-centric method enhanced by units of analysis (Webster and Watson, 2002), covering the Scopus and Web of Science databases. The main searched concepts were "regeneration", "built environment", and "human-data interactions". The emerging units of analysis included, indicatively, "DTs for regeneration". This led to about 10,000 initial hits, which were then gradually reduced by applying the exclusion and inclusion criteria (Dundar and Fleeman, 2017) of contextual relevance (5,000 hits), temporality (2,000 hits), significance of content (500 hits), originality (76 hits), and integrational capability (the final 49 references included in this paper). Finally, we contextualize the literature insights into building production using the phenomena construction methodology (Alvesson and Sandberg, 2023) (see Fig. 1).

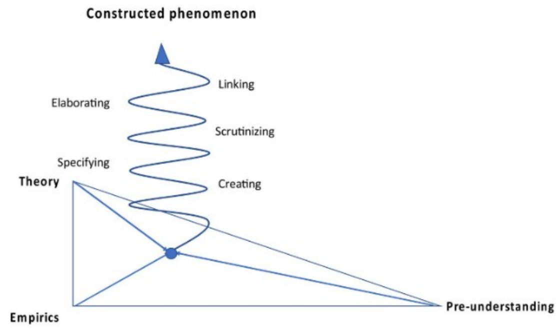

Figure 1: The methodology of phenomena construction (Alvesson and Sandberg, 2023)

Specifically, the three angles shown above translate as:

- Theory: The definition, principles and aspects of HDI in the built environment.
- Pre-understanding: The authors' existing knowledge of research and praxis in building production, HDI and regeneration, and the gap in integrating all three.
- Empirics: Reflexively understanding the literature findings (i.e., HDI and regeneration in the built environment) and then placing them in the previously non-utilized context of building production.

Given those angles, the framework's five steps (Alvesson and Sandberg, 2023) are translated as:

- Creating: Realizing the new phenomenon based on previously established cornerstones – i.e., HDI in regenerative building production, based on HDI in regeneration for the (general) built environment.
- Specifying: Giving the emerging phenomenon an initial meaning – i.e., the importance of HDI in supporting the transformation of building production towards being regenerative.
- Scrutinizing: Examining whether the emerging phenomenon is interesting and promising – in this paper, this is postulated to be true in the connotations of the existing research gap.
- Elaborating: Identifying the phenomenon's most distinct features – i.e., the HDI dimensions in regenerative building production.
- Linking: Relating the phenomenon to the relevant research domain (i.e., the scholarship of HDI and regeneration in the built environment).

Literature review

Aspects of regeneration in the built environment

Notable, albeit few, examples of regeneration in the built environment include buildings functioning as carbon sinks, self-repairing or pollution-cleaning facades, and biodiversity-supporting techniques (Churkina et al. 2020).

However, regeneration should extend beyond purely ecological measures, integrating environmental restoration with socioeconomic benefits. For example, it requires addressing social inequalities, fostering green economic growth, urban planning that encourages human and environmental co-evolution (Mang et al., 2016; Attia, 2018), design that emphasizes ecological balance and resilience through the collaboration between human activities and nature (Watson, 2019), and strategic development that emphasizes human–nature cohabitation, enhanced biodiversity, and shared spaces (De Wolf and Bocken, 2024). In the following, examples of such aspects are presented on the level of materials, products, projects, neighborhoods, communities, and business models.

At the material level, regeneration focuses on renewable, non-hazardous resources and the development of self-repairing materials (Seymour et al., 2023). Materials such as bio-based mycelium and biochar – created by converting wood waste – lock carbon while reducing environmental harm, offering sustainable, end-of-life solutions (Bitting et al., 2022).

At the product level, regenerative products turn waste into resources, support biodiversity, and enhance energy efficiency (De Wolf and Bocken, 2024). Examples include green roofs and facades that improve air and water quality, reduce heat islands, and generate renewable energy (Calheiros et al., 2021), while products like vertical gardens, urban farming systems, and emission-capturing materials are integrating nature with urban design (Dring and Schwaag, 2021).

At the project level, buildings and infrastructural projects designed for regeneration should incorporate renewable energy, water conservation, natural ventilation (when applicable), natural symbiosis (e.g., internal gardens) (De Wolf and Bocken, 2024), and considerations for climate change-induced threats like heat waves and air pollution (Coady, 2020) – while integrating digital technologies like smart sensors for energy efficiency (Jalia et al., 2022). Nonetheless, as mentioned earlier, such design-related regenerative concerns on the project level have not been followed by production-related ones.

At the neighborhood level, regeneration should focus on social equity, resilience, environmental health through walkability, and public transport, green infrastructure prioritizing biodiversity and inclusivity (Newman, 2014).

At the community level, regeneration can turn underused spaces into productive areas, potentially integrating endemic practices with modern aquaculture for purifying wastewater and restoring ecosystems (Saha, 2019).

Finally, at the business model level, and although traditionally discussed in nature-focused contexts, regenerative models are gaining traction among businesses and policymakers – albeit mostly in the food and agricultural industries (Konietzko et al., 2023). Regenerative business models should prioritize planetary health and societal well-being, as well as advocate for creating value across stakeholders – nature, society, employees, and investors – through regenerative leadership, equitable practices, and nature-focused partnerships (Konietzko et al., 2023). While not yet mainstream, regenerative innovation can enhance resource security, reduce costs, and provide long-term competitive advantages (Bocken and Geradts, 2022).

In the built environment, such business model considerations could translate to collaboration across different stakeholders to implement regenerative principles like repair, adaptability, and resilience within local systems (De Wolf and Bocken, 2024). This approach can address complex challenges, such as climate change adaptation and mitigation (Polman and Winston, 2021).

Aspects of HDI fostering regeneration in the built environment

System thinking in regenerative environments can lead to emphasizing adaptable designs that evolve over time to enhance environmental, social, and economic performance (De Wolf and Bocken, 2024). This approach can dissolve boundaries between nature and human-made spaces by utilizing traditional practices while integrating modern digital technologies like IoT, AI, and blockchain; on the same vein, smart cities and net-positive buildings can foster circular economy and promote resource sharing and localized energy systems through platforms like smart grids (Kirli et al., 2022).

Relevant literature postulates that digital technologies hold immense potential to drive regeneration in the built environment by fostering collaboration, optimization, and innovative design approaches – with the interaction of such technologies and their data with humans being a critical factor in this process (De Wolf and Bocken, 2024). In the following, examples of such HDI in the contexts of technologies potentially used for regeneration in the built environment (including BIM and DTs, GIS, smart cities and IoT, and others) will be presented.

BIM and DTs can provide HDI platforms for integrating sustainable design optimization, resource management, and predictive maintenance related to materials, energy use, and lifecycle analysis (Koutamanis, 2024). While BIM focuses on real-time monitoring, DTs add insights by simulating past and current building states to inform HDI in guiding decision-making (Koutamanis, 2024).

GIS can support regenerative urban planning by analyzing spatial data to optimize resource flows, transportation, natural area restoration (including locating recycling centers, managing waste collection, and planning decentralized renewable energy systems), and even aid in water management strategies in urban areas (Tsui et al., 2024).

Smart cities can leverage IoT and smart grids to enable HDI through real-time monitoring and resource management (Tsui et al., 2024). At the same time, citizen engagement through digital platforms can empower communities to adopt regenerative practices and enhance a sense of ownership (Tsui et al., 2024).

Reality capture technologies, like LiDAR scanning, can create accurate digital representations of buildings for inventory management and heritage preservation (Gordon et al., 2024). These tools can support HDI for sustainable restoration, tracking maintenance needs, and optimizing building performance through predictive maintenance and energy-saving simulations (Gordon et al., 2024).

AI can analyze data on material properties, lifecycle potential, and market demand to guide material selection, design for disassembly, and circular supply chains (Armeni et al., 2024). It can also identify regenerative synergies and facilitate stakeholder collaboration (Armeni et al., 2024). Material passports can then standardize data on materials' composition, performance, and regenerative capabilities, ensuring transparency in HDI and long-term sustainability (Honic et al., 2024).

HDI in computational tools, such as parametric design software, can enable architects to integrate regenerative principles early in design (Heisel and McGranahan, 2024). Picking up from that, additive manufacturing (e.g., 3D printing) can then support waste minimization and the use of bio-based or recyclable materials, such as natural fiber-reinforced polymers (Chadha et al., 2024).

HDI between robotics and their operators can enhance precision, efficiency, and waste reduction in construction and regenerative design, while also being able to integrate with plants to produce food, improve microclimates, promote biodiversity, and foster a symbiotic urban environment (Bruun et al., 2024; Vasey et al., 2024).

XR technologies (AR/VR) can help with immersively visualizing and testing regenerative designs – to enhance HDI in collaboration, reduce design errors, and promote community engagement through participatory design processes (Soman et al., 2024).

Finally, blockchain can facilitate decentralized collaboration, transparent data management, and value governance for regenerative projects, while redefining HDI in data ownership and stakeholder roles and aligning social, economic, and technological systems to achieve regeneration (Shojaei and Naderi, 2024).

Empowering regeneration through HDI while using such technologies depends on project-specific implementation (De Wolf and Bocken, 2024), need assessment, trade-off evaluation, stakeholder engagement, and continuous monitoring (Nussholz et al., 2024).

HDI in regenerative building production

By realizing the angles (theory, pre-understanding, and empirics) of the phenomena construction methodology to analyze the literature findings through the deployed theoretical framework, we can conceive the following HDI dimensions when using digital technologies for regenerative building production, found in the intersection of legibility, agency, and negotiability:

- Perceptual and cognitive dimensions

  Data awareness and understanding: Perceiving and interpreting data related to regenerative materials, building processes, construction management, energy use, and lifecycle impacts of production.

  Cognitive load and decision support: The extent to which digital tools (e.g., production planning platforms) enhance or burden decision-making for regenerative approaches in building production.

  Trust in data and AI outputs: The level of confidence users can have in predictive models, simulations, and automation in relation to building production processes and management (including site management) that implement regenerative strategies.

- Interaction and interface dimensions

  Non-immersive interfaces: The users' interaction with technologies like BIM, DTs, or IoT dashboards for tasks related to regenerative building production processes and management (e.g., detecting constructability problems when installing carbon-absorbing building components).

  Immersive interfaces: The users' interaction with XR (AR/VR) in real-time visualizations of production processes realizing regenerative design aspects.

  Sensor-based feedback loops: Real-time data interactions through IoT sensors and AI-driven analytics connected to smart materials that can also be used for regenerative purposes (e.g., shape memory alloys and transparent wood).

- Behavioral and social dimensions

  User adaptability and learning curves: The way different stakeholders (e.g., architects, contractors, suppliers) engage with new data-driven tools when there is (client) demand that regeneration is applied during building production.

  Collaboration and knowledge sharing: The role of digital platforms in facilitating interdisciplinary cooperation during regenerative building production. This could for example affect the collaboration between the architects and the site managers for clarifying regenerative design aspects during early production stages – especially in design-build projects, when construction begins before the designs are fully finished.

  Ethical considerations and data bias: The way biases in data collection and AI decision-making may impact regenerative goals in building production (e.g., regarding energy usage in site operations in areas with outdated electrical grid infrastructure).

- Environmental and systems dimensions

Data-driven material flows: The use of digital systems to optimize circularity, material reuse, and carbon footprint analysis – not only in the tendering phase, but also during building production itself.

Energy and performance monitoring: Real-time tracking of the performance of building processes to ensure regenerative outcomes. This can be integrated into production management concepts like lean construction and tools like Last Planner.

Systems thinking and complexity management: Leveraging digital tools to realize environmental, social, and economic sustainability considerations in design, for net positivity into production itself.

- Governance and policy dimensions

  Regulatory compliance and standards: The ways digital technologies can support adherence to green building certifications and carbon reporting (both of which also account for production processes) or even surpass current net neutrality requirements towards net positivity.

  Data ownership and privacy: Addressing the ethical and legal challenges of data collection in "smartified" building production processes (e.g., workers wearing smart sensors tracking their physiological responses when working with regenerative materials on site).

  Open-source vs. proprietary data models: Data accessibility and interoperability implications in regenerative building production and management.

- Business model dimensions

  Prioritizing the planetary boundaries: The ways stakeholders can utilize collaborative technologies like blockchain to decentralize and democratize data on the impact of certain construction materials and building production processes on the topical and/or planetary resource boundaries.

  Investing in upskilling: The ways digital technologies can gather, store, and process data related to regenerative building development, which can then be invested in managers' and laborers' upskilling – thus capturing long-term repair, adaptability, and resilience within local building production contexts.

Table 1 (see next page) connects these HDI dimensions with building production processes, relevant digital tools, and possible utilization cases. Each of these aspects is connected to the conceived HDI dimensions based on the realization of the HDI principles. As there is no established research and praxis on regenerative building production (apart from isolated cases; see Churkina et al. (2020)), the examples in Table 1 are conceptual – aligning with the phenomena construction steps of creating, specifying, scrutinizing, elaborating, and linking. The steps are realized as we move from the left to the right side (i.e., the corresponding columns) in Table 1.

Conclusions

This paper initiates an investigation into how HDI can contribute to transforming building production towards regeneration. Through a systematic literature review and the application of the phenomena construction methodology, we conceptualize regenerative building production-related HDI dimensions reflecting aspects of legibility, agency, and negotiability: perception and cognition, interaction and interface, behavior and social context, the environment and systems, governance and policy, and business models – and then connect them with conceptual examples of production processes, digital tools, and utilization cases. In theoretical terms, this implies that realizing HDI this context particularizes the principles of HDI in the built environment with a specific, but also narrower, scope. Moreover, we conceptually show that HDI can be pervasive for successful implementation of regeneration in building production – which practically implies it affects not only all processes, stakeholders, and sociotechnical ecosystems and contexts in the building site, but also around it, connecting it more thoroughly with the surrounding community and even the planetary boundaries.

Despite its detailed conceptualizations, this study is limited – primarily due to absence of empirical data and cases that can corroborate the function of the conceived HDI dimensions in regenerative building production. To improve this, acquiring data from the few existing flagship cases would not be enough; monitoring the implementation of regeneration principles and the realization of HDI dimensions using digital tools during building production should rather be sought.

As such, recommendations for future work include the potential use of a small to medium building project as a case study and testbed of, simultaneously, implementing regenerative principles during its production, and utilizing relevant digital technologies to monitor HDI.

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Appendix

Table 1: Elaboration on the conceptualized HDI dimensions in regenerative building production

HDI dimensions	Production process examples	Potentially used digital tools	Potential utilization cases
Perceptual & cognitive	• Site management • On-site logistics and material handling • Frame installation • Connection of installed HVAC to smart sensors	• AI-driven decision support systems (e.g., Autodesk Spacemaker, Delve by Sidewalk Labs): Helping optimize regenerative site planning with real-time feedback. • Environmental impact dashboards (e.g., Arc Skoru for LEED projects): Improving data awareness when translating regenerative building design into on-site production. • Life cycle assessment (LCA) software (e.g., One Click LCA, SimaPro): Helping stakeholder teams understand embodied carbon impacts of on-site processes and material handling.	• Production of a smart building using IoT and AI to provide real-time energy optimization and intuitive dashboards helping occupants understand energy consumption and CO_2 footprints. • Using DTs in building production to model material reuse, requiring intuitive data visualization for better decision-making.
Interaction & interface	• Site management • On-site energy generation • Envelope elements installation • Insulation	• DTs for building process performance monitoring (e.g., Bentley iTwin, Matterport): Create real-time data simulations for building production emphasizing on the application of regenerative principles. • AR and VR) (e.g., Unity Reflect, Fologram): Enabling immersive interactions with regenerative materials and building systems during building production. • IoT-based feedback systems (e.g., Envio Systems, IBM Watson IoT): Smart sensors monitoring the real-time performance (e.g., CO_2e) of built assets during production.	• Using IoT and interactive dashboards to manage regenerative design-responsive building processes using hyperlocal data-driven planning. • Utilizing AR-based regenerative material visualization during building production.
Behavioral & social	• Production stakeholders meeting with the wider community • Production planning • Earthworks • Connection of the building site to utility networks	• Collaboration platforms (e.g., BIM 360, Miro): Facilitating real-time interdisciplinary teamwork and management of regenerative building production processes. • AI-driven community engagement tools (e.g., UrbanFootprint, Commonplace): Help production stakeholders (e.g., contractors, subcontractors, suppliers, site managers, planners) integrate local community input during building production for regeneration-related aspects (e.g., contributing to the community's economy by preferring employing local construction crews). • Blockchain (e.g., Circulor, Everledger): Contributing to ethical sourcing and lifecycle transparency and traceability for regenerative building materials.	• Regenerative building production hackathons as social coding events that facilitate knowledge-sharing among interdisciplinary teams working on regenerative solutions for building production. • Participatory building production with digital platforms to engage communities in supporting regenerative building production processes.
Environ-ment & systems	• Site management • On-site energy generation • Material and component logistics • Connection of the building site to utility networks • Superstructure erection using carbon positive concrete	• Building performance simulation software (e.g., EnergyPlus, IES VE): Analyzing thermal, lighting, and energy dynamics during on-site building production. • IBM TRIRIGA, Siemens Navigator: AI-powered smart building management systems that can be utilized during on-site production. • Material passports and circular platforms (e.g., Madaster, MaterialDistrict): Digitally tracking material and component reuse potential. • Digital fabrication and robotic construction (e.g., Grasshopper, Autodesk Generative Design): Enabling precision-based offline and real time regenerative material optimization during building production.	• Using material passports to digitally track building components for reuse. • Integrating digital material databases for cradle-to-cradle building certification to ensure all building production materials and components are regenerative.

Governance & policy	• Site management • Installation of building envelope panels • Installation of doors and windows • Procurement of electric construction vehicles • Insulation	• Regulatory compliance software (e.g., LEED Online, Breeam In-Use): Facilitating adherence of building production to sustainability policies, and benchmarking them for elevated, net positive goals. • AI-based code compliance checkers (e.g., UpCodes, Symetri Compliance Tools): Automating checks for aligning building production with the project's (regenerative) design to avoid constructability issues. • Digital contracts and smart contracts (e.g., Ethereum-based solutions, Procore): Facilitating the transparent procurement and handling of building materials and components based on regenerative properties.	• Using digital platforms for reporting carbon emissions, sustainability and even regenerative potential compliance in production planning portfolios with the EU taxonomy for sustainable buildings. • Using digital building permits and AI-driven compliance checking for sustainability standards and regenerative potential in building production.
Business model	• Site management • Production stakeholders' management • Procurement and billing of subcontractors • Procurement of electric construction vehicles • Insulation	• Excess Materials Exchange (EME): AI-driven marketplace for surplus building materials. • Material Passports (EPEA, MaterialDistrict): Tracking embodied carbon and regenerative (including circular) potential of building materials and components • Propy (Real Estate Transactions on Blockchain): Facilitating transparent and secure building property transactions with criteria potentially based on regeneration-compliant production processes. • WillowTwin (Willow): Optimizing sustainable, and potentially regenerative, strategies in smart building production (along with operation and maintenance).	• Engaging with digital passports and analytics to inform reuse, resale, and recycling of building materials and components. • Users interacting with AI-powered matching engines optimizing building component reuse based on regeneration metrics. • IoT-enabled systems providing real-time performance data to optimize energy efficiency and billing during building production. • IoT sensors tracking wear of regenerative materials and suggesting maintenance or replacement during logistics.