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Digitalisation of the Built Environment

3rd 4TU-14UAS Research Day

Extended abstracts

25 April 2024

Delft

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Giorgio Agugiaro, Perica Savanović and Rizal Sebastian

Colophon

Digitalisation of the Built Environment
3rd 4TU-14UAS Research Day

Editors:
Giorgio Agugiaro[1], Perica Savanović[2], Rizal Sebastian[3]
[1] 3D Geoinformation group, Department of Urbanism, Faculty of Architecture and Built Environment, Delft University of Technology – g.agugiaro@tudelft.nl https://orcid.org/0000-0002-2611-4650
[2] Research and Innovation Centre Engineering, Design and Computing, Inholland University of Applied Sciences – perica.savanovic@inholland.nl https://orcid.org/0000-0003-3232-1362
[3] Future Urban Systems Research Group, The Hague University of Applied Sciences – r.sebastian@hhs.nl https://orcid.org/0000-0003-1714-8418

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Preface

Our built environment faces critical environmental and societal challenges owing to climate change, housing crisis, aging population, and many other factors. Therefore, large-scale sustainable transitions in the built environment are urgently required. These transitions comprise, among others, a transition towards renewable energy, the use of bio-based and circular materials in construction and renovation projects, and the climate resilience of buildings and urban infrastructures for the well-being of citizens.

Digitalisation has immense potential for accelerating sustainable transition. A large amount of data on the built environment is available; various digital technologies and tools have become mature and more affordable, and the awareness and acceptance of the role of digitalisation in our society has grown broader. At the same time, there is still a need for new knowledge, for instance, the development and application of Artificial Intelligence techniques for generative design and predictive maintenance, remote sensing and cyber-physical systems for Digital Twins of built assets, and mixed reality for an immersive experience of urban spaces and construction processes. Furthermore, there is a need for knowledge of data interoperability and open standardisation to facilitate the efficient management, analysis, and sharing of built environmental data at the component, building, and urban scales.

The universities of technology and the universities of applied sciences in the Netherlands complementarily address these needs for new knowledge through fundamental and theory-oriented research as well as applied and practice-oriented research. The research was conducted by students and researchers, together with lecturers and professors. Through collaboration, they strengthen and expand their body of knowledge in science and industry.

The annual **Research Day on Digitalisation of the Built Environment** is an initiative of four Dutch universities of technology (4TU) in collaboration with 14 Dutch universities of applied sciences (14UAS), which form the national platform for research professors in the built environment (NL-GO). The 3rd Research Day was jointly organised on 25 April 2024, by the Inholland University of Applied Sciences, The Hague University of Applied Sciences, and Delft University of Technology. This event was hosted in Delft, where three institutions had campuses adjacent to each other.

The 3rd Research Day emphasised inclusiveness and interaction. Students and researchers at bachelor's, master's, PhD, and post-doctoral levels were encouraged to share their knowledge, engage in dialogue to exchange their theoretical and practical perspectives, and demonstrate tangible results from their research. This approach aimed to amplify the impact of research-based knowledge. Building on this approach, the 3rd Research Day dedicated time to a plenary session for software demonstrations and an informal session for poster presentations.

Thematically, two keynote presentations were delivered on currently relevant research topics, i.e. "Urban Digital Twins: The role of semantic 3D city models in the energy transition path" by prof. Volker Coors (Hochschule für Technik, Stuttgart, Germany), and "Awareness for cyber risks in construction" by dr. Peter Roelofsma (The Hague University of Applied Sciences).

Parallel sessions were held for the research presentations and discussions. The topics of these sessions, that is, Artificial Intelligence, Robotics and Automation, Augmented/Virtual/Mixed Reality, and Digital Twins – both at building and urban/territorial scales – align with the strategic programme of the Digitalisation Domain Acceleration Team[1] outlined by the 4TU and UAS partners. The complete conference programme, including hyperlinks to presentations and posters, can be found online[2].

This open-access book contains the proceedings of the 3rd 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-14UAS community.

On behalf of the organising committee,

Giorgio Agugiaro, Perica Savanović, Rizal Sebastian

Organising committee:

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Miriam Lof	Inholland University of Applied Sciences
Lucas Mastenbroek	The Hague University of Applied Sciences
Perica Savanović	Inholland University of Applied Sciences
Rizal Sebastian	The Hague University of Applied Sciences

Scientific committee:

Giorgio Agugiaro	Delft University of Technology
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[1] https://www.4tu.nl/bouw/Research/Digitalization

[2] https://www.thuas.com/about-thuas/events-activities/research-day-digitalization-built-environment

Thematic session 1:

Augmented/Virtual/Mixed Reality and Robotics

Teaching parametric design by automating fabrication and assembly

Ekko Nap

The Hague University of Applied Sciences, Bouwkunde programme, The Hague, The Netherlands – e.j.nap@hhs.nl

Keywords: Education, Visual Programming, Fabrication, Integrated Assembly Instructions.

Extended Abstract

The Bouwkunde programme at The Hague University of Applied Sciences (THUAG) aims to introduce its students to the concept of parametric design by presenting it as a means to a tangible end. A parametric script combined with a random triangular solid mesh drives the generation of laser cutting instructions as a set of 2D dxf files, generation of dovetail connectors integrated with the mesh shapes, and laser engraving instructions to annotate the mesh shapes with identity tags and neighbouring mesh shapes to facilitate the assembly of the cut shapes (example: Figure 1). This gives students the means to embark on a design iteration process for physical 3D models that is orders of magnitude faster than the manual work they are accustomed to.

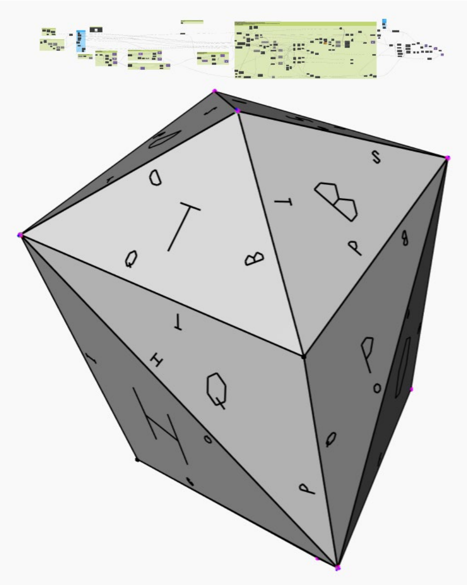

Figure 1. Example of integrated assembly instructions by means of annotated mesh edge relationships on a triangular solid mesh.

In the optional educational unit ‘Technical Innovation, second-year students at Bouwkunde receive instructions in utilising laser cutter machinery for a fast and predictable production process, as well as instruction in parametric design to generate a CAD file with instructions for the laser cutter from any given planar mesh shape.

Prior to this point in the current Bouwkunde curriculum, the students were assessed on their working knowledge of CAD software to generate basic shapes. Additionally, they applied scripts in the Open Source parametric design language Dynamo (DynamoDS/Dynamo, 2024) for self-assessment and for the generation of complex shapes for simple building elements, such as a finish floor that continues through door openings from room to room. Currently, there are no other educational units in the programme that target insights and skills in CAD and/or programming. Students are encouraged to apply their knowledge to group projects based on their own initiatives. In these projects, only a few individuals utilise this knowledge.

The key concept of the approach taken in the educational unit ‘Technical Innovation’ is that students can enjoy the immediate benefits of utilising parametric scripts. The main objective is to create a one-off product that can be assembled and de-assembled; its parts are constrained by the materials and dimensions of the laser cutting machines in the workshop. Product goals and intended locations change each year. The assessment was performed by judging a portfolio of design iterations made during the course. The unit lasts for eight weeks, with one day per week reserved for instruction, presentations, and coaching, and one day for self-study.
On the first day, the DXF CAD file format, which is required for coding instructions for the laser cutter, is explained by analysing a simple Dynamo script. This also served as an introduction to the default dynamic IDE interface. In consecutive instruction sessions scheduled once a week, students are introduced to scripts of increasing complexity, always starting with a simple input (some numerical parameters and a given geometric object, or an image file) and always ending with a dxf export node. This means that the inputs can be swapped for something that students can generate themselves, and the output can always be manufactured on a laser cutter (example: Figure 2).

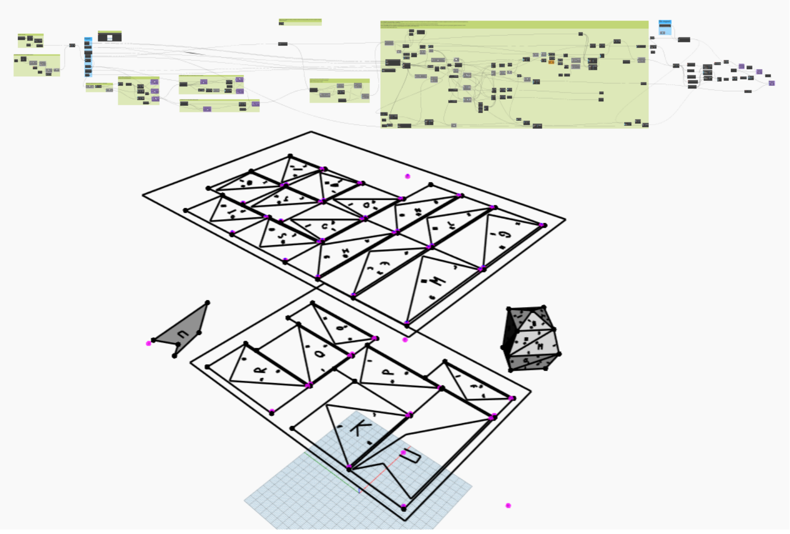

Figure 2. Generated 2D shapes and annotations for laser cutting instructions, organised by sheet.

The first few of these instruction lessons revolved around annotating the planar parts to allow for easy recognition of shapes and their neighbouring shapes in the larger geometric input form (example: Figure 1) with assembly instructions that allow for fast assembly once the shapes are processed by the laser cutter, a simple box packing algorithm (not optimised for material waste for a triangular mesh but quite fast in terms of calculation time) that creates several DXF files with each file containing shapes that fit on a sheet with given dimensions (sheet dimensions available for varying by material), and a script that creates dovetail connections along the edges of a given shape so that assembly can be carried out with no extra materials or glue needed (example: Figure 3). In the fifth instruction session, these scripts were combined in one master script, allowing the students to fabricate and assemble their design iterations as fast as the laser cutter can produce them. The gradual approach also helps students recognise the part of the final combined script that performs each function. This allowed students to make small adaptations to the script for personal experimentation or further design iterations.

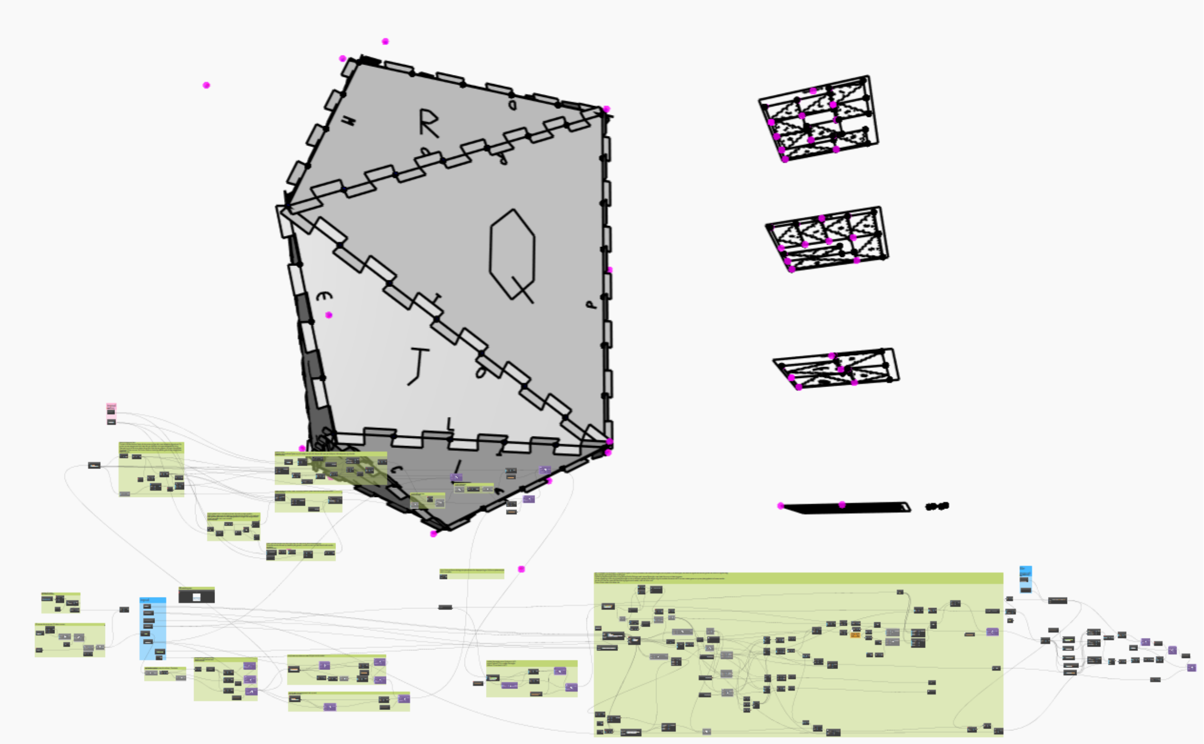

Figure 3. Dovetail connections integrated with the mesh shapes, and an overview of the combined script.

Lessons learned:

- It appears to be very difficult to keep students invested in making iterative improvements or trying new experiments. This seems to be unrelated to the course material described here. Setting clear short-term goals can mitigate this hesitation, but this can also cripple a sense of autonomy. The audience appreciates the pointers.
- Once their creative process takes a student in a direction that does not favour dovetail connections between elements, the given scripts lose their relevance. The assignment and given examples should favour solid faceted design proposals.
- Attempts to cater to different design concepts by adding scripts to the curriculum often results in missing the mark for the students engaged with a targeted design concept and lowers the relevance of the course material for other students. This should only be attempted after most students have successfully applied the combined master script to boost their iteration process.

Further possible experimentation in robotics: An earlier iteration of this course involved a script to place bricks along a double-curved surface (Figure 4). It did not contain an algorithm to predict the stability of the resulting structure, but it did garner a lot of enthusiasm among the students. If we could swap out the laser cutter for a robotic brick assembly installation, we would have another design vector for the students to explore and iterate.

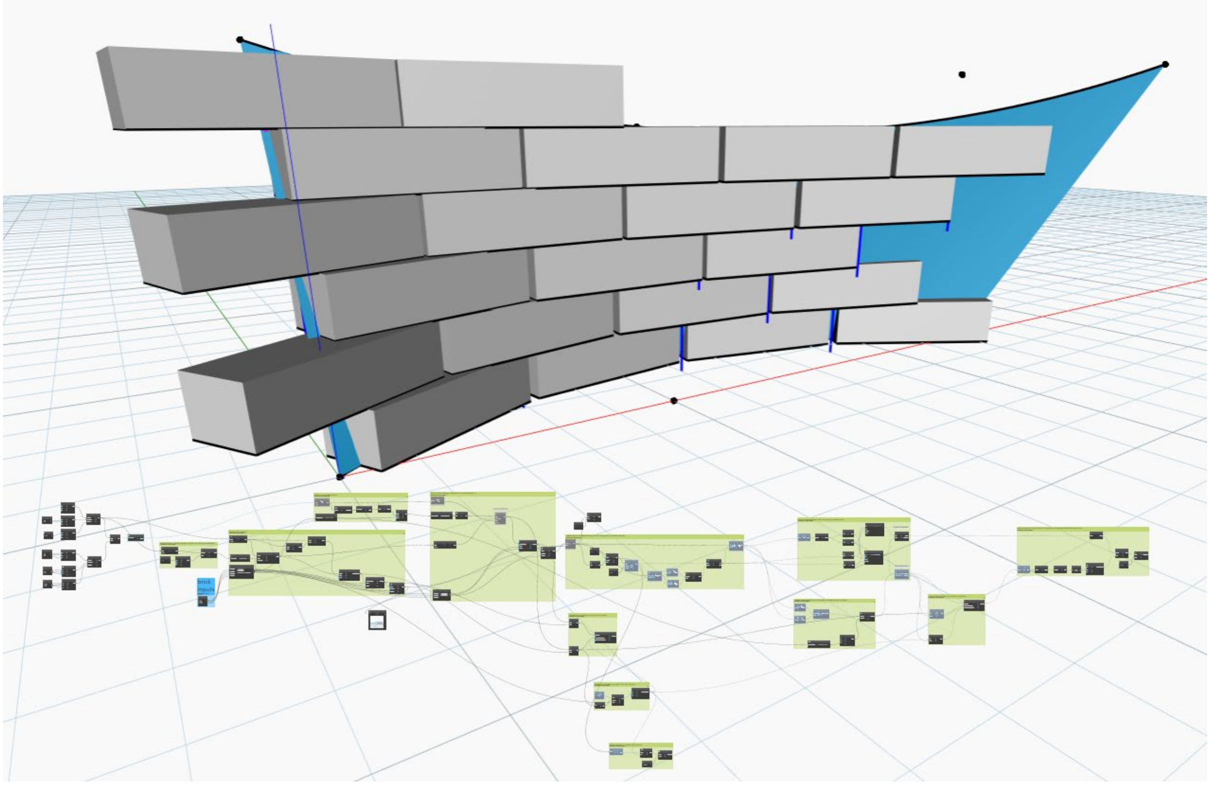

Figure 4. Bricks stacked along a double-curved surface.

Acknowledgements

I would like to thank the educational unit's coordinator Cees Verweij for giving me leeway to write the required course materials and experiment with the course setup. I would like to thank the students for putting up with being experimented with and for coming up with the dovetail connection.

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A hybrid learning environment for collaborative learning in architectural robotics

Serdar Aşut

Delft University of Technology, Faculty of Architecture an Built Environment, Department of Architectural Engineering and Technology, Chair of Design Informatics – s.asut@tudelft.nl

Keywords: Hybrid Learning Environments, Virtual Reality, Architectural Robotics, Human-Robot Interaction

Extended Abstract

We present a Hybrid Learning Environment (HLE) that supports collaborative learning in architectural robotics. The demand for robotics education has been growing owing to changes in related industries. This education requires specific physical equipment and skilled instructors, making it both time- and resource-intensive. To address this issue, new teaching methods and technologies are needed to make them more accessible using scarce resources. We introduced an ongoing project that responds to this need by integrating Virtual Reality (VR) and Human-Robot Interaction (HRI) technologies in an educational context. This project addresses educational activities in study programmes in which hands-on design thinking is fundamental, such as architecture, building technology, and product design studies. These programmes involve courses in which students use tangible tools and materials to develop, analyse, and present their ideas. They built physical models and prototypes to explore the spatial and material qualities of a design concept and to understand how a design would work in the physical world. These models are tools for students to think and interfaces for communication between fellow students and educators.

Similarly, this project focuses on a course that introduces students to architectural robotics in the Building Technology MSc. programme. It is a hands-on course based on experiential learning and learning-by-doing using a physical fabrication laboratory equipped with a UR5 robotic arm. In this course, students learn how to program and operate the robotic arm and use it to assemble a complex architectural design (Figure 1). There is a growing interest in the student community following this course. However, it is only offered to a limited number of students because of limited resources. The project aims to make education on this subject more accessible by enhancing the utilisation of existing infrastructure and staff hours, enabling students to personalise their learning experiences based on their skills and expectations, and ensuring continual access to the laboratory by utilising developments in online and blended learning. Moreover, it aims to enrich education through constructivist learning approaches that facilitate student-centred learning, aligning with theories within educational sciences (for example Bashabsheh *et al.*, 2019; Marougkas *et al.*, 2023).

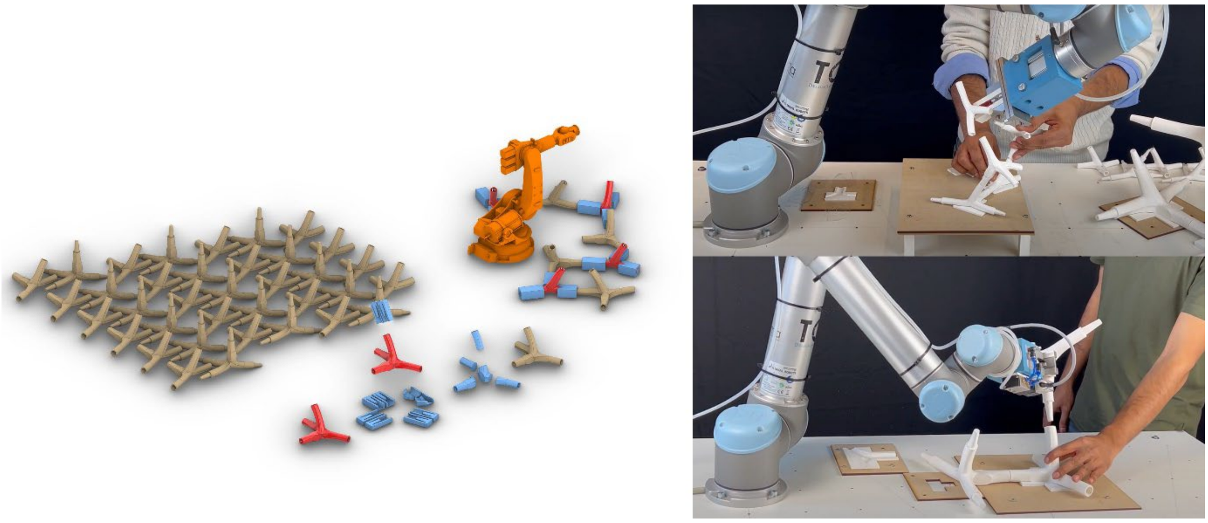

Figure 1. Example of a student project in which the robotic arm is used for discrete assembly of an architectural design.

According to (Norberg *et al.*, 2011), online and blended learning is a new normal, and they increase access to education for students, responding to their lifestyles through flexible learning opportunities. Current multimedia-based materials and platforms are fairly efficient and are widely used for audiovisual and verbal communication in online and blended learning. However, they cannot replace a workspace with physical materials and tangible tools such as model-making workshops or laboratories.

The technology of HLE was developed following related studies that aimed to integrate virtual environments with robotic fabrication (e.g., Cimino *et al.*, 2019; Coronado *et al.*, 2023; Dianatfar *et al.*, 2021; Wang *et al.*, 2018). It was developed by creating a digital twin of the existing laboratory and combining the two environments for real-time interaction. A digital twin was created using the Blender and Unity software. Communication between the virtual and physical workspaces is achieved through Transmission Control Protocol (TCP) (Figure 2) and a dedicated Web Server developed using JavaScript.

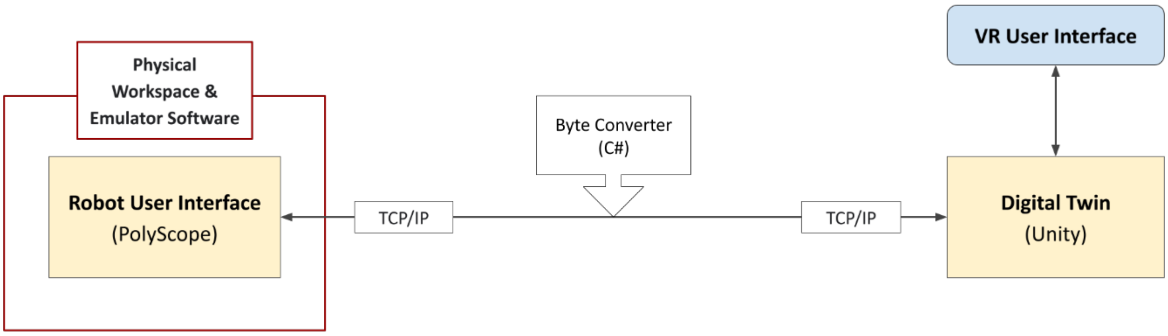

Figure 2. The diagram illustrating the communication between the physical robot and its digital twin through TCP.

The HLE enables students to practice the learning exercises in the virtual environment, allowing the scaling of the education to more extensive groups while making it possible for the students to experience customised learning based on their changing needs and skills. In addition, it enables hybrid real-time collaboration between students and teachers, in which some users participate on-site, while others participate remotely.

Currently, tailor-made learning exercises are being developed to effectively utilise HLE and integrate it into courses. A series of test workshops was implemented to assess and improve its functionalities (Figure 3). These workshops demonstrated that the learning experience through VR is more intuitive, engaging, and realistic than the standard computer setup. This facilitates enhanced robot observation from multiple angles, helping in a comprehensive 3D understanding of its operations. Therefore, the empirical analysis of the initial project outcomes confirms that the acquisition of robot programming and operational skills can be sustained in a blended format by adopting an HLE that integrates the physical workspace with its digital twin in a VR environment. Moreover, it can facilitate effective remote and on-site collaboration, provided that communication methods are defined and well structured within the learning exercises.

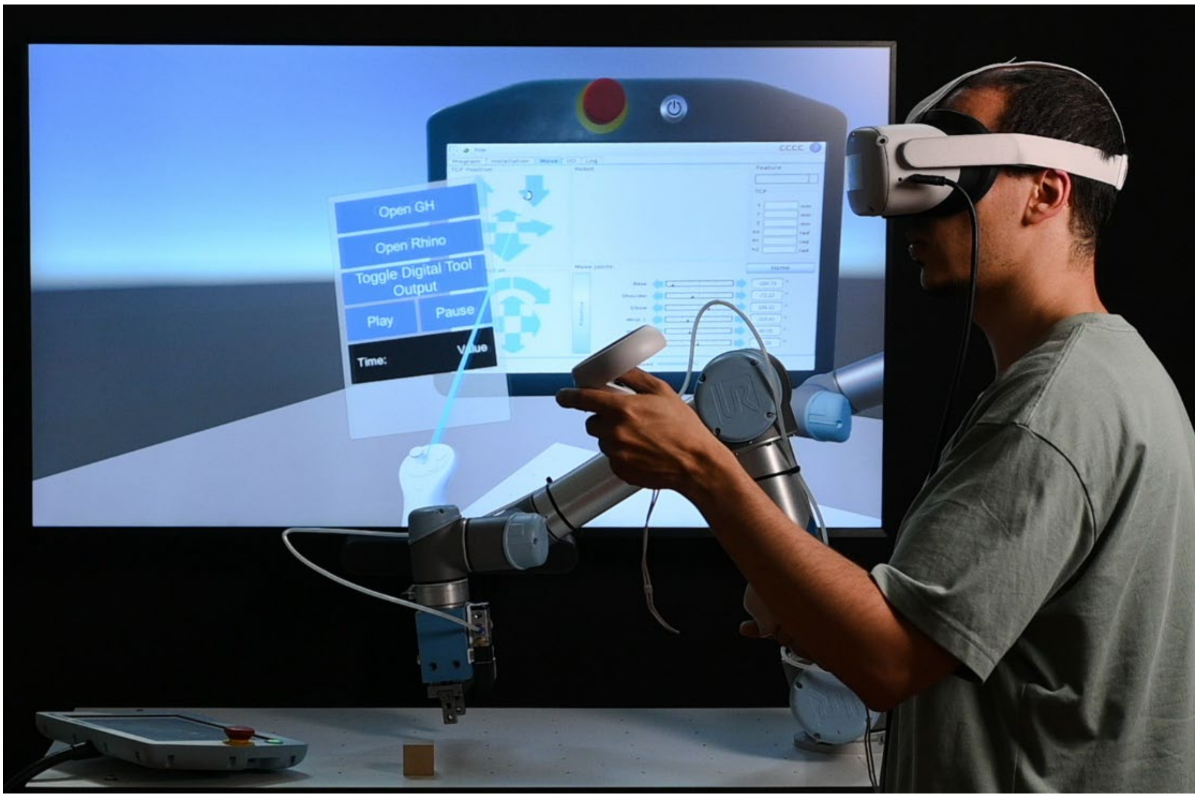

Figure 3. An image that shows the HLE in use.

According to the findings of this research, the most effective approach for establishing communication between a physical robot and its digital twin is to use the TCP protocol and manage the traffic between several software and hardware through a custom web server. This choice for TCP is justified by its capacity to mitigate latency issues, cost-free nature, and integration within existing robot software. The web server is used for accessible communication between several platforms, including multiple users. Using this method, multiple users can collaboratively participate in learning activities, enabling a blend of on-site and remote engagement.

Several aspects, including hardware accessibility, network safety, and network speed, must be discussed for future improvements in HLE. They can also incorporate tactile sensations into the VR experience and adopt a multisensory and multimodal approach for more effective learning. Learning exercise design plays a crucial role in the effective use of HLE. Collaboration between on-site participants and those engaging remotely requires precise structuring of learning exercises. They should include strategies to communicate information effectively. Eventually, the development of HLE will provide useful insights into the development of similar hybrid environments that can be used in actual fabrication tasks at construction sites.

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Shifting gears, shifting paradigms: entrepreneurial considerations for construction robotic firms

Alexander N. Walzer[1], Daniel M. Hall[2]

[1] Federal Institute of Technology Zurich, Department of Civil, Environmental and Geomatic Engineering, Institute of Construction and Infrastructure Management, Zurich, Switzerland – awalzer@ethz.ch
[2] Delft University of Technology, Faculty of Architecture and Built Environment, Department of Management in the Built Environment, Delft, The Netherlands – d.m.hall@tudelft.nl

Keywords: Entrepreneurship, Innovation, Socio-economics, AEC, VC, Robotics.

Extended Abstract

In the rapidly evolving organisational fields of construction robotics and digital fabrication (DFAB), the pace of technological advancement contrasts with the slow rate of adoption within the industry. This discrepancy raises critical questions regarding the factors influencing the integration of these innovations into construction practices. In response, entering its concluding phase, this doctoral study reexamines the seminal frameworks that Kangari and Halpin (1990) and Brown and Katz (2009) established. This project aims to uncover the complex dynamics that govern the adoption of construction robotics and DFAB technologies by embracing multiple research paradigms. This approach acknowledges the multifaceted nature of technological integration, suggesting that barriers to adoption extend beyond technical considerations to encompass a broader range of socioeconomic, organisational, and cultural dynamics.

For the past decade, DFAB research has predominantly focused on assessing technological feasibility (e.g., see Taha *et al.*, 2019; Ma *et al.*, 2020) and has been rooted in design science methodologies and demonstrator projects (Graser *et al.*, 2023). This focus is suitable for technologies with low readiness. However, as these technologies evolve, a compelling argument can be made from a broader analytical perspective. As such, this doctoral research project aims to explore the dynamics of innovation and its economic integration within the construction sector by weaving together insights from entrepreneurship, construction management, and socioeconomic factors. The distinctive core element of this study is its diverse methodological approach. This approach is crucial for challenging the convention that limits the discourse to technical utility and is done through three independent studies (see Figure 1).

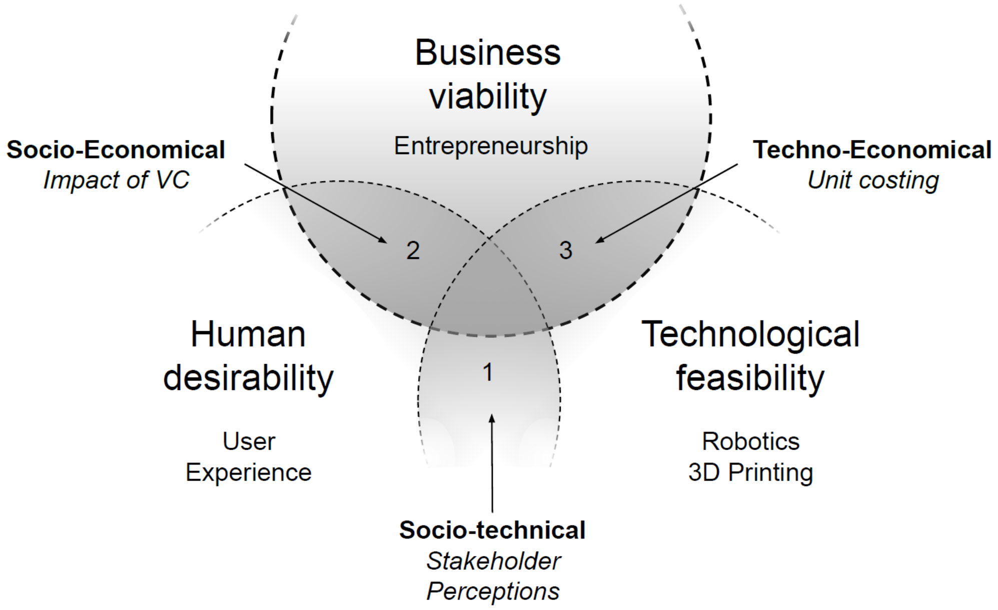

Figure 1. Overview of the doctoral research project and its three involved studies.

At the outset, a significant gap in the existing literature was identified: the limited understanding of construction professionals' perceptions of robotics and DFAB. To address this, the first study leverages a mixed-methods approach, combining qualitative interviews (n=5) with quantitative surveys (n=2) to gain insights into stakeholders' perceptions (N=161). Based on binary logistic regression, this approach yields insights into robot design, which in turn offers implications for usability, functionality, and job security (Walzer *et al.*, 2022). These insights mark a progressive step in understanding the assimilation of construction technology into industry practices from the perspective of stakeholder perceptions.

In the second study, the doctoral project focused more on the socioeconomic landscape, specifically the role of venture capital (VC) in the construction robotics sector. This study used a qualitative approach based on semi-structured interviews (N=127) and an abductive thematic analysis. Employing the analytical lens of institutional logic, this study highlights the economic considerations of technology adoption and identifies the alignments and misalignments between founders and investors (Walzer *et al.*, 2024a). However, such divergences could benefit industry innovation and are discussed as potentially leading to new practices that require more longitudinal studies.

Finally, the third study includes a more comprehensive economic approach to the role of production uncertainty by employing quantitative methods that enrich this doctoral research. This study combines scenario, sensitivity, and uncertainty analyses, mainly focusing on concrete 3D printing, to assess the potential for economies of scale and cost efficiency (Walzer *et al.*, 2024b). This exploration contributes to the economic viability of emerging production technologies and furthers the discussion of their economic feasibility and scalability.

In conclusion, this doctoral project significantly contributes to our understanding of the complex dynamics surrounding the adoption and integration of construction robotics and DFAB through its diverse topics and methodologies. It interlinks technological, socioeconomic, and institutional perspectives, offering a holistic framework for probing the implications of these technologies in the construction industry. Through three independent studies, this research project enhances the comprehension of how construction technology innovations assimilate into industry practices, potentially highlighting their implications for the sector's future.

Acknowledgments

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Digital crack recognition in dikes

Erik Ellinger

Inholland University of Applied Sciences, Research and Innovation Centre Data Driven Smart Society, The Netherlands – erik.ellinger@inholland.nl

Keywords: Digitalisation, Robotics

Extended Abstract

The North Holland Water Board (HHNK) is responsible for 1586 km of dikes and dunes, along the coast, along canals and lakes and around polders. The HHNK must maintain, manage and, if necessary, reinforce these. One of the long term goals is an automated risk-based analysis of dike safety based upon an integrated dataset consisting of data with regard to cracks, fauna, water levels, precipitation, grass moulds, vegetation and so on.

The dikes were inspected several times a year. Inspecting dikes is still a labour-intensive process in which a group of levee inspectors check in groups of two dikes on site and log (severe) damages in an app. This study investigates whether visual inspection can be automated using AI techniques. Therefore, attention is paid to which data are needed, how the data are to be labelled and pre-processed, and what deep learning algorithms work best.

The first proof of concept (POC) "Dike inspection" (Stenfert *et al.*, 2021) focussed on the detection of cracks and fractures in the top layer of the dike. Using still images collected by drones flying over the dikes, a neural network checks for cracks and fractures. If cracks or fractures are detected inspectors can examine the situation in the field. In this way, low-risk areas can be inspected with a lower frequency or not at all, leaving more time for more thorough inspection of areas where the risk is higher.

POC showed that a neural network could detect cracks based on drone images. To train the neural network, specialists manually labelled the cracks in 1800 drone images, as shown in Figure 1. The labelled images were fed into the network (the network was *trained)*. From the manually labelled images, the network learns to recognise cracks in the new images. A U-net neural network was used for the proof of concept. This type of neural network is often used to segment images and is relatively easy to train[1].

Only 609 images from two locations were available, indicating that the algorithm did not receive sufficient input to properly learn patterns from the cracks. A method that is frequently applied in Machine Learning in the event of data scarcity is "Data augmentation." Based on available images, this method generates additional data in a synthetic manner. This method has been proven[2] effective in enlarging datasets for segmentation problems. Consequently, 11302 images were available to train the model.

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[1] https://en.wikipedia.org/wiki/U-Net

[2] https://journalofbigdata.springeropen.com/articles/10.1186/s40537-019-0197-0

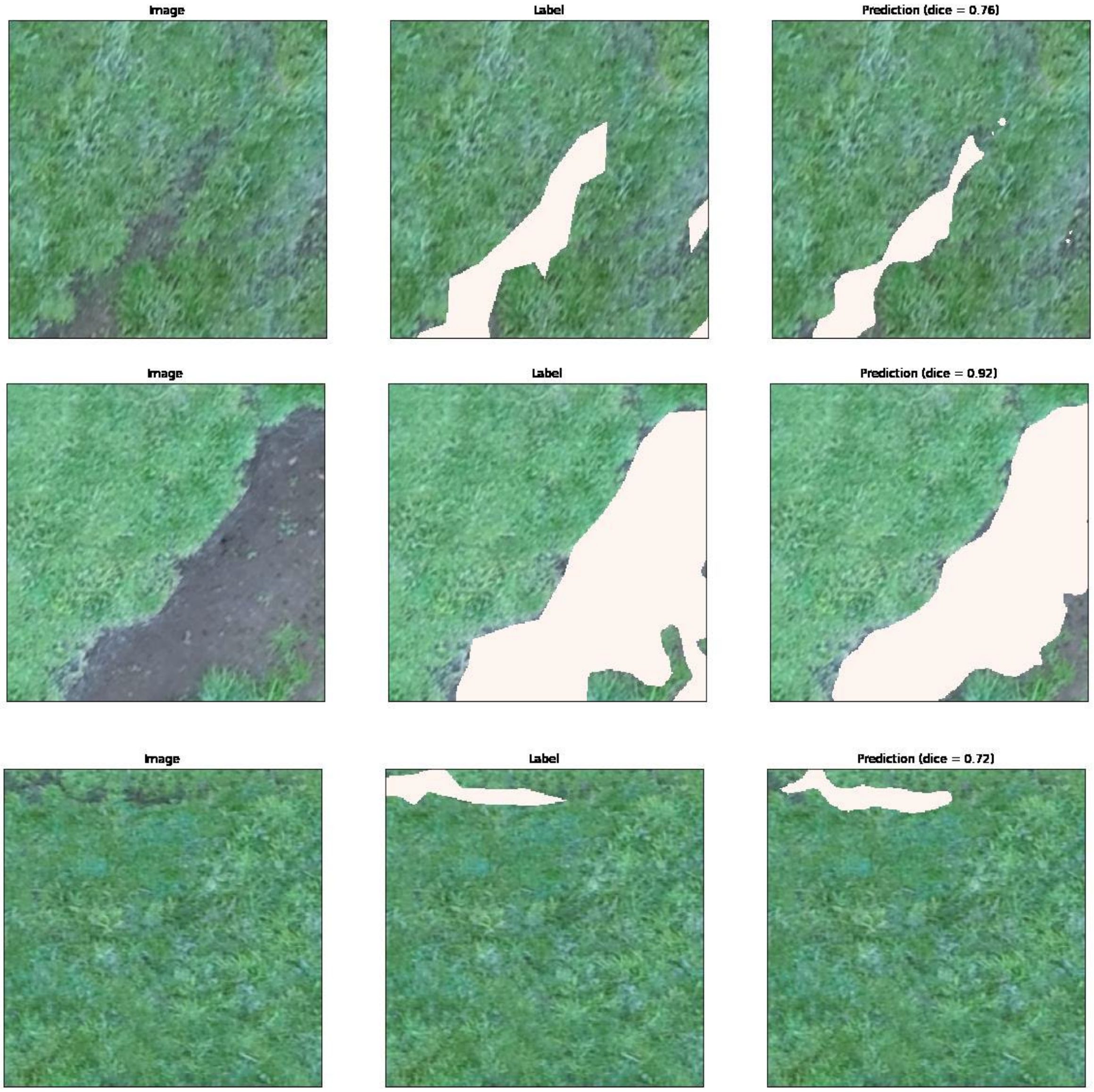

Figure 1. Image, labelled image and crack recognition

At the first test location, 73% of the cracks were correctly predicted. A false alarm occurred 93 times, which means that a crack was predicted while it was not labelled. However, at the other locations, the predictions were less correct: 43% of the het cracks were predicted correctly, and there were 1001 false alarms due to many molehills in the collected images. In addition, many open areas were incorrectly labelled as cracks during labelling.

These results show that the network has the ability to detect cracks that have never been detected before, but improvements are still needed before implementing the algorithm in an operational system.

To make image collection effective, it is necessary to inspect more types of damage in a single drone flight. Therefore, a follow-up project is to expand the algorithm to detect elements other than cracks (Stenfert *et al.*, 2022). This can be used as a filter method for finding cracks in asphalt covering or vegetation in stone revetments. Once the covering is known, a targeted search can be performed for cracks or vegetation in a specific covering part. In addition, this cover can be recorded in the official geological registers.

In this project, we first trained a network to recognise the type of dike *covering*: grass, asphalt, water, or reed. To train the network, the same set of images was used for crack detection. In these images, water, reeds, grass, and asphalt coverings were manually labelled.. Table 1 shows the percentage of occurrences of each covering that the algorithm recognised correctly.

Table 1 Confusion matrix prediction/algorithm percentages. The white cells show the percentages of correctly recognised coverings of each type.

		Prediction				
		Nothing	Water	Grass	Asphalt	Reed
Correct	Nothing	**85.10%**	1.00%	13.40%	0.30%	0.20%
	Water	20.80%	**60.60%**	2.30%	0.10%	16.20%
	Grass	11.40%	0.20%	**86.10%**	0.50%	1.80%
	Asphalt	16.30%	4.30%	7.90%	**71.40%**	0.10%
	Reed	7.10%	4.60%	16.80%	0.10%	**71.40%**

In addition to cracks, burrowing animals are another major factor that poses a threat to dikes. Animals such as beavers, muskrats, moles, and rabbit dig holes, which can weaken the dikes. Therefore, a follow-up project for fauna detection was initiated. The goal is to develop a neural network that can discover the presence of animals that might be damaged. Regular drone images are less suitable for this task because animals often hide in reeds and other vegetation. It is currently being investigated whether neural networks can recognise animals based on infrared images made by drones.

Further development of the algorithm and simplification of the process of collecting and processing data are necessary to ensure robust operation at new locations in new circumstances. A successful implementation can only be realised if the algorithm is used in the work processes of the organisation. It is important for the organisation to learn to work with this type of analysis. This requires changes to the current inspection process, existing work processes, and organisation of inspection and monitoring. Eventually, by combining all computer vision research projects conducted by HHNK, a truly highly automated risk-based analysis of dikes can be created.

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Thematic session 2:

Artificial Intelligence

Towards enhancing AI-based crack segmentation for masonry surfaces through 3D data set synthesis

David Boerema[1], İhsan Bal[2], Eleni Smyrou[2], Jiří Kosinka[1]

[1] University of Groningen, Bernoulli Institute, Groningen, The Netherlands –
{d.h.boerema, j.kosinka}@student.rug.nl
[2] Hanze University of Applied Sciences, Research Center for Built Environment NoorderRuimte, Groningen,
The Netherlands – {i.e.bal, e.smyrou}@pl.hanze.nl

Keywords: Masonry, Crack Segmentation, Convolutional Neural Network, Synthetic data.

Extended Abstract

Automated crack detection and segmentation for concrete and masonry surfaces has been a field of interest for many years now, as it can provide many benefits like early detection of structural damage without the need for manual inspection. This task has traditionally been tackled manually or by using image processing techniques, but over the last few years neural networks have shown to be more effective (Deng *et al.*, 2022). The downside to this approach, however, is that neural networks typically rely on large volumes of high quality and diverse data for model training. This data is often expensive and time-consuming to collect and inconsistent due to the manual annotation required. Especially for tasks like crack segmentation on masonry surfaces, which are more complex than the standard concrete segmentation, this becomes a problem (Özgenel *et al.*, 2018).

In the past, this data collection issue has been mitigated by using 2D synthetic image generation approaches for concrete and pavement surfaces (Barisin *et al.*, 2022; Rill-García *et al.*, 2022; Lee *et al.*, 2019; Xu *et al.*, 2023). One might be able to boost the performance of a neural network by padding an existing data set of real images with synthetic images such that the data set becomes larger and more diverse. The key downside to these approaches however is their applicability: it is very hard to generate complex and realistic 2D crack images from scratch given a set of parameters such that they fit the function of the existing data without reusing the existing data. Because of this, many approaches either overlay cracks on top of existing images or use noise to generate crack-like shapes (Lee *et al.*, 2019; Xu *et al.*, 2023). These methods have shown to improve the segmentation performance on concrete surfaces, but are not applicable for masonry surfaces due to their simplicity. Cracks in masonry surfaces are often harder to distinguish from the surface and are formed based on the shape of the surface, which is hard to replicate using existing 2D image generation methods.

To address the challenges of data collection and synthetic data generation for masonry surfaces, we propose a novel data set generation framework that can generate semi-realistic cracks in masonry surfaces in 3D. The use of 3D scenes allows for more complex and realistic data set generation compared to previous 2D approaches as the data set is a result of direct modelling rather than image manipulations. 3D approaches have also shown to result in performance improvements for segmentation tasks (Ros *et al.*, 2016). The proposed framework consists of 3 components: 1) scene modelling, 2) crack generation and 3) scene composition and rendering. Scene modelling allows a domain expert to model complex 3D scenes in the Blender 3D modelling software which can then be used for data set generation through framework bindings. Secondly, the crack generation component projects the wall surfaces from the 3D scene to a 2D mask which is used for iteratively generating cracks using a semi-realistic pivot point algorithm. Finally, the generated 2D crack is projected back into 3D and a scene is composed from which an image and label are rendered. These components allow the framework to generate data sets of arbitrary size and complexity through the modification of the 3D scene and framework parameters. Figure 1 shows examples from a synthetic data set generated by the framework.

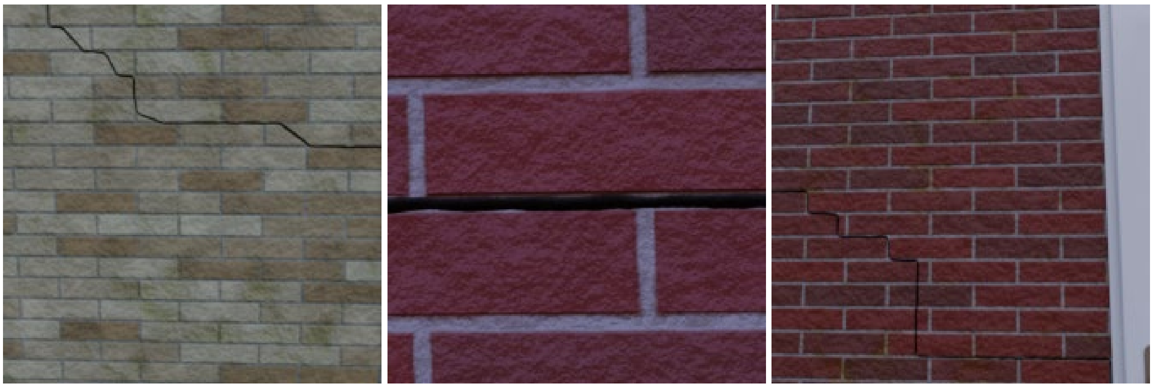

Figure 1. Examples of artificially generated cracked masonry walls.

Using partially synthetic datasets, we were able to match the segmentation performance of non-synthetic datasets for a segmentation network developed at the Hanze University of Applied Sciences in a previous study (Dais *et al.*, 2021). This network was originally trained on a large volume of real data, but we show that by mixing different ratios of synthetic data, we can achieve similar segmentation performance while relying on a smaller real dataset. In total, two synthetic datasets were generated using different render approaches and combined with two real datasets to create 12 datasets with different synthetic-to-real data ratios. These datasets were then trained and tested on the segmentation network, resulting in multiple networks trained on partially synthetic data to achieve an F1-score of approximately 72%, similar to the results of the real datasets. By analysing the effects of data filtering, synthetic to real data ratios, and differences within the synthetic datasets, insight is gained into the influence of dataset composition on the segmentation results. Additionally, the results of the framework demonstrate the potential for future extensions and applications of 3D dataset generation for different construction surfaces.

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Supplementing clustering techniques with regression analysis for uncovering energy behaviour patterns in buildings

Noelle Choong

The Hague University of Applied Sciences, Future Urban Systems Research Group, The Hague, The Netherlands – n.b.y.choong@hhs.nl

Keywords: Machine Learning, Energy Consumption, Building Data Analysis, Air Infiltration

Extended Abstract

In response to the pressing issue of energy conservation, predictive building control strategies have become increasingly popular over the last decade. These control strategies use data-driven models that aim to mitigate inefficiencies in building operations by forecasting energy demand and optimising energy use in buildings (Castilla *et al.*, 2014). While predictive control strategies have significantly advanced (Taheri *et al.*, 2022), more research is needed to acquire deeper understanding of energy consumption in buildings. Existing literature predominantly focuses on using energy consumption data for refining predictive models (Chen *et al.*, 2022), thereby neglecting the development of methods essential for analysis. Contrary to focusing on refining predictive accuracy, this current research prioritises methodological innovation that may offer practical insights in the underlying dynamics of building energy behaviour to suggest broader pathways towards informed energy management practices. Among various techniques, clustering has proven effective in grouping similar observations based on their similarities (Deng *et al.*, 2021; Tardioli *et al.*, 2018; Wickramasinghe *et al.*, 2022). However, deriving practical insights from the data post-clustering remains yet another underexplored domain.

This study explored the benefits of using regression analysis subsequent to k-means clustering. This study aims to enrich the analytical toolkit for dissecting and understanding building energy consumption patterns. The subject building, a cultural heritage site in The Netherlands, is an office building that employs model predictive control (MPC) for energy management. It is divided into two adjacent zones: east- and west-oriented. This study focused on the impact of infiltration on indoor zone temperatures, as the infiltration-induced heating load constitutes a significant portion of the total energy demand in buildings(Younes *et al.*, 2012). Infiltration occurs when outdoor air unintentionally enters the building through small openings and cracks in the building envelope. Hence, this study examined the impact of outdoor temperature and wind direction on indoor temperature gain in the building zones of a subject building. The data collection period spans from 21 September 2022 to 21 March 2023, encompassing the colder months of the year in The Netherlands. In addition to the energy consumption data collected by the MPC, this study used weather data measured by the Royal Netherlands Meteorological Institute (KNMI), which describes the prevailing meteorological conditions during the observation period.

After collecting and structuring the data, the k-means clustering algorithm partitions the data points based on similarities in the outdoor temperatures and wind direction. Cluster 1 consists of data points associated with wind directions from the northeast and lower outdoor temperatures, while Cluster 2 is characterised by southwest winds with higher outdoor temperatures (Table 1). Subsequent linear regression analysis within each cluster elucidated the relationship between the indoor temperature gain and heat transfer into the building zones, as depicted in Figure 1.

Table 1. Statistical description of formed clusters.

		Temperature gain Zone 1	Temperature gain Zone 2	Outdoor temperature	Wind direction	Manifold temperature (supply-return)
cluster1: NE	count	33	33	33	33	33
	mean	0.43	0.55	2.43	85.56	4.10
	std	0.33	0.28	3.73	89.24	0.51
	max	1.20	1.10	11.40	360.00	5.33
	75%	0.60	0.80	4.00	90.00	4.30
	50%	0.40	0.50	2.20	70.00	4.05
	25%	0.20	0.30	-0.10	40.00	3.91
	min	-0.20	0.00	-5.40	10.00	2.72
cluster2: SW	count	92	92	92	92	92
	mean	0.35	0.47	7.47	207.62	3.36
	std	0.33	0.38	4.04	34.10	1.04
	max	1.10	1.20	16.30	284.17	5.78
	75%	0.50	0.60	10.33	230.00	3.96
	50%	0.40	0.40	8.00	210.00	3.55
	25%	0.10	0.20	4.98	190.00	2.74
	min	-0.30	-0.30	-5.30	125.00	-0.13

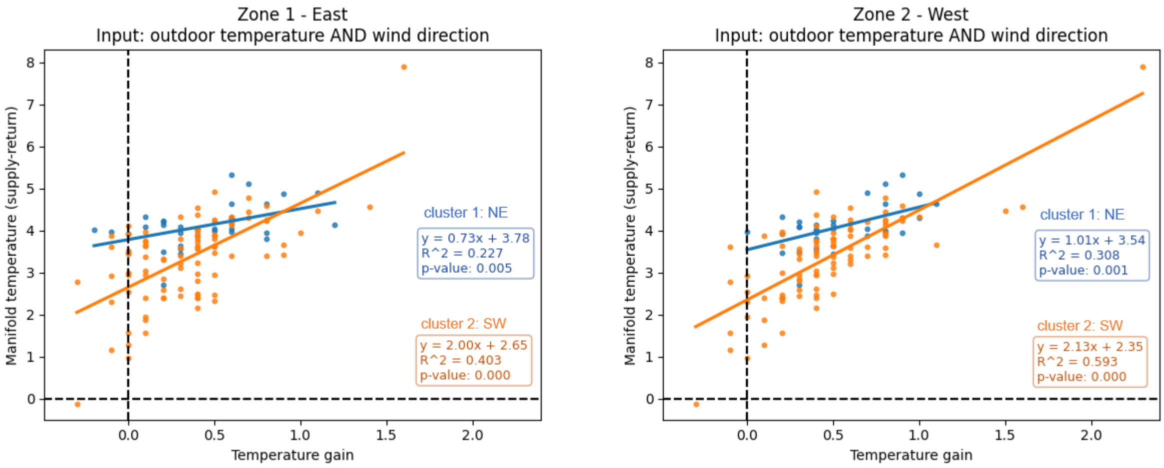

Figure 1. Relationship between heat transfer and indoor temperature gain in the east (left) and west (right) zone.

Regression analysis revealed that indoor temperature gain is significantly influenced by wind direction, requiring more than twice the amount of heat transfer in conditions with southwest winds compared with when winds originate from the northeast. Furthermore, the differences in R-squared values indicate a stronger linear relationship in the west-oriented building zone between heat transfer and indoor temperature gain in this building and using this combination of input features in the k-means clustering algorithm.

In conclusion, this study demonstrates that while the k-means clustering algorithm effectively groups similar observations, it is the application of regression analysis that uncovers energy behaviour patterns from the data. The most valuable result of this study is the synergised potential to uncover the differences across the formed clusters. This outcome transcends mere data classification for improving energy prediction, offering practical insights that may contribute to broader sustainability practices, such as verifying construction integrity and fostering socioeconomic interventions. Although the preliminary results are promising, more research is needed to validate the consistency of the differentiated results from this supplementary approach. In addition, future research should explore the use of other clustering algorithms in conjunction with regression analysis to enhance the practical value of the current research and the development of analytical methods for extracting actionable insights from building energy consumption data.

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AI-based roof tile recognition

Tilmann Koster[1], Jan Willem van Crabbedam[2], Orel Israel[3]

[1] Inholland University of Applied Science, Data Driven Smart Society Research Group, Design and Computer Science, Alkmaar, The Netherlands – tilmann.koster@inholland.nl
[2] Inholland University of Applied Sciences, Data Driven Smart Society Research Group, Design and Computer Science, Diemen, The Netherlands – janwillem.crabbendam@inholland.nl
[3] Inholland University of Applied Sciences, Applied Mathematics, Design and Computer Science, Diemen, The Netherlands – 666903@student.inholland.nl

Keywords: Digitalisation, Artificial Intelligence, Roof tiles, Circular economy, Computer Vision, Machine Learning

Extended Abstract

A successful implementation of a circular economy within the built environment needs a good digitalisation of materials and products. Only in case products and materials in a building are known, it is possible to set up quick and efficient “reuse planning” during demolish or renovation projects (Foldager Jenson *et al.*, 2023). Currently there is a lots of research about implementing digital material or product passports (Plociennik *et al.*, 2022). By having product passports, the products that will be released during renovation projects are known from the beginning and no intensive reengineering process of product identification is needed. Additionally, in an ideal situation buildings will be built modular, the building products will be known, interchangeable and reusable like in the automotive industry. Such digital products passports in combination with more modular constructions can finally lead to a circular economy in the built industry that supports reuse on the highest level.

Currently, circularity in the built industry is mainly implemented at the lowest level, which is the recycling of materials. The built industry still mainly uses one-time-use products that are not reusable, for which mostly no track records exist or when it exists than information is not easy to retrieve (e.g., hidden in different building information model files). For older buildings, this is always the case, and therefore, the identification of building products and materials requires time-consuming and costly investigation. Specialists are required to identify all the products and materials.

Artificial intelligence has great potential for speeding up the identification of building materials. AI models can be developed to automatically identify products or materials from photos. The research described herein demonstrates the opportunities and challenges associated with this idea.

Here, we focus on a particular building product, roof tiles. Roof tiles are very suitable for reuse because they are modular and easy to remove. Moreover, high-quality roof tiles have a long lifecycle. Therefore, a large second-hand market for roof tiles exists. One problem for

customers and second-hand dealers is that there are many different types of roof tiles that are mostly not interchangeable. In general, people struggle to identify the correct tiles needed during roof maintenance, and in most cases, a roof tile specialist is required for the identification of the correct type. The non-availability of knowledge at the right time often leads to renovation decisions where roof tiles will not be reused as products but will be down-recycled to materials.

In our project, we conducted research to explore the possibility of automating the identification of roof tiles using AI techniques. Within the research project, a neural network model (CNN) (Mishra, 2020) and other AI models and methods[1] (Gareth *et al.*, 2021) were used[2]. The input for the identification models was photos of the complete tiles, as shown in Figure 1. In general, two photos play a role in digital identification: one photo of the front and one photo of the back of the tile. It should be noted that the back of a tile contains the most specific characteristics that can be used to determine the difference between two tile types. The first picture below is the front, and the second is the back.

Figure 1. Example of tile images: front side [left] and back side [right].

In one approach, a neural network (CNN) was developed that could recognise nine different tile types. To create the model, 400 photos of each side of each tile type were required. The only prerequisite for a photo was that it contained the complete front or back of the tile and that only one tile was included in the photo. Such a model, as part of an app, could be used by house owners to quickly identify the type of tiles on their houses. A user simply takes two photos with their phone, and the AI model identifies the tile type.

In another approach, classical techniques for identification are used. Here, the photos used for identification must be taken in a restricted environment with stable light and a fixed distance between the camera and tile. These models distinguish between tiles based on their physical properties such as size and colour. These models can be used in roof tile stores: the house owner brings a tile to the store, where it is placed in the right position under the camera. The model then identifies the type of tile.

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[1] https://opencv.org

[2] https://www.tensorflow.org

The first results from our research show that it is possible to create AI models that can quicker and cheaper identify roof tiles and minimise the review time of specialists. However, it also showed that considerable efforts must be made before models with good results can be developed. Because 400 photos for each tile side had to be taken to develop a reliable neural network model, this approach is time consuming to extend to a large number of different tile types. The second approach does not require such a large number of pictures, but has the restriction of a stable environment.

For both approaches, it is challenging to distinguish between very similar tiles. In the first approach, it is difficult to distinguish whether the main difference is the size of the tile. In the second approach, it is difficult to distinguish tiles that have the same size but different patterns. Further research should be conducted to combine both approaches to achieve even better results for more difficult cases.

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Thematic session 3:

Digital Twins (at building scale)

An ontology-based framework for building material performance assessment

Julia Kaltenegger[1], Kirstine Meyer Frandsen[2], Ekaterina Pertrova[1], Pieter Pauwels[1]

[1] Eindhoven University of Technology, Faculty of the Built Environment, Information Systems in the Built Environment Group, Eindhoven, The Netherlands – {j.k.kaltenegger, e.petrova, p.pauwels}@tue.nl
[2] Aalborg University, Department of the Built Environment, Thomas Manns Vej 23, Aalborg, Denmark – kmf@build.aau.dk

Keywords: Artificial intelligence, Ontology engineering, Web development

Extended Abstract

Material Information Modelling (MIM) (Kaltenegger *et al.*, 2024) is a fundamental enabler of Building Performance Simulation (BPS) in the context of Architecture, Engineering, and Construction (AEC). In this regard, Building Information Modelling (BIM) (Borrmann *et al.*, 2018) enhances the richness, transparency and precision when exchanging data across building modelling and simulation tools. However, data exchange between BIM and BPS shows notable deficiencies, particularly in the granularity and precision of material information descriptions (Porsani *et al.*, 2021). While decomposition and information structures for building systems commonly follow international standardisation and building codes, the material data models miss a deeper vertical level addressing different granularities of material property data (Soust-Verdaguer *et al.*, 2023). As a result, material performance simulation in the context of BPS is commonly executed in separate, isolated workflows and software applications. Thereby, relying largely on manual information input and case-by-case management of their internal material property databases. Domain knowledge is kept in software-specific data silos while relying on uniform data definitions and standards for data sharing are crucial to improving BPS and making material data accessible in the design process. In other words, advanced material classification schema must be utilised in a BIM-based BPS, following the MIM approach. Adopting the Findable, Accessible, Interoperable, and Reusable (FAIR) principles holds significant potential for accurate MIM within the AEC domain.

This study introduces an ontology-based framework leveraging Semantic Web technologies (Berners-Lee *et al.*, 2001) and Linked Data (Bizer *et al.*, 2009) to support MIM for BPS and BIM. The framework relies on Ontology Engineering to represent the domain knowledge related to building material performance (i.e., hygric and thermal material performance). Systems Engineering, coupled with test-driven development, navigates through requirement engineering, semantic data modelling, system definitions, implementation, and validation processes. The main contributions of this work encompass a user-friendly web-based application (BIM-MAT) that delivers FAIR material property data to end users during the building design phase.

In the requirement engineering process, user groups are identified as architects, construction engineers, and material scientists. The user aims to access and analyse material-related performance of a 3D building model within a web-based environment. The hygric and thermal properties of materials are stored in machine-readable web-based databases and linked to BIM data modes. Hygric performance is represented by the water vapor sorption isotherm, commonly called the moisture content (MC). MC relies on the GAB Model, calculated using the Ad- and Desorption coefficients. The MC formula and example coefficients for wood fiber insulation are given in (1). Thermal performance is commonly expressed by Fourier's law and occurs because of thermal conduction in the building element layers (2). Each building element layer is described by Thermal Resistance (3).

Hygric Performance: Water Vapour Sorption Isotherm

$$MC = \frac{W_m * k * C * RH}{(1 - k * RH)(1 - k * RH + k * C * RH)} \tag{1}$$

Where:	Wm [-]	k [-]	C [-]	RH [%]
Adsorption	3.6604	0.992	5.399	0..90
Desorption	4.3621	0.936	6.393	0..90

Thermal Performance: Thermal Resistance

$$Q =\sim A \cdot \Delta T \tag{2}$$

$$R = \frac{d}{k} \tag{3}$$

Where: *A* Cross-sectional area of building elements
T [°C] Temperature difference across the material
d [m] The thickness of the material layer
k [W/m·K] Thermal conductivity of the material

The underlying data model follows ontology engineering implementation techniques and introduces Building Material Performance (BMP) ontology, as shown in Figure 1. BMP ontology captures the MIM data schema in a machine-readable manner and contributes to a structured representation of material classification and property definition. As such, it formally describes building elements, layer functionalities, material categories, material types, and material subtypes in line with international classification codes such as Eurostat (Eurostat, 2018) and other ISO standards. Material property classifications rely on the construction standardisation of object-oriented information modelling, for example, ISO 23386 (ISO, 2020) and ISO 12006 (ISO, 2015). Furthermore, the definition of property grouping follows specifications in building simulation sub-domains, for example, BPS thermal, physical, mechanical, and acoustic.

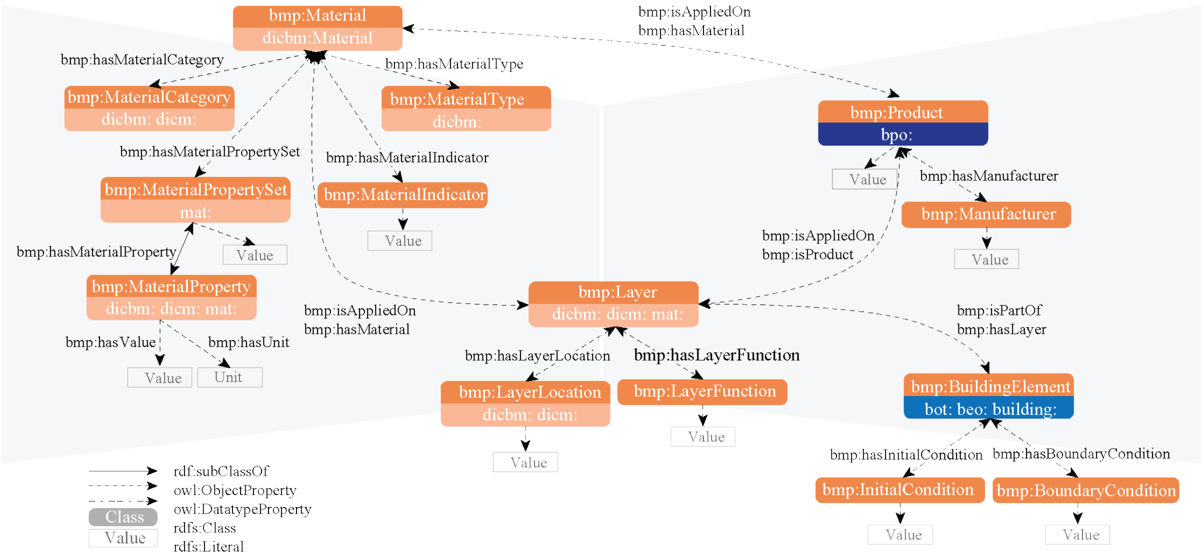
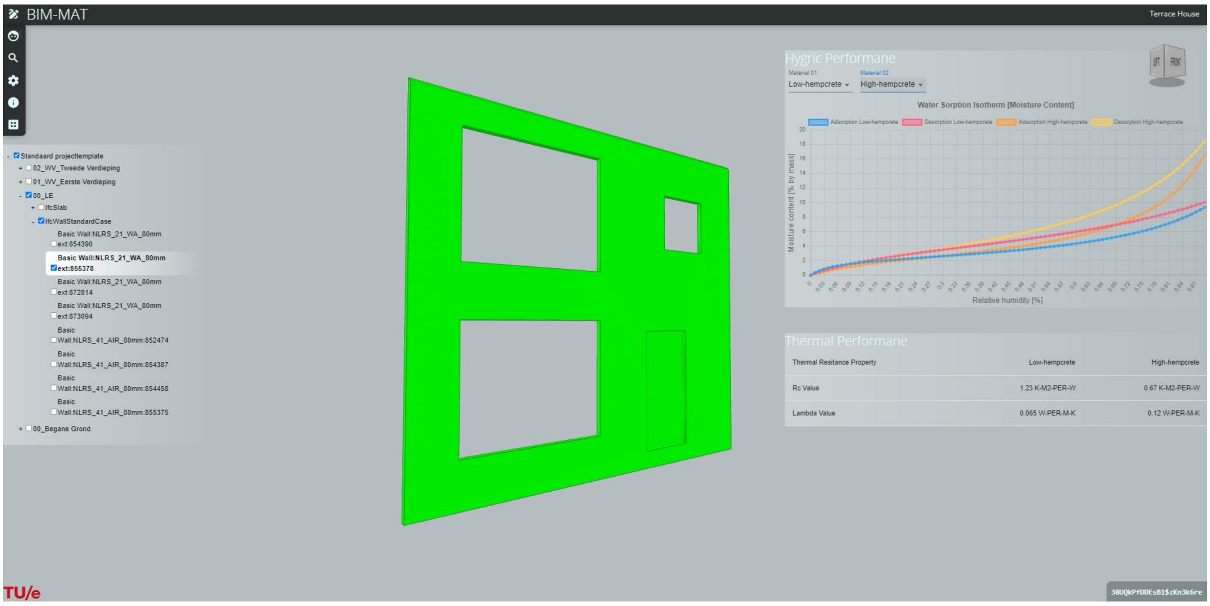


Figure 2. BMP Core Ontology (i) the material typology, (ii) the property classification, (iii) the element layers, (iv) the building element classification and (v) the manufacturing.

System development for the web-based application BIM-MAT follows a service-oriented system architecture. The application was built on the BIM-SIM API V1.0, as defined by Chamari *et al.* (2023). The BIM-MAT system architecture was structured into three subsystems. The first is the user interface (UI) and front-end components; the second is the Application Programming Interface (API) and back-end microservices; and the third is the databases and web-based data models. The front-end development followed Model-View-Control (MVC) design patterns. ReactJS is used as a framework, and UI components are Material UI and ChartJS library to present the material performance assessment results in tables and multi-line charts. Signia is used as a state manager to asynchronously initialise, execute, and update the states in the component functions. The back-end development framework uses microservices as a design pattern and NestJS, utilising Node.js as a runtime environment. The microservice design pattern structures the API components and subordinates material performance computations and other functional requirements. Furthermore, the REST API follows the open API specifications and uses endpoints to access the RDF databases, that is, Graph DB and Create, Read, Update and Delete (CRUD) operations.

The interactive UI allows users to engage with the building model inside the 3D web viewer by clicking on individual objects and applying material types from drop-down selection (see Figure 2). Material data from a sample database lists material types, such as stone wool and hempcrete, and their associated properties are aligned with the MIM data schema. As such, the inherent material properties were derived from the selected material types, and the hygric and thermal material performances were computed in line with the selected building object properties. Performances are visualised in data charts and tables, enabling the user to determine which material type and property performance best fits the condition of the building elements. Consequently, a residential building was used for validation. Design decision-making on an object level is supported as a benchmark of material performance. However, it lacks agglomeration of performance on a building scale, which will be addressed in future work.



Material 01: Low-hempcrete
Material 02: High-hempcrete

Thermal Resitance Property	Low-hempcrete	High-hempcrete
Rc Value	1.23 K-M2-PER-W	0.67 K-M2-PER-W
Lambda Value	0.065 W-PER-M-K	0.12 W-PER-M-K

Figure 3. BIM MAT Indicating Water Sorption Isotherm Component and Thermal Conductivity Component.

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Development of software solutions for advancing GeoBIM integration in digital twins

Amir Hakim, Siham El Yamani

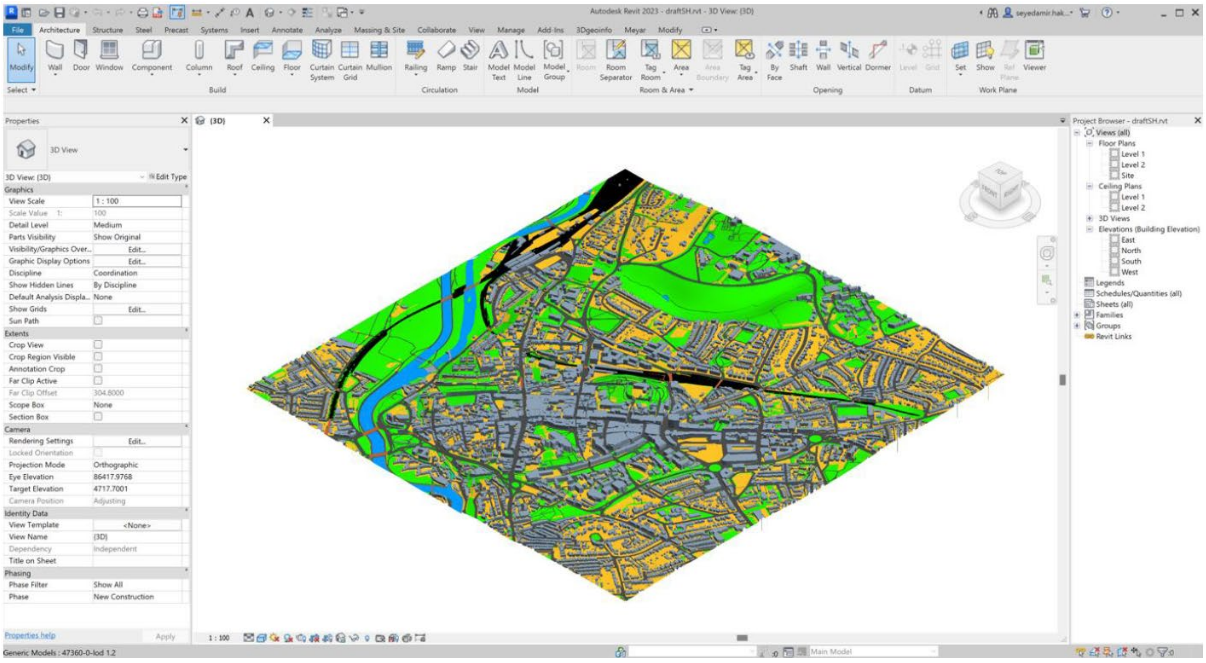
Delft University of Technology, Faculty of Architecture and Built Environment, Department of Urbanism, 3D Geoinformation Group, Delft, The Netherlands – {s.hakim, s.e.elyamani}@tudelft.nl

Keywords: Digital Twinning, GeoBIM Interoperability, Georeferencing, Geospatial integration, BIM.

Extended Abstract

The digitalisation of the built environment is a key challenge and opportunity for the construction industry. One of the emerging trends in this field is the development and use of digital twins, which are virtual representations of physical assets that can be used for simulation, analysis, and optimisation. However, creating and maintaining digital twins require interoperable and geospatially accurate data from different sources and formats. During the presentation, we introduce two software tools that have been developed by our team to facilitate the integration of geospatial and Building Information Modeling (BIM) data for digital twin applications.

The first tool is the CityJSON importer for Autodesk Revit, which allows users to import and visualise 3D city models in CityJSON format. By creating individual geometries for each city object and their associated attributes as parameters, the plugin empowers users to assess the environmental impact of the BIM during the design phase. This method promotes a unified workflow, simplifies the management of GeoBIM information within an integrated environment, and improves the interoperability between the geospatial and BIM data. The direct integration of CityJSON data into Autodesk Revit streamlines processes, preserves attributes, enhances analysis capabilities, fosters GeoBIM interoperability, and offers a specialised Revit solution, surpassing the need to convert CityJSON to IFC for Revit importation. Another distinction of this tool is its ability to generate individual objects separately. This is unlike existing tools, which primarily generate each file as a shell without separating each city object. During development, numerous challenges have been addressed, including georeferencing, data format importation, handling of different geometry representations, attribute hierarchies, code optimisations, user-friendliness, and improved visualisation.



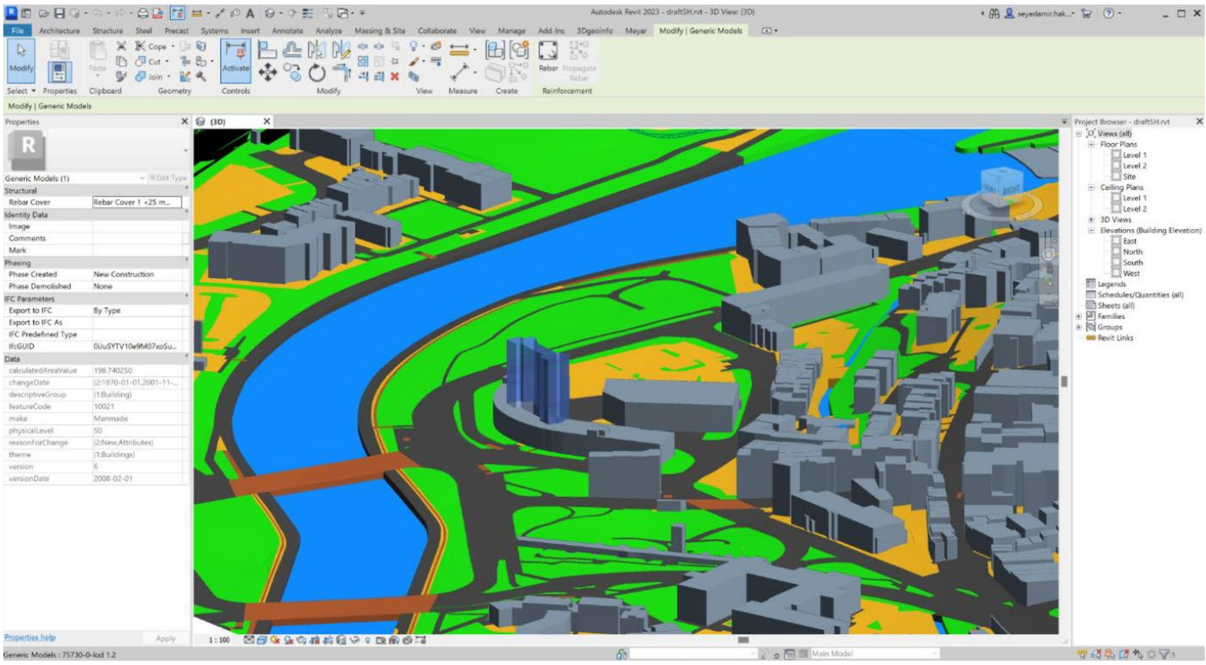
Properties

3D View

3D View: {3D}	Edit Type
Graphics	
View Scale	1 : 100
Scale Value 1:	100
Detail Level	Medium
Parts Visibility	Show Original
Visibility/Graphics Over...	Edit...
Graphic Display Options	Edit...
Discipline	Coordination
Show Hidden Lines	By Discipline
Default Analysis Displa...	None
Show Grids	Edit...
Sun Path	☐
Extents	
Crop View	☐
Crop Region Visible	☐
Annotation Crop	☐
Far Clip Active	☐
Far Clip Offset	304.8000
Scope Box	None
Section Box	☐
Camera	
Rendering Settings	Edit...
Locked Orientation	☐
Projection Mode	Orthographic
Eye Elevation	86417.9768
Target Elevation	4717.7001
Camera Position	Adjusting
Identity Data	
View Template	<None>
View Name	{3D}
Dependency	Independent
Title on Sheet	
Phasing	
Phase Filter	Show All
Phase	New Construction

Generic Models : 47360-0-lod 1.2

Figure 1. 3D City Model of Southampton, England created via CityJSON importer plugin.



Modify | Generic Models

Properties

Generic Models (1)	Edit Type
Structural	
Rebar Cover	Rebar Cover 1 <25 m...
Identity Data	
Image	
Comments	
Mark	
Phasing	
Phase Created	New Construction
Phase Demolished	None
IFC Parameters	
Export to IFC	By Type
Export to IFC As	
IFC Predefined Type	
IfcGUID	0UuSYTV10e9M07xoSu...
Data	
calculatedAreaValue	196.740250
changeDate	(2:1970-01-01,2001-11-...
descriptiveGroup	(1:Building)
featureCode	10021
make	Manmade
physicalLevel	50
reasonForChange	(2:New,Attributes)
theme	(1:Buildings)
version	6
versionDate	2008-02-01

Generic Models : 75730-0-lod 1.2

Figure 2. Visualisation and selected geometry information from Southampton City Model in Autodesk Revit Software.

This application primarily focuses on creating generic models within a BIM environment by using CityJSON geometries. Looking ahead, it would be greatly advantageous to generate geometries incorporating semantic attributes tailored to Autodesk Revit for future advancements. The application conducts a re-projection of CityJSON points to the EPSG 4326 coordinate reference system (CRS) as the fundamental reference point.

The second tool is a web app for georeferencing, named IfcGref, which enables users to control, assign, or modify georeferencing information in IFC models, a standard format for exchanging

BIM data, and visualise the roof outlines of the IFC models on the target CRS map. In the context of integrating Building Information Models (BIM) and city models, a critical challenge arises in ensuring consistency between the localised, three-dimensional, Cartesian coordinate system of BIM models and the projected coordinate system of city models. Georeferencing has become a fundamental task, requiring the transformation of coordinate systems to facilitate integration and decision making in GeoBIM projects. To address the georeferencing challenge, an IfcGref Web-Based Application was developed. This lask-based tool[1] provides a comprehensive solution for designers, engineers, and software developers. IfcGref supports georeferencing operations starting from IFC4, thereby ensuring backward compatibility with earlier versions. The tool utilises IfcMapConversion, incorporating attributes such as SourceCRS, TargetCRS, and other key parameters to enable precise coordinate transformation. The workflow of IfcGref involves a user-friendly interface for file uploading and verification. Georeferenced files are promptly confirmed, whereas non-georeferenced files undergo a guided process, including EPSG code selection, optional surveyed point input, and visualisation. The tool employs scientific computing libraries to ensure optimal solutions for coordinated operational values. A visualisation feature allows users to observe the real-world impact of georeferencing on the geometry of the IFC model and its location on the map.

Figure 3. 3D view of a georeferenced BIM model (left) and its visualisation on the map (right).

These tools serve distinct purposes in GeoBIM. The CityJSON importer facilitates the import of geospatial information for a widely used commercial BIM platform, whereas IfcGref aids in integrating open BIM formats into the geospatial domain. However, the georeferencing methodology employed by IfcGref can potentially be adapted for future developments aimed at implementing precise coordinate reference systems from city models in Autodesk Revit.

Demonstrating with a real-world example:

In showcasing the functionalities and benefits of integrating Building Information Modeling (BIM) and geospatial data, real-world projects such as the CHEK project serve as exemplars. The 'Change toolkit for DBP' (CHEK) project[2], a European initiative, illustrates the development of digital tools and methodologies for performing Development-Based Planning (DBP) checks. Central to this initiative is the seamless integration of buildings and 3D city data.

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[1] https://ifcgref.bk.tudelft.nl

[2] https://chekdbp.eu

Georeferencing tools play an important role in ensuring accuracy, particularly in terms of regulatory compliance. For instance, consider the computation of regulations, such as the maximum building height. Accurate georeferencing enables precise measurements such as determining the distances between buildings or computing building heights from the ground level to the roof. Without accurate georeferencing, these computations can yield erroneous results. An illustrative case study involved four municipalities with distinct regulatory frameworks. For example, in Prague, the regulated building height is defined as the distance from the lowest point of the adjacent terrain to the main cornice level. As presented in Figure 1, to assess the maximum building height in this context, workflows include the following steps.

1) IFC Modeling and Georeferencing: Utilising tools, such as the IFC Georeferencing solution, the initial step involves georeferencing the IFC model.
2) Visualisation and Verification: Following georeferencing, visualisation tools were employed to verify the outcomes, ensuring accuracy and compliance.
3) Storage of Georeferencing Data: Georeferencing data, crucial for subsequent computations, are stored in CityJSON files based on the IFC building envelope extractor during the conversion process.
4) Building Height Computation: Utilising a voxelisation approach, such as the extraction-based highest point roof method, building height computations are performed, adhering to regulatory data requirements.

IFCMapConversion Data

	property	value
0	id	259882
1	type	IfcMapConversion
2	SourceCRS	[None, Model, 3, 1e-05, [[(0.0, 0.0, 0.0)], [(0.0, 0.0, 1.0)], [(1.0, 0.0, 0.0)]], [(0.0, 1.0)]]
3	TargetCRS	[EPSG:25832, None, None, None, None, None, None]
4	Eastings	479338.600506
5	Northings	5444142.430127
6	OrthogonalHeight	0.0
7	XAxisAbscissa	0.85
8	XAxisOrdinate	0.758
9	Scale	1.0

```
"metadata": {
        "referenceSystem": "EPSG:25832",
        "title": "AC20-Institute-Var-2_georeferenced Auto export from IfcEnvExtractor"
    },
    "transform": {
        "scale": [
            0.001,
            0.001,
            0.001
        ],
        "translate": [
            479338.600506154,
            5444142.43012653,
            0.0
        ]
```

Figure 4. IFC georeferencing in maximum building height showcase (CHEKDBP project).

Improvements have been made to this example, particularly in enhancing interoperability and georeferencing. One notable improvement is optimising the process of storing georeferencing data in the process of conversion from IFC to CityJSON. This transition is facilitated by solutions such as the IFC Georeferencing tool and the IFC EnvelopeExtractor envelope solution, demonstrating progress towards resolving this challenge.

The impact of smart technology on the footprint of a fully digitised educational floor within the Hague University of Applied Sciences

Frans Joosstens[1], Rachel van Kuijlenburg[2], Lucas Mastenbroek[1]

[1] The Hague University of Applied Sciences, Future Urban Systems Research Group, The Hague, The Netherlands – {f.g.l.joosstens, l.mastenbroek}@hhs.nl
[2] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, Logius, The Hague, The Netherlands – rachel.kuijlenburg@logius.nl

Keywords: Digitalisation, BIM, Digital Twin Building

Extended Abstract:

We will provide insight into our Facility Management Living Lab, how the lab is used for education, research projects, and future development. In recent years, researchers at THUAS have set up a digital 'smart FM' Living Lab at the main branch of The Hague University of Applied Sciences for the Facility Management programme. An IoT sensor network was set up by the FM Living Lab in collaboration with the technical service provider Unica. The network, consisting of more than 300 sensors on a 1100 m^2, makes data and analytics available on, among other things, temperature, humidity, CO_2 concentration, energy consumption, and occupancy. These data make it possible to make connections with other disciplines and systems, recognise patterns, and perform analyses. The data are momentarily available through a dashboard developed in collaboration with Unica and supported by embedded Power BI. The measurement interval varies per sensor, varying between every minute, hour, or every time a door opens or closes. Rapidly accumulating data serves as a valuable repository of information for users, enabling them to gain insights, visualise resource utilisation, predict patterns, and save time in data analysis.

With the support of these data, lecturers and students can gain insight into how organisational decisions influence occupancy, air quality (including temperature, humidity and CO_2-levels) and the energy use of premises. Thus, the FM Living Lab contributes to achieving the climate objectives and improving the comfort of the occupants of our building. Technology, data, and facility management came together in the FM Living Laboratory. Integrating this environment offers students the opportunity to challenge employees based on their own professional profiles to become acquainted with the usefulness of new technologies, such as smart buildings and data-driven management. Experience in recent years has led to exercises, demonstrations, and practical research. This enables (future) facility managers to interpret results from augmented analytics and translate them into better use of the spatial environment with regard to liveability, comfort, and findability. Augmented analytics refers to the use of enabling technologies, including AI and machine learning, to augment how people use data in analytics by assisting with data preparation, generation, and explanation. Using augmented analytics, facility managers can now perform tasks previously performed only by specialised data scientists. The

FM Living Lab facilitates multidisciplinary collaboration and a connection between technical and non-technical courses. The sensors are connected to the Unica dashboard, which not only students from the Facility Management course, but also from the departments of Architecture, Spatial Development, the Smart City minor programme, Safety Science, Applied Data Science, and HBO ICT learn to work.

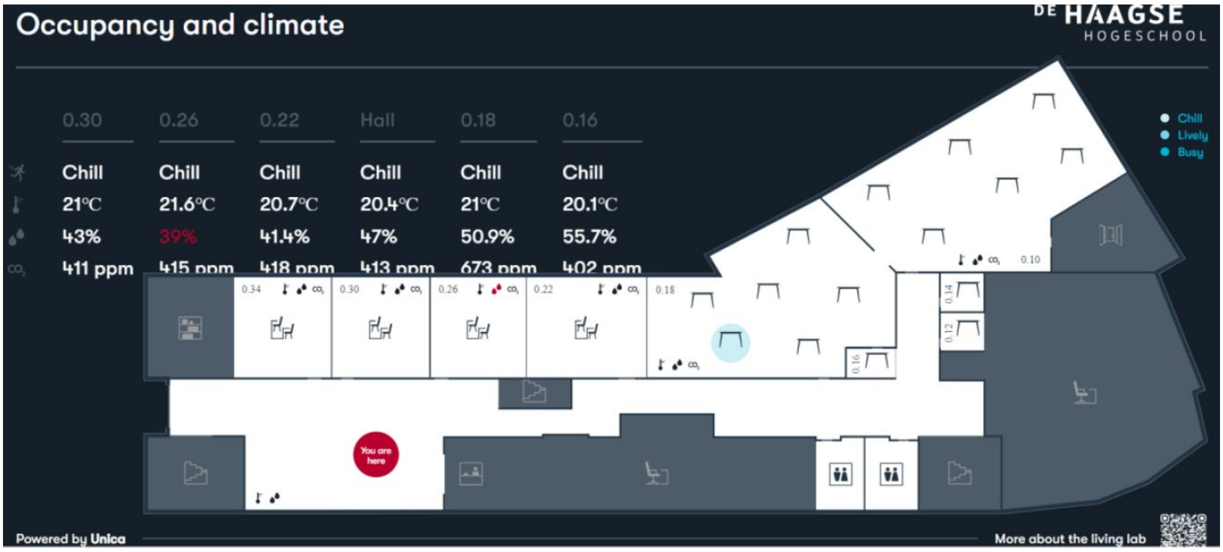
These interdisciplinary interactions allow for the contribution of innovative solutions to facility management and the development of smart buildings. One field of study that can be explored is the influence of smart technologies on end-user behaviour by influencing behavioural psychology. Other important aspects include organistic management, building management systems, technical maintenance, cyber security, and privacy ethics.

There are various specific use cases, analyses, analytical methods, and results related to improving operational efficiency, applications for educational purposes, and thermal. Examples include the B4B or Brains for Buildings project, BE and FM study programmes, housing department of facilities, and waste collection monitoring. The B4B project is a multi-year stakeholder project aimed at harnessing big data from smart meters, IoT, and building management systems to reduce energy consumption, increase comfort, flexibly respond to occupant behaviour and local energy supply and demand, and save on plant maintenance costs. One of the goals of B4B projects is to use validated integrated prototypes of software plug-ins for smart monitoring and control of buildings and facilities to reduce energy consumption by 20-30% and lower maintenance costs in utility buildings. Data from the FM Lab are also used to assist students in the designs for isolation, greening, and solar panel instalment on the southern facade of the THUAS campus. Another project was the use of sensors in various recycling bins to improve waste collection efficiency by indicating the proximity of the waste to the sensor installed above the bin. Eventually, this could enable the implementation of these data in the scheduling of the THUAS hygiene provider. The data collected on energy use showed that turning off monitors and night and weekends could significantly reduce energy consumption costs. It is estimated to accumulate annually to the hiring costs of two full-time equivalent (ftes) teachers.

Smart technologies in buildings aim to enrich facility managers with valuable data to achieve strategic goals, including sustainability targets, such as energy reduction and efficient space utilisation. Facility managers face numerous external and internal challenges, including the increasing complexity of digital infrastructure, complexity of integrating the facility management information system (FMIS) with BIM, high service fees for accessing dashboards and data, rising demand for digitally trained employees, and evolving regulations concerning privacy and ethical considerations, which sometimes hinder the realisation of sustainable development. Moreover, the intensification of digital infrastructure for the realisation of smart buildings comes with its own environmental impact or digital footprint, such as the mining of materials, manufacturing, and shipping of sensor modules, and the energy and material costs associated with storing the collected data and end-of-life considerations of both hardware and software. By understanding the challenges and advantages associated with smart educational buildings and true pricing, stakeholders can make informed decisions, optimise resource allocation, and create learning environments that foster innovation and sustainability.

Despite the challenges and environmental impacts of smart technology on the footprint, the FM Living Lab ultimately contributes to the establishment of a sustainable smart campus. The lessons learned in the experimental setting of the Living Lab can be applied when scaling up smart solutions from a single segment of a building to encompass an entire campus. Successful implementation requires a structured project approach that faces the complexity of IT, including a detailed business case, elaborate stakeholder analysis, and the development of intersectional expertise among IT, facility management, and corporate real estate management. In conclusion, the journey of the FM Living Lab revealed the complexities of integrating smart building principles, highlighting the importance of a methodical project strategy and deeper IT expertise in facility management. As technology and sustainability continue to progress, it is crucial for upcoming FM professionals to adopt a mindset of 'flexpertise' and incorporate sustainable smart building solutions to enhance organisational effectiveness and promote environmental stewardship.

Figure 1. Example of floor map available in the application. Image source: THUAS (2024).



Occupancy and climate

	0.30	0.26	0.22	Hall	0.18	0.16
	Chill	Chill	Chill	Chill	Chill	Chill
	21°C	21.6°C	20.7°C	20.4°C	21°C	20.1°C
	43%	39%	41.4%	47%	50.9%	55.7%
CO_2	411 ppm	415 ppm	418 ppm	413 ppm	673 ppm	402 ppm

Figure 2. Snapshot of the hallway monitor at Facility Management visualising the data captured by the sensor network in a comprehensible manner. Source: THUAS (2024).

Acknowledgements

We would like to express our gratitude to our colleagues, partners, and students for their efforts in developing the FM Living Lab, future improvements, and lessons learned from this valuable project.

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Towards digital twin-based dynamic fault detection and diagnosis for heat pumps: a case study of the Smart TinyLab

Rio Saijo[1], Rob Meester[1], Christian Struck[1], Masayuki Ichinose[2], Haitham Alkhalaf[2]

[1] Saxion University of Applied Sciences, School of Business, Building and Technology, The Netherlands –
{r.saijo, r.meester, c.struck}@saxion.nl
[2] Tokyo Metropolitan University, Department of Architecture and Building Engineering, Tokyo, Japan –
{ichinose, haitham}@tmu.ac.jp

Keywords: BIM, Building Management systems, Digital Twins, Smart TinyLab, Fault Detection and Diagnosis, Heat Pump

Extended Abstract

The Paris Treaty (United Nations, 2015), states the goal of maintaining the global warming below 2°C and to push towards limiting the temperature rise to 1.5 °C. The European Union has set a goal to reduce emissions by at least 55% by 2030 compared to 1990 and also achieve net zero greenhouse gas emissions by 2050 (European Parliament, 2021). Energy use in the built environment accounts for approximately 39% of the total energy use, indicating that energy reduction in the Architecture, Engineering, Construction and Operation (AECO) industry plays a significant role in achieving a carbon-neutral built environment.

Digitalisation of the AECO industry is an effective measure to reduce energy use in buildings. Smart technologies in buildings have the potential to reduce, on average, 30% of energy use (Verbeke *et al.*, 2020). Digital twins and digital representations of buildings and services can provide solutions for optimising, monitoring, predicting the performance of building assets, and providing support for informed decision-making.

One such implementation is the use of fault detection and diagnosis (FDD) processes, which enables the identification of faults by analysing the performance of a system's time-series sensor data in comparison to its digital twin. This guides the proper maintenance of the systems, allowing them to run with higher efficiency, leading to a reduction in energy consumption. Many studies have been published on the general subject of digital twins. However, research activities on the development of Digital Twins within the built environment have only recently (Hodavand *et al.*, 2023) only a few case studies are available that focus on the practical challenges of developing and integrating a digital twin for the continuous commission of an existing building.

Table 1. Pros and cons of integrating methods(Tang *et al.*, 2019).

	Software applications APIs	Relational databases	Semantic web technologies
Pros	Often already exists in software, and if properly documented easy to access/implement.	The ease in linking model data and sensor data.	Better scalability(e.g. having capability in linking data from different domains due to the homogeneous data format.)
Cons	It is necessary to create the virtual objects to represent sensors manually.	There are limitations in updating the BIM data in database since only properties and parameters are exported.	The data structure based on RDF is inefficient and storage consuming.

This study had three aims. First, an appropriate method for integrating a Building Management System (BMS) with Building Information Modeling and Internet of Things sensors to develop a Digital Twin. Here-in, challenges, and solutions were identified for the practical case of the Smart Tiny Lab (STL) (Mohammadi *et al.*, 2022) in Enschede. There are several methods to integrate heterogeneous building data, using functionalities obtained from APIs of software applications, relational databases, and semantic web technologies. For instance, Linked Data (Berners-Lee, 2009) and RDF (Resource Description Framework) (W3C, 2014). Table 1 indicates the advantages and disadvantages of each method. This study uses the software API-based method, which is the easiest to implement because API connections are already used by STL software (Revit, Tandem, Skyspark) to obtain and transfer time-series data.

Chamari *et al.* (2022) presented a framework to implement a prototype. Data from the BMS and IoT sensors in the STL were centralised on the Skyspark platform. The building models that represent STL were developed in Autodesk Revit, synchronised with the model in Autodesk Tandem, and updated through the Autodesk Construction Cloud. The time-series data in JSON format are imported and assigned to objects in Tandem using web APIs.

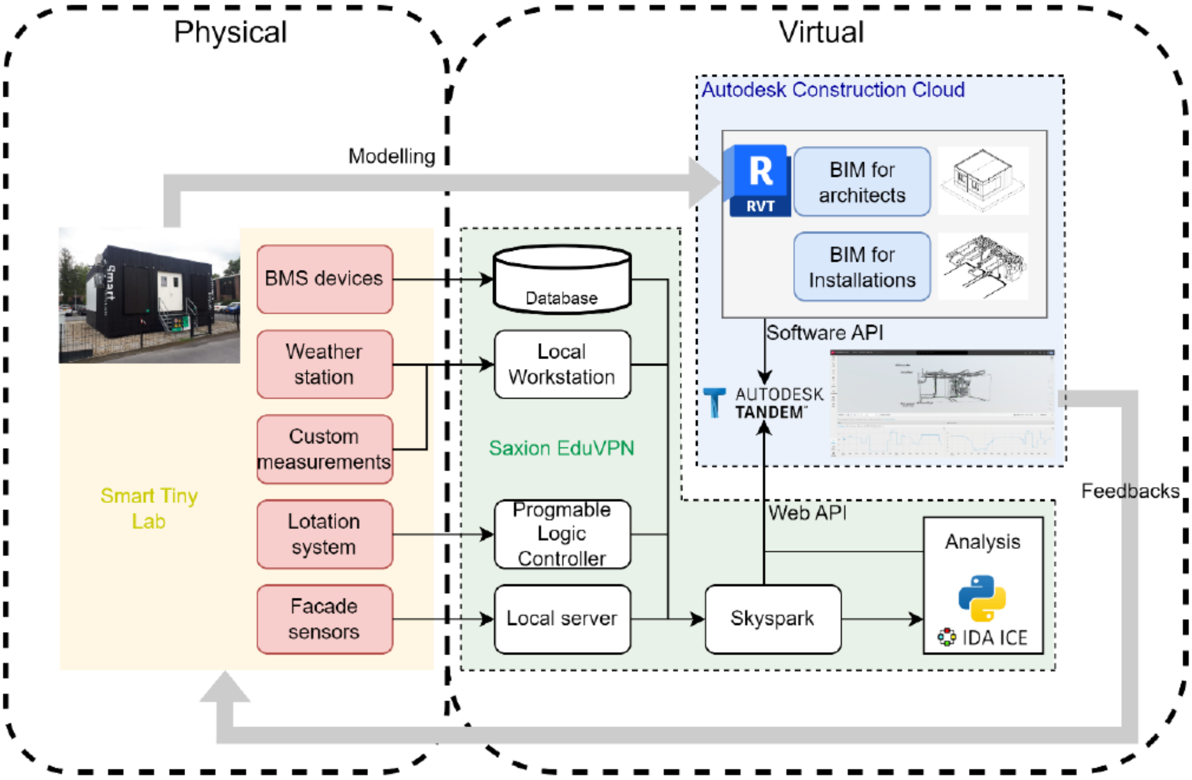

Figure 1 Framework for developing the digital twin of the STL

Second, we quantify and evaluate the performance of the HVAC system components dynamically by comparing the monitored performance with reference performance data in the context of digital twins.

This study focuses on the behaviour and performance of an air-sourced heat pump system. To obtain reference data, a system analysis was performed, and simulations were performed using IDA ICE in combination with the Python programming language. The resulting data are converted into the JSON format and integrated into the digital twin prototype, where it is compared with the measured data of the STL to estimate the actual performance. (Figure 2). To date, owing to the limited timeframe of the gathered and simulated data, the simulation model has not been completely validated and will need to be improved once more data are available.

Figure 2. Comparison of the digital twin prototype with the actual building and visualisation of COP.

Third, we tested and selected the appropriate FDD methods for the heat pump. To formulate and validate FDD-algorithms, it is necessary to obtain faulty and nonfaulty data. In addition, the history of maintenance and repair is often utilised in formulating models for FDD. However, this data by itself is not sufficient because installations in the STL are still new. Thus, data to generate FD algorithms for the heat pump are obtained experimentally through STL systems and sensors. For the experiment, condenser fouling was physically emulated by blocking the heat exchanger. The parameters mentioned in (Barandier *et al.*, 2023) in combination with available sensors within the STL, such as temperature, flow rates, and electrical data, were used for the datasets.

This work describes the first practical working prototype of a digital twin for the STL, integrating geometric and semantic information of the building and services with data describing the dynamic performance of the heat pump. This digital twin was built based on web applications. Each data component is integrated via APIs, which leads to usability in each system and accessibility through the internet. Additionally, when the data sources are modified, it is possible to automatically update the 3D models and real-time data without export. However, this study has some limitations. To apply this API-based digital twin approach, heterogeneous data for integration must be managed on the web and exchanged via APIs. Additionally, the implementation of a feedback system for BMS control, based on the analysis results, has been found to be challenging owing to security issues.

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Thematic session 4:

Digital Twins (at urban and territorial scale)

Urban solar potential analysis through semantic 3D city models

Longxiang Xu[1], Camilo León-Sánchez[2]

[1] MSc in Geomatics, Delft University of Technology, Delft, The Netherlands – l.xu-18@student.tudelft.nl
[2] Delft University of Technology, Faculty of Architecture and Built Environment, Department of Urbanism, 3D Geoinformation Group, Delft, The Netherlands – c.a.leonsanchez@tudelft.nl

Keywords: Semantic 3D city models, Solar potential, UBEM, NTA8800

Extended Abstract

Currently, approximately 60% of the global population lives in urban areas (UN. Population Division, 2018). Incorrect quantification of the current and expected energy demands of buildings can lead to erroneous decisions and misguided planning for energy supply. Additionally, society is transitioning to adopting more sustainable energy sources to reduce environmental impacts. Solar gains play a major role in energy demand simulations. Therefore, it is important to perform precise calculations of the solar radiation for a given area of interest. However, this energy source faces challenges, such as shadowing, which rapidly decreases the performance of any solar panel, and it is constantly changing owing to the movement of the sun across the sky. Figure 1 shows a sketch of the considerations for computing shadowing calculations and the components of the solar irradiance.

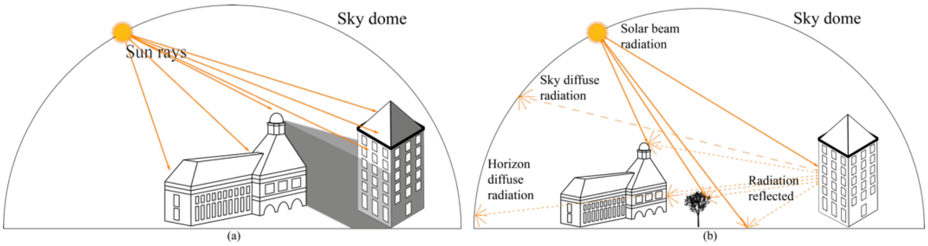

Figure 1. Shadowing computation sketch (a) and solar irradiance components (b).

Shadowing analysis is crucial in urban planning (Palme *et al.*, 2020), especially for assessing the solar potential (Figure 1(a)). It helps identify suitable locations in urban areas by considering existing structures and future developments. This analysis is relevant for policymakers, as they encourage the population to adopt solar energy while ensuring efficient utilisation of available resources for a given location.

To perform solar potential analysis, it is essential to consider the geographical location and its surroundings. These include factors such as topography, construction, and vegetation (De Sá *et al.*, 2022). These city objects can be represented using semantic 3D city models [3DCM] (Agugiaro *et al.*, 2020), which provide datasets that allow for a coherent geometrical and semantic representation of urban features in a well-defined data structure. The solar irradiance received on a tilted surface can be categorised as direct beam irradiance, sky diffuse irradiance,

and (ground)reflected irradiance. Figure 1(b) illustrates these, with the diffuse components further divided into diffuse sky and diffuse horizon components.

We present the development of a solar potential analysis tool based on 3DCM. Our work uses the 3DBAG (Peters *et al.*, 2022), an open dataset containing 3D models of all buildings in the Netherlands. This dataset is available for downloading in several formats and multiple levels of detail (LoD) (0, 1.2, 1.3, 2.2) (Biljecki *et al.*, 2016). We used the pvGIS database (EU Science Hub, 2022) as the input weather data for our computations.

The hourly solar irradiance values were calculated using the Python package pvlib (Holmgren *et al.*, 2018). These values are aggregated for each surface. Additionally, we aggregated the solar irradiance values for each month, as shown in Figure 2. The final values were compared according to the statistical parameters defined by Dutch standard NTA8800:2024 (NEN, 2024), which specifies a method for assessing the energy performance of buildings in the Netherlands. The statistical values provided by the standard were categorised based on the orientation and inclination of the boundary surfaces enclosing a building. Our simulations were conducted in the municipality of Rijssen-Holten, located in the eastern part of the Netherlands. The municipality has approximately 38000 inhabitants, corresponding to approximately 23000 buildings.

Figure 2 shows a scatter plot comparison for each boundary surface of buildings in the study area, with the red line representing the computed correlation coefficient. Figure 3 shows aggregated values per month for better comparison with norm values. Additionally, we include some statistical metrics such as MAE, n-RMSE, R, RMSE.

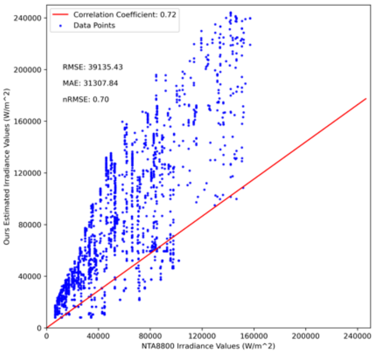

Figure 2. Scatter plot of monthly solar irradiance values.

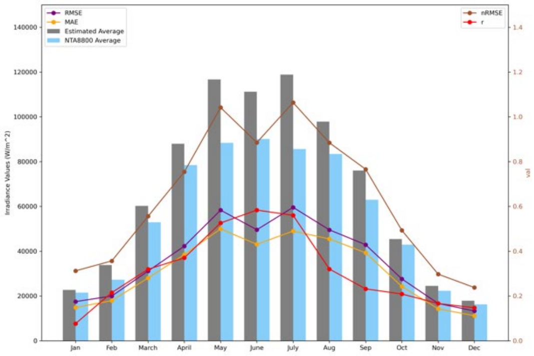

Figure 3. Bar plot of monthly solar irradiance values.

Figure 4 shows the solar irradiance per surface in May for Rijssen-Holten. Both images used the same colour palette, ranging from blue (lowest value) to orange (highest value).

(a) (b)

Figure 4. Rijssen-Holten solar irradiance output visualisation in May for NTA880 (a) and our computation (b).

The comparison of irradiance values between the NTA8800 standard and our method highlights the significant differences between purely statistical approaches and analytical methods that account for urban morphology. The correlation coefficient for the study area was 0.72, indicating a moderately linear relationship between the two values. This suggests that there is still a fundamental alignment in the irradiance patterns captured by both the datasets.

Error metrics in the bar plot in Figure 3 indicate that discrepancies between the NTA8800 values and our computed values were higher during warmer months. This divergence may be attributed to clearer skies during warmer seasons as opposed to predominantly overcast skies during colder skies. During colder seasons, the shadowing effect is not the primary source of energy loss, as overcast skies largely block direct beam solar irradiance, thereby reducing its impact (Tuononen *et al.*, 2019). One limitation of our approach is the inadequate treatment of light-ray diffusion and reflection, as illustrated in Figure 1(b). Our analysis simplifies the complex interactions between diffusion and reflection, which may affect the precision of our findings.

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Integration of GIS and CAD data to perform preliminary environmental analyses at district scale

Bing-Shiuan Tsai[1], Lars Huizer[1], Michele Giampaolo[1], Sérénic Monté[1], Sicong Gong[1],
Francisco Gabriel García González[2], Giorgio Agugiaro[3]

[1] MSc in Geomatics, Delft University of Technology, Delft, The Netherlands –
{b.tsai, l.c.huizer, m.giampaolo, s.g.m.monte, s.gong}@student.tudelft.nl,
[2] Royal HaskoningDHV, The Netherlands – gabriel.garcia@rhdhv.com
[3] Delft University of Technology, Faculty of Architecture and Built Environment, Department of Urbanism, 3D Geoinformation Group, Delft, The Netherlands – g.agugiaro@tudelft.nl

Keywords: CAD, GIS, data integration, Grasshopper, solar analysis, wind analysis.

Extended Abstract

With the current high speed and scale of urbanisation, there is a growing demand for affordable housing – together with all other aspects that are tightly related to it: infrastructure for transportation, utility networks, etc. For this reason, integrated planning is playing more and more a crucial role as the impacts of a new construction project should be investigated, evaluated and minimised from the very early stages of the design process (Josuf *et al.*, 2017; Agugiaro *et al.*, 2020).

However, there still exists a "scale-dependent" dichotomy between the different disciplines involved in the different types of analyses (Ohori *et al.*, 2017). For example, a new building is generally planned and designed by practitioners (architects, engineers, etc.) using tools from the AEC (Architecture, Environment and Construction) domain that, traditionally, follow the CSG (Constructive Solid Geometry) modelling paradigm and use a local coordinate system. On the other hand, in order to estimate the impacts of the new building in the urban context (e.g. at district level), information about the "surroundings", i.e. its urban context, is needed. As a matter of fact, such information is more and more digitally available nowadays thanks to the growing availability of 3D city models that however generally consist of GIS data. The recent advances of spatial data acquisition and processing technologies have brought a considerable yield of 3D data, with particular focus on the built environment. These data often consist either in point clouds, or in polygon-based models – the latter following the B-rep model. Additionally, data are georeferenced, and semantics may be also added, as in the case of city models based on the international standard CityGML (Gröger and Plümer, 2012). Collecting, harmonising, integrating and merging these kinds of heterogeneous data (both from AEC and from GIS domains) can still be a challenging task for a practitioner that may lack deep knowledge on data integration strategies.

This work provides a possible solution to this problem when it comes to performing speedy and interactive preliminary environmental analyses at the district scale in the case of a newly planned project (e.g., a building). The proposed methodology is the result of an initial analysis in terms of data and software requirements carried out between GIS specialists and practitioners from the AEC domain. In particular, the latter have expressed their needs in terms of data and functionalities as well as set some limitations in terms of software solutions. The reason behind these choices, both in the form of functionalities and constraints, stems from the desire not to create a new *ad hoc* tool, but to extend and adapt (as far as possible) existing tools and workflows that are mostly used by end users, that is, AEC practitioners. The main topics that have been subject to specific research work are summarised in the following text.

First, regarding the software platforms to be used and the accompanying constraints, a set of tools to be used within Grasshopper/Rhinoceros[1] 3D was developed. This is because Grasshopper is one of the most commonly used software solutions in the AEC domain for parametric modelling and design. Additionally, it has been decided to avoid, as far as possible, adding or linking to existing external libraries, unless already natively supported by Grasshopper, as this would represent a welcome simplification in terms of software management within a large(r) company (Figure 1).

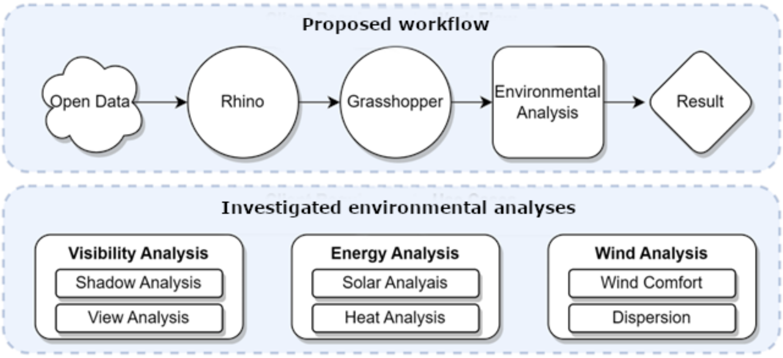

Figure 1. Schematic overview of identified workflow and of the use cases resulting from the interaction between GIS and AEC specialists.

Second, regarding the initial step of GIS data import, the availability of open geospatial data (e.g., buildings, vegetation, terrain, and land use) has been explored in 10 different countries, together with the possibility of accessing these data sources ideally via existing web-based APIs instead of file downloads (Figure 2). Although Grasshopper scripts have been developed to import and integrate the GIS-based “urban context” data into Grasshopper, research in different countries has highlighted the extreme heterogeneity of open data available (or not) and *de facto* a lack of common solutions to access such data despite the existence of open standards.

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[1] https://www.rhino3d.com

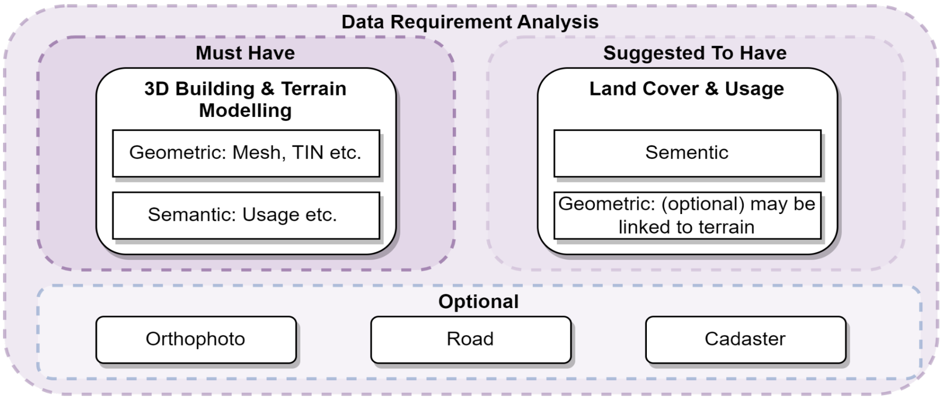

Figure 2. Schematic overview of the data requirement analysis resulting from interaction between GIS and AEC specialists.

Third, when it comes to the actual data usage in Grasshopper, the integration of the GIS data of the "urban context" with the parametric model of a building (representing the actual object being planned or designed by the AEC practitioners) has been investigated. This means that the resulting urban scene model (building + surroundings) had to be prepared in order to be compatible with the Ladybug tools[2], that is, a set of tools for environmental building design that can also be used in Grasshopper, which have been identified by AEC practitioners as target tools. Therefore, several tests were conducted in this study. The goal was to evaluate and compare the simulation results and the overall usability and user experience of the workflow of the operations carried out on the urban scene model (either as B-rep or voxelised) for a) visibility analysis, b) solar irradiation, and c) wind simulation (Figures 3 and 4). Finally, an assessment of the developed methodology (and the implemented prototype) was carried out by both GIS specialists and AEC practitioners to identify current strengths and limitations, and to reason for possible future improvements. Further information and details regarding the entire project can be found in Tsai *et al.* (2024). The developed software and Rhinoceros scripts were freely available on GitHub[3].

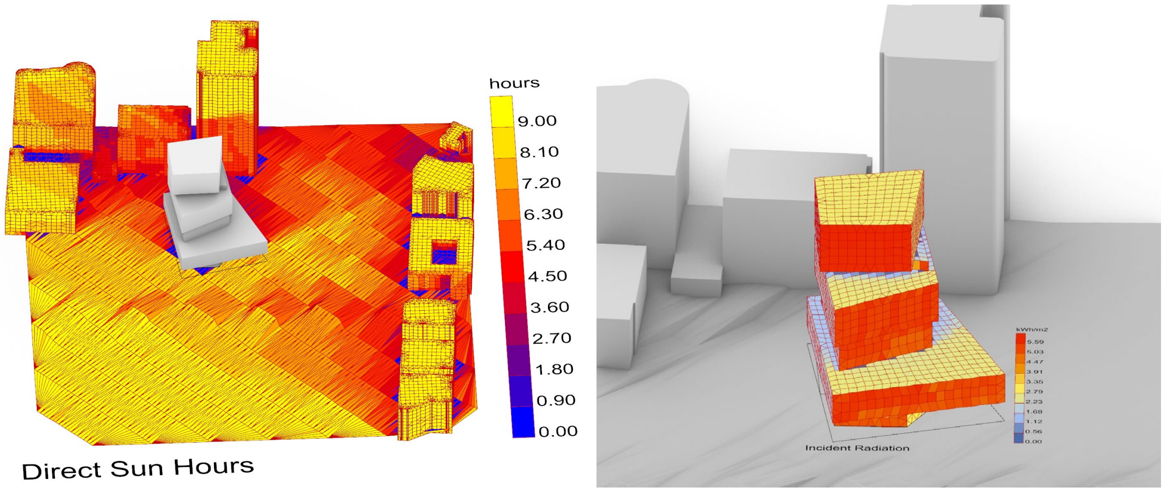

Figure 3. Example of visualisation of results from solar simulation on the urban context [left] and on the planned building [right].

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[2] https://www.ladybug.tools

[3] https://github.com/biscuittsai1022/Synthesis-project_1-repository_2023

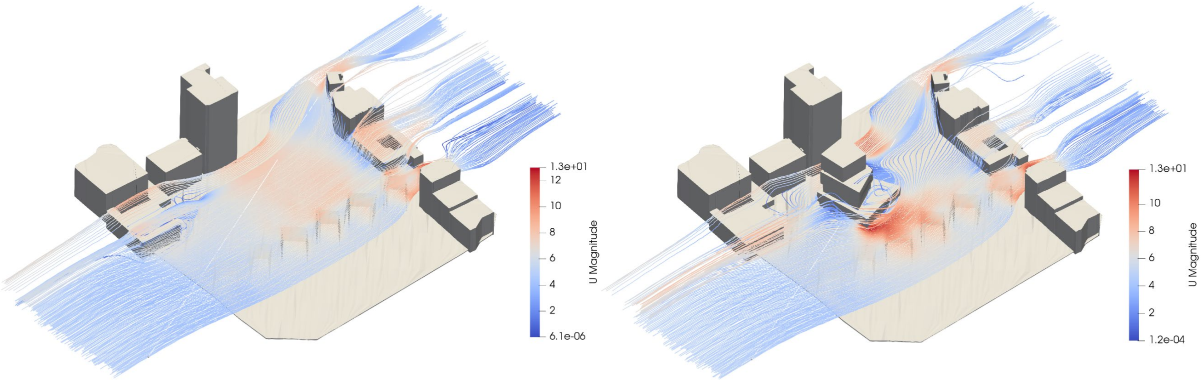

Figure 4. Example of visualisation of results from wind simulation before [left] and after [right] insertion of the planned building in the urban context.

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Development of Digital Twin framework for flood risk reduction and mitigation planning

Sruthie Rajendran[1], Mila Koeva[2], Bastian van den Bout[3]

[1] Faculty of Geo-information Science and Earth Observation (ITC), University of Twente, 7522 NH Enschede, The Netherlands – s.rajendran@student.utwente.nl
[2] Faculty of Geo-information Science and Earth Observation (ITC), Department of Urban and Regional Planning and Geo-Information Management (PGM), University of Twente, 7522 NH Enschede, The Netherlands – m.n.koeva@utwente.nl
[3] Faculty of Geo-information Science and Earth Observation (ITC), Department of Applied Earth Sciences (AES), University of Twente, 7522 NH Enschede, The Netherlands – b.vandenbout@utwente.nl

Keywords: Digital Twin, Flood modelling, Decision-making, Web application, Open source

Extended Abstract

Flooding is among the most frequently encountered disasters and is extravagant in terms of both economic and physical losses, among all disasters that could be triggered by climate change and other anthropogenic activities (Oulahen, 2021). The reason for flooding is not always constant in every other area and it varies depending on the local topographical and weather conditions. These can include rapid urbanisation, frequent high-intensity precipitation events, river overflows, deforestation, and blockage of water channels. The frequency of urban flooding disasters grows with the number of metropolitan regions, emphasising the necessity of understanding why and when flooding happens in urban contexts. Numerous studies have been conducted for building urban flood resilience however conventional methods have often failed to provide completely effective preventive or mitigation strategies for disasters over the years, as the interaction between disasters and physical assets is difficult to understand (Guo *et al.*, 2021). Traditional 2D flood models provide information on flood extent and depth, but understanding the interaction of flood water with surrounding elements-at-risk is critical for flood resilience planning. Digital twin, a state-of-the-art technology for urban studies was explored for tackling the issue. A city digital twin is a dynamic digital replica of the real city that allows real-time data transfer between the two realms using Internet of Things (IoT) sensors, simulation features, and other means to facilitate improved decision-making (Digital Twin Geohub, 2023; Koeva *et al.*, 2023). Digital twin technology offers a solution by allowing for the testing of policies or infrastructure before real-world implementation, thus saving resources and time while empowering policymakers to make data-based decisions.

Thus, this research focuses on integrating the city digital twin modelling with the 'Fastflood'[1] flood model to deliver a decision-support tool for flood risk management applications. This integration allows the beneficial features of both technologies to be blended, resulting in a synergy of information that aids stakeholders including policymakers, urban planners, disaster management representatives, and city authorities, in making informed decisions while planning

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[1] https://fastflood.org

and implementing disaster prevention or mitigation strategies. A 2D flood simulation tool called ‘Fastflood App’ is developed at the University of Twente that computes highly accurate flood modelling outputs rapidly in comparison with most other flood modelling (Bout, 2021). This web-based application developed in 2021, leverages various unique algorithms to simulate flood scenarios providing results as highly accurate as traditional heavy simulation models while reducing the processing time (Bout *et al.*, 2023).

The datasets utilised for this research include rasters, such as digital elevation model (DEM) and digital surface model (DSM) of the pilot study area followed by Open Street Maps (OSM) building footprint shapefiles (OpenStreetMap, 2024). For this study, surveys were conducted using a well-curated questionnaire to understand the requirements and needs of stakeholders prior to the design and development of the decision-support tool. The 34 collected responses were analysed to comprehend the needs of users effectively. Second, different approaches for developing the 3D scene of a city were undertaken while ensuring that these approaches employ open-source techniques or software. One approach employs Cesium JS and OSM 3D building layers coupled with HTML and CSS for web-based 3D visualisation of the city in a global context. Figure 1 shows the preliminary results obtained using this approach. Another approach involves the utilisation of local datasets along with Python scripts, where a pipeline was created to generate a normalised DSM from DEM and DSM, followed by populating the height attribute for the building layer to output a 3D scene. Both approaches were coupled with the simulated flood outputs of the Fastflood app to visualise elements-at-risk in case of flooding events. Figure 2 depicts the outputs achieved through this method of utilising Python scripts, Fastflood outputs, DEM, and DSM datasets.

The 3D model of the study area was developed using open-source 3D modelling techniques and integrated with the Fastflood web platform using web development programming languages, including HTML, CSS, and JavaScript. Additionally, web libraries, including CesiumJS, three JS, and others, were explored as part of the methodology. The real-time component integrated into this digital twin model is the precipitation forecast data employed for flood simulations. Furthermore, the object placement facility of the Fastflood app enables users to analyse the effects of mitigation strategies by simulating flood outputs before and after object placement. Through this, the tool enables effective and informed decision making for policymakers and city planners/authorities. The next stage of development in this tool involves classifying the buildings based on the water level around the buildings in the case of a flood event and exporting an analysis report for the bounding box of interest.

Cesium ion This application is using Cesium's default ion access token. Please assign *Cesium.Ion.defaultAccessToken* with an access token from your ion account before making any Cesium API calls. You can sign up for a free ion account at https://cesium.com. Data attribution

Figure 1. Preliminary results of 3D visualisation using CesiumJS.

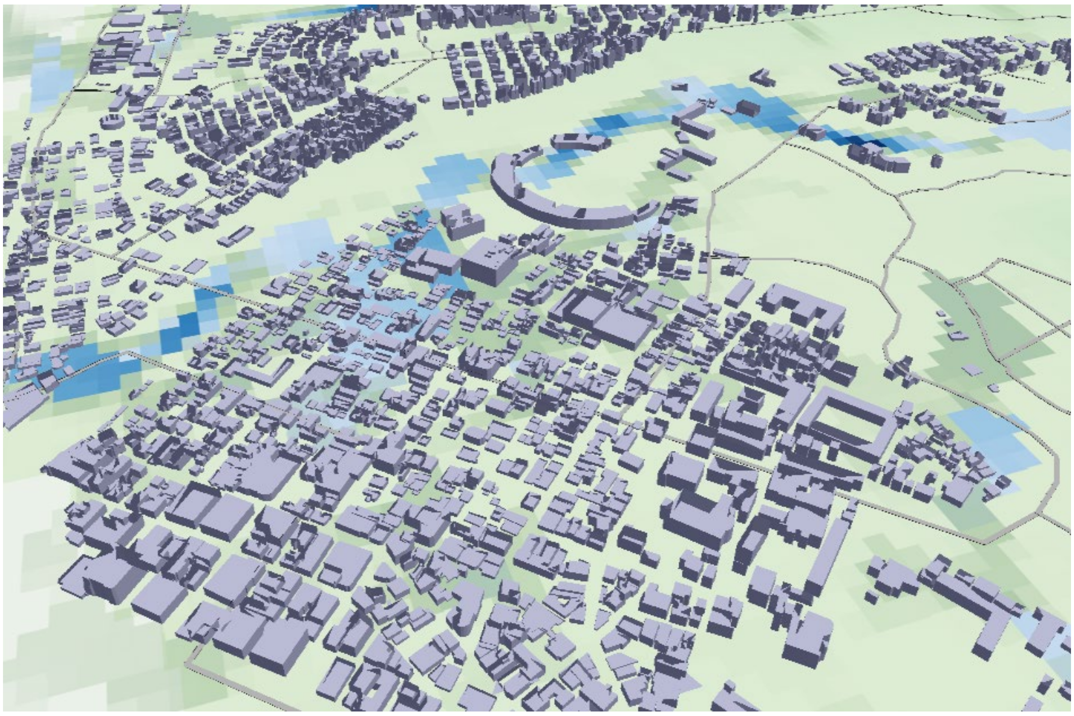

Figure 2. Preliminary results of 3D visualisation using developed python pipeline, QGIS 3D view and Flood output.

The tool is designed and optimised to be user-friendly by utilising the input collected from stakeholders through surveys. Potential applications of the tool include enhanced stakeholder understanding of flood risk, disaster impact assessment in both horizontal and vertical directions, emergency and evacuation planning, and deducing disaster mitigation strategies. Future advancements include combining other datasets such as satellite imagery, traffic data, population data, and atmospheric factors, as well as the extension of the tool's capabilities to interact with external GIS systems, importing and exporting capabilities, and communicating risk to stakeholders.

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Exploiting big point clouds: unveiling insights for sustainable development through change detection in the built environment

Vitali Diaz[1], Peter van Oosterom[1], Martijn Meijers[1], Edward Verbree[1], Nauman Ahmed[2], Thijs van Lankveld[2]

[1] Delft University of Technology, Faculty of Architecture and the Built Environment, GIS technology, Delft, The Netherlands – {v.diazmercado, b.m.meijers, p.j.m.vanoosterom, e.verbree}@tudelft.nl
[2] Netherlands eScience Center, Amsterdam, The Netherlands

Keywords: point cloud, cloud-to-cloud distance, change detection

Extended Abstract

Change detection in the built environment is essential for sustainable development practices including Urban Planning and Development, Environmental Monitoring, and Conservation. Change detection provides valuable insights into dynamic processes, facilitates informed decision making, and supports sustainable development initiatives. Point clouds serve as foundational data sources for change detection in built environments, enabling analysts to detect, quantify, and interpret spatial changes with unparalleled accuracy and granularity. By leveraging the inherent characteristics of point clouds, researchers and practitioners can gain valuable insights into dynamic processes, inform decision making, and foster sustainable development in an ever-evolving built environment. We present the preliminary results of cloud-to-cloud (c2c) distance calculations for further change detection analysis of the entire Netherlands. This study utilises point cloud data from AHN2, 3, and 4 (Actueel Hoogtebestand Nederland[1], The Netherlands). A method based on a 3D space-filling curve (SFC) was developed to calculate the c2c distances between AHN2, 3, and 4. This SFC method will allow change detection analysis to be carried out for the entire Netherlands. The change detection analysis outcomes can be accessed for future analysis in Potree[2], a web-based point cloud rendered for large point clouds. The final implementation will allow the visualisation of AHN point clouds and their attributes, among which is the change in detection-related information. This research contributes to sustainable development practices by offering enhanced spatial insights and informed decision-making tools for further analysis and monitoring of the (built) environment in the Netherlands.

Various sustainable development practices, including urban planning and development and environmental monitoring and conservation, benefit from the information that comes with change detection analysis. Point clouds, comprising large collections of 3D points representing the surfaces of objects, have emerged as crucial data sources for change detection in the built environment. Leveraging the inherent characteristics of point clouds allows analysts to detect, quantify, and interpret spatial changes with unparalleled accuracy and granularity.

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[1] https://www.ahn.nl
[2] https://potree.github.io

We present herein preliminary findings on utilising cloud-to-cloud (c2c) distance calculations for change detection analysis across the Netherlands. Our study utilises point cloud data sourced from the AHN2, 3, and 4 datasets. By employing these datasets, we aim to enhance spatial insights and provide informed decision-making tools built into Potree for development, monitoring, and further analysis to help carry out the aforementioned sustainable development practices in the Netherlands (Figure 1).

The methodology was based on a 3D space-filling curve (SFC), which was developed to calculate the c2c distances between AHN2, 3, and 4. The accuracy of the c2c distances depends on the accuracy and density of each AHN point cloud. Typically, the density was approximately 10 points/m^2. A true change is likely to occur when the c2c distance is greater than 10 cm. The outcomes from the c2c distance calculations will be visualised in Potree, a free, open-source Web Graphics Library (WebGL)- based point cloud renderer for large point clouds. This tool will help extract insights into the dynamic processes that shape the (built) environment.

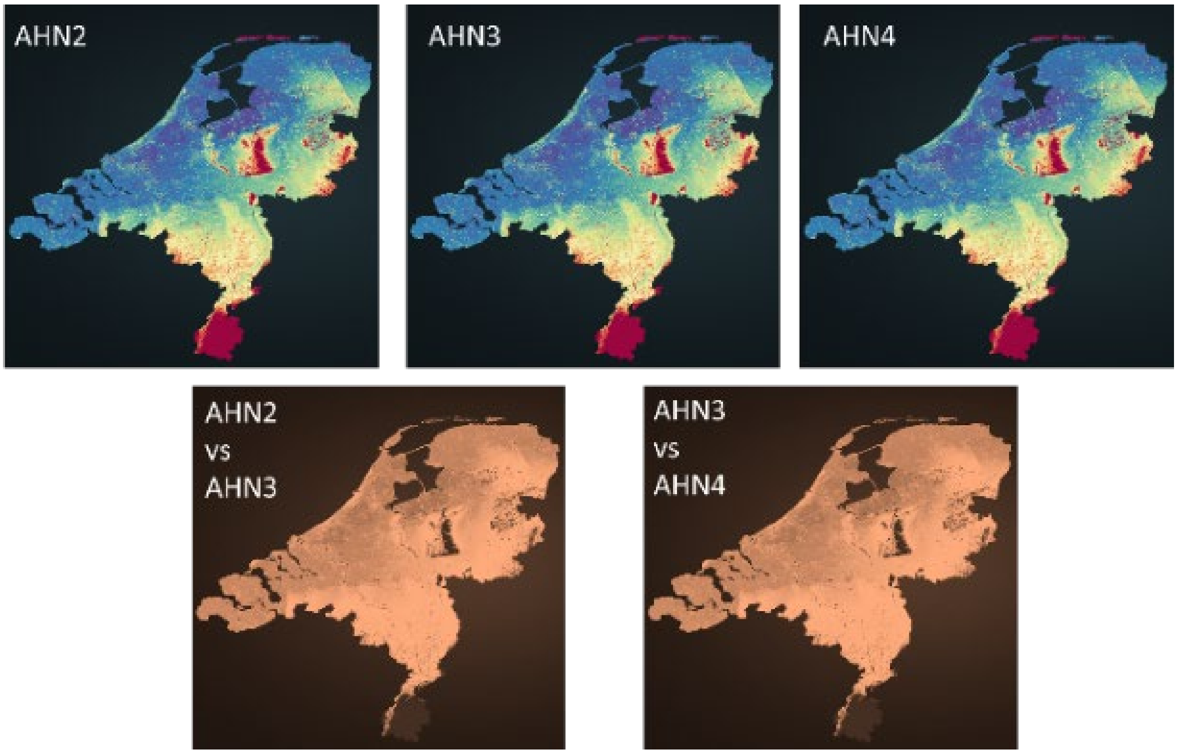

Figure 1. Schematic representation of the point clouds used for all of Netherlands and the changes that are being calculated.

Change detection within the built environment is essential for several reasons, particularly for urban planning and development. Monitoring changes in urban areas helps to identify patterns of urban expansion or invasion into other spaces.

Although this project initially focuses on the outside (built) environment, because of the nature of the point cloud databases, in the future, it will be possible to include analyses with other point clouds, such as the interiors of buildings, thus allowing a more complete analysis of the changes.

Regarding integration with the digital twin framework, although our work may not directly align with traditional digital twin methodologies, it serves as a preliminary step in generating valuable outputs that can be further integrated into digital twin models. By providing information on spatial changes within the (built) environment, our approach contributes to the broader goal of enhancing digital representations for decision support and simulation purposes.

In conclusion, this research highlights the significance of change detection in the (built) environment and demonstrates the value of c2c distance calculations for facilitating sustainable development activities. By leveraging big point cloud data and advanced analytical techniques, we aimed to provide actionable insights and decision-making support tools for urban planning, infrastructure management, and environmental conservation stakeholders.