Digitalisation of the Built Environment

4th 4TU-14UAS Research Day

Extended Abstracts

9 April 2025
Groningen

Edited by
İhsan E. Bal, Amar Bennadji and Jos Arts

Colophon

Digitalisation of the Built Environment
4th 4TU-14UAS Research Day

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Keywords:
built environment, digital technologies, artificial intelligence, robotics, augmented/virtual/mixed reality, digital twins

Published by:
Hanze University of Applied Sciences, Research Centre for Built Environment NoorderRuimte, Groningen, Netherlands. www.noorderruimte.nl

DOI:
10.5281/zenodo.15162470

ISBN:
978-90-9040027-3

To cite this publication:
Bal I.E., Bennadji A., Arts J. (2025). Digitalisation of the Built Environment: 4th 4TU/14UAS Research Day. Hanze, Research Centre for Built Environment NoorderRuimte, Groningen, The Netherlands

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Preface

The built environment is under pressure from climate change, housing shortages, an aging population, and other societal challenges. To address these, large-scale sustainable transitions are urgently needed, such as shifting to renewable energy, adopting bio-based and circular materials, increasing efficiency of monitoring and maintenance of aging infrastructure, and enhancing the climate resilience of buildings and infrastructure.

Digitalisation plays a key role in accelerating this transition. With growing availability of built environment data, mature and accessible technologies, and increasing societal acceptance, the potential is vast. However, further knowledge is needed, particularly in areas like AI for generative design and predictive maintenance, remote sensing and cyber-physical systems for Digital Twins, and mixed reality for immersive urban and construction experiences. Data interoperability and open standards are also crucial for managing and sharing information across scales.

The universities of technology and universities of applied sciences in the Netherlands address these knowledge gaps through complementary research approaches. Collaborations among students, researchers, lecturers, and professors drive both scientific advancement and practical innovation in the field.

The annual **Research Day on Digitalisation of the Built Environment** is a joint initiative by the four Dutch universities of technology (4TU) and fourteen universities of applied sciences (14UAS), united under the national platform for research professors in the built environment (NL-GO). The fourth edition, held on 9 April 2025, was co-organised by Hanze University of Applied Sciences and University of Groningen. The event took place in Groningen, at the Zernike Campus, which is shared by the two organizing institutions.

We are pleased to present an engaging program featuring two distinguished keynote speakers. Saskia Hesselink, from the Ministry of the Interior and Kingdom Relations (Ministry BZK), and Jakob Beetz, from RWTH Aachen University, will share their perspectives on the role of data in the digitalization of the built environment, addressing both regulatory and practical dimensions.

The program of the 4th year features a diverse set of presentations that explore the digitalization of the built environment from multiple angles. With a total of 20 accepted papers, the sessions cover topics such as AI-based decision-making, data-driven design, digital twins, large-scale testing, and circular construction. Several papers examine the role of digital tools in education, regulatory processes, and sustainable development. Collectively, these contributions highlight both academic and practical advancements in leveraging data, models, and digital workflows to shape the future of our built environment.

This open-access book contains the proceedings of the 4th Research Day on Digitalisation of the Built Environment in the form of extended abstracts. All contributions were blindly peer reviewed by the scientific committee, which consisted of scientists from the 4TU and 14UAS communities. We are thankful to everyone who made this event possible.

On behalf of the organising committee,

İhsan E. Bal, Amar Bennadji, and Jos Arts

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Event Program

Time	Event	Location
09:00-10:00	Welcome coffee and registration	Smitsborg Building, Donald Smits Zaal (5431.0053), RUG
10:00-10:15	Opening Speeches	
10:15-10:45	1st Keynote Speech - Saskia Hesselink, Ministry BZK	
10:45-11:00	Coffee Break	
11:00-11:30	1st Round of Demonstrations	Cinema at Smitsborg Building & Atlas Lab at Mercator Building, RUG
11:30-12:00	2nd Round of Demonstrations	
12:00-12:15	Walking to BuildinG	from Smitsborg Building to Zernikelaan 17
12:15-13:15	Lunch Break	BuildinG, Zernikelaan 17, Hanze
13:15-13:45	2nd Keynote Speech - Prof. Jacob Beetz, University of Aachen	
13:45-14:15	Demonstrations	
14:15-15:45	Sessions 1a & 1b	
15:45-16:00	Coffee Break	
16:00-17:30	Sessions 2a & 2b	
17:30-18:30	Borrel - Snacks & drinks	

Session 1a

Shaping Design Solutions: Integrating Education, Research, and Practice with Cutting-Edge Technology

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Keywords: Virtual Reality (VR), Urban Design; Spatial Transformation; Urbanism; Reality Theater; Design Education.

Extended Abstract

In today's rapidly evolving urban landscapes, the integration of advanced technologies into spatial planning and design has become essential for addressing complex societal and environmental challenges. Industries are increasingly recognizing the need to innovate in response to cultural shifts, global competition, and the demand for sustainable development (Johnson et al., 2010). This transformation requires a rethinking of traditional design processes, particularly in disciplines that rely heavily on visual communication and interdisciplinary collaboration. At the University of Groningen, the adoption of cutting-edge tools like virtual reality (VR) has emerged as a cornerstone of this evolution, bridging education, research, and professional practice to create more resilient and inclusive urban environments.

Modern urban environments face multifaceted challenges, including population growth, climate change, and resource scarcity, which demand innovative solutions. Traditional 2D design methods, while foundational, may fall short in conveying the complexity of these issues. This is where VR and other digital tools come into play, offering immersive, interactive, and data-driven approaches to urban planning and design. This technological shift is evident in facilities like the Reality Theatre at the Center for Information Technology (CIT) and the Atlas VR Lab at the Faculty of Spatial Sciences. These spaces serve as hubs for experimentation and learning, enabling students and researchers to engage with VR tools in meaningful ways. The Atlas Lab, for instance, is equipped with high-performance computers and VR headsets, allowing users to create and manipulate 3D models of urban spaces. This hands-on experience not only builds technical proficiency but also fosters a deeper understanding of spatial relationships and design possibilities.

Similarly, the Reality Theatre uses immersive VR environments to explore pressing urban issues such as density, identity, and environmental sustainability. By rendering real-world scenarios in VR, students, researchers, practitioners, and invested citizens alike can visualize the impact of design decisions in real-time. Such initiatives demonstrate how VR can serve as both a pedagogical tool, a platform for critical discourse, and a pathway for community debate and engagement.

A key example of integrating technology into education is the Virtual Reality Experience Days, hosted by the Visualization Team at the Faculty of Spatial Sciences on November 15th and 20th, 2024. This event, designed for 120 second-year students in the Bachelor's programme in Spatial Planning and Design, aimed to inspire innovative approaches to urban design while bridging the gap between theoretical knowledge and practical application.

The sessions focused on two contrasting case studies: the Island of Schiermonnikoog and Lauwersoog Heritage Center, a UNESCO World Heritage site facing challenges related to tourism and conservation, and the Paddepoel neighbourhood near Zernike Campus, a suburban area undergoing densification. In the Schiermonnikoog scenario, students used VR to explore strategies for balancing natural landscape preservation with infrastructure development. The Paddepoel case, on the other hand, challenged students to discuss the redesign of a shopping mall to accommodate population growth while maintaining community identity. This hands-on approach not only enhanced students' technical skills but also encouraged them to think critically about the social and environmental implications of their work. By exposing undergraduates to VR's potential, the initiative strengthened connections between bachelor's and master's curricula while fostering early engagement with innovative research methodologies. Feedback from participants highlighted the event's success, with many students expressing increased confidence in using VR for design tasks and a heightened interest in pursuing advanced studies in digital spatial planning.

The use of VR extends beyond education into research and professional practice, where it is increasingly being adopted for data-driven decision-making and participatory planning. Urban simulations using VR have demonstrated the potential for collaborative urban development, allowing planners, designers, and local stakeholders to visualize and modify projects in real-time (Zhang et al., 2020). This participatory approach is also able to ensure that urban development aligns more closely with community needs while addressing environmental sustainability. For example, VR has been used to simulate the impact of new infrastructure projects on traffic flow, noise pollution, and green space availability. By creating immersive environments that stakeholders can explore, planners can gather valuable feedback and make informed decisions before construction begins. Research has also shown that immersive VR environments improve spatial cognition and decision-making, offering more effective means of exploring architectural designs compared to traditional 2D representations (Johnson et al., 2010; Zhang et al., 2020).

In professional practice, VR is being used for everything from public engagement to design validation. Architects and urban planners are leveraging VR to create interactive 3D models of proposed developments, enabling clients and communities to "walk through" designs long before they are built. This not only reduces the risk of costly revisions but also fosters greater transparency and trust in the planning process. Despite its many advantages, the widespread adoption of VR in spatial planning and design faces several challenges. Accessibility and affordability remain significant barriers, as high-end VR systems can be prohibitively expensive for smaller firms or educational institutions. Additionally, the learning curve associated with advanced VR tools can deter non-technical users, limiting their potential impact.

To address these challenges, efforts must be directed toward making VR technology more user-friendly and cost-effective. The development of cloud-based VR platforms, for instance, could reduce reliance on expensive local hardware, allowing users to access immersive environments via web browsers. Similarly, advancements in AI-driven generative design could streamline the creation of VR models, making the technology more accessible to a wider audience.

Looking ahead, the integration of VR with other emerging technologies, such as artificial intelligence (AI) and big data analytics, holds immense promise. AI-driven predictive modelling, when combined with VR environments, can allow urban planners to test multiple future scenarios under varying conditions, leading to more sustainable and adaptable urban designs (Zhang et al., 2020). Additionally, VR-supported geospatial analysis provides a dynamic approach to landscape evaluation, enabling real-time data overlays that aid in environmental impact assessments (ibid.). The integration of VR and other advanced technologies into spatial planning and design represents a transformative shift in how we approach urban challenges. By bridging education, research, and professional practice, these tools offer new possibilities for collaboration, innovation, and sustainability. The University of Groningen’s initiatives, from the VR Experience Days to the state-of-the-art Atlas VR Lab, exemplify the potential of technology to shape the future of spatial sciences.

Inspired by the success of these initiatives, the Faculty of Spatial Sciences is excited to offer participants of the upcoming 4th Research Day on Digitalization of the Built Environment a unique opportunity to engage with these technologies first-hand. Attendees will be invited to experience a short VR demonstration, showcasing how immersive tools can transform urban planning and design. Through interactive simulations and expert-led discussions, this experience will highlight the practical applications of VR in addressing real-world challenges, from climate adaptation to community engagement. By bridging theory and practice, this initiative underscores the Faculty’s commitment to advancing innovation and fostering collaboration in the digital age.

Acknowledgements

The original event and this proposal are orchestrated by the Faculty's Visualization Team in collaboration with the Centre for Information Technology’s (CIT) Visualization Team under the leadership of Dr Gert-Jan Verheij. This would not be possible without dr. ir. S. Gerd Weitkamp and dr. ir. Terry van Dijk.

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Identifying the Gaps between Research and Real-World Needs in Structural Inspection using Digital Tools

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Keywords: Inspections and Maintenance, Lifecycle Monitoring, Asset Management, Infrastructure.

Abstract

Europe faces significant challenges in maintaining its aging infrastructure due to extreme weather events, fluctuating groundwater levels, and rising sustainability demands. Ensuring the safety and longevity of infrastructure is a critical priority, especially for public organizations responsible for asset management. Digital technologies have the potential to facilitate the scaling and automation of infrastructure maintenance while enabling the development of a data-driven standardized inspection methodology. This extended abstract is the first phase of a study that examines current structural inspection methods and lifecycle monitoring activities of the Dutch public and private entities. The preliminary findings presented here indicate a preference for data-driven approaches, though challenges in data collection, processing, personnel resources and analysis remain. The future work will experiment integrating advanced tools, such as artificial intelligence supported visual inspection, on the existing inspection datasets of these authorities for quantifying their readiness levels to the fully automated digital inspections.

Introduction

A substantial portion of Europe's infrastructure is potentially in a critical condition, as many assets were constructed during the mid-20th century. The research by Del Grosso et al., (2002 shows that the majority of the infrastructure in developed world was built in the decades following the WWII, while Jonkman et al. (2018) presents a very similar picture specifically for the Netherlands. Ordinary engineering structures are typically designed for a 50-year service life, while some critical infrastructure is designed for a 100 year life expectancy. Given these design lifespans, much of the infrastructure of Europe is now approaching or exceeding its intended use. Consequently, there is a pressing need for a comprehensive evaluation to identify structures in critical condition and determine the appropriate measures for renovation or replacement.

The problem at hand has reached critical safety limits, as recent examples of structural collapse have been observed in Europe, such as the Morandi Bridge in Genova, Italy, which collapsed in 2018, and even more recently, the Carola Bridge in Dresden, Germany, which collapsed in 2024. Despite the infrastructure becoming older, the traffic loads are increasing on this infrastructure. Hanley et al. (2016) and Del Grosso et al. (2022) indicat an increase of 4-5% annually in the coming years.

On top of the increasing human activities on this aging infrastructure, that climate change is increasing the frequency of extreme droughts and heavy rainfall. Droughts lead to soil subsidence, causing cracks and settling in infrastructure (Corti et al., 2009). Heavy rainfall saturates soil rapidly, resulting in runoff, flooding, and erosion, which can trigger mudslides or landslides (Vardon, 2014). These events damage infrastructure by eroding surfaces, washing away roads, and weakening foundations.

It is now widely recognized that existing infrastructure can no longer be maintained safely and efficiently using traditional methods, especially in the face of increasingly limited financial and human resources. The adoption of digital technologies is no longer optional but essential, a reality acknowledged across all sectors. However, a critical question remains: are institutions truly prepared for this digital transition, and to what extent? To explore this, a preliminary study was conducted involving visits to various Dutch institutions and participation in on-site structural inspections to gain firsthand insights. This study presents the results of this series of inspections.

Current Inspection Processes and Challenges

The work presented here focuses on current methods of structural inspection and lifecycle monitoring, with particular emphasis on assessing the extent to which Dutch institutions effectively utilize digital technologies in these processes. As part of this study, several inspections were carried out in collaboration with various Dutch public and private entities, including Water Authority Noorderzijlvest, Rijkswaterstaat (the Dutch Ministry of Infrastructure and Water Management), Province of Groningen, and Fugro. These organizations are actively engaged in conducting inspections and asset management activities for infrastructure assets such as dikes, storm surge barriers, roads, bridges, and viaducts. Images from these inspections, taken by the authors, are presented in Figure 1.

Public entities are responsible for a significant portion of infrastructure in the Netherlands. During inspections the authors have participated, it became clear that most stakeholders prefer a data-driven approach to inspection and management for obvious reasons. Stakeholders emphasized that assets such as roads and dikes, along with their pavements and coverings, face increasing risks due to subsidence, soil settlement, and heavier traffic loads, all of which have worsened the last years. Additionally, these assets cover vast inspection areas, such as kilometres of dikes, requiring optimization due to financial and personnel constraints. This also applies to high bridges or difficult-to-reach locations, such as underwater areas, where technologies like drones can aid in performing inspections.

Current climate policies mandate the use of innovative materials, such as bio-based or recycled materials, for both new pavements and repairs. One of the findings of this preliminary research, however, is that, experimentation with new pavement types (e.g., warm asphalt, recycled asphalt) is necessary by climate policies, but their lifespan remains uncertain, necessitating extensive field testing, which increases costs. Despite their potential merit in more sustainable construction, such experimental methods increase the workload of inspection of these authorities, bringing in several uncertainties into long term maintenance planning.

All institutions the authors joined in inspections use one or multiple sorts of digital tools. These tools include custom platforms, GIS-based tools, drones or simple image storage and processing tools devised specifically for the purposes of the inspection. One common problem manifested by these visits is the handling of the data. The handling refers not only to storage, but also to efficient processing of these data. Some examples are,

- comparison of multiple images taken from the same (or almost the same) location at different times,
- clustering similar pictures, similarity laying either on the type of the problem or type of the structure (i.e. bring all photos of corrosion in the last period, filter all cracks photos observed on dikes in the last number of years, etc.)

Figure 3. Performing an inspection of a dike, including pavements and coverings; photos taken by R. Veenstra, March 2025 – walk-through inspection of dike and coverings (a, b and c), drive-by inspection of the asphalt (d), use of drone (e) and GIS tools (f) for more efficient data collection.

The steps within a data-driven approach typically include stages such as data collection, processing, and analysis, among others. Public entities often contract private firms for inspections, primarily relying on technologies like drones and LiDAR for data collection. However, technological advancements vary across firms, with some innovating faster than others. While outsourcing data processing and analysis incurs high costs and limits knowledge retention within public organizations, discussions with stakeholders indicate that many still face challenges in these areas. One of the main barriers identified in this research is the uncertainty among institutions regarding which technologies they truly need. The abundance of solutions offered by technology providers does not necessarily align with the actual needs of these institutions. As a result, a significant gap remains between what is available on the market and what is perceived as necessary on the ground.

The fact that institutions 'seemingly' use some sort of digital tool does not necessarily mean that they, and efficiently, involve these tools into their processes and get the planned return of investment of time and money. The research reported here yielded two reasons why this is happening:

- depending on the size and budget of the institution, the digital tools may be managed by a very limited number of rather "curious" personnel, while the majority of the personnel either prefer legacy methods, or stay distanced to these technologies because of lack of knowledge, or simply not believe their efficiency,
- the amount and versatility of the collected data become overwhelming, so the energy is mostly spent on collecting the data while processes for largely or fully automatizing the entire process is largely lacking.

Next Steps and Future Research

One aspect that became clear from the interactions with the institutions, as reported above, is that they collect and possess large databases. Furthermore, and in most cases, these datasets are annotated and labelled up to a certain degree. Following the initial study and based on this finding, the second phase of the research will focus on integrating advanced tools, such as AI, into the data analysis process using the existing databases. These databases often include tabular data, such as the reported structural problems, locations and decision made, a set of data very suitable for machine learning or simple regression algorithms to make projections and predictive maintenance activities. The overwhelming size of such data probably does not allow human experts to easily come up with patterns repeating themselves in such data. Furthermore, a vast database of images is also available in all cases. During the next phase of this research, key parameters like ravelling, cracks, and other factors affecting the infrastructure will be collected and analysed, considering climate impacts and other hazards influencing the built environment. One large link missing in these endeavours will be the labelling of the data, something that will need to be co-organized with the institutions owning the data since they do have the expertise in correct labelling. Labelling is crucial for developing effective tools and making use of the existing databases.

Finally, a methodology will be proposed to create a projection scheme for maintenance and planning, making use of the existing databases, which will form a key component of this approach. This comprehensive methodology aims to provide organizations with a deeper understanding of the lifecycle of their assets, enabling more efficient asset management strategies that reduce costs, minimize labour requirements, and streamline time-consuming processes.

One good example that will be used in the next phase is the detection of cracks on infrastructure. Cracks are often manifestations of structural problems, and their sequential and continuous monitoring is essential. Several studies on crack detection using artificial intelligence have primarily focused on identifying crack formation. To assess the efficiency and effectiveness of these approaches, various Convolutional Neural Network (CNN) techniques, including patch classification, boundary regression, and pixel-level segmentation, were tested (see Dais et al., 2021 for an example). Figure 2 presents a visual representation of the output of an automated AI algorithm used on a traditional inspection photo from a dike, highlighting cracks in a covered dike surface. However, the tool currently struggles to accurately detect cracks in higher-resolution, noisier images, suggesting the need for further refinement. These kinds of tools can be enhanced through additional training with labelled data, an improvement that can benefit from the existing and very large databases the institutions have. Re-training such models on these existing databases will also help customicing such models, for instance, using it more efficiently on cracks on dikes rather than cracks on masonry walls.

Figure 2. Crack detection using an AI algorithm on a traditional dike inspection photo (photo taken by Veenstra, March 2025; the purple overlay, which is the pixel-wise prediction of location of cracks, is generated using a model trained via a CNN-based crack detection model[1]).

In the subsequent phase, the focus will shift to rigorously testing and validating the models developed for structural inspection problems (crack detection concrete spalling, structural deterioration due to vegetation and water intrusion etc.), which involves comparing model outputs with real-world asset management case studies from the participating organizations to assess their accuracy and practical applicability. Through these phased studies, this study seeks for practical implementation of the available technologies to the existing issues, while identifying the gaps and the readiness levels of the institutions for a fully automated structural inspection work stream.

[1] Available on GitHub: https://github.com/DavidHidde/CNN-masonry-crack-tasks

Conclusions

This study highlights the challenges and opportunities in transitioning toward digital infrastructure inspections in the Netherlands. While there is growing interest in data-driven methods, several barriers limit effective implementation.

First findings from inspection participated by the authors in the above-mentioned institutions include:

- Institutions often lack clarity on which technologies they need, leading to a mismatch between market offerings and operational requirements.
- Digital tools are often in use, but sometimes managed by a small group of tech-savvy staff, limiting organization-wide adoption.
- Data collection is extensive, yet processing and analysis remain underdeveloped, reducing the value extracted from inspections.
- Many organizations already possess large, partially annotated datasets that are suitable for AI-based analysis and customization of the existing anomaly detection models, but lack standard labelling practices.

Future work will focus on integrating AI tools, such as crack detection and other anomaly finding algorithms, with existing inspection data to evaluate their performance and help quantify institutional readiness for automated workflows.

Acknowledgements

This is part of the doctoral study conducted by Veenstra, supported and funded by the Hanze University of Applied Sciences, Research Centre Built Environment NoorderRuimte, in collaboration with the University of Groningen. We also extend our gratitude to the public and private entities involved thus far, including Rijkswaterstaat, the Province of Groningen, Fugro, and Water Authority Noorderzijlvest.

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A System Dynamics-based Serious Game for Circular Decision-Making in the Built Environment

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Keywords: Gamification, Circular Economy, Decision-support, Stakeholder Engagement, Digitalisation

Introduction

The Dutch government's 2050 goals envision a fully circular economy, where material cycles are closed, waste is minimised, and materials from deconstructed buildings are reused in new construction (Ministry of Infrastructure and Water Management, 2019). Achieving these goals requires systemic and collaborative approaches to facilitate the circular decision-making and elevate the understanding of stakeholders in the built environment of the current and future challenges. Serious games are seen as means to break down complexity and expose players to realistic decision-making scenarios and respective consequences. As such, this study focuses on a serious game designed to engage stakeholders on the complexities of circular design and construction on material, product, building and city levels. This serious game is called "6C: Compete, Collaborate, and Co-Create Your Circular City," and has participatory and pedagogical nature.

The game simulates material flows from decommissioned buildings to new construction projects in the Dutch residential housing scenarios, incorporating trade-offs and dynamic factors such as material availability, policy changes, and external disruptions. The game integrates circular data-driven facts, interactivity and playability. Previous research has successfully integrated system dynamics into gamification to enhance the realism of serious games (Mostafa et al., 2021). System dynamics is highly relevant for game mechanics that require modelling resource flows, decision impacts, and collaborative or competitive dynamics. At the same time, it is a method that delivers realistic insights into the linear flows (e.g., resource extraction to landfill) and circular flows (e.g., reuse, recycle, refurbish) in the built environment (Zhang et al., 2024). Through the mixture of the methods mentioned the game objectives are:

(1) exploring the complexities of circular design and construction decision-making in a realistic and open environment,

(2) Experiencing the trade-offs between environmental, economic, and functional priorities in a simulated environment, and

(3) Observing the systemic impact of individual and collective design choices on circular goals.

The core scientific challenge we aimed to address is the misconception that reuse alone can meet future construction material demands. While there is a growing emphasis on reusable products, the availability and desirability of reusable products are variable and uncertain in the future (Yang et al., 2022). Likewise, bio-based materials, although promising, face limitations in terms of availability (Metabolic Consulting, 2023). The C6 serious game explores this tension by simulating a future in which neither reusable nor oil-based materials can fully meet construction demand and have varying stock with varying scores. The game creates a semi-realistic scenario that prompts players to reflect on their impact and engage with the broader systemic limitations. The C6 also prompt users to think ahead about future challenges. The added value lies in integrating bio-based and reusable materials within a single gameplay framework and showing their advantages and disadvantages. Current literature often focuses on one or the other. This study bridges this gap, enabling players to explore design situations that involve a scarcity of resources, a limited budget, and adherence to circular and sustainable missions within this round-based game.

Method

The first step involves creating a system dynamics model to define the key components and interactions of the system. This includes creating Causal Loop Diagrams (CLD) to map feedback loops and understand relationships between system elements, identifying relevant stocks and tracking their inflows and outflows, and using feedback mechanisms that influence system behaviour. Once the system components are defined, they are mapped against gamification mechanics (such as rewards) to explore viable gameplay possibilities.
A game narrative is developed based on the system dynamics model (initially using dummy data). This approach allows for the conceptualisation of gameplay mechanics, decision-making processes, and event dynamics in a controlled setting. After refining the scenario, real-world data will be collected to be used for a realistic simulation.
Next, physical prototype of the game was created to test its gamification dynamics, mechanics, and components based on the gamification framework of Werbach and Hunter (2012). The game was first prototyped using a Miro board, followed by paper-based testing with an overall 10 groups to refine the game mechanics before developing the digital version. The final version of the web-based game will undergo a second round of playtesting. Feedback on user experience, gameplay mechanics, and impact will be collected to ensure the serious game achieves its objectives.

Results

This serious game is a work in progress. A first draft of the causal loop diagram for the circular construction-city design is presented in Figure 1. It is created using the Vensim PLE software. This model illustrates the dynamic, interconnected relationships and flows between key system components in the building stock, including new construction, deconstruction, and the reuse and recycling of materials. However, one limitation is that the complexity of the circular construction cannot be fully captured.
The model incorporates several essential flows, stocks and events. Conventional, bio-based and reusable material stocks evolve dynamically in terms of quantity and diversity, modelled by categorising materials into time-bound batches. The simulation introduces players to the

challenges of sourcing materials for circular construction projects under dynamic constraints. This hybrid modelling is novel and intended to encourage critical reflection and dialogue amongst players.

Players assume role of a Designer since this is a role-playing type of game. After selecting an avatar, players choose between project types: (1) A two-story house, (2) A six-story apartment building, (3) A renovation project. Based on their choice, players are presented with a building plan and tasked with sourcing circular materials and products from the local Circular Material Bank. However, the material bank's stock, despite increasing deconstruction projects, is insufficient to meet the entire project's requirements, forcing players to incorporate new materials – as is the case in reality. Players must search the circular material bank's catalogue to find suitable reusable elements (e.g., reusable window) and evaluate their options based on a range of considerations, including costs as well as circularity and sustainability metrics.

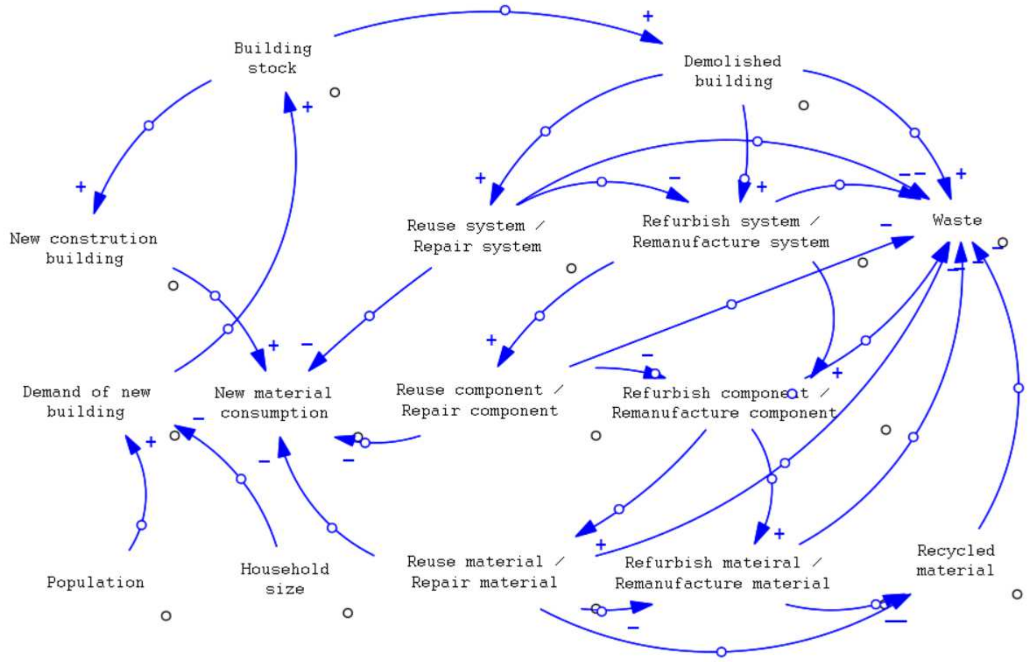

Figure 1. Schema of the draft of stock and flow diagram

Each component is associated with multiple footprints: cost, carbon footprint and circularity score. Higher carbon footprint indicates less sustainable option, while higher circularity score indicates better circular option. Once players select their building components, they finalise their designs and evaluate their layout's performance against these metrics. The goal is to demonstrate the complexity and interconnectedness of environmental, economic, and structural metrics and the trade-offs. For example, a material may have a higher carbon footprint but significantly lower circularity.

The game progresses through a five-year simulation cycle (start year: 2030), with players tasked to design another project for 2035 and subsequent periods. Each time-lapse reflects policy and climate changes that results in the change in stocks and their unique scores. The simulation is impacted by events, which influence the ecological scores and stakeholders' decisions (Emre Kaya & Monsù Scolaro, 2024). Therefore, the game incorporates event cards at the start of a round. Example events include, e.g., Policy Changes: governmental push for bio-based materials shift demand away from reusable materials.

The first phase of the game is more competitive but later uses also a collaboration gamification mechanism in order to challenge players towards a common final goal and eventual victory. This mixed-social strategy design aims to create a spike in the game flow and adds engagements. At the end, players receive their performance feedback, leaderboard and decision log: (1) Individual Impact: A cumulative score reflecting the avatar's career-long impact, (2) City-Level Impact: A broader evaluation of all their designs in the board game.
A challenge in this serious game was to balance the level of difficulty for players, while keeping the scenario realistic. The complexity of the system, with its many variables can be challenging for participants without a technical background. while designers may find the game intuitive, non-design stakeholders can become overwhelmed by the number of things to consider. Nonetheless, this also adds value, as it mirrors real-world constraints and market dynamics. For example, if the first player selects most of the reusable stock, the last player may face scarcity and is left with less sustainable or circular options.

Conclusion

The "6C: Compete, Collaborate, and Co-Create Your Circular City" serious game demonstrates a novel approach to engaging stakeholders in circular decision-making for the built environment. Through role-based gameplay and iterative decision-making processes, players gain a deeper understanding of the interconnected factors. This serious game provides a starting point for multi-stakeholder engagement in circular construction, offering a systems-based participation environment that combines realism with reflection.
By integrating system dynamics modelling with gamification, it simulates material flows, trade-offs, and systemic impacts in a dynamic, interactive urban built environment. However, this study acknowledges its limitations due to relying on a system's dynamics which is not entirely representative of all the stages in the life cycle of a built assets and cities. Future iterations of the 6C serious game can benefit from the integration of more granular real-world data and more a more complex and multi-dimensional system dynamic model.

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Universal Test Trench (UTT): A System for Sharing Test Trench Data

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Keywords: Trial trenches, Utility Mapping, Data Modeling, Federated Data Storage,

Extended abstract

Modern infrastructure development is contributing significantly to increased excavation activities, especially with nationwide rollouts of fibre-optic networks and the transition to renewable energy systems(Sahebali et al., 2021). In the Netherlands alone, roughly two million kilometres of cables and pipelines lie beneath the surface, and excavation-related damages are projected to exceed 40,000 incidents per year. Such damages lead to significant delays in construction projects, exposure to safety hazards and economic losses(Al-Bayati & Panzer, 2019). These challenges are due to uncertain and inaccurate information about underground utilities.

There have been efforts to enhance pre-excavation activities including; the implementation of guidelines such as CROW500 and Underground Network Information Exchange Act (WIBON), which regulate the excavation process, the Information Model for Cables and Pipelines (IMKL) that standardises vector-based data exchange among network owners, designers and groundworkers and the KLIC system that further supports this by providing 2D maps of underground networks to anyone that submits an excavation or orientation request. While such systems provide baseline information, they often fall short of accuracy needs, especially for older installations.

In practice, contractors commonly dig test trenches (also known as trial trenches or *’proefsleuven’* in Dutch) at select locations to physically locate and inspect underground assets(Racz, 2017). These test trenches validate the presence, position, condition, and attribute data of utilities before major excavation is done. However, current practice around test trenching is ad hoc and not standardised. Decisions on where and how many test trenches to excavate are often implicit and rely on individual experience rather than formalised criteria(Racz, 2017).

Further to this, the valuable data obtained during digging —precise utility depths, orientations and actual locations —typically remain confined to the project and are not systematically recorded for reuse in future works. Current frameworks offer no provision to systematically integrate the *results* of such on-site investigations back into a shared knowledge base. This absence of standardized

data capture, systemic storage or centralized dissemination post-project forces each project to "rediscover" the subsurface anew, resulting in redundant excavations, unnecessary societal disruptions, escalated costs and heightened risks of excavation damage. The issue is compounded by the fragmented and heterogeneous nature of current data storage practices among network operators and contractors(Yan et al., n.d..).

Test trench verification outputs vary widely, ranging from simple text reports with photographs to portable document formats (PDFs), 2D schematics, and increasingly, large datasets from 3D trench scans and ground-penetrating radar(Verhagen & Borsboom, 2009). This lack of uniformity hinders data interoperability and necessitates a comprehensive approach to harmonize data collection, storage and exchange.

Considering the value of this supplementary data, there is a clear need for a systematic, standardized, and shared approach to manage trial trench data as part of underground utility mapping and excavation risk management. (Open Geospatial Consortium, 2017) suggests that integrating multi-source utility data using common schemas can yield a "single source of truth" and greatly enhance decision-making. This need is further evidenced in feasibility studies conducted by Centrum Ondergronds Bouwen (COB, 2023, 2024) which determined that a trial trench database would make projects *"better uitvoerbaar, inzichtelijk and beheersbaar"* (more feasible, transparent, and manageable), particularly in the early phases of project development. (COB, 2024) further established that the value profile of a trial trench database aligns more closely with the objectives of *Basisregistratie Ondergrond* (BRO), whose aim is to support major societal challenges by making reliable subsurface data available, findable, and usable. While the legislative feasibility has been established, the technical implementation of such a system remains unexplored.

Building on this premise, the objective of this research is to create a systematic, standard and shared approach to managing trial trench data. This research recognizes the potential for reusing trial trench data through a Universal Test Trench (UTT) database. The core purpose of the UTT system is to enable utility owners, contractors, engineers and regulators to exchange and query field-verified trial trench information on a common platform. This research addresses how such a UTT environment should be designed, data modeling approaches, storage architectures, and integration mechanisms that would enable the effective sharing of field-verified utility information.

Research Questions & Scope

1. What are the minimum data requirements for effectively sharing trial trench information across stakeholders?
2. How can a federated data architecture be implemented to maintain data ownership while enabling unified access to trial trench data?
3. What query mechanisms and interfaces are needed to make trial trench data accessible to different user groups?

While a comprehensive system would include a complete ontology mapping, database implementation, and visualization interface, this research will prioritize on:

1. Developing a data model focused on essential trial trench attributes
2. Implementing a proof-of-concept federated query system
3. Creating a basic interface for data submission and retrieval

Conceptual Framework

The theoretical foundation for this work draws on two key technical principles:

a) **Ontology-Based Data Modeling**

In utility data modelling, (Fossatti, n.d.) describes domain ontology as a formal representation of the key concepts, relationships and rules within the utility domain that is designed to facilitate interoperability between different datasets. The first step toward this data organisation is to develop a detailed information model for test trench data. This involves defining classes and relationships that represent all relevant entities and their attributes (Wang, 2021) based on IMKL standards. This approach will ensure that the data has a well-defined meaning and can be linked with existing knowledge frameworks. Using semantic web technologies, OWL or RDF, the data model will enforce consistency rules and enable inference.

Building upon this ontological foundation, the UTT system will implement a two-tiered standardization approach to apply these semantic principles across diverse trial trench verification outputs. The primary tier will establish mandatory minimum data elements derived from core ontological concepts such as utility type, geographic coordinates, depth, material, orientation, verification date, and condition assessment. These elements will be standardized across all data submissions, regardless of their original source or format, to ensure critical information remains uniformly accessible and queryable within the semantic framework.

The secondary tier will expand the ontology through metadata schemas that accommodate richer, more complex datasets without requiring strict format conformity. For semi-structured content (PDFs, inspection reports), the system will extract key information and map it to the standardized model while maintaining links to source documents. For more complex data types (3D scans, GPR outputs), standardized metadata is stored alongside transformation parameters that enable cross-format interoperability. This approach aims to balance the preservation of data richness with sufficient standardization to facilitate integration, unified querying, and visualization, thus creating a coherent knowledge base that transcends individual data format limitations while retaining their distinct informational value(Wang, 2021).

b) Federated Data Storage Architecture

In parallel with ontology development, a system architecture for the Universal Test Trench (UTT) database will be designed using a federated data model. This model will allow independent data sources to remain autonomous while being accessible through a unified query interface(Ganzinger et al., 2023). Unlike centralized databases that store copies of all data, the UTT system will query distributed sources, ensuring that excavation teams access the most up-to-date, verified trench data directly from authoritative sources.

The federated model will be implemented based on the principles of wrapper architecture. (Nadal et al., 2017)defines wrapper architecture as a design pattern within a federated database system used for data integration, where specialized software components called wrappers are employed to homogenize data from diverse, autonomous, and potentially heterogeneous data sources. These wrappers act as an intermediary layer, abstracting the specific structures, formats, and access methods of each underlying data source. This allows a mediator component to interact with each source through a uniform query interface provided by the wrappers, enabling the system to process global queries by decomposing them into subqueries executable by the wrappers and subsequently composing the integrated results for the user, providing the illusion of a single database. For the UTT database, the Query Engine (mediator) will receive user queries, determine the relevant data sources, and distribute subqueries to the appropriate local trench databases. Each data owner, contractor, municipality, or utility company will retain full control over their dataset, with access granted only to authorized portions of their records based on defined permissions. Wrappers (data connectors) will be used to standardize responses from these diverse sources, ensuring seamless interoperability across geospatial data (GIS maps), sensor data (GPR scans), engineering models (CAD/BIM), and excavation reports (PDFs, textual logs).

To securely manage stakeholder data in the federated architecture, the governance model for the UTT system will implement a multi-tiered access control framework that respects the autonomy of data providers while enabling effective data sharing (Nadal et al., 2017). Each stakeholder will maintain sovereign control over their data assets through a delegated administration model. Data owners will define sharing policies at multiple levels: (1) public data accessible to all system users, (2) restricted data available to specific stakeholder groups, and (3) confidential data requiring explicit authorization. The system will support both attribute-based access control for fine-grained permissions and role-based access for organizational hierarchies. For cross-organizational data sharing, the UTT will implement a federated identity management system that allows stakeholders to authenticate users through their existing identity providers while maintaining a unified permissions framework. This approach ensures that sensitive infrastructure data remains protected while maximizing the value of shared information for legitimate excavation planning and safety purposes (Nadal et al., 2017).

Rather than establishing complex relationships between multiple mediators, the aggregation process will be handled directly by the UTT Query Engine, which harmonizes retrieved trench data into a coherent, standardized format before delivering the final results to the user. This eliminates redundant data storage, reduces inconsistencies, and facilitates the reuse of existing data.

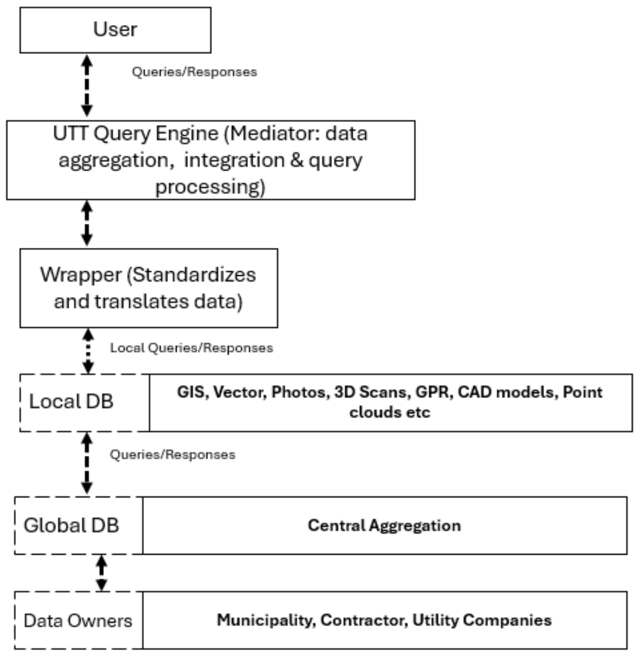

Figure 1. Proposed Data Federation Model

Implementation Methodology

To translate the conceptual principles into a practical UTT design, the following steps will be taken to develop and validate the UTT proof-of-concept (PoC) database system:

1. **Data Modeling:** Using the ontology as a blueprint, a unified data schema will be developed for the PoC database. (Ji, 2020) explains how this involves mapping each data source (each utility's dataset) to common ontology classes and properties. The result will be a coherent data model that can represent multi-utility information. This data modeling step will ensure that all federated sources conform to a shared structure, which will be essential for integrated querying and interoperability.

2. **Prototype Development and API Integration:** To validate the proposed UTT framework, a functional type of the UTT system will be developed and tested to demonstrate the end-to-end workflow of collecting, sharing and using trial trench data. This includes implementing the database and a set of web services for data input and retrieval. Key functionalities to implement and test this prototype include data ingestion tools to import heterogeneous trench logs, sensor data, etc., into the model, query and retrieval and visualization interfaces. A web-based front-end will be created to allow users to visualize the stored trench data and inspect it.

Throughout the implementation, stakeholder engagement will be conducted continuously through workshops and feedback sessions with representatives from utility companies and contractor firms at each major phase of development. In these workshops, the evolving data model and prototypes of the interface will be presented to validate that the data planned for inclusion and its presentation will meet real-world requirements. This participatory design approach will ensure the system's functionality is aligned with user needs and industry practices.

The PoC will be evaluated through usability testing involving actual end-users from stakeholder groups. The evaluation will adopt standard usability and performance metrics to provide an objective assessment of the system's effectiveness. In particular, these metrics will be measured:

1. Accuracy of results: The system will be tested to determine if it returns correct and complete information. Query outputs will be checked against known ground-truth data or scenarios provided by utility companies. This metric will correspond to the effectiveness of the system in fulfilling user goals.
2. Response Time: The speed at which queries are resolved in the federated setup will be measured. The time taken to execute various typical queries will be logged and any bottlenecks will be identified.
3. User Experience: Users' ratings of the ease of use and usefulness of the system will be collected. After hands-on testing, participants will complete a short survey or usability questionnaire using a Likert-scale rating on ease of navigation, clarity of information, and overall satisfaction. Attention from this qualitative feedback will be paid to comments on the interface design, the query process, and any difficulties encountered. High user satisfaction and positive feedback will indicate that the system is intuitive and meets their needs, whereas any recurrent issues will guide further refinement.

The results of this usability testing will be analyzed to identify areas of improvement and to verify that the theoretical benefits of the ontology-driven federated design are realized in practice. It will be expected that the PoC will demonstrate high accuracy and acceptable performance, given the relatively controlled scope of data, and that users will appreciate the integrated access to multi-utility information through one system. In summary, this methodology will provide a clear roadmap for the research by delineating the conceptual foundations from the implementation steps. The multi-utility federated model (Figure 1) will first be conceptualized using theory, and then realized through concrete development steps, all while being refined via stakeholder feedback and evaluated against real-world usability criteria. This will ensure that the UTT system development is systematic, transparent, and well-aligned with both academic foundations and practical user expectations.

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Establishing an Experience Centre at The Hague University of Applied Sciences

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Keywords: Experience Centre, Immersive Technologies, Interactive Research, Digitalisation, Sustainability, Just Society, Virtual/Augmented Reality

Extended abstract

The Hague University of Applied Sciences (THUAS) is working on the establishment of an Experience Center (EC). The aim of this space is to establish a dynamic space that allows for the interactive and immersive visualisation and demonstration of research at THUAS, assist in the translation to our applied form of education, and to invite cocreation with THUAS employees, students and external partners. The research agenda themes of THUAS will become visible in this space: a just society, the digital future and sustainable transition. Organizational changes according to these goals will become tangible in this space. Through prototyping, mockups, and simulations, students, staff, and external partners explore how transformations impact different stakeholders.

Vision & Mission

Vision

The Hague University of Applied Sciences aims to create an innovative and interdisciplinary environment where education, research, and practice come together. The Experience Center will be a dynamic space where students, lecturers, and researchers collaborate on complex societal and technological challenges using digital transformation, prototyping, and simulation. This space will allow visitors to truly experience the university's research in an interactive and immersive way.

Mission

The Experience Center supports research and co-creation between education, research, and industry. Its goal is to prepare students and professionals for the future by allowing them to experience and apply innovative methods and technologies. The centre contributes to the societal transitions outlined in the university's research agenda: digitalization, sustainability, and a just society.

Objectives

- Successfully transition the Innovation Playground into the Experience Center.
- Strengthen the connection between education and research by creating an inspiring, accessible, and interactive space.
- Support students, lecturers, and researchers in digital transformation and innovation projects.
- Contribute to major societal challenges, such as climate resilience, the energy transition, the circular economy, and the digital future.
- Increase the visibility and impact of research and innovation within and beyond the university.

Why an Experience Center?

The Hague University of Applied Sciences is committed to impact-driven, research-based learning. The EC plays a key role in this by offering a multidisciplinary, hands-on approach to solving real-world challenges such as the circular economy and digital transformation. The centre strengthens collaboration between education, research, and industry, while also offering professionals a space to develop digital skills for the future.

Development Timeline

From April 1, 2024, the current Innovation Playground (IP) is gradually evolving into the EC. Existing initiatives will be supported as long as they align with ongoing projects, and the projects on display will be constantly updated. As a pilot, a soft launch was organized on

October 16, 2024. Since January 2025, the first showcases have been in place, setting the stage for new projects. Th official internal launch will occur on April 22, 2025.

Projects currently in preparation or already on display

1. Paris Proof Campus 2030 & Net Zero Emissions 2040

This interactive exhibition will explore how digitalization can contribute to a sustainable, climate-resilient campus. Visitors will experience tools like 3D Building Information Modeling (BIM), Geographic Information Systems (GIS), VR/AR, and real-time sensor data. The project aligns with the The Hague Climate Agreement, with the research center Mission Zero playing a leading role. This project will include a physical and AR model of our university building visualization the various projects that will occur in order to achieve these goals

2. Expo Open over Open

The research groups Future Urban Systems and Civic Technology have been collaborating with the municipality of The Hague departments Open Governance Act (WOO) and Datalab to contribute to the exposition *Open about Governance.* The expo was available in the atrium of the city hall The Hague for the entirety of February and due to great success it has been extended and moved to the Experience Centre of THUAS for the month of March. The research explores how immersive technologies, such as Augmented Reality (AR) and Virtual Reality (VR), can enhance citizen participation in urban development, focusing on the redevelopment of The Hague's Central Innovation District. The Municipality of The Hague aims to improve transparency and citizen engagement by utilizing open data and innovative digital tools. A pilot project developed an AR Tabletop game where citizens could interact with a digital model of the city, shaping public spaces and observing the effects of their decisions. The project sought to answer key questions about the effectiveness of immersive techniques for communication and participation, both in physical and online settings. The results revealed that while immersive experiences were engaging, improvements in usability and audience engagement were necessary, with children engaging more easily than adults. The project aims to refine these methods to encourage broader citizen involvement in urban planning.

3. Smart Industry & Data-Driven Innovation

The EC will showcase how smart sensors and data analytics are revolutionizing industries, from greenhouse horticulture and climate control to manufacturing. Researchers from Smart Sensor Systems will demonstrate real-time dashboards and advanced sensors, such as a capacitive sensor for air quality.

4. The Waterworks of Money

The Waterworks of Money is a project by cartographer Carlijn Kingma, investigative journalist Thomas Bollen, and finance professor Martijn van der Linden that examines the creation, allocation, and inefficiency of the global financial system. The project compares money to water in an irrigation system, flowing to fuel the economy but leaving many areas underserved while a small elite controls most wealth. Over 14 months, the team studied hundreds of sources, interviewed over 100 experts, and collaborated on creating a detailed map to visualize the money system. The map and accompanying videos explore the future of finance through scenarios developed with global experts. The project has been exhibited at major institutions like the Rijksmuseum Twente and the Venice Biennale, as well as at financial and cultural festivals.

5. AI Expert Team

The AI Expert Team at The Hague University of Applied Sciences is focused on the responsible and effective integration of AI and Data Science into research and educational projects. They provide services across all departments, not limited to specific faculties or expertise centers. Their offerings include up to 16 hours of free consultation to explore AI and Data Science opportunities, assisting with project proposals, grant applications, and the analysis of existing research data. They also provide expertise to support projects by taking on technical responsibilities, advising on AI applications, and helping with the writing of scientific publications or grant applications. Additionally, the team can become embedded in a research group to contribute to long-term projects with clear goals, developing AI-driven systems, co-writing grant proposals, and advising on research directions. Their goal is to broadly strengthen projects within the organization, ensuring AI and Data Science are effectively integrated and addressing questions that other departments cannot resolve sustainably.

6. Serious Gaming Corner

This space will be dedicated to displaying various (serious) gaming applications developed by THUAS.

The Future of the Experience Center

The EC will continue to grow in step with the university's climate and digitalization strategy. As part of The Experience Center (EC) at The Hague University of Applied Sciences represents a bold step toward bridging the gap between education, research, and industry. By creating an interdisciplinary, innovative environment, the EC will empower students, lecturers, and researchers to tackle some of the most pressing societal and technological challenges of our time. Its focus on digital transformation, sustainability, and societal equity aligns with both the university's research agenda and the broader goals of preparing the next generation for an increasingly complex future.

Through its dynamic, hands-on approach, the EC will foster collaboration, co-creation, and experimentation, enabling students and professionals to experience cutting-edge technologies and methodologies in real-time. The center's role in driving societal transitions—such as the climate resilience, energy transition, and circular economy—further solidifies its importance as a cornerstone for innovation.

As the EC evolves from the Innovation Playground, it promises to serve as a catalyst for research visibility, interdisciplinary synergy, and impactful solutions to global challenges. By supporting digital innovation, education, and industry, the Experience Center will undoubtedly shape the future of higher education and contribute to a more sustainable and just society.

Key Stakeholders

- Centres of Expertise: Cyber Security, Digital Operations & Finance, Global and Inclusive Learning, Mission Zero, Governance of Urban Transitions, and Health Innovation.
- Our Faculties, currently mostly TIS & ITD
- Services FZ&IT & OK&C
- External partners, including but not limited to: The Municipality of The Hague, the Province of South Holland, and XR developer Dutch VR

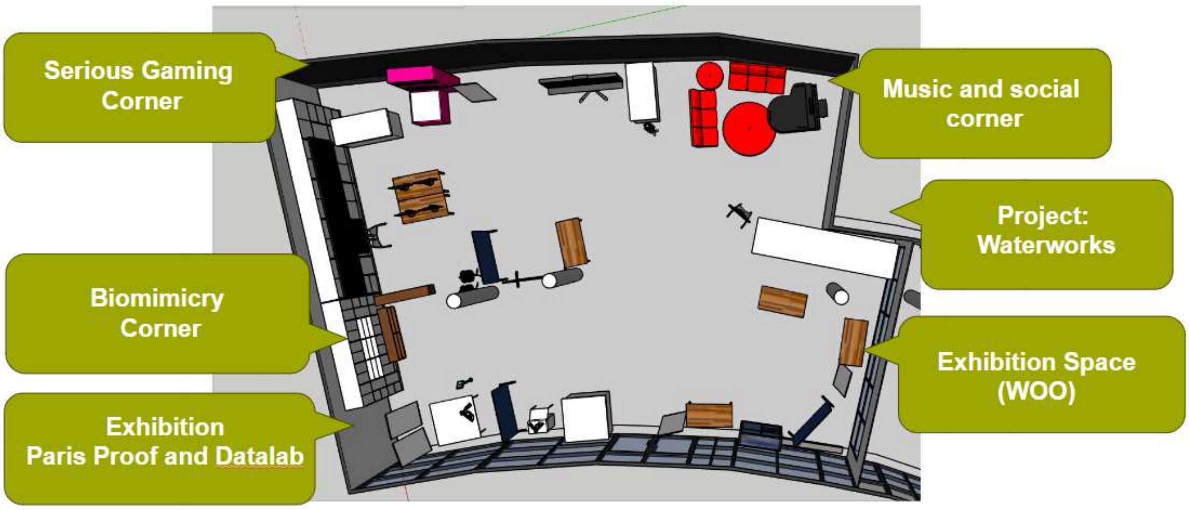

Figure 1. Floor plan of the Experience Centre in the THUAS Innovation Playground

Figure 2. The expo *Open about Governance*

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Session 1b

From P&ID to DBN: Automated HVAC FDD modelling framework using large language models

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Keywords: Fault Detection and Diagnosis, Diagnostic Bayesian Network, Large Language Model, Piping and Instrumentation Diagrams, HVAC.

Extended abstract

Buildings account for approximately 40% of energy consumption in the European Union and over one-third of energy-related greenhouse gas emissions, with a significant portion attributed to heating, ventilation, and air conditioning (HVAC) systems. Effective fault detection and diagnosis (FDD) are essential for reducing energy waste and lowering maintenance costs in HVAC operations. FDD methods for HVAC systems have been extensively studied and can be broadly classified into two categories: knowledge-based and data-driven approaches. Knowledge-based approaches heavily rely on predefined rules and domain expertise and remain the most widely used in existing HVAC systems. Over the past decade, data-driven FDD approaches have gained popularity. However, data-driven FDD approaches require high-quality labelled fault datasets for model training, which can be time-consuming and costly to obtain. To address this challenge, various studies have explored the use of generative adversarial networks (GANs) and other data augmentation techniques to synthesize realistic fault data and improve model performance. Despite these advancements, challenges related to generalization, scalability, and the interpretability of black-box models remain key concerns in the adoption of data-driven FDD approaches.

Diagnostic Bayesian networks (DBNs), as probabilistic graphical models, present a promising solution for HVAC FDD, providing several advantages such as robustness to uncertainties, modelling flexibility, scalability, and interpretability (Lu *et al.*, 2024). DBNs have been successfully applied to FDD for individual HVAC components as well as aggregated systems and whole building systems (Wang *et al.*, 2024a, 2024b; Mosteiro-Romero *et al.*, 2024). More systematically, Taal *et al.* (2018, 2020a, 2020b, 2020c) proposed the four symptoms and three faults (4S3F) reference architecture, which establishes a structured approach to HVAC FDD by linking system design in piping and instrumentation diagrams (P&IDs) with DBN modelling. However, constructing DBNs for HVAC systems involves several challenges in practice. One of the primary difficulties is that the current DBN development process is either a tedious and time-consuming manual task or heavily dependent on training data, much like data-driven approaches, which poses significant barriers to the widespread adoption of DBNs in HVAC FDD applications.

Recent advancements in large language models (LLMs) present new opportunities to overcome these barriers in DBN modelling for HVAC FDD. On the one hand, LLMs, pre-trained on large-scale real-world data, exhibit a strong ability to understand and apply domain knowledge, including key concepts in HVAC systems and FDD (Lu *et al*, 2024). On the other hand, LLMs have demonstrated powerful code generation, auto-correction, and reasoning capabilities (Zhang *et al.*, 2024). By leveraging these strengths, LLMs have the potential to streamline the traditionally labor-intensive DBN modelling process into automated construction, making FDD solutions more accessible for real-world HVAC applications.

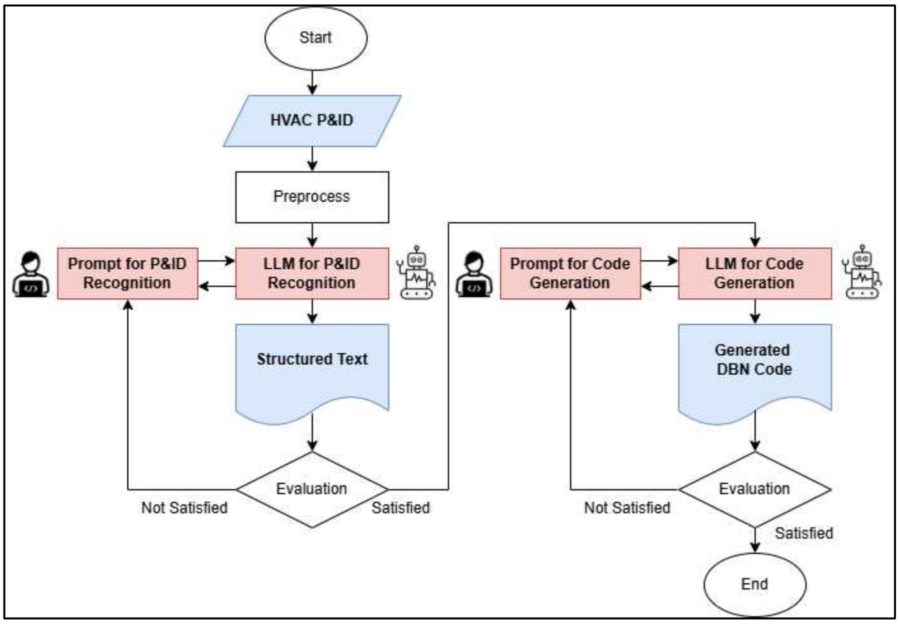

Figure 1. Automated DBN modelling framework for HVAC FDD

We propose a novel automated DBN modelling framework for HVAC FDD that utilizes LLMs to construct DBN from P&ID, shown as Figure 1. The proposed framework consists of two key stages, P&ID digitalization and DBN code generation.

- **Stage 1: LLM-based P&ID Digitalization**

  Many P&IDs exist as static PDFs or images, making automated processing challenging. Traditional P&ID digitalization involves multiple steps, including symbol detection, text extraction, line tracing, and graph reconstruction, which requires extensive training for different P&ID standards and extensive rule-based programming. Our framework utilizes multimodal LLMs (e.g., GPT-4V, Gemini, LLaVA) to simultaneously analyse both textual and visual information, transforming P&IDs into machine-readable formats (structured text) like JSON, IFC, or xgXML.

  Prompt engineering in this stage focuses on selecting the appropriate approach—zero-shot, one-shot, or few-shot prompting—based on the complexity and variability of the P&ID diagrams and the capabilities of the specific LLM employed. To evaluate the effectiveness of LLM-based P&ID digitalization, the assessment focuses on two key aspects: symbol and text recognition accuracy and completeness of the structured output. The first aspect ensures that component labels and system annotations are correctly extracted, minimizing errors in textual interpretation. The second aspect verifies the structural accuracy of the machine-readable output (e.g., JSON, IFC, xgXML), ensuring that all components, connections, and dependencies are accurately identified and properly represented.

- **Stage 2: LLM-based DBN Code Generation**
  Once the P&ID is transformed into structured text, LLMs, guided by carefully designed prompts, infer potential faults and related symptoms, and subsequently generate the corresponding DBN code. This step demands LLMs with strong inference capabilities to accurately interpret system behaviour, and proficient code generation abilities to translate the inferred information into executable DBN code, such as GPT-4o, Claude-sonnet.

  Prompt engineering for this stage focuses on the granularity and scope of the information provided to the LLMs. Key considerations include: 1) only providing the structured text captured from P&ID; 2) incorporating with additional information on the HVAC system's control strategies; 3) adding relevant FDD context, such as the 4S3F reference architecture and the generic modelling procedure for DBNs. Moreover, to further optimize performance, different prompt strategies will be explored, such as Chain of Thought (CoT) prompting. CoT prompting encourages the LLM to break down complex reasoning into smaller, more manageable steps.

  To evaluate the effectiveness of DBN code generalization, the assessment focuses on two key aspects: code examination and FDD performance evaluation. Code Examination ensures the generated DBN adheres to structural and semantic correctness. This includes verifying structural compliance (e.g., proper node definitions, dependency structures) and fault-symptom relationship accuracy, ensuring the inferred dependencies align with known HVAC fault mechanisms. FDD Performance Evaluation assesses the DBN's effectiveness in real-world fault diagnosis. The generated model is tested using fault case data, evaluating its diagnostic accuracy, robustness, and generalization.

The proposed framework aims to streamline the traditionally complex, time-intensive, and labor-intensive process of constructing DBNs, making it more intelligent and efficient. By leveraging LLMs for automated P&ID digitalization and DBN code generation, the framework accelerates model development while reducing manual effort and potential errors. This advancement supports the transformation of the building services industry toward smarter and more efficient operations, ultimately enhancing building performance and enabling seamless integration into large-scale energy systems.

Acknowledgements

This study is a part of the Brains4Buildings project, sponsored by the Dutch grant program for Mission-Driven Research, Development, and Innovation (MOOI). The authors appreciate Kropman for technical support.

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Geometric Compliance Checking of Heterogeneous Building Information

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Keywords: Geometric Engine, Linked Building Data, IfcOpenShell, Semantic Web Technologies, Automated Compliance Checking, SHACL

Extended abstract

The acquisition of a building permit is the starting point of most construction phases of buildings. Acquiring such a permit is a cumbersome process, that is characterized by manual rule checking and interpretation. Building regulations are often only available in natural language, leaving space for ambiguity, vagueness, and implicitness, while building information typically consists of a scattered collection of heterogeneous data in different file formats and locations, created by different stakeholders in different software packages.

Various researchers worked on digitizing building permit regulations to make them machine understandable. Simultaneously, researchers worked on methods to overcome the heterogeneity of building information, many using semantic web technologies (Pauwels *et al*., 2017). This led to advances in Automated Compliance Checking of building information (Zhang *et al*., 2023). It remains difficult to integrate geometric information into Linked Building Data graphs (Wagner *et al*., 2020). This leads to challenges related to the ACC of complex geometric regulations. Two issues can be observed:

It is difficult for the design team to design buildings that comply with all regulations, and it is difficult to understand how design choices of one stakeholder affect the overall compliance;

It is difficult for the contractor, who needs to find practical solutions to comply with the building regulations, to prepare budgets based on the available building information in the design stage.

This work therefore combines geometric functionalities of IfcOpenShell[1] with the semantic functionalities of LBD graphs to enable complex geometric compliance checking against heterogeneous building information.

This work follows a system architecture as shown in Figure 1. The end goal of this architecture is to generate a *data graph* (with building information in the RDF format) and a *shapes graph* (with digital regulations in the RDF format). A SHACL validator (such as pySHACL) can then be used to validate the *data graph* against the *shapes graph*.

To generate the *data graph*, multiple IFC files of the Tribune building (Strijp-S, Eindhoven, The Netherlands) were created and converted to RDF graphs using the IFCtoLBD converter. This process was enhanced manually, as the IFCtoLBD converter does not convert specific fire safety related concepts to RDF. The resulting RDF graphs do contain topological information

[1] https://pypi.org/project/ifcopenshell/

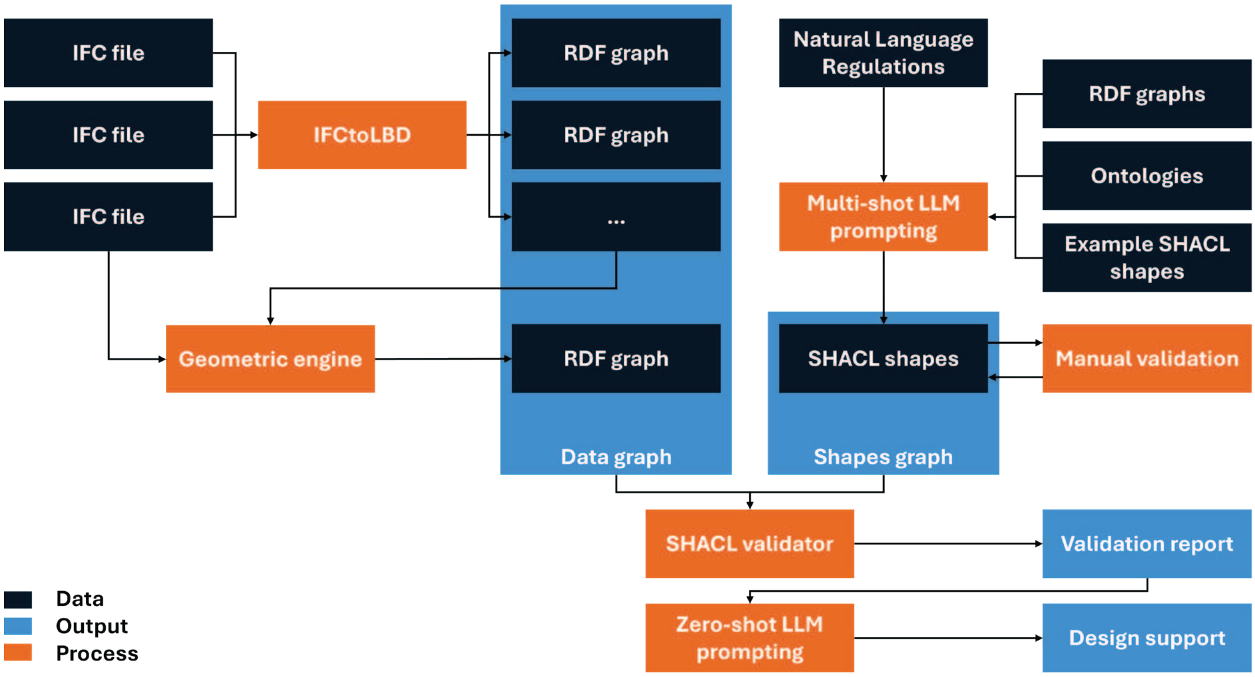

Figure 1. System architecture

following the BOT ontology (Rasmussen *et al.*, 2024) and fire safety related concepts in the FireBIM namespace (Donkers and Petrova, 2025). The graphs themselves do not contain geometrical information, but GUIDs to link nodes in the graphs to elements in the original IFC files exist.

Geometric information is then added to the RDF graph using an intermediate geometric engine, presented in earlier work (Donkers and Petrova, 2025). This engine was built in Python on top of the RDFlib and IfcOpenShell libraries. The engine, a collection of functions in a Python library, has functions to compute various geometric parameters for elements and zones in the RDF graph, based on specific input queries. One could for example query all elements of a specific type and all zones of a specific type, and check whether they intersect. The functions return the computed geometric parameters as RDF graphs. These RDF graphs, combined with the output from the IFCtoLBD converter, collectively form a machine readable, integrated version of the building information, and are collectively referred to as the *data graph*.

Building regulations are digitalized using the SHACL language (Shapes Constraint Language), which is a constraint language in the semantic web stack. Various approaches exist to convert natural language regulations to SHACL shapes. In previous work (Donkers and Petrova, 2024), a Natural Language Processing pipeline was tested to generate those SHACL shapes. In this work, an LLM-based approach is attempted, using GPT4.0. The first approach with zero-shot prompting was unsuccessful. While the LLM was able to produce SHACL shapes in correct syntax, it had difficulties producing a correct conversion of the regulatory text. Therefore, multi-shot prompting was attempted, in which the prompt contained a correct example of a SHACL shape. The LLM was also fed with context, namely the structure of the possible output graphs from the geometric engine, and the BOT and FireBIM ontologies. Although this approach improved the output of the LLM, a manual validation of the SHACL shapes was still performed to ensure that the SHACL shapes correctly represented the natural language regulations. The result is referred to as the *shapes graph*.

The *data graph* can then be validated against the *shapes graph* using pySHACL. pySHACL returns a validation report, that contains the nodes that violate the SHACL shape and a result message, returning the violation in natural language. This validation report is then used in a zero-shot LLM prompt asking for advise to the designer. Finally, to enhance the LLM results, the zero-shot LLM prompt was pretrained with a product book with fire resistant pipe segments to test whether the LLM could find a suitable solution for a pipe segment that did not comply with regulations.
The proposed methodology is tested on a small case study. Three IFC models (structural, fire barriers, and HVAC installations) are converted to RDF graphs using the IFCtoLBD converter. The first rule that is checked validates whether the distance between central junction boxes and sprinkler heads is at least 914 mm. To validate this rule, Listing 1 first queries all central junction boxes and sprinkler heads from the RDF graph. Then, the geometric engine computes the distances between all central junction boxes and sprinkler heads. Listing 2 shows a snippet of the RDF graph that is returned. A SHACL then validates whether there are central junction boxes and sprinkler heads with a distance below 914 mm.

```
SELECT ?centralJunctionBox ?guidCJB ?sprinklerhead ?guidS
WHERE {
    ?centralJunctionBox rdf:type firebim:CentralJunctionBox .
    ?centralJunctionBox bpt:hasGlobalIdIfcRoot ?guidCJB .
    ?sprinklerhead rdf:type firebim:SprinklerHead .
    ?sprinklerhead bpt:hasGlobalIdIfcRoot ?guidS . }
```

Listing 1. SPARQL query returning all instances of central junction boxes and sprinkler heads

```
SDK:CentralJunctionBox_001 a   firebim:CentralJunctionBox ,
    bot:Element ;
    geo:hasDistance                _:N2a51e56dc9af413f9f0d77bcf4b4b496 .
SDK:Sprinklerhead_001 a firebim:SprinklerHead ,
    bot:Element ;
    geo:hasDistance                _:N2a51e56dc9af413f9f0d77bcf4b4b496 .
_:N2a51e56dc9af413f9f0d77bcf4b4b496 geo:hasMetricLength “0.721” .
```

Listing 2. RDF snippet of the distance between a central junction box and a sprinkler head

A second SHACL shape checks that whenever a pipe segment goes through a compartment boundary wall, the pipe segment has a specific fire resistance or additional sealants to improve fire resistance. First, Listing 3 queries the pipe segments that go through compartment boundary walls. The geometric engine generates the intersections between those walls and pipe segments and stores these in RDF format (Listing 4). A SHACL shape can now validate whether the specific pipe segment complies with the regulations.

```
SELECT ?PipeSegment ?guidCJB ?CompartmentBoundary ?guidS
WHERE {
    ?PipeSegment rdf:type firebim:PipeSegment .
    ?PipeSegment bpt:hasGlobalIdIfcRoot ?guidP .
    ?CompartmentBoundary rdf:type bot:Element, beo:Wall .
    ?CompartmentBoundary firbim:hasFireResistance “60”.
    ?CompartmentBoundary bpt:hasGlobalIdIfcRoot ?guidC . }
```

Listing 3. SPARQL query returning all instances of pipe segments that go through compartment boundary walls

```
SDK:Wall_001          a bot:Element ,
    beo:Wall ;
    firebim:hasFireResistance “60” ;
    geo:hasIntersection       _:Ncf7f520b7ba0406e96f38c20f12c5b52 .

SDK:PipeSegment_001   a firebim:PipeSegment ,
    geo:hasIntersection       _:Ncf7f520b7ba0406e96f38c20f12c5b52 .

_:Ncf7f520b7ba0406e96f38c20f12c5b52 geo:intersectionType “pierce” ;
    geo:startCoordinate       “POINT (0.124 2.533 16.234)” ;
    geo:endCoordinate         “POINT (0.124 2.833 16.234)” ;
```

Listing 4. RDF snippet of the intersection between a compartment boundary wall and a pipe segment

The SHACL validator returns a validation report. As in this BIM model (see Figure 2) the pipe segment has no additional sealants, and the fire class of this segment is not given, the pipe segment does not pass the SHACL validation.

Finally, GPT4.0 is pretrained with a product book with fire resistant pipe segments. Then, a zero-shot prompt asking for a suitable solution for this specific pipe segment, returned a product based on the semantic and geometric information from the RDF graphs. An expert validated the result and agreed that this product was the best option from this product book.

This work aimed to find how semantic capabilities of LBD graphs and geometric capabilities of IFC (and IfcOpenShell) to enable ACC on regulations that require both geometric and non-geometric information. A geometric engine is presented that enables the computation of geometric information using a collection of functions in a Python library. The proposed framework is tested in a case study in the Tribune building in Strijp-S, Eindhoven. The results

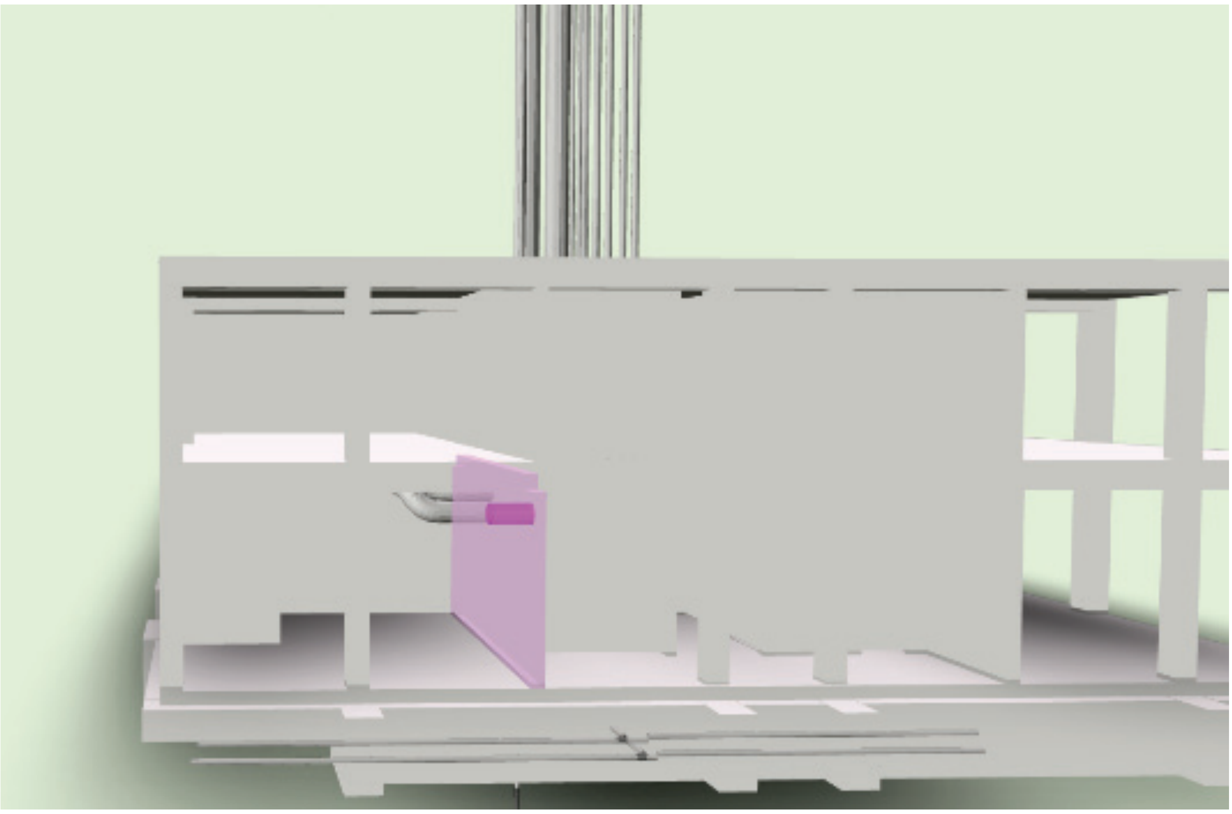

Figure 2. Visualization of a pipe segment that goes through a compartment boundary wall

show that the framework enables ACC on geometric and non-geometric regulations, and that it is also able to provide targeted feedback to the designer or contractor. Future work will enhance the geometric engine with more functions, create a dedicated user interface for it, and provide more testing and validation.

Acknowledgements

This paper is funded by the Eureka ITEA4 FireBIM project (22003) and the Netherlands Enterprise Agency.

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CircleTool: a prototypical tool to determine environmental impact and circularity scores for residential buildings

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Keywords: Digitalization, BIM, Circularity, Environmental Impact, Material Value Retention

Abstract

The Architecture Engineering Construction (AEC) sector requires easily applicable tools which allow a seamless integration into the digital design process of buildings. The tools need to be able to support the iterative design process, based on broadly accepted indicators for the quantification of circularity scores and alternative building design concepts. For this reason, the core measurement methods described by CB'23 have been prototypically incorporated within an Excel Workbook. This makes it possible to determine the Environmental Cost Indicator (MKI), Environmental Performance of Building (MPG) and material flows. In this contribution, the concept, structure and results of applying this prototypical tool, CircleTool, on a specific use case will be illustrated. The results have been tested on plausibility. Furthermore, the next steps for extending the tools functionality are documented.

Introduction

With the European goals to reduce greenhouse gas emissions by at least 55% in 2030 as compared to 1990 levels and achieve a fully circular built environment by 2050, the AEC sector is expected to embrace innovative approaches to become carbon neutral and circular. In the Netherlands, the built environment is responsible for roughly 45% of the used resources (Hanemaaijer, et al., 2023). That makes resource use and reuse significant factors to achieve a circular built environment.

To pave the path towards a circular built environment, the calculation of the Environmental Performance of Buildings (MPG) is mandatory according to the Dutch Building Decree. The Dutch Ministry for Interior and Kingdom Relations (BZK) sets the required benchmark values. Currently, the required MPG value to be achieved for new buildings is 0.8 EUR/m^2 and will be reduced to 0.5 EUR/m^2 in 2030 (Nationale MilieuDatabase, 2025). As of today, 8% of the material used in constructing the built environment comes from reuse (Conde, et al., 2022). Much of the building material which is recycled, is downcycled. Reuse of material and building components does extend the life cycle of materials and reduces waste, but in the longitudinal process, it loses its quality, functionality and value.

Improving the availability of information with regards to, material use, environmental impact and the retention of material value, will help to make informed decisions before and during the design and building phase of new constructions. Evaluation methods like the "Environmental Cost Indicator (MKI)" method or the MPG method can provide information on the environmental impact but doesn't cover all previously mentioned aspects. Often the results are summarized into a total score, which do not give insight into the components that make up this score. Neither do they provide information where improvements could possibly be realized on the selection of building components and material. This was the motivation to develop a tool that could evaluate and compare concepts for residential buildings when integrated into the digital design process.

CB23 core method for quantifying circularity

To evaluate the circularity of building concepts, the core measurement methods developed by CB'23 (CB'23, 2022) was chosen to be implemented within an Excel Workbook. The method focuses on quantifying the three aspects: "protection of material stock", "environmental impact" and "protection of functional-technical value" within circular construction.

The aspect "protection of material stock" gives insight into the input- and output flows of materials. They are split into several subcategories like primary/secondary material, material scarcity and end of life use. An example of the formulas used is seen in Equation 1.

$$R_x = \frac{\sum_i (m_i * m_{s,ri})}{\sum_i m_i}$$

Equation 1. Calculation of recycled percentage of object

R_x = Percentage recycled input material from object
$m_{s,ri}$ = mass percentage of recycled input materials from object
m_i = mass of object in kg

"Environmental impact" is determined based on environmental-declaration reports for the buildings' used materials. The reports contain scores for 11 or 19 environmental indicators, respectively, and can be summed up for the building materials and totalled for a final environmental impact score.

"Protection of functional-technical value" is determined through the application of Equation 2.

$$W_f = K_f * K_t * D * H$$

Equation 2. Functional-technical value of object

W_f = functional-technical value of the object
K_f = functional quality
K_t = technical quality
D = degradation
H = reuse potential

Guidelines on determining the 0 to 1 scores for the formula elements, are given in the measurement method. However, these have been mentioned to still be open to interpretation.

Following the guidelines for the three circularity aspect methods, detailed information as well as a final score can be generated to determine the circularity of a building concept.

Methodology

To develop the tool, an iterative development process was used to realise the functionality along the steps described in the core measurement method. Additional functionality is visualized in Figure 1 sections 2, 3 and 4. For every step, requirements for input, functionality and expected output were set up, from which it was developed. The result was tested and evaluated, returning to the first step until the desired output could be obtained.

CircleTool and how its used

The CircleTool which is implemented within the workflow shown in Figure 1.The first section revolves around gathering of the required data with regards to a material list, expected reused materials and expected new materials used. This information is imported into the CircleTool which generates an overview of the building materials. These materials are (semi-) automatically linked to a material database, which in turn, link to their material stock values and environmental declarations retrieved from the Dutch environmental database (Nationale MilieuDatabase, 2025) and Ecoinvent (Meyer, 2025). At this point building meta-data and project specific information can be added, leaving a final overview for the user to approve.

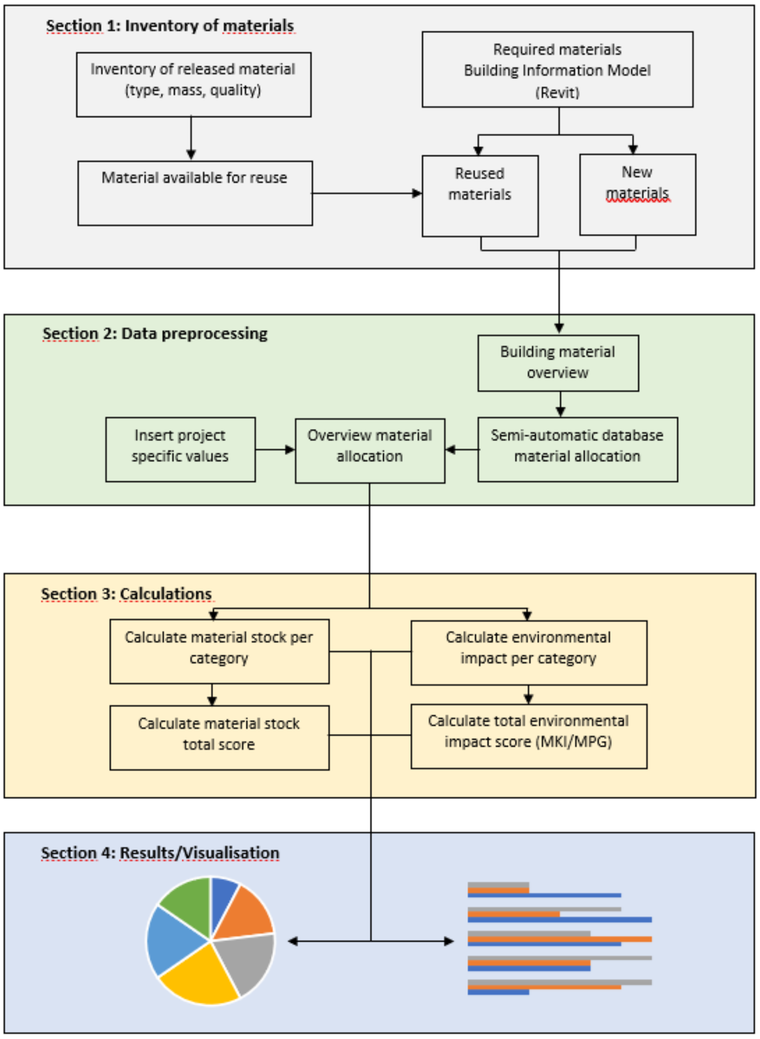

Figure 1 Workflow building assessment and CircleTool

Once the materials are properly allocated, the CircleTool calculates the circularity of the building within section 3. It calculates the values for the given categories, environmental indicators as well as final scores for the building material stock and MKI/MPG. Section 4 then generates a report which can be used to obtain detailed information and visualizations for their project.

Case Study “Sloopnieuwbouw: Een Toekomstbestendig Bouwconcept”

To test the plausibility of the tool, a case study is used in the context of the project “Sloopnieuwbouw: Een Toekomstbestendig Bouwconcept”. Within this project, 36 houses are demolished and replaced by 28 new houses, split into 2 phases. The approach here is that this demolition and new construction takes place in a circular manner with as much material as possible being reused. In phase one, material from demolished buildings is reused for the construction of 16 new residences. In phase two, 12 houses are build using sustainably produced and renewable primary materials. In this case, sustainably produced timber. Herein, the circularity of the realised buildings and their construction methods are needed to be determined. For the application of the CircleTool, 2 residences from phase 1, and 2 residences from phase 2 are selected for analysis.

Exemplary results

The resulting figures describe material flows with regards to input flows and their origins, output flows and their end-of-life cycle, and the environmental impact of the new housing. The generated results can be summarized to a final score for the entire building, split into categories, or scored on a per component basis.

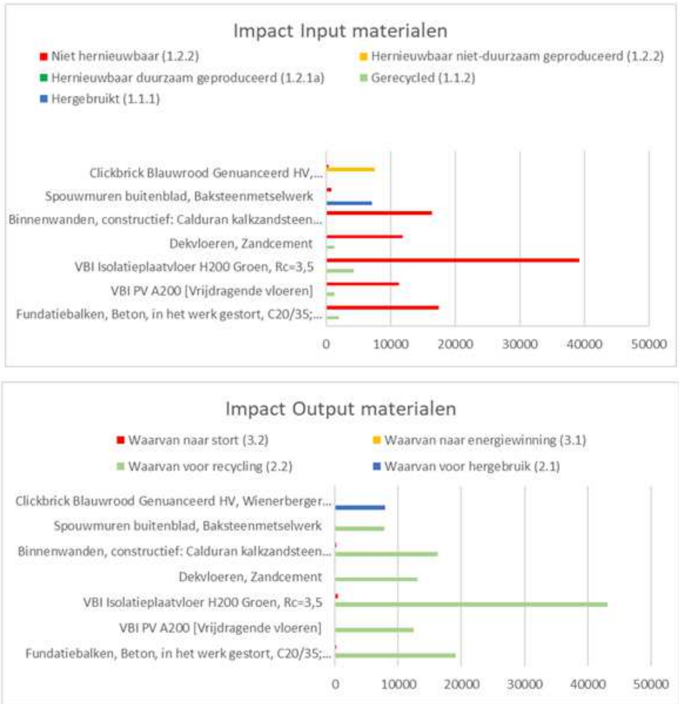

Figure 2. Material flows per kg (input and output)

Results from the CircleTool have been compared for validation, against a report, calculating the MPG-score of the same buildings within the project. In comparison, the CircleTool calculated a higher MPG-score up to 0.20 (€/m2 BVO). After evaluation, the cause was found in the materials used by the report. They were incomplete and often used smaller quantities for higher impact materials than used in the realized project.

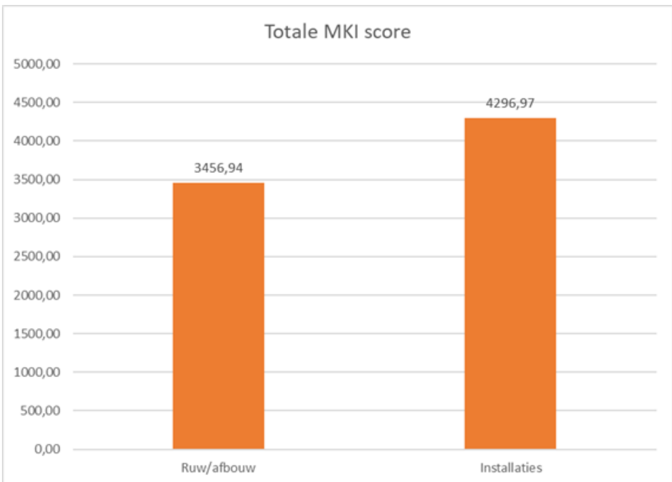

Figure 3. Categorised MKI score

Summary

In its current version the CircleTool, can provide an overview on the build-up of the material use and the environmental impact of the building and its materials/components. For the material flows it allows insight into the input and output flows on a per material basis as well as the total overview. With regards to the environmental impact, the tool can calculate the final MKI and MPG-scores. It also provides an overview on the impact of a single material and how it scores per environmental impact indicator. The analysis can also group materials for ease of use.

Next steps

For future work, development towards the functional and technological retained value is still being worked on. While the calculations are in place, data on retained material value is often lacking or is only interpretable on a case-to-case situation. Guidelines are given by the CB’23 method to define these values and are under development to get implemented. Further automation and improvements towards the available data as well as assigning building materials also needs improvements. While the material lists were able to be used and materials were semi-automatically assigned, some still needed manual assignment. Lastly, the ability to suggest improvements with regards to materials and components hasn’t been implemented at all yet in its current state. Currently, the user has to manually reassign materials and components, and do a comparison from there. Future work is looking into providing an initial relative comparison for materials as a first step.

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Low-cost Sensor Solution for Performance Monitoring of Construction Vehicles Using Location and Vibration Data

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Keywords: Construction vehicle monitoring, signal processing, GNSS, accelerometer, engine vibration, fleet management.

Abstract

While modern construction vehicles often come equipped with proprietary telematic systems, a substantial portion of the global construction fleet consists of older machines that lack any form of digital monitoring. The exact share is unknown, but in many companies, legacy equipment still plays a critical role in daily operations. This gap limits the ability to track performance, optimize usage, or assess environmental impact. In response, this study presents a proof of concept for a low-cost, low-maintenance, plug-and-play solution designed to monitor the operational behaviour of such vehicles. The system combines a modular hardware unit with integrated Global Navigation Satellite System (GNSS) and accelerometers to capture data such as location, motion patterns, activity cycles, and engine RPM. All processing is performed locally on an edge device, eliminating the need for centralized computation or cloud connectivity. The goal is to provide a scalable and accessible tool for construction companies to better understand and manage their fleets, with future potential to link activity data to fuel consumption and emissions.

Introduction

The construction industry is a major contributor to global greenhouse gas emissions, accounting for approximately 37% of energy-related CO_2 emissions when including building operations and construction activities (World Green Building Council, 2023). A significant share of these emissions arises from fuel consumption by heavy equipment and machinery, much of which is still composed of aging vehicles lacking modern digital monitoring capabilities. While newer construction equipment often comes with integrated telematic systems, a large portion of the global fleet remains analog and untracked, particularly within smaller and medium-sized construction firms. Although precise data on the share of such legacy vehicles is lacking, their widespread use presents a major blind spot in efforts to improve operational efficiency and environmental performance across the industry.

Directly measuring exhaust emissions from these vehicles is not only technically challenging but also economically impractical at scale. It requires specialized and costly instrumentation, regular calibration, and substantial maintenance, logistically difficult under the dynamic and rugged conditions of construction sites, especially when dozens or even hundreds of vehicles are in use simultaneously. To address this gap, this study introduces a low-cost, plug-and-play device for estimating and logging the operational performance of construction vehicles, with a specific emphasis on older models. The solution consists of a modular hardware platform that integrates Global Navigation Satellite System (GNSS) tracking with accelerometers to collect data on location, motion, and engine activity. The device operates as a standalone system with internal power supply and network connectivity, enabling real-time data logging and remote access without dependence on centralized infrastructure. It continuously records vibration data, which is analyzed locally using signal processing techniques such as Fast Fourier Transform (FFT) and spectrogram analysis to extract engine frequency signatures. These signatures are used to estimate revolutions per minute (RPM), a key parameter linked to fuel use and potential emissions (Chiavola et al., 2024), as well as activity (off, idle, or moving). GNSS allows the determination of distance covered and the speed.
This approach lays the foundation for scalable, cost-effective performance monitoring across heterogeneous construction fleets, enabling future extensions toward indirect emissions estimation, maintenance planning, and fleet optimization.

Hardware and Application

Previous research has demonstrated the viability of MEMS accelerometers for capturing vibration parameters at various vehicle locations to analyse automotive dynamics (Ahmed et al., 2023). Additionally, the accelerometer captures slope/tilt and temperature, while the GNSS system records total distance travelled, velocity, and movement patterns. By combining these measurements, the system enables comprehensive vehicle monitoring, including the identification of engine state transitions such as idling, moving, or stationary operation. This integration supports the potential of the system for broader vehicle diagnostics and operational assessments. Such an integration of various states of the vehicle can be done by continuously monitoring the frequencies and their amplitudes generated.
The sensor system has been tested on a variety of construction vehicles, including several older models for which no baseline performance data is available. Therefore, cross-validation of the results on these vehicles is not yet possible. More recently, tests have begun on modern construction vehicles that are equipped with embedded monitoring systems. This offers the opportunity to compare the outputs of the developed system with those of the built-in systems, which is a key objective in the next phase of the study. Such comparisons were not yet available in the writing of this extended abstract.
As illustrated in Figure 1, the setup consists of a standalone unit that includes a computing module, a GNSS board, and a power supply. The system is created using a low-cost computer, MEMS and GNSS board combination, that sums in less than 500€ in total, including cabling and boxing. The antenna of the GNSS module is mounted externally, and the accelerometer is placed at a carefully selected location on the vehicle to capture engine vibrations. To ensure reliable signal acquisition, the accelerometer must be positioned in such a way that it receives vibrations as directly as possible from the engine, while avoiding interference caused by the vibrations of secondary structural elements. Placement on the chassis of the vehicle is considered the most promising option and will be investigated in the upcoming tests.

Data Processing

To illustrate the data processing workflow, Figure 2 shows vibration frequencies which were analysed using a spectrogram. A spectrogram represents the frequency content of the vibration signals over time. The x-axis shows the time, the y-axis represents frequency, and the colour intensity indicates the vibration amplitude, with higher intensity (yellow regions) corresponding to stronger vibrations. Different operational states of the excavator can be identified based on these frequency patterns: during traveling (a), higher spectral density is observed at specific frequency bands, while excavating (b) shows a different distribution with varying intensity. Idling (c) exhibits lower overall energy levels, indicating minimal engine activity.

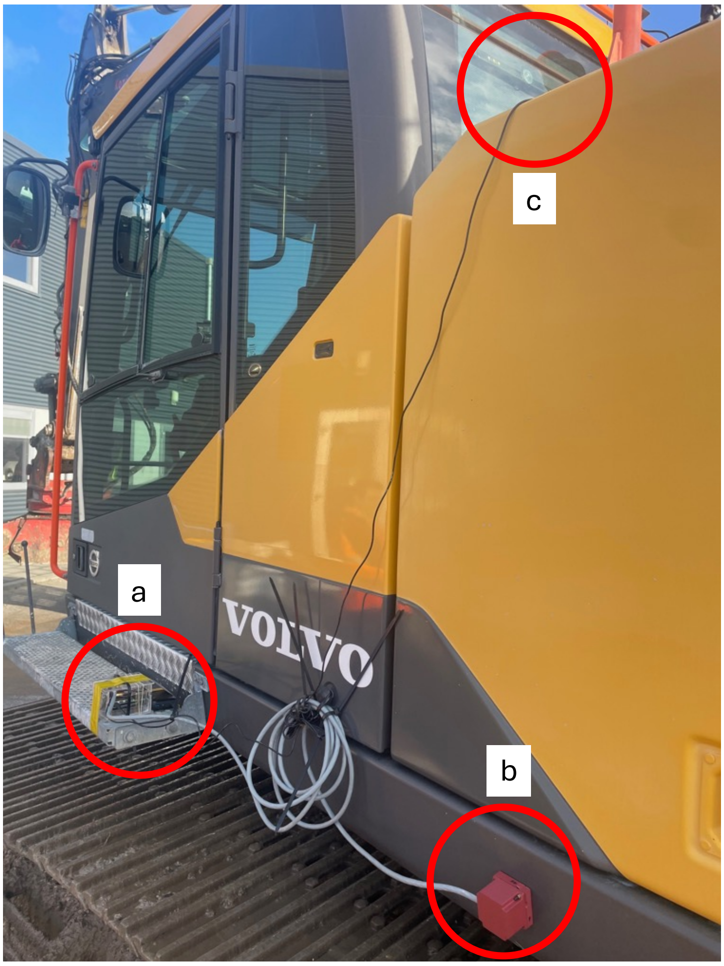

Figure 1. An example application to a modern construction vehicle, which has its own embedded data collection system, to be used for further comparisons: (a) power unit, computing unit and GNSS board (b) accelerometer placed to the body with a magnet, and (c) GNSS antenna.

A significant contribution of this research is the shift from conventional direct exhaust measurement techniques to an indirect estimation method based on operational parameters such as the distance covered, speed when covering that distance, vehicle motion states, engine load manifested by the RPM (motor rotation-per-minute). Exhaust sensors, while precise, are costly and require frequent maintenance, limiting their practicality for widespread adoption (Shahnavaz & Akhavian, 2022). Instead, this study focuses on developing a modular system that collects operational data from vehicle movement and vibration patterns to eventually improve emissions estimation. The feasibility of using alternative sensor-based monitoring systems has been demonstrated in various studies, showing that accelerometer-based measurements can effectively capture vehicle dynamics and engine conditions.

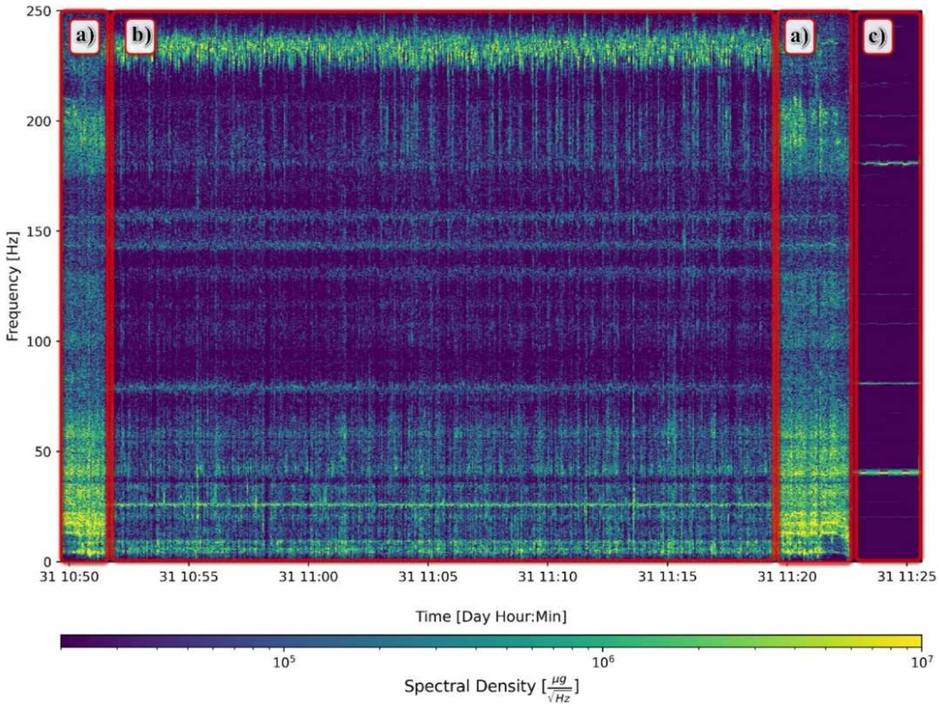

Figure 2. Spectrogram of test data collected from an excavator, showing different operational states: (a) traveling, (b) excavating, and (c) idling.

Fleet management is another major application of this system. The data gathered from GNSS and accelerometer sources enable detailed insights into vehicle position and activity. This allows fleet operators to analyse vehicle usage patterns, detect inefficiencies, and optimize scheduling. By integrating historical data with machine learning models, this approach can support predictive maintenance, minimize downtime, and improve resource allocation within fleet operations.

While the current system does not directly estimate emissions, it establishes the groundwork for a robust methodology that can be refined with additional calibration data and modelling techniques. Research such as (Baratia & Shen, 2021) has demonstrated that emissions modelling can be achieved by tracking field operations, suggesting that future iterations of this system could incorporate similar approaches to develop predictive emission models.

Preliminary testing of the device on a forklift and an excavator confirmed the feasibility of this approach. A synchronised dashcam is also used in these tests for validation purposes. The system successfully synchronized dashcam footage with GNSS and accelerometer data, providing a comprehensive view of vehicle operation. The collected raw data enabled the identification of key parameters such as total distance travelled, velocity, movement status, engine state, and RPM estimates. The results demonstrated the capability of the system to integrate and process multiple data sources effectively, offering a detailed assessment of vehicle behaviour and usage patterns (see Figure 3).

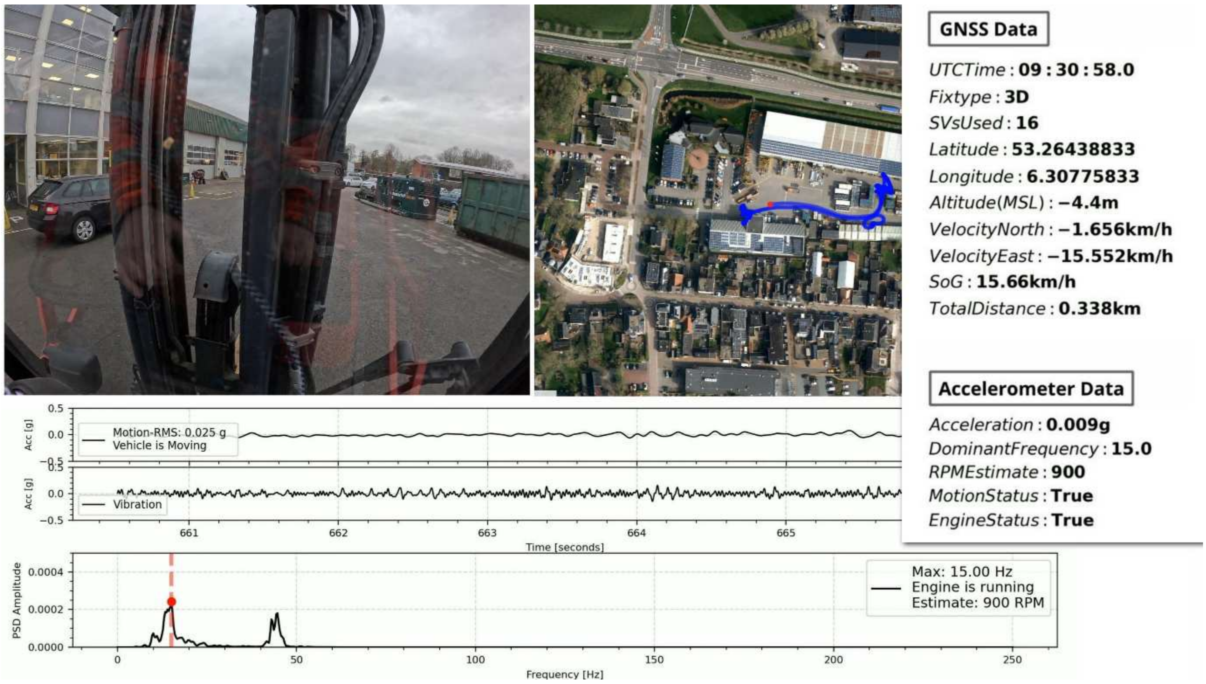

Figure 3. Screenshot from the data processing interface showing synchronized GNSS data mapped alongside dashcam footage and vibration data, providing monitoring of vehicle movement, operational states, and RPM estimation through calculated metrics.

Conclusions and Future Work

This study introduced a low-cost, low-maintenance, and plug-and-play sensor system for monitoring the performance of construction vehicles, particularly older models that lack built-in telematic solutions. The developed system integrates MEMS accelerometer and GNSS board to assess operational parameters such as vehicle movement, distance, speed, engine state, and estimated RPM. Data are processed locally on a compact computing unit, eliminating the need for centralized infrastructure and enabling scalable deployment across large and diverse fleets. Cloud integration is also possible, but not has been tested yet.

Preliminary tests confirmed the feasibility of the approach. The system successfully recorded and synchronized multiple data streams, including GNSS signals, accelerometer readings, and dashcam footage. This enabled the identification of key vehicle behaviours such as idling, movement, and transitions between operating states. The system also demonstrated the capability to estimate engine RPM through frequency analysis, which is an essential step toward understanding energy consumption patterns.

The hardware remains cost-effective, with a complete setup including sensors, computing unit, power supply, and enclosure costing less than 500€. This makes the solution accessible to construction companies that rely on a large number of older vehicles currently operating without digital monitoring.

Although direct emissions estimation is not yet part of the current implementation, the collected data form a strong basis for future modelling efforts. By correlating engine load, RPM, and movement data with standard emission curves or manufacturer data, indirect estimation of emissions may become possible. Further validation against embedded telematic systems of modern vehicles is planned to benchmark accuracy and calibrate the developed algorithms.

Future work will focus on three main areas:

1. Expanding the test campaign to include more vehicle types and operating environments.
2. Refining the placement of the accelerometer to optimize signal clarity, particularly by evaluating attachment to the chassis.
3. Developing data-driven models for predictive maintenance, fuel usage estimation, and eventually emission modelling, potentially incorporating machine learning approaches.

This work lays the foundation for a scalable vehicle monitoring framework, contributing to improved operational insights, fleet management, and environmental impact assessment within the construction sector.

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The digitization of the built environment at the territorial scale: The role of Cellular Automata Models in simulating evidence-based decision-making

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Keywords: Urban growth, Territorial urbanization, Evidence-based decision-making, GIS, Sustainability

The challenges of rapid urbanization at the territorial scale

The uncontrolled urban growth as a result of rapid contemporary territorial urbanization led to massive spatial outcomes concerning land use transformation, housing, infrastructure, and endangered ecological systems and the long-term sustainability of these areas. This rapid urban transformation challenged decision-makers and required new urban planning strategies, designs, and policies that relied on evidence-based decision-making.
Digitization of the built environment at the territorial scale has offered a diverse set of tools, essentially in the field of GIS, to support decision-makers for evidence-based decision-making for sustainable spatial development at the territorial scale. Urban growth models are among these tools and they can support decision-makers by providing new spatial analysis methods for land use, infrastructure design and resource management, and scenario planning for long-term urban and environmental sustainability. On the other hand, due to fragmented data resources and the lack of technical expertise, there are knowledge gaps in the operationalization of urban growth models in the territorial scales of the global north and the developing countries.

Aim of the study

The purpose of this paper is to demonstrate how urban growth models as scenario planning tools can be used for territorial planning and policy decisions, specifically in planning contexts with limited data resources and institutional capacity to tackle the spatial problems of the territorial scale. To this end, the presentation will focus on Cellular Automata urban models that predict urban sprawl and discuss their role in supporting urban planners and decision-makers in informed decision-making at the territorial scale. Cellular Automata models can contribute to the digitization of the built environment at the territorial scale by simulating the transformation of spatial patterns. Therefore, they have been used for multiple purposes, including scenario testing, policy impact assessment, environmental monitoring, and the like. These models are flexible, and they can be used for different scales, and they provide visual clarity. Among different Cellular Automata models, this paper will focus on SLUETH urban modelling. Besides simple computational and data input needs, SLUETH also embodies the aforementioned advantages of the Cellular Automata models. These qualities render SLEUTH a key tool for predicting urban growth and supporting evidence-based decision-making.

Data and methods

SLEUTH is an acronym that stands for slope, land use, excluded area, urban extent, transportation network and hill shade. SLEUTH comprises four growth rules: the spontaneous growth rule, the spreading center growth rule, the edge growth rule, and the road-influenced growth rule. The SLEUTH model couples the Land Cover Deltatron with Urban Growth Model. The growth rate is computed based on five growth coefficients—dispersion, breed, spread, slope, and road gravity.
One of the main data sets that SLEUTH requires is land cover data that demonstrates how much of a particular area is occupied by urbanized land, agricultural areas, forests, waterbodies, and the like. It is a fundamental data category for the digitization of the built environment, as it documents a detailed categorization of Earth's surface. In territorial planning, land cover data is used to monitor urban growth patterns and sprawl, as well as infrastructural, agricultural, and ecological changes. What is more, land cover data plays a crucial role in the digitization of the built environment and evidence-based decision-making as it supports decision-makers by providing accurate visualizations of existing built environment conditions, and it is particularly useful for land use planning and zoning and other strategic decisions as well as assessing sustainability risks.

Case study and scope

This study will focus on metropolitan areas in Turkiye at the territorial scale. Recently, the metropolitan centers of Turkiye such as Istanbul have witnessed large-scale investments and infrastructural interventions and substantial population and urban growth. All of these changes triggered a rapid spatial transformation at the territorial scale. In order to safeguard the sustainability and resilience of the area against future shocks such as climate adaptation and the earthquake risk, currently there is an urgent need for a comprehensive territorial planning approach that can assess different future scenarios.

Scenarios

In the presentation, several urban growth scenarios generated by using SLEUTH will be demonstrated. These scenarios will include different urban growth patterns such as sprawl and peri-urban growth that will be discussed in the context of the recent infrastructural interventions including the mega projects and new urban regulations that impact the territorial scale in metropolitan centers in Turkiye as well as other risks such as the earthquake.

Results and discussion

The results (as represented in maps) reveal the sustainability risks of different urban growth patterns against the built environment and natural reserves and demonstrate the importance of scenario-based urban planning approaches to safeguard sustainability at the territorial level, in that sense, the results also inform other urban planning decisions on housing, infrastructure management, public services and public health, livability, disaster risk, and the like. More importantly, beyond general decisions on zoning and land use, the outputs of the SLEUTH model provide insights into the potential urban growth dynamics of peri-urban areas that are vulnerable to the negative impact of rapid territorial urbanization. The results are generalizable as they demonstrate the importance of evidence-based territorial planning for metropolitan areas. This study contributes to territorial urban planning by demonstrating that these scenarios can be further used to implement sustainable territorial design solutions such as green corridors and blue-green infrastructure, and they can enhance the effectiveness of land use and zoning plans. Moreover, they can be used for policy testing as part of feedback mechanisms and knowledge transfer among institutions to enhance institutional capacity. Furthermore, they can be part of more comprehensive and integrative approaches in territorial planning that include community involvement programs and can be used as part of co-creation sessions, supporting qualitative scenario planning methods.

Limitations of the study

While this study demonstrates the contribution of the Cellular Automata models to the digitization of the built environment at the territorial scale, the model used in the study has certain limitations concerning the data resolution, calibration, and prediction processes. Important parameters concerning demographic and economic growth are also not included in this model. It should also be noted that land cover data sets also embody certain limitations concerning their resolution, scope, and accuracy. Future research should focus on incorporating different land cover data sets as well as different Cellular Automata models to generate more comprehensive scenario planning methods that contribute to the digitization of the built environment and evidence-based territorial planning. Such studies will surely contribute to integrative approaches in territorial planning.

Session 2a

Immersive experience of public data for inclusive urban development: Case of The Hague, The Netherlands

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Keywords: Immersive experience, participation, Open Government Act, public data, urban development, Extended abstract

1. Research problems and objective

Cities in the Netherlands are facing a major challenge: a housing shortage. The Municipality of The Hague is addressing this issue by redeveloping several large areas of the city. This transformation affects many residents, employees, and other people who live, work, and spend their leisure time in these areas. For such large-scale projects, open communication with citizens and stakeholders is essential. In addition to sharing ambitions and plans, it is crucial to provide and discuss information about the use and function of different locations. This requires an inclusive and participatory approach to decision-making.

The Municipality of The Hague has a long-standing tradition of being a transparent government organization. Data from administrative processes are generally made publicly available as open data, unless privacy, unfair competition, or security concerns prevent this. Previously, citizens could request information through the Government Information Act (WOB). Since May 2022, this has been replaced by the Open Government Act (WOO), which obliges government organizations to proactively publish information. Despite these efforts, awareness and usage of open data remain limited.

Datalab, a municipal department for (geo-)data management, explores how visual data representations can improve accessibility and understanding of urban developments. This way, Datalab aims to better inform citizens and involve them in participation processes.

Participation activities often happen in physical meetings with a selected group of citizens, where the municipality invites input and feedback on plans. In this project we explore whether the use of a digital environment for citizen participation (1) reaches a larger group of citizens, (2) provides citizens with more time and space to consider plans, and (3) offers a broader and more integrated perspective through visual data representations.

2. Collaboration and previous work

This project is a collaboration between the Municipality of The Hague, two research groups of The Hague University of Applied Sciences (THUAS) and agency DutchVR

Municipality of The Hague

The Municipality of The Hague has invested in various visual data representations. Datalab developed an online workspace where residents explore data using thematic building blocks. ‘Spiegelstad’ features the city’s Digital Twin, offering 3D insights into issues like water management. ‘Den Haag in Cijfers’ provides a dashboard with key municipal indicators. While these initiatives share data within their domains, an integrated approach is lacking. Datalab aims to create a more unified representation, combining current data with future plans.

THUAS research group Civic Technology

The Civic Technology research group explores how technology can enhance dialogue between citizens and governments. As part of this effort, the online deliberation platform ‘Public Dialogues’ (http://www.publicdialogues.nl) was developed. This platform allows participants to engage in discussions, exchange ideas, and collaborate on relevant topics at neighbourhood, city, and regional levels. It provides low-threshold tools for dialogue and co-creation in synchronous, asynchronous, or hybrid settings. While mainly text-based, it accommodates visual contributions. The research group aims to integrate data visualizations and geographical representations to help citizens better understand complex topics during discussions.

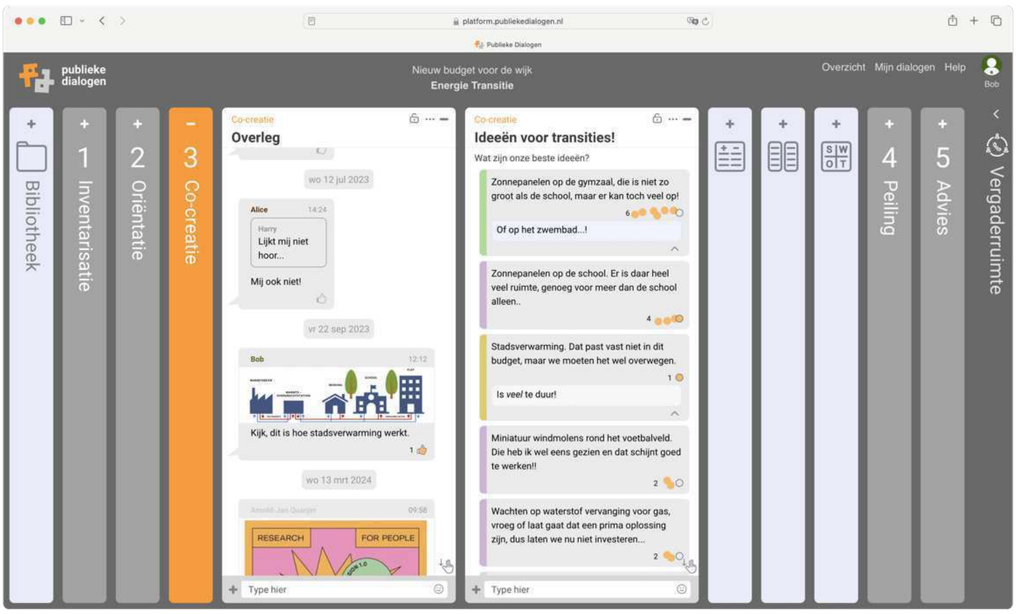

Figure 1. Online deliberation platform ‘Publieke Dialogen’

THUAS research group Future Urban Systems

The Future Urban Systems research group focuses on urbanization and methods to accelerate transitions towards smart, sustainable and inclusive cities, also in alignment with the international vision for people-centred smart cities (Sebastian, 2024; UN

Habitat, 2023). Proof of concepts and outcomes of this research effort will be showcased in the Innovation Playground – Experience Centre at the main university campus.

DutchVR

DutchVR is an agency in The Hague, dedicated to creating high-quality experiences in virtual environments. Through its platform or custom applications, DutchVR tailors solutions to clients' needs. Early in The Hague's city development plans, the municipality commissioned DutchVR to develop a serious game for citizen participation. In this game, participants shape the area around The Hague Central Station by placing virtual buildings and designing public spaces. Their choices impact variables like safety, greenery, and relaxation, allowing users to see the effects of their urban planning decisions.

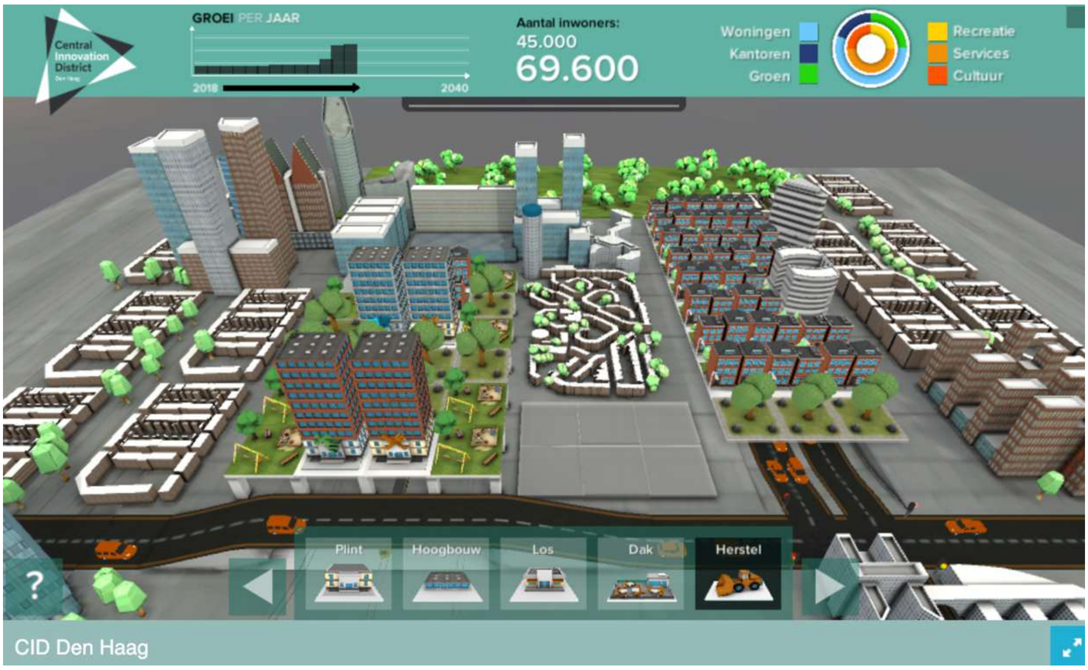

Figure 2. Demonstration of immersive experience in inclusive development of Central Station. Image source: DutchVR.

3. Research, development and demonstration

In the search of immersive ways to shape citizen participation on a more visual way the following research question has been defined:

How can immersive techniques such as Augmented Reality and Virtual Reality effectively contribute to the communication of local spatial data and to citizen participation in municipal activities, both physically and online?

1. What processes are essential for creating an effective immersive representation of local spatial data?
2. Which immersive visualization forms are most effective for citizen participation?
3. How can a physical immersive experience of local spatial data contribute to citizen participation during municipal meetings?

4. How can immersive techniques be integrated into an online participation process, possibly following a physical citizen participation meeting?

3.1 Development of serious gaming in AR Tabletop using the data from Data Lab

The pilot project introduced an Augmented Reality (AR) Tabletop, combining AR with physical interactive elements for an immersive experience. Using DataLab data, the installation presents a small section of the city (Vijverhof, The Hague), allowing residents to shape the area by placing virtual buildings and designing public spaces, while monitoring impacts like safety and greenery. These images can be uploaded to the Public Dialogues platform, encouraging broader discussions on urban development ideas. In public dialogues, you can admire and comment on the designs created, as well as gain insight based on three parameters: safety, green spaces, and relaxation. These metrics are based on the number of elements that influence those parameters.

This pilot informs future iterations of this project: (1) an immersive representation of the new Campus Quarter, (2) a representation for other neighbourhoods, and (3) a virtual version integrated into Public Dialogues. With that iterations this visual participation tool can be widely used throughout The Hague and other cities.

In February 2025, citizens of The Hague can visit an exposition with the five best examples of an Open Government at the Atrium of the city hall. In addition to these examples, the AR Tabletop installation is presented to gather first observations of how people experience using this form of participation.

Figure 3. Players using the AR Tabletop Game during the exposition Open over Open located at The Hague city hall

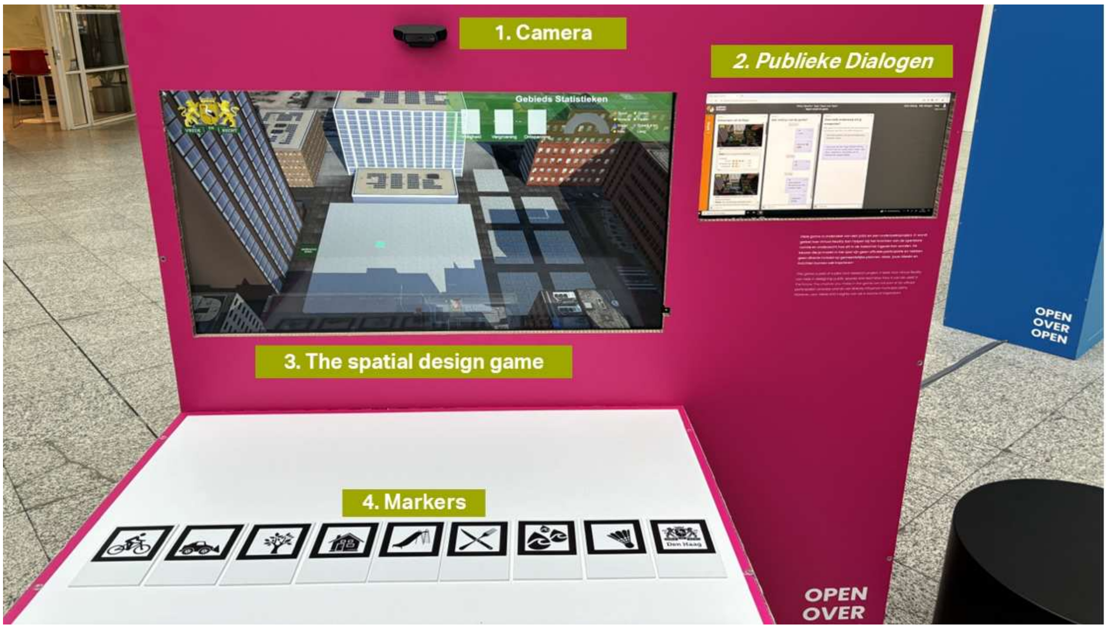

Figure 4. Overview of the components of the AR tabletop game
1. Camera – Scans markers.
2. Public Dialogues – Online platform to view and discuss designs.
3. Spatial Design Game – Players digitally shape the Vijverhof area, impacting safety, greening, and socialization.
4. Markers – Physical icons detected by the camera to place buildings, parks, and facilities or remove objects.

4. Outcome and reflection

During the exhibition, we identified several areas for improvement:

Usability & Intuitiveness : A grid helps users orient markers, but fine positioning remains challenging, leading some to give up. Simplifying the grid (8x8 instead of 12x12) made placement easier. Flipping the camera also improved intuitiveness.

Interaction & Experience : Animations (e.g., cyclists on bike paths) enhanced engagement. Marker switching was too fast (one second). Extending this to three seconds improved usability.

Target Audience & Engagement : Children engaged more easily than adults, who often lacked time or interest. Providing seats and headphones for video content could encourage deeper engagement. The interactive installation has a 1-3 minute learning curve, impacting participation rates.

5. Conclusion and discussion

This project aimed to explore how immersive technologies could enhance citizen participation in urban planning of a city. By integrating data with immersive experiences, we aim to create engagement in and understanding of city developments. The pilot demonstrates that such approaches can engage residents in meaningful ways, allowing them to shape urban spaces, monitor the impact of their decisions, and discuss their plans afterwards.

The outcomes reveal several key insights. First, usability improvements, such as simplifying the grid and extending interaction times, made the installation more user-friendly. Additionally, targeting a broader audience, especially children, was successful, though engaging busy adults remained a challenge.

Acknowledgements

This practice-oriented research is performed in collaboration between The Hague University of Applied Sciences, the departments of Geo-Information and Data Lab of the City of The Hague, and DutchVR.

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Digital Twin for Disaster Management of Electric Power Networks: Enabling Risk-Informed and Adaptive Decision-Making in Post-Hurricane Scenarios

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Keywords: Digital Twin, Probabilistic Risk Assessment, Dynamic Bayesian Network, Electric Power Network Resilience, Post-Disaster Recovery, Hurricane-Induced Infrastructure Disruption.

Extended abstract

Hurricanes are among the most devastating natural hazards, causing widespread damage to infrastructure, communities, and economies. The electric power network (EPN) is particularly vulnerable to the multi-hazard threats posed by hurricanes, including wind, flooding, and storm surge. As one of the most critical infrastructure systems, its failure can trigger cascading disruptions in other essential networks, such as transportation, water distribution, and emergency services.

Ensuring the EPN's resilience requires both proactive measures, such as pre-hazard mitigation and preparedness, and reactive measures, including post-disaster emergency response. Pre-hazard mitigation and preparedness can be effectively approached through a probabilistic risk assessment framework, which models the causal relationships between hazard exposure, infrastructure vulnerability, resulting losses, and subsequent recovery through uncertainty quantification. However, extending this framework to the post-disaster phase remains a challenge.

In post-disaster settings, situational awareness is crucial for effective decision-making. However, obtaining complete and real-time data on damage and outage states across all EPN components—often numbering in the tens of thousands in even a mid-sized city—is rarely feasible. As a result, decision-makers must operate with partial knowledge. Additionally, the repair and restoration states evolve rapidly as response crews work, necessitating a framework capable of real-time updates. Furthermore, the outage and restoration states of EPN components are interdependent, as changes in upstream elements impact downstream elements. Connectivity within the network also means that partial knowledge in one area can improve predictions for other regions.

To address these challenges, this research proposes a dynamic Bayesian network (DBN) framework for integrating probabilistic predictions with real-time data updates, while preserving the connectivity dependencies within the EPN. The framework operates in three key stages:

1. *Initial Damage Estimation*: The survival and failure states of EPN components are first estimated using a probabilistic risk assessment approach that incorporates hazard exposure and fragility analysis.
2. *Bayesian Network Prior Estimation*: A Bayesian network is then employed to estimate prior outage probabilities based on network topology and interdependencies.
3. *Dynamic Updating with Real-Time Data*: The model extends into a dynamic Bayesian network, where real-time observations are continuously integrated through Bayesian belief updating, refining the outage and restoration estimates as new data becomes available.

This high-fidelity framework effectively serves as a digital twin (DT), generating prior risk estimates through probabilistic modeling and dynamically updating predictions using real-time data. Figure 1 illustrates the proposed framework's workflow.

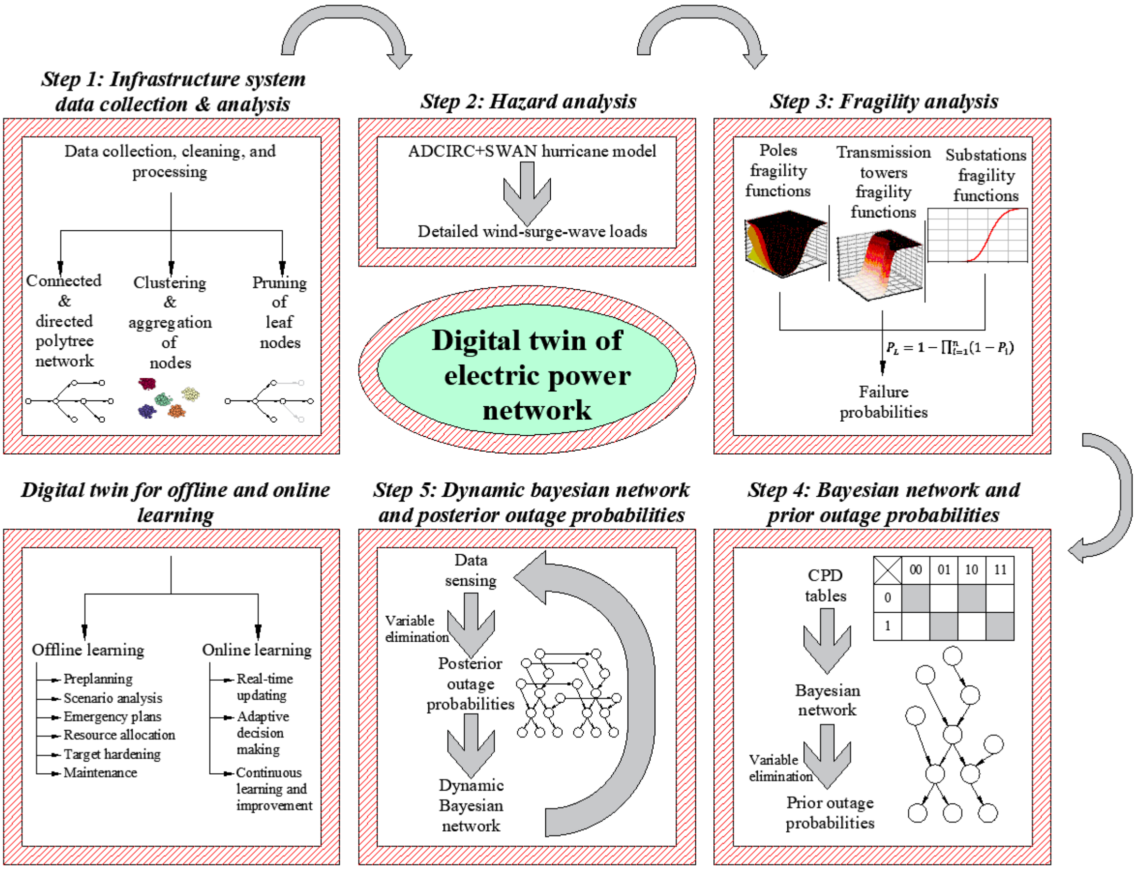

Figure 1. Flowchart showing key steps of the proposed digital twin framework of electric power networks (Braik and Koliou, 2023).

The DT extends its capabilities from risk assessment to disaster management by enabling adaptive decision-making. At each time step, all possible repair choices are analyzed and prioritized based on their expected worth in restoration, considering uncertain knowledge, restoration time, and the importance of downstream facilities for community resilience. Immediate decision-making can initiate after the disaster with incomplete knowledge by utilizing probabilistic estimates, becoming more efficient as real-time data is integrated. Interdependencies between the EPN and the road network are incorporated to account for repair crew mobility, and a repair-worth prioritization formula is introduced to optimize the restoration sequence.

The framework is validated using the Galveston testbed in Texas subjected to Hurricane Ike hazard loads, demonstrating its applicability in both pre-hazard mitigation (by evaluating restoration strategies) and post-disaster emergency response (by monitoring and guiding the restoration process). Detailed data of Galveston testbed EPN (locations, properties, and connectivity of substations, transmission towers, and utility poles) and building inventories (locations and properties), in addition to Ike's simulation data, were obtained for existing literature (Darestani et al., 2021; Incore, 2023). To support decision-making, a dynamic dashboard for the EPN DT is developed, as shown in Figure 2. This dashboard provides real-time monitoring of key recovery indicators, including the EPN damage map, customer outage distribution, road damage and flooding status, and the progressive restoration of residential, commercial, and essential infrastructure. Moreover, it tracks the location and progress of EPN and road repair units throughout the recovery timeline, offering a comprehensive situational awareness tool for stakeholders. Notably, it assigns tasks to the repair crew units while ensuring synchronization and real-time updating.

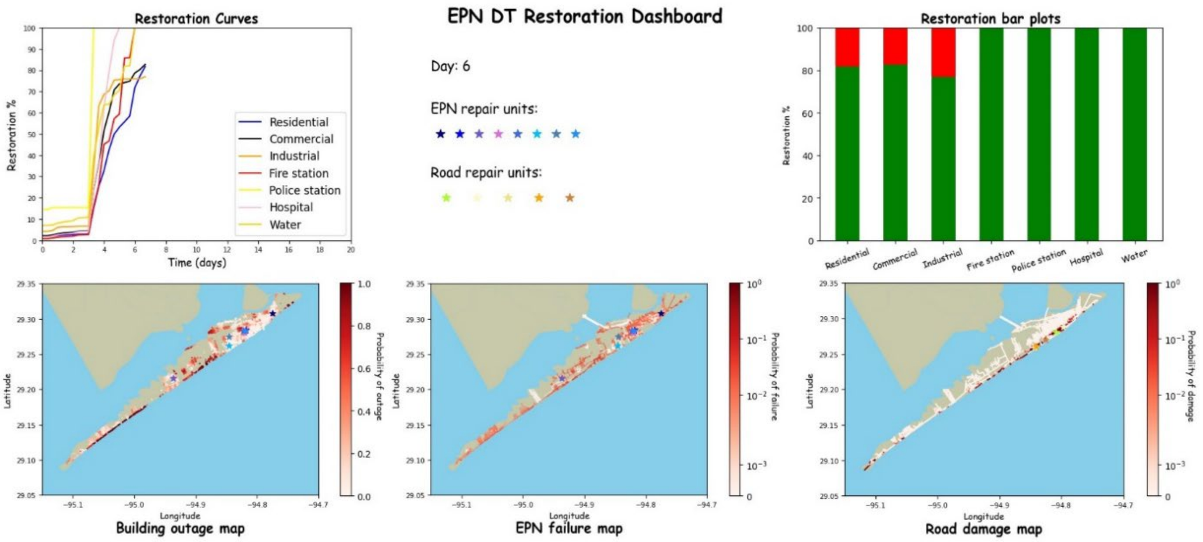

Figure 2. Digital twin dashboard for electric power network restoration and decision support (Braik and Koliou, 2024).

The proposed framework has the potential to transform disaster recovery strategies by enabling faster restoration, enhancing emergency response, and strengthening community resilience in the aftermath of hurricanes. By integrating probabilistic risk assessment, dynamic Bayesian networks, and real-time data updating, the framework provides a robust decision-support tool that bridges the gap between pre-hazard mitigation and post-disaster response. Its ability to capture interdependence between the EPN and road network ensures a more coordinated and efficient allocation of resources, minimizing downtime and economic losses. Moreover, the development of a DT offers a real-time, data-driven approach to disaster management, allowing stakeholders to dynamically assess evolving conditions and optimize restoration strategies. Ultimately, this framework can aid policymakers, emergency planners, and utility operators in making informed decisions that not only accelerate recovery but also build long-term resilience against future extreme events.

Acknowledgments

Financial support for this work was provided by the US National Science Foundation (NSF) under Award Number 2052930. This financial support is gratefully acknowledged. Any opinions, findings, conclusions, and recommendations presented in this paper are those of the authors and do not necessarily reflect the views of NSF.

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Cloud-computing for designing virtual environments

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Keywords: Cloud computing, virtual environments, real-time rendering, virtual machines.

Extended abstract

This paper presents insights from a pilot study exploring the use of cloud computing to design virtual environments in the 3D Modeling Studio course, part of the Psychology and Technology bachelor's program at Eindhoven University of Technology. These findings contribute to evaluating the potential for scaling cloud computing to other courses, projects, and professional applications.

3D Modeling Studio is a first-year bachelor's course in Psychology and Technology within the Industrial Engineering and Innovation Sciences department. In this course, students develop fundamental skills and knowledge to design and build interactive desktop Virtual Environments (VEs). They create VE-based experiments to study the effects of building design on human experience and behaviour (Figures 2, 3). However, students face significant technical challenges, particularly as their models become more advanced, due to the limitations of individual laptops with limited computer power (e.g., inadequate GPU and CPU capabilities). Most students own university-provided laptops with Intel i7-13700H processors, 16GB of RAM, and Nvidia RTX A1000 GPUs. The software essential for real-time rendering and 3D modelling (e.g., Twinmotion and Unreal Engine) requires substantial computing power.

VEs, particularly immersive Virtual Reality (VR) using head-mounted displays, are crucial tools in environmental psychology research (e.g., Kort et al., 2003; Stankovic, 2016; Loomis et al., 1999). They also play a key role in developing essential visual analysis, design, and simulation skills. However, technical constraints can hinder the learning process, making it necessary to find solutions that enable students to work with these tools effectively. To address these challenges, this pilot project explored integrating cloud computing solutions to support students using advanced rendering software to design virtual environments. During quartile 2 of the 2024-25 academic year (between 11 November 2024 and February 1 2025), we initiated this pilot study with 57 students, with the workflow illustrated in Figure 1.

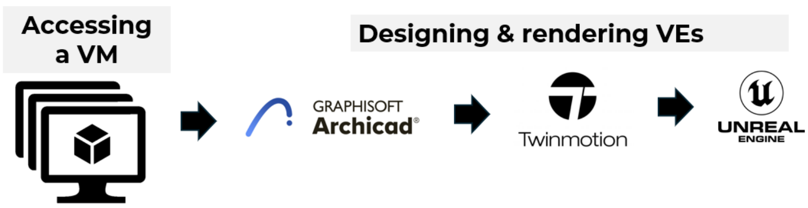

Figure 1. Workflow for 3d modelling to design VEs, integrating accessing to a VM on Surf Research Cloud

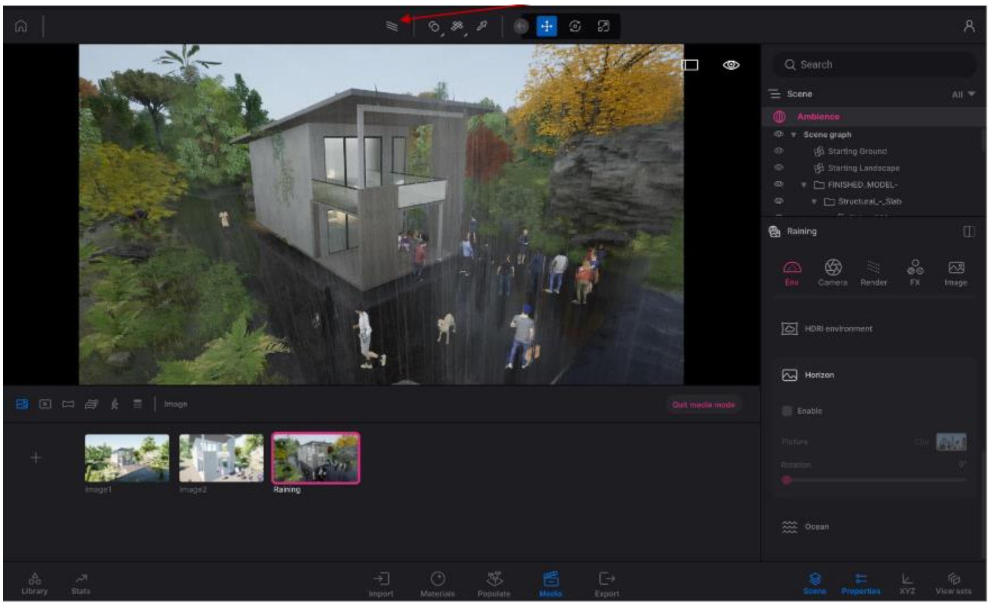

Figure 2. Example of a screenshot from designing a virtual environment in Twinmotion

Figure 3. Example from VM that a student-designed (QR code shows the interactive environment)

Setting up VMs & Implementations

Cloud computing is an emerging new computing paradigm providing network access to shareable virtual machines (VMs) with self-service provisioning on demand. They are mainly high-performance computing resources and are provided by a cloud-based solution. After multiple discussions and knowledge exchanges with another instructor experienced in implementing Azure Lab in the classroom, we conducted trials on Surf Research Cloud, which is essentially an Open Source Cloud computing Infrastructure (OpenStack, https://www.openstack.org/), can be connected to various clouds, such as HPC Cloud (servers in an academic computing centre in Amsterdam with limited GPU types of RTX 2080 and A10), and Microsoft Azure Cloud (a large number of servers with GPUs of all sizes, ranging from very small to very large).

Based on the experiences after the test period, we decided to set up the VMs on HPC Cloud in combination with the Windows Server 2019 operating system on Surf Research Cloud. The setup process and inviting students (as members) to the platform where they can access the VMs included the following steps:

- We created a 3D Modeling group on SURF Research Cloud.
- We set up virtual machines for each student, naming them accordingly, and installed the necessary software, including Archicad, Twinmotion, and Unreal Engine.
- We invited students to the platform via email, which went relatively smoothly.
- We provided instructions (digital manuals) to guide students in accessing the platform both in the classroom and outside of class hours. Students used the cloud computing solution to complete exercises in class while having the flexibility to continue their work remotely.

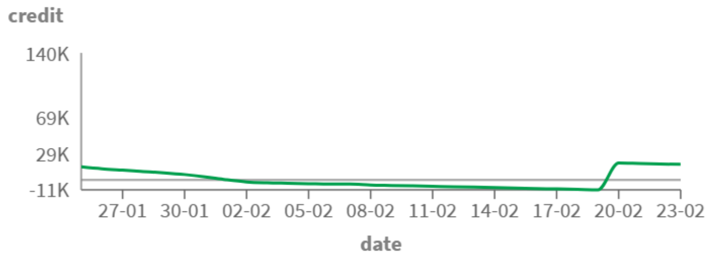

Figure 4. Example data usage shown on the Surf Research cloud

In the classroom, we continuously monitored how effectively students used cloud computing for tasks such as rendering and designing virtual environments. While students were invited to use the platform when it was first introduced, they were not required to do so and had the option to work on their own laptops if preferred. Since this was a pilot project being implemented for the first time, several challenges arose. For instance, we were initially unaware that different versions of Windows required different applications to access the VMs. Such issues may have discouraged some students from fully utilising the VMs. However, a few students reported that they continued using the VMs beyond classroom hours, finding them particularly helpful as their laptops struggled with performance. In addition to our observations, we conducted a classroom survey to gather student feedback. Below, we summarise the key takeaways based on our observations and student survey results.

Key Takeaways

- The system operates based on credits (tokens), and monitoring usage (Figure 4) was sufficiently compelling. However, a more detailed tracking system showing credit usage per VM or student would have been beneficial.
- Students accessed the VMs using the Microsoft Remote Desktop app, but the app had a different name in the Dutch version of Windows, which was confusing. Additionally, MacBook users faced difficulties accessing the platform.
- While setting up the VMs was relatively straightforward, the inability to clone them added significant setup time, particularly when creating 57 VMs.
- A VM can be shared among multiple users and used at different times without issues, but performance may decrease if multiple users access it simultaneously.
- Based on various experiences, the best approach for next year is to provide VM access only to students who need it due to laptop issues, as only some benefit from it while others do not.
- Some students reported performance issues, requiring further investigation to determine whether these were related to internet connectivity in the classroom. Others did not

experience significant problems. For students who struggled to start up Unreal Engine or faced long downloading times, the VMs provided a valuable alternative.

- Additionally, we tested a VM for research analysis to evaluate its performance in handling large datasets, which were highly promising.
- Students received unnecessary or irrelevant system notifications, which should be addressed to improve the user experience.
- Summary of the survey results:
    - Many students found it interesting to learn about cloud-based computing.
    - Some noted that the performance was slightly better than their laptops, but the difference was not substantial.
    - Several students highlighted the need for improved accessibility and a smoother login process.
    - While most students had neutral experiences, some still appreciated the option of accessing a remote desktop (Figure 5).

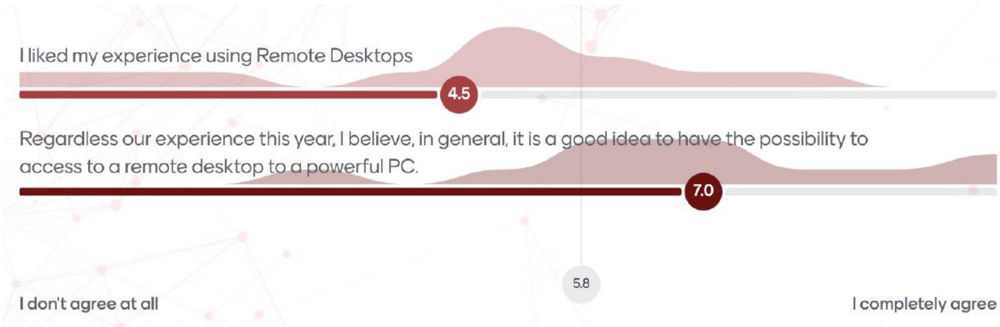

Figure 5. Part of classroom survey result (N=19)

Altogether, this pilot with cloud computing is a showcase for research applications and professional virtual environment designs. The lessons learned from this smaller-scale implementation can be instrumental in scaling cloud computing solutions to other courses, projects, and professional applications.

Acknowledgements

We would like to thank the TU/e BOOST project for financially supporting this pilot and EAISI for their valuable technical support.

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Detect and Compare: An Image-Based Deep Learning approach for comparing the As-Built situation with As-Planned BIM models

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Keywords: Construction Industry, Quality Management, Computer Vision, Artificial Intelligence, Deep Learning, Robotics.

Extended abstract

Within the construction industry quality management has become an increasingly important task. Quality management and quality inspections ensure that construction projects meet the required regulations such as building codes and specifications (Luo et al., 2022). During quality inspections, important aspects of the construction project are observed to identify possible quality defects, deformations and deviations (Luo et al., 2022). When the quality inspections are not performed or carried out late, there is a risk of not identifying possible defects, which results in cost overruns (Akinci et al., 2006). To be able to perform quality inspections, the existing building data from the as-planned BIM model and the quality requirements are compared manually to the as-built situation of a construction project (Bouwkamp & Akinci, 2007). Identified deviations between the as-planned BIM model and as-built situation allow project managers to take corrective measures (Ekanayake et al., 2021). Despite the importance of these inspections, quality management requires manual labor, making it a time-consuming and labor-intensive task which is prone to human errors (Bouwkamp & Akinci, 2007; Braun et al., 2020).

A possible approach to assist in facilitating this process would be to automate quality management, by utilizing Computer Vision (CV) and Deep Learning (DL) in combination with Robotics. Digital technologies such as computer vision and deep learning can help with making automatic detections of objects and defaults based on the input data. Input data such as images and videos of the as-built status of a construction site are often gathered manually as well, which can result in low-quality data (Lin & Goldparvar-Fard, 2020). By using mobile robots, this process can be automated (Ilyas et al., 2021). Integrating these digital technologies can enhance quality inspections, by improving the comparison between the as-planned BIM models and the captured as-built data.

The aim of this research is to develop a 2D image-based object detection method to compare the as-built situation of a construction project with the as-planned BIM model, by integrating computer vision, deep learning, and mobile robots. A mobile robot is deployed to capture images on the construction site during the data collection phase. This data is then used as input to train a deep learning model for the object detection method. This method detects certain objects and compares their as-built placement with the expected placement based on the BIM

model. The proposed method is named the Detect and Compare method. A real world use case is carried out to conduct the research, which consists of two main activities "*Image-Based Object Detection*" and "*Comparison with BIM model*". During the first activity, a system engineering approach is used to train a deep learning model to be able to detect sockets on a construction site. The second activity uses the results of the object detection method to compare the location of the detected sockets with their expected placement based on the BIM model. One apartment type was selected from the real word use case, which was used for testing purposes. This apartment type contained eight sockets. Waypoints were added to each socket in the BIM model, which represent the exact location in a room where a mobile robot should take a picture of the as-built situation. These pictures are then used to compare the object detection results with the BIM model placements. The pictures of the sockets were taken indoors in finished rooms under controlled conditions, ensuring consistent lighting. In addition, the pictures for comparison should be taken perpendicular to the socket to ensure high accuracy during the comparison activity. Figure 1 shows a side by side of a socket in the BIM model and a picture taken of the same socket at the waypoint location.

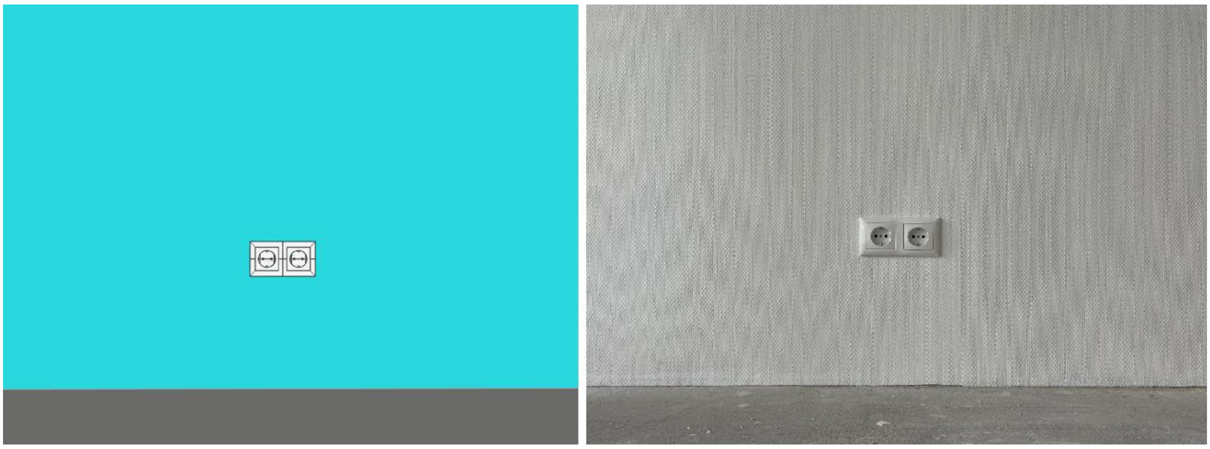

Figure 1. A view of the socket from the waypoint perspective in the BIM model (left) and the same socket in the as-built situation (right)

Using an iPhone 12 and a ROSbot with an RGBD camera images were taken of sockets on a construction site. With data augmentation, the dataset was expanded to 999 images. LabelIMG is used to label the data and create the bounding boxes which are exported to PASCAL VOC format for training purposes. This format exports the images in each bounding box as an XML file that contains the labels and positions of each box in an image. A 70/20/10 split was used to divide the images in a training, validation and testing dataset. A transfer learning method is used to facilitate the training process. The chosen deep learning model is a Faster R-CNN model with a pre-trained ResNet50 backbone model architecture. Faster R-CNN is a region-based Convolutional Neural Network (R-CNN) that makes detections in two stages. An object detection code is written using the PyTorch[1] framework. To train the model the number of epochs was set to 25. An early stopping algorithm was used to prevent overfitting. Due to early stopping, the training halted at epoch 8, where the average training loss was at a value of 0.04 and the validation loss had a value of 0.06. The average precision (AP) of the trained model was calculated, which determined that the model has an accuracy of 94.8% for the AP50 metric.

[1] https://pytorch.org/

After training the model could successfully return an image with a bounding box around the detected object. The BIM model contains geometric information of the sockets. The width and height of the sockets were taken from the BIM model and transformed to pixel dimensions, before being added as an overlay to the object detection results. The pixel coordinates of the expected region overlay, and the predicted bounding box are compared to determine the as-built placement of the sockets. Figure 2 shows the results of the object detection process, here the red bounding box is predicted by the trained model, and the green bounding box represents the expected region of the socket based on its location in the BIM model. After comparison each socket gets a status which can be *"Within Region"*, *"Partially Within Region"* and *"Outside Region"*.

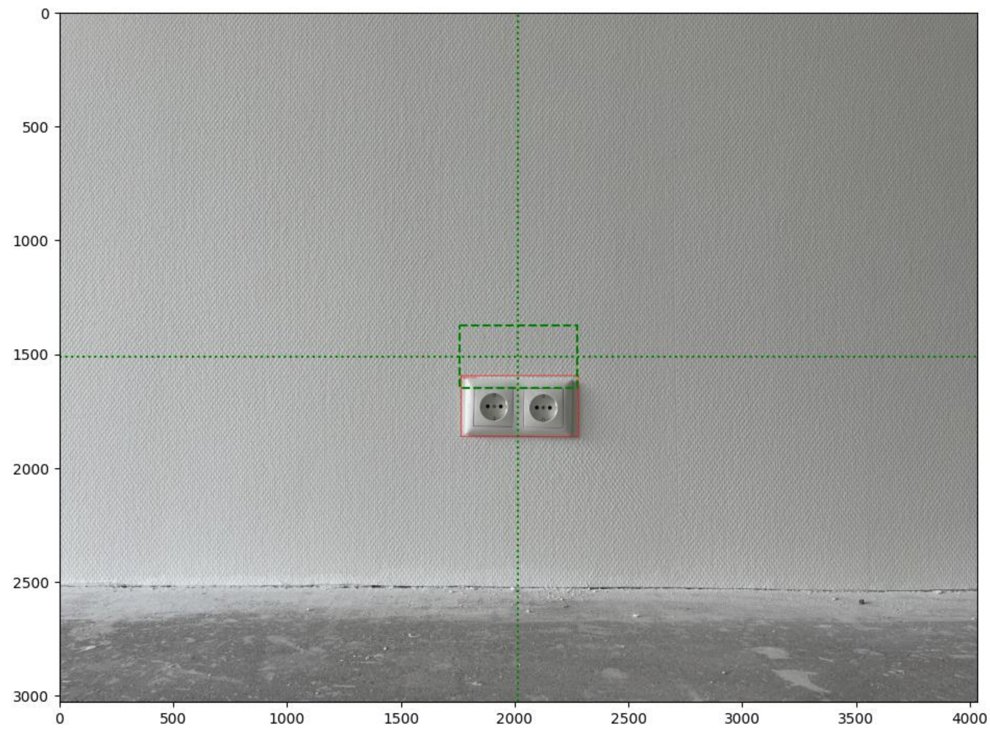

Figure 2. Example of a socket prediction (red bounding box) with the expected region overlay (green bounding box)

The results of the proposed Detect and Compare method provide an opportunity for additional explorations in various fields. For example, the Detect and Compare method was expanded using IfcOpenShell[2] to be able to add a custom "As-Built Placement" IFC property to the existing IFC model. In addition, using the deviations between the pixel coordinates, this method can be expanded to automatically adjust the positions of the sockets in the IFC model, allowing automatic As-Built Modeling. Furthermore the Detect and Compare method can be used as a foundation for robot localization. The existing BIM models can be used to create semantic maps which are then used for robot navigation purposes. Using the BIM model to create semantic maps eliminates the need to manually create and label these maps. In addition to semantic maps, occupancy grids are used for robot navigation as well, which represent a room and the occupied spaces (Pauwels et al., 2023). These maps are created by 2D or 3D laser

[2] https://ifcopenshell.org/

scanners. The BIM model used for the Detect and Compare method can be utilized to create a semantic map for the robot. Then the robot can navigate itself through a room in the model. The ROSbot that was used during data collection contained a 2D laser scanner and RGBD camera. The 2D laser scanner can be used to create a map of the room where the robot is situation. The robot can recognize its position by comparing the 2D laser scan with the semantic map. Object detection can be used as an additional step to improve the localization process of the robot. Using the RGBD camera and real-time object detection the robot can detect and recognize certain objects in a room. Based on these detections, the robot can make a query to the BIM model to find apartment types that match its detections. When the robot has localized itself successfully, it is then able to navigate to the proposed waypoint locations in real life and sequentially carry out the Detect and Compare method to check whether the placement of the as-built objects correspond with their as-planned location.

Besides the proposed implications, further research can focus on modifying the Detect and Compare method to be able to conduct real-time detections. In addition, the exploration of semantic segmentation in combination with the Detect and Compare method can be valuable. As semantic segmentation is more suitable for detecting objects with organic shapes, such as Mechanical, Electrical, and Plumbing (MEP) installations which often include curved pipes.

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Transitioning to AECO Data Spaces: Challenges, Opportunities and User Requirements

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Keywords: AECO Industry, Data Space, Stakeholder Requirements, Industry Analysis

Extended abstract

Stakeholders in the Architecture, Engineering, Construction, and Operation (AECO) industry have been adopting digital technologies, such as Building Information Modelling (BIM), Internet of Things (IoT), Digital Twins (DT), robotics, and Artificial Intelligence (AI). These technologies generate different types of data across the entire building life cycle, which is predominantly stored in isolated, centralized, and project-focused systems. These information systems are difficult to interconnect due to technological, managerial, and governance challenges (Donkers et al., 2020), resulting in information silos. It is important to connect these islands of information, as they hinder the seamless data flow, innovation, and informed decision-making, leading to ineffective collaboration, errors, and higher costs (Jaskula et al., 2024).

Decentralized Data Systems and Data Spaces

A potential solution to connect these islands of information is to shift from centralized information systems, where data is stored in a single, centralized repository controlled by one entity, to decentralized systems, where data is distributed across multiple stakeholders with no single authority controlling the entire system, enabling more flexible and collaborative data exchange (Naderi & Shojaei, 2024; Stas & Abrishami, 2024). An emerging concept in decentralized systems is data spaces, which facilitate secure and controlled data access while enabling seamless integration between software tools and disciplines within an industry. A data space can be seen as '*a data integration concept which does not require common database schemas and physical data integration, but is rather based on distributed data stores and integration on an "as needed" basis on a semantic level*' (Nagel & Lycklama, 2021, p.7). Using a decentralized network architecture, a data space ensures secure, interoperable, and effective data exchange (Bader et al., 2020).

Despite their potential, practical examples demonstrating what a data space should look like and how it should function in the AECO industry have not yet emerged. The International Data Space Association (IDSA) suggests that data spaces should be tailored to domain-specific needs (IDSA, 2024). However, given the industry's fragmentation, a single monolithic dataspace is unlikely to be effective. Instead, a network of interconnected data spaces may be more appropriate, allowing different subsectors, such as infrastructure, materials manufacturing, facility management, and urban planning, to adopt subsector specific data-sharing approaches while adhering to overarching interoperability principles. This approach does not replace domain-specific ontologies or standardized data schemas like the Industry Foundation Classes (IFC) but rather enables connections between these different domains without enforcing a monolithic structure.

Research Aim

To develop these data spaces, academic research should focus on identifying the industry's specific needs and challenges. While existing research primarily addresses back-end development considering issues such as data interoperability, data safety, machine-readability, or decentralized data storage, little attention has been given to how data space end-users, such as architects, structural engineers, or building managers, would interact with these data spaces to improve their workflows. This research aims to identify the key user requirements needed to develop a data space that facilitates seamless and secure exchange of building data.

Methodology

The research builds upon an industry analysis of the Dutch AECO sector, mapping stakeholder perspectives on transitioning to a data space. The analysis is twofold. First, an interactive stakeholder workshop is organized, involving eight participants from various disciplines within the building construction sector, all focused on data exchange related to buildings. The workshop builds upon the Transition Model Canvas (TMC) tool, developed by Van Rijnsoever and Leendertse (2020), which is a practical tool designed to systematically map the key elements and their interactions within socio-technical transitions. The tool can be used both by researchers and by stakeholders directly involved in the socio-technical system (Van Rijnsoever & Leendertse, 2020), which are interconnected networks of people, technologies, institutions, and processes that work together to achieve a specific societal function . The TMC tool explains socio-technical system change through niches, regimes, and landscapes. Niches represent protected spaces where innovations emerge, regimes comprise dominant industry structures, and landscapes include external pressures that influence change (Geels, 2002). Large-scale transitions occur when niche innovations disrupt regimes under landscape pressures (Geels, 2002). The workshop explored norms, values, and institutions shaping stakeholder behaviours, identifying challenges, opportunities, and system needs in adopting a data space.

To validate and complement these results, the second phase of the methodology involves a literature study that supplements the workshop findings. This includes research on data spaces, information systems in the AECO industry, digitalization within the sector, and European, national, and industry-specific data policies and standards. The literature study deepens the understanding of the workshop findings and ensures that the identified requirements are grounded in both empirical insights and scientific literature.

Results

As shown in Figure 1, the stakeholder workshop revealed motivation to transition towards AECO data spaces but noted cultural and structural barriers in the industry. Participants described the industry as fragmented and disorganized, with a lack of standardization, coordination, and a strong blame culture that discourages transparent data sharing. This issue is strengthened by a lack of standards and the absence of a leading entity to develop these. Participants find it hard to identify entities actively working on innovative solutions to accelerate the transition to a data space paradigm. Participants noted that the industry's unique characteristics make it challenging to adopt solutions from other sectors, resulting in a reliance on limited in-house innovations.

The literature study confirms that most stakeholders operate at the regime level, with few niche-level players driving change. The industry is a fragmented, multidisciplinary, project and client-focused industry, with a conservative and rigid culture and low innovation rates (Oesterreich & Teuteberg, 2016) . Digitalization benefits are often perceived indirectly and are less visible compared to immediate barriers (Perera et al., 2023). This makes it difficult to justify long-term investments. Few companies, such as Autodesk Construction Cloud (ACC) and Trimble Connect, operate at the niche level, offering cloud-based data-sharing platforms. However, these are project-focused and costly, limiting broader industry adoption.

While workshop participants emphasized the need for third-party initiatives to develop open data standards, the literature revealed existing niche-level efforts, such as OpenBIM, DigiGO[1],

Transition Goal

Realizing a data space for the AECO industry to achieve an European data market stimulating data reuse

The Regime - Current Situation

Key elements & interacties & stakeholders

The current regime is rather chaotic; different systems are used to exchange information, such as local servers, share point, teams, ACC. In addition to that, sometimes files are sent using email. The client does not have access to the source models but only to the information selected by employees. To make correct models, a lot of effort, which is time and money, is put into the correctness of the models, but this is not necessarily better for the project. The client is decisive here; Are they willing to invest extra for more correct models while this may not yield much for the completion of the project itself?

Employees are very aware of what is shown to the client. It is not standardized that the customer has insight into all versions at all times; it is often a deliberate and tactical choice which data exactly is shown to the customer.

Strenghts & Weaknesses

Strength: client involvement, collaboration. Freedom to chose how to work makes it possible to find a solution that meets the requirements of the project or the client.

Weakness: file ownership and property rights. Currently there are no agreements on how and when data is exchanged; not within the company, but also not within the industry; every project choses different platforms. This makes it hard to guarantee data safety and to back-up the data. Also, sometimes different versions are created, resulting in miscommunications and no single truth.

The Niches - Innovations & Alternatives

Key elements & interacties & stakeholders

Present:

ACC, Teams 2.0

DSGO

Missing:

Mutual trust between client and company. There is often no single source of truth. There is a lack of industry knowledge, which makes it hard for innovations to develop something industry specific; barrier to use some current innovations. There is a need for one single model instead of separate systems that do not communicate with each other.

Strenghts, weaknesses, uncertainties

Strengths: Quality of data, innovation possibilities; lot of space to improve the process. Never too old to learn something new/ change the way you do things.

Weaknesses: everyone within the entire industry is working on its own way; no uniform standards for data (exchange). The technological developments in the industry happen super quickly and seem to accelerate. When something is finally standardized, you are actually already behind. There is no party that takes the lead in this. There are some concerns about the quality and reliability of the data that will be provided by an open data economy; how do you know the quality and reliability of this data?

The Landscape - External Socio-economic Influences

Customer is king culture; you ask, we deliver. Contractor is subordinate to client. Risk driven decision culture.
Data driven paradigm. The added value and activities of a consultancy firm will change as a result.

Strategies for the Regime

To defend the regime

Moving towards a new contract form; The aim should be to create together instead of strictly agreeing on liability and responsibility. In this new contract, the contractor takes the risk. At the moment, everyone works very individually with the focus on saving their own skin.

To demotivate the niches

Within the regime, companies should keep their product unique in order to continue to distinguish themselves from niche developments; stay ahead of the competition. At the same time, they should be responsive to what happens in the niche so that they keep up with developments in the industry and thus remain competitive. The development of industry-wide rules.

Strategies for the Niches

To destabilize the regime

Instead of generating customer-made solutions with data, developing the systems that create the data for the customer. So shifting the market demand to creating a framework that creates the solution rather than creating the solution itself.

To strengthen the niche's position

Experiments. Taking initiative within the industry
Creating/ Indicating problems (and thereafter providing the solution yourself). Publish the data; one party has to start with this and force other parties to share as well. Once data is public, other parties will have a hard time making a profit model out of it. It is of social importance to share the data.

Strategic Resources

To destabilize the regime

Present:

Authority and influence over the client

Missing:

,Sector-wide agreements on publishing and sharing data

Om de niche's positie te versterken

Present:/nothing mentioned by any participant/

Missing:

Data sharing culture. Mutual trust between client and company.

Figure 1. Transition Model Canvas Workshop Results

[1] A Dutch umbrella organization that aims for industry-wide collaboration through standardized data to achieve faster and more efficient construction and to stimulate innovation.

and the IDSA. However, initiatives like DigiGO's Digital System for the Built Environment (DSGO) and the IDSA's data space concept are hardly adopted yet. The landscape analysis showed that European policy has shifted toward leveraging open data for economic growth, enhancing Europe's competitive position through a single European data market that encompasses both public and private sector data. Additionally, ISO 19650 plays a critical role in shaping industry data practices, requiring data to follow four states of information containers: Work in Progress (W.I.P.), Shared, Published, and Archived. Aligning the AECO data spaces with these structures would facilitate industry acceptance.

The results of this industry analysis could be translated into four key themes that reflect the challenges and needs of the stakeholders in the adoption of AECO data spaces. These key themes are; (1) Data quality, governance, and ownership; (2) Interoperability and standardization; (3) Transparency and trust; and (4) Collaboration and stakeholder engagement. Data governance and ownership are central, emphasizing the need for clear policies on intellectual property rights and data sovereignty to ensure stakeholders maintain control over their data while facilitating shared use. Second, interoperability and standardization are critical, requiring unified data standards, and cross-data space interoperability, particularly by aligning with ISO 19650 to enhance industry adoption. Third, transparency and trust are prioritized through mechanisms for traceability, accountability, and robust privacy and security measures to protect sensitive data. Finally, collaboration and stakeholder engagement are essential, highlighting the importance of training, awareness programs, and economic incentives to drive adoption.

Conclusion and Future Research

This research defines the key user requirements for AECO data spaces, focusing on building-related disciplines. However, other subsectors, such as infrastructure and urban planning, have their own unique data-sharing needs that require further research. Future research should expand across these disciplines to develop a comprehensive AECO data space framework. The identified user requirements provide a foundation for system development, guiding conceptual design and eventual implementation. Future studies should explore use case definitions, system architecture, user interface design, and data governance policies. Additionally, enhancing cross-platform interoperability, trust-building mechanisms, and sustainable business models will be crucial for ensuring widespread adoption.

Acknowledgements

This work was supported by the UPSCALE project, funded by the Dutch Organization for Scientific Research (NWO). The research has been part of my graduation project, supervised by Dr. ir. Alkemade and Dr. Raiteri from the Department of Innovation Sciences and Industrial Engineering at the Eindhoven University of Technology. The graduation project was conducted in collaboration with the consultancy firm Witteveen + Bos, under the supervision of Ir. Ingrid Bolier and Ir. Jerry Pollux.

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Session 2b

Additively Constructed Concrete (ACC) Buildings: Design Methodology, Large-scale Testing and Numerical Modeling

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Keywords: Additive Construction, 3DPC Design, Large Scale Testing, FE Simulation

Extended abstract

The emergence of three-dimensional (3D) extrusion-based concrete printing, a form of additive construction (AC), holds the potential to revolutionize the construction industry by reducing production costs, shortening construction timelines, and lowering environmental impact. Despite these benefits, the widespread adoption of additively constructed concrete (ACC) structures has been hindered by the lack of design standards and limited understanding regarding the structural behavior of ACC elements. This gap in knowledge, which particularly concerns the load-bearing capacity and the design of ACC components, has resulted in these elements often being treated as non-load bearing or purely decorative. To address this challenge, a structural design methodology tailored specifically for low-rise ACC buildings has been proposed (Aghajani Delavar et al. 2023; Sharma et al. 2025). This methodology may be viewed as a first steps towards addressing the lack of design methods for ACC structures.
The proposed design methodology discusses typical ACC building configurations and establishes load paths for transferring vertical and lateral loads. The proposed building configuration employs ACC walls, which may or may not have printed infill patterns, interlayer reinforcements and further include internal RC columns at wall-to-wall intersections and reinforced concrete (RC) grouted cells over the wall length and around openings, such as doors and windows (see Figure 1). The methodology provides detailed analysis for both out-of-plane loads and in-plane loads and additional guidelines for maintaining structural integrity. A three-stage out-of-plane wall analysis method is presented, which explicitly designs interlayer wire reinforcement and the spacing of grouted cells in the walls based on local out-of-plane load transfer mechanisms in 3DPC walls, bypassing the reliance on prescriptive rules and offering a more quantitative approach to wall reinforcement design (Aghajani Delavar et al. 2023; Sharma et al. 2025). For in-plane design of 3DPC walls, following a limit states approach,

strength capacity equations for different in-plane failure mechanisms namely axial failure, flexural failure, diagonal shear failure and interface shear failure are presented (Aghajani Delavar et al. 2024). To demonstrate the design methodology, two prototype buildings representing typical one story residential buildings in the US, were designed using the proposed methodology. These buildings were analyzed using continuum continuum finite element (FE) analyses to examine the adequacy of proposed design methodology to result in conservative design. The FE analyses validated the load transfer paths adopted in the proposed designed methodology, as demonstrated by the good agreement between analytically calculated and computationally predicted loading demands. Analytically calculated out-of-plane loading demands appeared to be more conservative compared to analytically calculated in-plane loading demands, which were observed to slightly exceed the computational predictions.

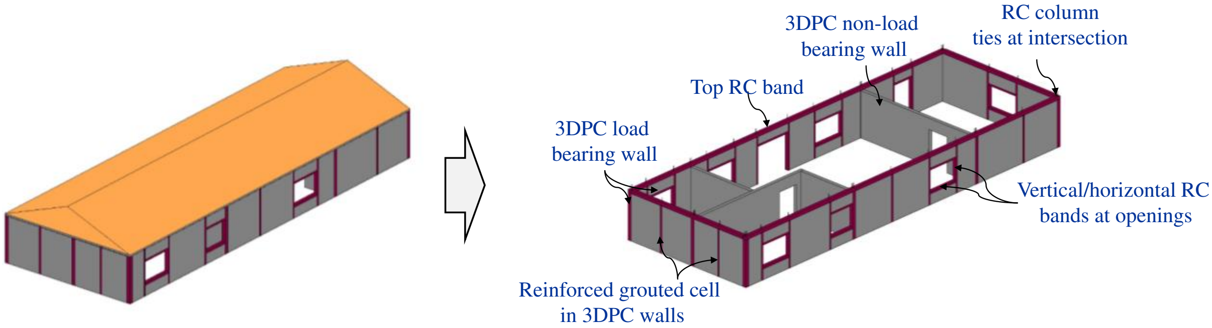

Figure 1. Proposed structural configuration for ACC buildings

The design equations developed as part of design methodology are being validated using experimental testing. For in-plane loading, the experimental program involved testing four full-scale 3DPC walls, which varied in aspect ratio and printing path (with and without infill patterns), and failure modes (Aghajani Delavar 2024). An important design aspect of the 3DPC walls is the incorporation of a reinforced concrete (RC) frame, similar to the boundary elements found in masonry shear walls, which enhanced the lateral load carry capacity thus making it applicable even for seismic regions. The walls were subjected to a constant vertical load simulating gravity effects and in-plane lateral cyclic loading, which mimics the forces that would occur during wind or seismic events. The measured results from the tests were in close agreement with the capacity predicted using the proposed design equations. The 3DPC wall tests provided additional insights into the strength, deformation capacity, and damage progression of 3DPC walls. Additional large scale testing programs are being executed to validate design equations presented in the design methodology for out-of-plane loading and axial loading of 3DPC walls.

The in-plane design equations presented in the design methodology were also examined through a parametric study using finite element analysis, consisting of 96 3DPC walls, which varied in terms of bed-joint reinforcement, concrete compressive strength, height-to-length ratio, layer width, and cross-section infill pattern. The investigation showed that the proposed strength design equations could predict the mechanical strength and failure mechanism of 3DPC walls with reasonable accuracy, across wide range of design configurations (Aghajani Delavar et al. 2024). The validated finite element models were used to evaluate seismic performance of 3DPC buildings using the FEMA P695 methodology (Chen 2023). The evaluation was used to quantify the Seismic Performance Factors (SPFs) for buildings. Two types of lateral force-resisting systems (LFRSs) were evaluated. In the first type, selected 3DPC walls were used to resist majority of the lateral load like reinforced masonry shear walls in

CBM buildings. The experimentally investigated RC framed 3DPC shear walls were used to design shear walls in 3DPC buildings. In the second type, the entire 3DPC wall along the perimeter of the building were designed to resist lateral loads. The findings indicated that 3DPC buildings with the first LFRS showed seismic performance similar to that of reinforced masonry. On the other hand, 3DPC buildings with the second LFRS exhibited low ductility and high stiffness, with their strength largely controlled by the minimum dimensions of the walls. These findings suggest that 3DPC buildings could be viable in earthquake-prone areas, provided the LFRS is appropriately designed to meet seismic demands.

In conclusion, this study provides a step forward towards understanding the structural behavior of 3DPC buildings and offers a comprehensive framework for their design. These strategies are especially relevant for low-rise residential buildings, where 3DPC technology offers the most promise for cost-effective and sustainable construction. By integrating experimental validation, numerical modeling, and innovative design methodologies, it addresses the critical gaps in knowledge regarding the structural behavior of 3DPC walls. The proposed design methodology is expected to provide engineers with a reliable tool for designing low-rise 3DPC buildings that can withstand both gravity and lateral forces

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Enhancing Building Product Reuse Through Digital Platforms: A Simulation-Based Analysis

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Keywords: Circular Economy, Building Product Reuse, Reverse Logistics, Simulation Modeling, Digital Platforms.

Extended abstract

Introduction

The construction sector is increasingly recognized as a critical domain in the pursuit of a circular economy (CE) (Adams et al. 2017). In the Netherlands, the landfilling of construction and demolition waste (CDW) is already minimized, underlining the transition outcome to CE, but most of the CDW is currently only processed low level recycling or backfilling (Azcárate-Aguerre 2023). Among the various strategies to circularity, reuse of construction products has shown particular promise, where materials and components are recovered, refurbished if necessary, and reintroduced into new or ongoing building projects(Tsui 2023; Van Uden et al. 2025). Yet, despite its potential, this approach faces a series of practical challenges that impede mainstream adoption: fragmented stakeholder networks, inconsistent or incomplete data about available used materials, and a general lack of robust, integrative logistics mechanisms (Tjahjono 2010).

This paper presents a study conducted as partnership between a digital platform service provider and a university research group, investigating the above issues specifically in the urban mining and reverse logistics hub space for construction components. The analysis uncovered how and to what extent data-driven solutions, particularly information platforms and ontologies could streamline the recovery of building materials and facilitate efficient coordination among demolition contractors, warehouse operators, re-manufacturers, and use in new projects.

By focusing on the role of digital interoperability and integration of product and process data, this study uses a process model based approach incorporating discrete event simulation (DES) and linear programming approach (LP) to demonstrate how the integration of relevant data from multiple stakeholders can reduce uncertainty, create economic value, and achieve tangible environmental benefits in reuse processes. This extended abstract presents key insights from the study, the following contents first elaborates the background and information collection to build up the process model, then explains the modelling process, and finally, presenting the brief results and implications.

Background and case investigation for modelling

The construction industry has historically followed a linear supply chain characterized by a "take–make–dispose" paradigm. Buildings and infrastructure are commissioned, constructed, and eventually demolished, generating large volumes of waste (Abadi et al. 2023). In response, the concept of a CE in construction strives for closed-loop resource flows by prioritizing reuse, recycling, and remanufacturing. Hence, the idea of "urban mining" emerges: rather than looking to virgin resources, builders and designers turn to existing or soon-to-be-demolished structures to harvest "secondary" materials.

Despite the conceptual appeal, various systemic barriers remain. Through interviews with stakeholders with urban miners and reverse logistics service providers, a few key barriers are identified in this study. Urban mining practitioners often struggle with: Fragmented information: Data on salvageable materials is seldom aggregated. Once a demolition contractor is appointed, they typically have only a few weeks to remove materials; a lack of advanced knowledge about the building's inventory reduces the likelihood that these materials will find new uses. Logistical inefficiencies: Transport and storage costs can quickly erode the economic margin for second-hand products, leaving materials in a no-man's-land between demolition sites and potential new projects. Uncertain valuations: The demand and resale value for recovered materials is not always clear. Even if re-manufacturers or integrators are prepared to undertake the cleaning and refurbishment, they must guess which materials might be valuable. Regulatory compliance and quality assurance: Construction products must meet stringent standards for safety and performance. Used items may need testing, certification, or refurbishment to guarantee reliability, raising perceived risks and administrative burdens.

The research team conducted interviews with demolition contractors, re-manufacturers, warehouse operators, and digital solutions providers. These conversations yielded critical insights about data flow bottlenecks, the time pressure typically faced by demolition teams, and the intangible organizational friction that hampers reuse deals. A key finding across our case observations and gaps addressed by prior research is that data-driven approaches can mitigate these issues (Blackburn, Ritala, and Keränen 2023; Çetin, Gruis, and Straub 2022; Van Uden et al. 2025). Well-structured information on quantity, quality, location, and timing of material flows improves coordination in the reverse logistics chain. This is where digital platforms, often described as "information platforms" or "digital intermediaries", can enable CE flows by acting as virtual logistics coordination hubs. Through them, various stakeholders can upload or retrieve data about demolition timelines, material stocks, prices, refurbishment possibilities, and best logistic planning. Particularly, when physical reverse logistics hubs that handle consolidation, inspection, and partial reconditioning, are integrated with forward flows of construction materials, these platforms can close material loops more effectively (Ding, Wang, and Chan 2023; Tjahjono 2010).

Simulation Modeling

The study builds a process model combining DES and LP approaches to gain insights on the dynamics and potential effects of integrating a digital platform to support reuse and reverse logistics of secondary construction products:

DES: Researchers constructed a simulation of a reverse logistics network for the specific categories of construction product, the aluminium metal façade components. One scenario

assumed limited information about building components, while another assumed robust, real-time data integration. By simulating the flows of materials and supporting processes, the study could quantify the impact of improved data availability on cost, resource efficiency, and greenhouse gas emissions.
LP Optimization: In detail, an optimization model was built that takes potential demolition sites, transportation routes, warehouse capacities, and end-user demands into account. By adjusting variables (e.g., how much material is stored or recycled, which routes are used, how refurbishment costs scale), the model estimates a cost-minimizing or revenue-maximizing approach. Comparison across different scenarios revealed how "imperfect" versus "perfect" information changes the outcome.
Case Scenario: Although the study aimed for a generalizable framework, it grounded the analysis in a typical scenario of recovering, storing, and re-manufacturing aluminium window frames. This case highlighted the viability and pitfalls of reuse: while aluminium frames often have good material value, their shapes, sizes, coatings, and attachment details vary widely, complicating direct reuse.

Key Results

Enhanced Data Management Reduces Risk
A major hurdle for urban miners and remanufacturers is the uncertainty around which materials can be profitably recovered, and for whom. Because of short demolition windows (often just a few weeks) and lack of robust data before demolition begins, valuable components end up landfilled or downcycled to low-grade scrap. The study's simulations showed that having an information platform capable of providing advanced, accurate inventories of materials, combined with early awareness of potential buyers, can reduce guesswork and raise the percentage of components diverted from waste. The effects may include: Earlier identification of buyers and Dynamic pricing and quantity forecasting.
Cost and Revenue Implications
Many stakeholders assume that reclaimed materials are always cheaper than new. In practice, costs vary greatly. Some components require extensive labor or specialized cleaning to meet building codes. The modeling indicated that: Transport costs can escalate rapidly if materials must be moved multiple times. Storage costs remain a critical factor, particularly for large items with uncertain demand. Remanufacturing costs must be carefully weighed against the net value of selling a reconditioned product.
Environmental Benefits
When the simulation accounted for avoided primary materials, disposal impacts, and transport emissions, the improved data scenario consistently led to lower carbon footprints. Although additional journeys were sometimes needed to bring items to refurbishment facilities, the net effect was positive.

Recommendations

Platforms gain value when multiple parties can seamlessly share and interpret data. While small-scale pilots are common, the real challenge is scaling up. Merely collecting data without market engagement may not suffice to shift entrenched behaviours. Government procurement rules that favor reused materials can also help. In synergy, robust data systems measure the carbon savings achieved, enabling carbon credits or subsidies for reuse. Information platforms can help re-direct flows, but physical capacity to sort, store, and upgrade materials is equally crucial. Local authorities might provide land or subsidies to establish these centralized hubs. Industry must be assured that supply volumes will remain high, so that the hubs can reach economic viability.

Conclusion

The collaborative research project highlights the transformative potential of well-implemented information platforms for advancing the reuse of construction products through urban miners and reverse logistics hubs. By systematically optimizing cost, logistics, and environmental factors, the team's modeling based on real world scenarios and assumed values reveal that better-managed data flows can substantially reduce the risks faced by urban miners and other players in the circular construction ecosystem. A few recommendations are thereby proposed to guide future development of circular information platforms in the construction ecosystem and the results also underscored limitations of digital solutions and need for tangible investment in upgrading reuse infrastructure.

Acknowledgements

The authors wish to express their sincere gratitude to the National Growth Funds (NGF). We also extend our appreciation to Semmtech BV for their domain insights, and the 2024 Joint Interdisciplinary Project (JIP) student group.

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Closed-Loop Control of 3D Clay Printing Using Machine Learning

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Keywords: 3D Printing, Additive Manufacturing, Clay, Robotic Fabrication, Machine Learning, Computer Vision, Quality Monitoring

Extended abstract

Introduction and Problem Statement

This paper presents ongoing research that aims to develop a closed-loop and real-time error detection and correction system in 3D clay printing (3DCP) using computer vision and machine learning.

3D printing (3DP) enables the fabrication of objects by depositing material layer by layer based on a digital model. Liquid Deposition Modelling (LDM) is one of the 3DP methods in which a fluid/dense material is extruded through a nozzle to construct an object by depositing layers on each other (Gentile et al., 2024). 3DCP refers to the LDM process in which clay (or earth-based materials) is extruded to fabricate objects. It requires precise parameter control to ensure printing quality (Xing et al., 2021). Similar to other LDM processes, it is sensible to mixture composition (Gentile et al., 2024). There is growing literature on the use of 3DCP in the built environment (Abedi et al., 2025; Asaf et al., 2023; Gomaa et al., 2022; Sahoo & Gupta, 2025; Yin et al., 2023).

In 3DCP, clay, a naturally occurring, malleable material, is mixed with water and additives. Its variability in water content and viscosity, which results from the non-standard mixing process, poses challenges related to extrusion defects, weak inter-layer bonding, and shape deformation. These challenges affect structural integrity and printing quality. Even within a single prototype, variations in printing quality can occur across different layers due to changes in the clay mixture. Traditional fixed-parameter methods fail to adequately accommodate these rapid and unpredictable shifts in material state, typically requiring human intervention during the printing process, which is not always possible or effective enough.

Traditional open-loop approaches operate based on pre-set parameters without real-time feedback, assuming constant material properties and environmental conditions (Zhu et al., 2021). As a result, they cannot dynamically adjust to fluctuations in extrusion consistency and inter-layer adhesion, which makes them especially prone to printing errors caused by the natural variability of the material (Figure1). Without real-time sensing and adjustment, these systems struggle to compensate for changes in material behavior and it often leads to inconsistent results and defects.

Figure 1. Samples of printing failures due to material variability.

Employing computer vision, coupled with machine learning (ML) techniques, can offer a more robust solution for monitoring the 3DCP process. It can allow to dynamically detect and respond to real-time variations in clay properties, adjusting printing parameters actively and automatically rather than relying on static presets. Recent research has explored automated solutions using computer-vision based ML for quality monitoring and improvement during various 3DP processes primarily with concrete, thermoplastics, and metals (Brion & Pattinson, 2022b; Farrokhsiar et al., 2024; Geng et al., 2023; Kazemian et al., 2019; Mehta et al., 2024; Najjartabar Bisheh et al., 2021; Shojaei Barjuei et al., 2022). These materials typically exhibit relatively stable and predictable behaviors under standardized printing conditions. Thus, they allow consistent quality control and parameter optimization. In contrast, clay's inherent variability makes it more challenging to manage. More research is needed to develop closed-loop systems integrating computer vision and ML for real-time monitoring and correction specific to 3DCP.

Objective

This research aims to develop an ML-assisted closed-loop quality monitoring and improvement system for 3DCP to mitigate printing quality problems that can result from the non-standard viscosity of extruded clay.

ML is a subset of Artificial Intelligence (AI) that has an increasing potential to develop the capabilities and efficiency of AM, and it can handle the challenges and optimize the various aspects of AM processes by extracting patterns, learning from data, and building effective predictions (Ukwaththa et al., 2024). ML can play a crucial role in real-time defect detection, process optimization, and adaptive control in 3DP and help to ensure more precise and reliable printing outcomes.

In deep learning-based image classification (a subset of ML), models such as Residual Attention Networks (ResNet) can enhance defect detection by focusing on relevant image regions while minimizing background noise. So, they can be particularly effective for identifying fine-grained defects in 3DP (Wang et al., 2017; Zhao et al., 2017).

Unlike open-loop systems, closed-loop systems can process sensory data by recognizing changes in material properties, environmental disturbances, and calibration errors in real-time. They can continuously update the printing parameters and allow real-time correction of extrusion inconsistencies and printing errors (Zhu et al., 2021).

In this project, we aim to integrate computer vision into the control loop for real-time data collection during printing, along with a ResNet to detect printing failures and adjust the printing speed to mitigate them. This method is suggested to enable automatic and dynamic adjustment of printing speed to ensure consistent material extrusion, and to enhance the quality and reliability of clay-based 3D printed structures.

Methods

The research methodology includes the following steps:

1. Printing multiple prototypes at various speeds to create a dataset, resulting in different levels of print quality due to material extrusion.
    1.1 Evaluating the prototypes' print quality to identify optimal and poor outcomes.
    1.2 Capturing images and relevant G-code data as a CSV file during the printing process.
2. Labelling the collected dataset according to print quality.
3. Training a ResNet model using the labelled data to teach correlations between the images and print quality.
4. Implementing a closed-loop system that adjusts G-code parameters (printing speed) in real-time, responding to changes in material extrusion.
5. Printing a final prototype using the closed-loop system to verify its functionality.

In this research, an LDM WASP Extruder XL 3.0 (with an 8 mm nozzle) mounted on a COMAU NJ60 2.2 industrial robot arm is used for 3DCP (Figure 2). Two Raspberry Pi Camera Module 3, each equipped with additional lighting sources aimed at the nozzle, are mounted on both sides of the extruder to monitor the extrusion continuously and capture images with a specific interval throughout the printing. Preliminary research shows that consistent lighting is crucial for computer vision-based ML accuracy, as variations such as reflections or shadows can negatively impact predictions. Thus, mobile lighting sources attached to the nozzle are used to ensure uniform conditions. This setup is used to print a series of prototypes at varying speeds, which results in different print qualities across the prototypes (Step 1).

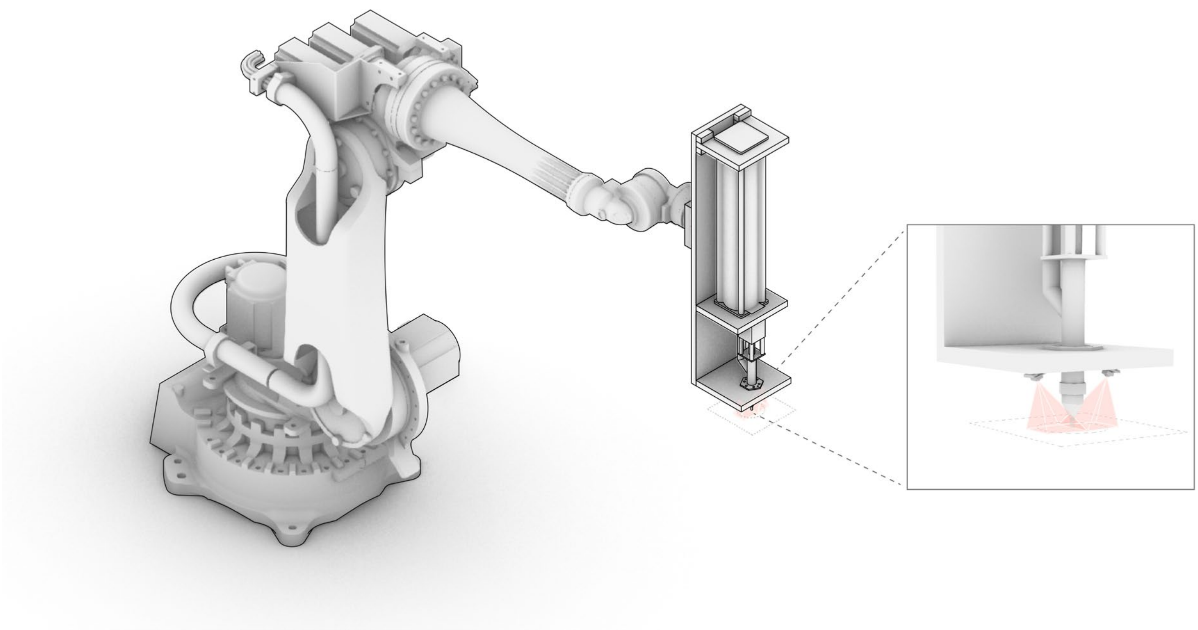

Figure 2. The 3DCP setup design with the extruder and cameras integrated into the robot arm.

The printed prototypes were assessed based on their quality, with a focus on the amount of extrusion, and sorted by their shell thickness (Step 1.1). The prototypes that matched the nozzle diameter (8 mm) were used as the standard benchmark and labeled as the optimum (good) extrusion. The remaining ones were sorted from very thin (low extrusion) to very thick (high extrusion).

The dataset includes images and G-code data (mainly printing speed) stored in a set of Comma Separated Values (CSV) collected while printing prototypes at different speeds (Step 1.2). Then, it was augmented with techniques like rotation, scaling, mirroring, brightness adjustments, and normalization. After that, the data is labeled into three categories (Step 2): low, good, and high extrusion, following the assessment in the previous step.

The defect detection system used in this research (Step 3) utilizes the ResNet Attention-56 deep learning model developed by Wang et al. (2017). It was also applied by Brion and Pattinson (2022a) to control the material flow rate in thermoplastics. This model integrates attention modules and residual blocks to improve feature extraction, reduce noise sensitivity, and enhance defect detection accuracy. It uses a deep residual attention network to process deviations from optimal printing parameters and improves feature extraction by selectively focusing on critical areas of the images. It allows the model to learn the complex relationship between extrusion amount and printing speed to predict and correct errors dynamically (Brion & Pattinson, 2022a). Additionally, Gradient-weighted Class Activation Mapping (Grad-CAM) visualizes the model's decision-making process. Grad-CAM generates heatmaps that highlight the parts of the image most influential in the model's predictions. It offers a more transparent approach that improves trust and interpretability in defect detection. Together, they enhance the system's reliability and adaptability to different 3DCP conditions.

For real-time adjustment of G-code parameters (Step 4), a closed-loop correction mechanism is being developed to dynamically adjust the robot arm's movement speed (RAMS) and optimize extrusion. This loop (Figure 3) first processes the captured images through ResNet to predict shell thickness deviations (due to low or high extrusion). The predictions are monitored within a defined time window (Pm). Corrective actions (increasing or decreasing the speed) are triggered if the shell thickness is predicted to deviate from the optimal value for more than 10 seconds. In this case, the system overwrites the remaining robot program by increasing or decreasing the RAMS parameter. A 40-second monitoring pause follows each execution of speed correction. This allows the system to stabilize before resuming real-time monitoring.

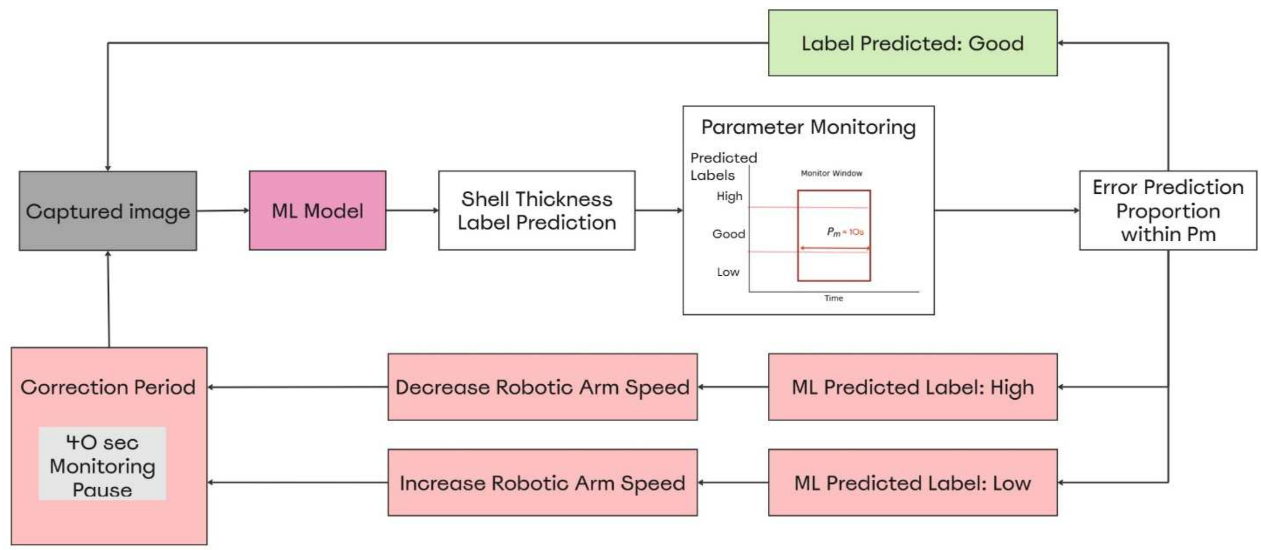

Figure 3. Closed-loop correction workflow

The key factor in determining print quality is the relationship between the nozzle diameter and the observed shell thickness in the specific printing section. By monitoring whether the deposited shell thickness matches or deviates from the nozzle diameter, the system can assess whether the extrusion amount is appropriate or needs to increase or decrease to ensure optimal print quality. Other factors, such as surface texture quality, inter-layer bounding, or structural integrity, can be included in the assessment and training of the ResNet. However, these aspects are left out of the scope of this research for now. Currently, our main challenge lies in the real-time adjustment of the robot programs to update the printing parameters dynamically. After this step is completed, the project will continue validating its results on a large-scale prototype (Step 5).

Conclusions

This ongoing research provides insights into using ML and computer vision techniques to develop a closed-loop system for real-time error detection and mitigation in 3DCP. It mainly focuses on detecting undesired changes in material extrusion due to clay mixture inconsistencies and correcting them by adjusting the printing speed in real time. Additionally, the closed-loop control system can adjust the printing speed as triggered by the trained model. Our experiments so far have shown that ResNet is effective in the real-time detection of extrusion amounts. We also conclude that two-head or multi-head ML models perform better than single-head models in this context. Future studies should involve comparisons with different ML architectures to determine the most effective method for this task.

To ensure reliable results, it is crucial to maintain consistency in dataset collection and calibration conditions. Conditions such as lighting, print base color or patterns, and background environments should remain uniform during dataset collection and calibration. If varying conditions are unavoidable, a significantly larger and more comprehensive dataset is required to ensure robust generalization by the ML model.

Images must be labeled clearly to avoid confusion and potential degradation of model performance. Clear labeling significantly reduces prediction errors arising from manual labeling inconsistencies.

Finally, aligning image sizes between the dataset collection and calibration phases enhances overall performance. Variations in image size can negatively impact model predictions by shifting the model's focus away from important regions. Ensuring that the calibration images match the size of the dataset images maintains consistency. It helps achieve more reliable predictions. This can be particularly important after reinstalling or repositioning the cameras.

The next phase of this research will evaluate different ML architectures to find the best model for the specific 3DCP application. Instead of broadening our dataset to capture varying conditions, we plan to keep our experimental conditions uniform throughout the data collection and calibration phases.

Acknowledgments

This article is developed within the ongoing MSc thesis of Xiaochen Ding, supervised by Serdar Aşut and Charalampos Andriotis at the Building Technology MSc program of the Faculty of Architecture and the Built Environment of TU Delft. The authors acknowledge the contributions of Paul de Ruiter, Vera Laszlo, and Henry Kiksen for their support during the 3D printing experiments.

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Research on the interoperability of circular construction material data

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Keywords: Circular Construction, Data Interoperability, Material Data Management, Building Information Modelling (BIM), Digital Product Passport (DPP)

Research context: Challenges in Construction Material Circularity

The construction sector contributes 35% to the European Union's (EU) waste generation, and legislation is increasingly being put in place to improve material efficiency (European Commission, 2020). The collection, processing and utilization of construction material data for the purpose of circularity in the built environment is thus a critical factor in the movement towards a more sustainable construction industry. However, there is currently no standard methodology to enable interoperability between existing digital solutions that enable this data lifecycle. Varying data standards, methodologies, and applications further complicate the development of an integrated and standardized approach to managing material data. Developments in Building Information Modelling (BIM) have contributed to software and data-capturing applications with which material data can be stored and used in decision-making (Azhar *et al*., 2015). However, a comprehensive solution aimed at material circularity is missing.

Research Objective

The SUM4Re project, funded by the European Commission, aims to minimize waste and advance circular construction practices by developing material banks through urban mining and automated on-site data acquisition technologies. This initiative focuses on identifying building components and materials suitable for reuse, thereby promoting sustainability in the construction sector. The project's systemic methodology encompasses three main activities: identification, analysis, and contribution to circularity. For these activities to be done effectively, a range of software tools and databases are required. While the project's aims do not include developing new software, enabling the interoperability between existing software is key for achieving the project's objectives. Therefore, an important part of this research involves enabling interoperability between software tools and databases. Additionally, the project will give recommendations about the enhancement of Industry Foundation Classes (IFC) standards to address current circular challenges, ensuring interoperability with a variety of databases (SUM4Re, 2025).

Research Question

As part of the SUM4Re project, the interoperability of three existing proprietary platforms are investigated to enable the data lifecycle required to achieve construction material circularity as outlined above. They include: Concular, an application in which material inventories are captured and utilized for lifecycle assessment calculations (Concular, 2025); Genia, a web-based tool initially developed for the inspection and structural assessment of large infrastructure and which supports the integration and enhancement of IFC models (Genia, n.d.); and Cirdax, a platform for inventorying building materials and creating material passports and building logbooks (Cirdax, 2024).

The IFC standard provides the open, platform agnostic data schema to facilitate a part of this interoperability. As an open standard, it allows the creation of associated libraries for circularity, and serves as a container for data exchange between platforms.

The platforms investigated in the SUM4Re research project differ in their specialized functionalities, and each platform fulfils a part of the requirements. Achieving interoperability is crucial for ensuring efficient data exchange across different stakeholders in the construction industry.

The main research question is how to solve the interoperability between these existing data platforms. In particular, this research question is concerned with how to enable automated workflows and reduce data silos. This can enhance decision-making for material reuse and circularity. Furthermore, aligning these platforms with open standards will not only improve compatibility but also facilitate regulatory compliance. Establishing a scalable, replicable framework will help drive long-term adoption of circular practices across the industry. Thus, the interoperability of these platforms is an important focus of this investigation.

Research Methodology

To address the data and software related challenges in construction material circularity, several data concepts have been developed over time, and are being adopted in the SUM4Re project. Digital product passports (DPPs) are structured records that contain detailed information about materials, such as their composition, origin and properties, and serve as a shared database to enable material reuse and recycling (European Commission, 2022). Digital Building Logbooks (DBLs) are centralized digital repositories for building data and include, amongst others, data about construction materials (Volt *et al.,* 2020). Capturing construction material data in material passports and building logbooks is a significant step towards enabling the reuse of materials in a cost-and-labour efficient way.

In the SUM4Re project, three pilot cases of renovation and deconstruction projects are used. In these cases, material data from buildings in the pre-demolition phase are captured using manual inspections and a range of specialized technologies, each with a different data output type. Material data from these inspections are pre-processed and input to the respective platforms, based on their data input types.

Preliminary Results

To enable interoperability between the Genia, Concular and Cirdax data platforms, as well as a user interface for visualizing IFC models and refining data sets to be used in eventual passports, the following interoperability architecture is being tested.

Each platform performs its business logic using its own server and database. This allows for the specialized database requirements of each platform, based on its functionalities, local laws and technical architecture, to be maintained.

Genia serves as the user interface and visualization of IFC models, data and dashboards, due to its original architecture already supporting these functions. This allows the user to interact with the material data and gain insight into both the detailed material properties as well as an overview of the building data. The user can then perform additional calculations as required, for example to determine the amount of a certain material that can be reused, or generate cost schedules for use in a construction project. These calculations are made using the business logic of Concular, which is already designed to facilitate this. Data exchange between the platforms and shared database is enabled using Application Programming Interfaces (APIs). After the appropriate calculations and data transformations have been made, Cirdax generates digital material passports and building logbooks in an open standard and with a live connection to the material data in the platforms. This allows an always up-to-date passport and logbook, as well as data transparency and reliability. Additionally, Cirdax implements blockchain technologies to ensure the secure, immutable tracking of materials.

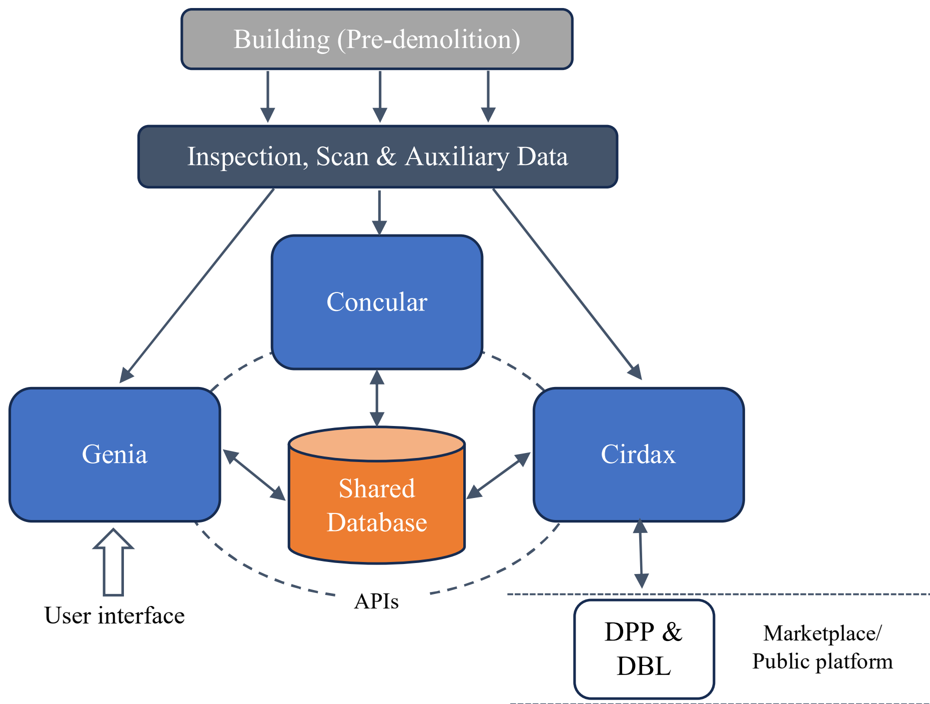

Figure 1. High-level proposal for interoperability of circular construction material data in three proprietary platforms for integration in DPP and DBL. Image source: Authors.

This architecture is being tested via a web-based prototype of the user interface, utilizing material data from the three pilot sites. The final interoperability architecture will serve as a foundation for the adaptation and creation of future software tools, as well as standards for the processing, calculation and visualization of data for use in DPPs and DBLs. Additionally, it will indicate requirements and baseline solutions for the digital hosting of DPPs and DBLs that can guarantee their transparency, traceability and validity.

Acknowledgements

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

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Noise-resistant crack segmentation through the application of transfer learning on the Segment Anything Model 2

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Keywords: Crack Segmentation, Segment Anything Model, Transfer Learning.

Abstract

Manual crack inspection is labor-intensive and impractical at scale, prompting a shift toward AI-based segmentation methods. We present a novel crack segmentation model that leverages the Segment Anything Model 2 (SAM 2) through transfer learning to detect cracks on masonry surfaces. Unlike prior approaches that rely on encoders pretrained for image classification, we fine-tune SAM 2, originally trained for segmentation tasks, by freezing its Hiera encoder and FPN neck, while adapting its prompt encoder, LoRA matrices, and mask decoder for the crack segmentation task. No prompt input is used during training to avoid detection overhead. Our aim is to increase robustness to noise and enhance generalizability across different surface types. This work demonstrates the potential of foundational segmentation models in enabling more reliable and field-ready AI-based crack detection tools.

Problem Definition

With each passing day, the built environment becomes less safe as a result of structural deterioration. To uphold public safety standards, it is imperative to monitor and strengthen affected structures in time to prevent further decline. Manual inspection by trained professionals is often employed to this end. Although effective, it is infeasible to deploy this method on the scale needed to monitor the entire built environment. As a result, automatic solutions have gained major traction as a potential solution for this problem.

Nowadays, the best-performing solutions for automatic crack detection and segmentation employ artificial intelligence (AI). Compared to traditional image-processing methods, AI-based methods can more accurately and consistently segment cracks from surfaces like concrete and masonry (Deng et al., 2022). Especially for masonry surfaces, which are generally more noisy and less homogenous compared to concrete, these methods provide many benefits over traditional image processing (Dais et al., 2021).

Although AI-based methods have shown promising results, the limited complexity of the datasets used to train them prevents the use of these methods by anyone unaware of their limitations. Often, a crack segmentation dataset consists of images without any context outside of the cracked surface, limiting a model's capacity to deal with outside noise. This is further diminished by the small size of these datasets compared to regular deep-learning datasets. For a field such as crack segmentation, where it is essential to retrieve pixel-accurate segmentation masks for downstream tasks, the lack of data significantly hinders the large-scale deployment of these methods.

One solution to this problem is transfer learning. Transfer learning allows the reuse of models trained on larger unrelated datasets, fine-tuning them on the task at hand. This allows for the use of more complex models, which would normally be out of reach for use with smaller datasets, as well as a faster training process. Transfer learning provides a solution to the lack of complexity and size in existing crack segmentation datasets by imbuing models with outside knowledge, potentially making the models more robust to noise and applicable to usage by a more general public.

In image segmentation, one of the main ways to apply transfer learning is to replace the encoder (backbone) of a network with a pre-trained model. Often, these backbones are pre-trained on the ImageNet dataset (Deng et al., 2009), which is suitable for image classification tasks. Although this has shown to be effective in the field of crack segmentation (Dais et al., 2021, Chen et al., 2024), the downstream segmentation task differs quite significantly from the pre-trained image classification task. This discrepancy between tasks may cause transfer learning to not live up to its full potential.

Proposed Method

In this research, we present a novel crack segmentation model, which utilizes transfer learning on the Segment Anything Model 2 (SAM 2) (Ravi et al., 2024) to segment cracks from masonry surfaces. SAM 2 is a foundational image segmentation model, trained on a large set of segmentation masks, with the aim of segmenting images and videos using visual prompts. The original SAM (Kirillov et al., 2023) has been shown to lend itself to transfer learning in previous research, outperforming domain-specific models on both the test sets of seen and unseen datasets (Ge et al., 2024). Our goal is to utilize the strength of the newer SAM 2 model to improve the segmentation performance in the domains of concrete and masonry crack segmentation compared to existing methods. The aim is to develop a model that can be used with fewer restrictions, enabling the use of the model in field applications where many models currently fail due to noisy environments. Additionally, we investigate whether the higher capacity of SAM 2 leads to models with higher generalizability between different structural surfaces. Such a model could serve as a general crack segmentation model, able to identify and segment cracks regardless of which kind of surface the camera is pointed at.

During training, the Hiera encoder and FPN neck of SAM 2 are frozen to avoid the loss of pretrained knowledge. The LoRA adaption matrices, prompt encoder and mask decoder are unfrozen to allow the model to adapt to the crack segmentation task. An empty prompt input is used to retain the network architecture without adding any extra object detection overhead. An overview of the training procedure is given in Figure 1.

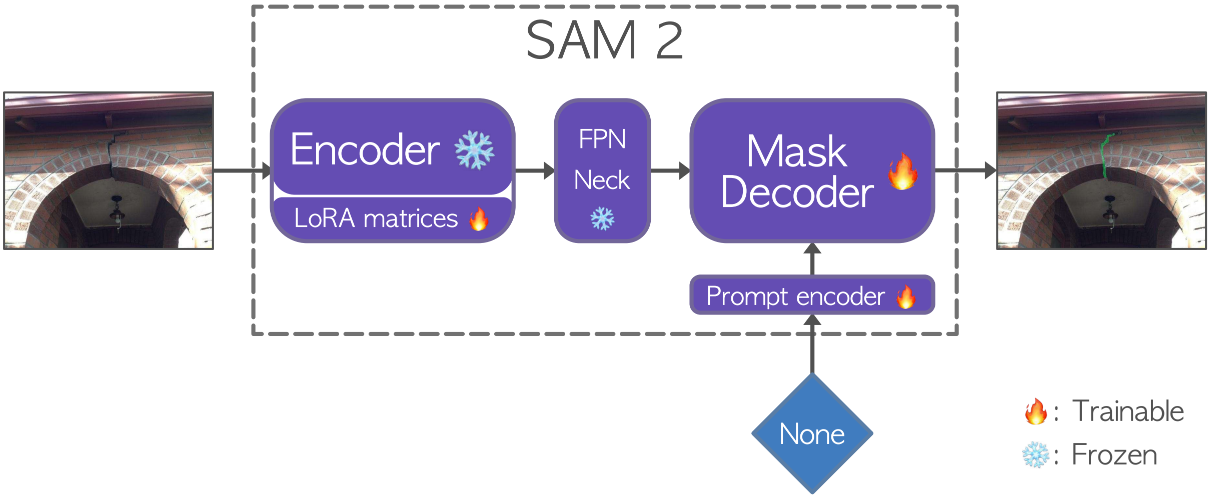

Figure 1. An overview of the training procedure used in this research

Figure 2. An example crack prediction by the proposed method (the green shade is the crack prediction overlay)

Conclusions and Future Research

This study demonstrates that transfer learning with the Segment Anything Model 2 (SAM 2) has the potential to enhance crack segmentation performance on challenging masonry surfaces. By fine-tuning selected components of SAM 2, we retain its strong general segmentation capabilities while adapting it to the specific demands of pixel-level crack detection. The resulting model shows robustness in noisy environments and holds promise for broader field deployment and probably a better success when fine-tuned properly. Future research will focus on validating performance across more diverse datasets and structural materials, exploring the integration of multi-modal inputs, and investigating lightweight adaptations for real-time or edge-device applications.

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ISBN 978-90-940027-3