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DURABLE DATA MODELS FOR FOR CIRCULAR BUILDING PRACTICES IN BIO-BASED CONSTRUCTION – THE HISTORY STACK

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Abstract

Circular building practice involves creation, maintenance, repair, and reuse of components. This positioning paper highlights the lack of digital models for such practices and proposes the History Stack framework for sustainable bio-based building economy. It advocates avoiding monolithic data models in favor of flexible structures reflecting dynamic changes. Key elements include access to foundational data like material sources, fabrication methods, and design logics, ensuring adaptability throughout a building's lifecycle. The History Stack links diverse digital models, supporting the evolution of practices and heterogeneous data types aligned with EU intentions for the Building Logbook and next-generation BIM-like systems.

Introduction

Current Building practice is based on intertwined digital and physical components. Data informed digital design tools specify fabrication and assembly processes of matter, which are executed by humans operating digital machines (Sheil et al., 2020). In parallel, Digital Twins of buildings do not only provide support for and control of their design and fabrication processes, but are also instrumental to the building’s long-term operation, where they support maintenance and repair through monitoring and coupled analysis (Tamke et al., 2023).

Despite the BIM communities effort to develop a unified digital model that is able to describe all aspects of a building in a single modelling paradigm (Holzer, 2007), domains involved in the AEC sector developed their own digital models that address their specific use-cases and provide efficient workflows (Tamke et al., 2014). The range of highly specific digital models for buildings is therefore vast, built with different modelling paradigms and not designed to be interconnected. Differences exist regarding data formats, modelling practices, level of abstraction, and resolution, but as well in regard to their longevity - the expected and actual time a model should serve its purpose, before it is superseded by newer models (the working model), changes in the physical buildings (the as built model) or technological changes (any archived model). While physical buildings are made to last for many years, the digital models that describe them are in most cases time-limited (Tamke et al., 2014). They describe a particular architectural process, such as concept development, fabrication or assembly, towards a defined goal, e.g. the completion of the assembly. Few models follow a building over time. Material passports attempt to capture the material setup of a building at a certain point in time and preserve this information for a later reuse scenario (Heinrich & Lang, 2019). A challenge is how to keep them up to date with the frequent changes, which occur in any built structure. This lack is addressed in new European Initiatives, where Digital Building Logbooks (European Commission, 2022; European Commission et al., 2020) are proposed as a collection that can continually receive new data, and should as such be able to represent a building and its changes over time. While the definition of logbooks currently omits any definitions of modelling standards, it extends the well-known set of *static models* with a definition of *dynamic models*, as e.g. fed by sensor networks installed in buildings. These models are designed to monitor continuously changing states in a building and trigger actions for inspection and repair by humans or machines (Chiujdea et al., 2024). Dynamic models are typically lean in detail yet built to collect data over long periods of time, whereas many static models, such as those for design and fabrication, are highly detailed and carry in-depth information about e.g. machining and materials. The latter, however, are often solely made to increase efficiency of a single task in the building process and are maintained only for a relatively short period of time e.g. during the design (Tamke et al., 2014), while dynamic models are made to last for longer periods of time, e.g. during a buildings operation for monitoring and maintenance planning.

Background: models for circularity, repair and reuse

The way we model buildings is characterized by a practice of dissection, where domain specific models are made for many different tasks with a throwaway attitude, when it comes to the reuse and potential data valorization of digital models. This contrasts starkly with the transformation of our societies, economies, and the built environment towards circular practices. Herein a new sustainable paradigm is emerging that foregrounds maintenance, repair, and reuse with minimal material losses and CO2 impact (Churkina et al., 2020). This transformation goes hand in hand with a shift of our material practices from finite materials from the geosphere to renewable bio-based materials, which are free of toxic chemical treatment and can be reused.

Most bio-based materials exhibit material variability and age and deteriorate quickly. Therefore, a future building practice needs to address issues related to maintenance, repair, adaptation, disassembly, and reuse, among others. This impacts the way we build and the place that maintenance actions take during the operation of a building. As we restrain, for example, the use of toxic fungicides and insecticides in timber buildings to allow reuse, we increase simultaneously the necessary amount of maintenance.

While the best balance between material choice and its ecologic and economic impact are case dependent, any action of care, repair, adaptation, disassembly, and reuse of a building requires specific knowledge about the system's tectonics and its material composition. Today this data is often not present for existing buildings, as it was never documented, has been lost over time or is incomplete (Litleskare & Wuyts, 2023; Tamke et al., 2014). The current method of choice to decide on repair and conservation practices is therefore to thoroughly inspect the deteriorated or damaged building elements, using a combination of deduction from general knowledge, material probes, 3D scanning and estimation (Wuyts et al., 2023). This archeological approach is costly with respect to the effort and time it requires to reestablish knowledge and models of the building. It also leaves insecurities, which result in expensive "surprises" on the building site, which are anecdotally reported in renovation practice. The lack of precise information is especially problematic for buildings that are produced with digital techniques, such as additive manufacturing, where the elements' internal structure and behavior is not only determined by material properties, but to a high degree by the fabrication process itself, e.g., the pattern of the toolpaths. A lack of fabrication information inhibits therefore an efficient reproduction or repair.

A future building practice needs a means for continued access to and adaptation of its foundational data. This includes the building's material sources, composition, and fabrication, but as well the underlying design and fabrication logics, as these connect individual elements into structures and an architectural whole.

In line with the intentions of the EU Building Logbook (European Commission et al., 2020) and next generation BIM-like systems (Bucher & Hall, 2020), this collection should avoid the current data structures, which are based in monolithic data models. It should instead embrace the heterogeneous nature of data on buildings and the fact that these are not static entities but rather undergo changes during their lifetime - both gradual and abrupt ones.

The question is how a digital framework can support not only the wide array of architectural datatypes, but as well the practices that emerge within the lifespan of a natural material-based buildings.

Method

In this positioning paper we investigate the content, potential data structure and related practices for a digital framework – *The History Stack* – which supports a circular building practice by aiming to establish and upkeep a connection between the range of digital models that emerge during a building's lifecycle (Fig. 1).

The History Stack builds upon existing concepts of semantic repositories for building data. It proposes to store the diverse range of digital data that emerges during design, fabrication, and operation, but importantly the relation between the different models. It provides means to capture static data describing a building's design, in e.g. design and simulation data, as well as dynamic data from e.g continuously monitoring sensors. We propose a minimal set of "semantic links" between these, with a bare minimum of temporal links (time of creation and last modification), and thereupon spatial links (e.g., global position of an element as well as its position within the building), and object links (e.g., object ID). Serving all phases of a building's lifecycle, this minimal set of links can connect data between material cataloging, design, specification, fabrication, maintenance, and decommissioning. Within the scope of this study we test the concepts of such a semantic database in software prototypes. These are further extended in ongoing work of the participating researchers (European Commission, 2024).

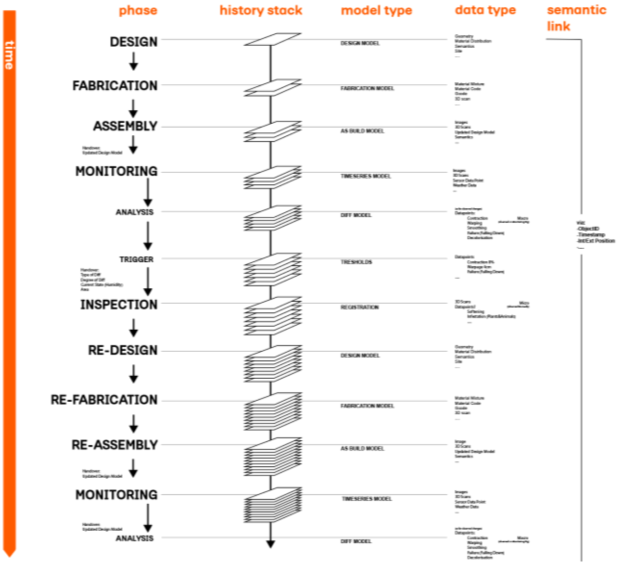


Figure 1: The History Stack as a continually expanding and refined set of interrelated media documenting and specifying a building.

The setup of the History Stack as a semantically linked collection of models, rather than a unified monolithic one, enables it to link to new data types and models as needed.

The History Stack can therefore follow not only the updates and adaptations of the physical building, but as well the ever-evolving digital technologies and data models that are continually being developed in digital building practice. This design of the History Stack makes it lean and addresses questions of data resilience and long-term survivability (Lindlar & Tamke, 2014). The use of established data formats and a good documentation of the different data models in the History Stack provide further resilience, while a semantic architecture using World Wide Web standards allows data crawlers to repeatedly check links between the models and help to reestablish these where they are missing (Beetz et al., 2016).

But most of all, the History Stack is operational. Its architecture is meant to support the immediate use of the stored data by its owners and their collaborators. This contrasts with models like the material passport that typically remain unused until the end of a structure's life. The History Stack provides a digital base that supports and enables the different practices that are necessary to design, maintain, or repair a building during its lifecycles. Investigating our method with bio-based materials we define here five key aspects of the model:

- **Data**: storage of static and dynamic models of a building.
- **Semantic Links**: the creation of links between entries in the History Stack, e.g. the registration in one common coordinate space of the position of initial design geometry as well as images and 3D scans of the physical building.
- **Difference Analysis & Visualization**: the correlation of different states of one or several data models to detect, analyse and quantify change. This detection might take place via visualization for human actors or computationally, where change is automatically detected and quantified. This might require transforming data into a unified data space.
- **Trigger**: the evaluation of logical conditions on the analyzed data, e.g. when a datapoint exceeds a certain threshold value. Once the condition is fulfilled, human or automated decision making can take place.
- **Action**: machine or human tasks to be initiated by the triggers, e.g. preparation of data for redesign and refabrication or alignment of historic design data to the subject's current state.

Results: Implementing the History Stack in the emerging circular practices of bio-based material systems

While buildings undergo changes over periods of many years, bio-based materials respond especially to humidity and water exposure in shorter timespans - ranging from years (timber) down to mere hours (the biopolymer studied for this paper). Biomaterials are thus well suited as a case study of the History Stack.

We exemplify and test the History Stack in our research practice with bio-based prototypes made from bio-polymer 3D printing and reclaimed timber within the European funded Ecometabolistic Architecture project (European Commission 2021). In this paper we investigate our practices used in two prototypes:

- *ReShelter*, a forest shelter under development at CITA, reuses curved timber elements from the earlier RawLam demonstrator structure (Svilans et al., 2022).
- *Bio-Polymer research*, which investigates the lifecycle and care and repair practices with 3D printed biopolymers, through deliberate exposure of these to outdoor weather conditions (Chiujdea et al. 2024). For these experiments, two wall-mounted "Rigs" and a standalone "Observatory" structure are constructed on which 3D printed panels are installed and exposed to the elements (Tamke et al 2024).

In our practice we develop future scenarios of builsing operation and maintenance with bio-based materials and find, that these call for automated timeseries data collection. We then demonstrate how the History Stack organizes these data according to semantic links, enabling their comparative analysis. Lastly, we demonstrate the functional application of the History Stack as a means of detecting events and automating behaviors such as registration or repair.

Data

Access to historic data of a building element is essential for circular practices, which often leverage information about a building lifecycle's many stages: from construction, to maintenance and repair, to extension and demolition. The increments in which this data is taken varies strongly – from *long increment*, such as years, as typically found in Material Passports, down to *very short increments*, as it can come data from automated sensor networks (Tamke et al., 2023). The History Stack, is designed to store and operate upon data with a diverse range of increments. A typical task of such models is to compare current data on a building with previous data from the time of fabrication, as in the ReShelter. The History Stack for these elements retains data regarding the customized material composition of the Glulam beams and their fabrication. When the recovered components are measured with a mobile phone-based LiDAR scanner, they are found to have deviated from the original spatial model (Fig. 2). To remedy discrepancies and create updated high precision 3D models, the historic design data are adjusted to the physical objects using a laser projector. These corrected models are then merged into the History Stack with a new timestamp. In this case data is recorded only at the start and end of the ReShelters structure's lifecycle, in line with modern practices around data storage.

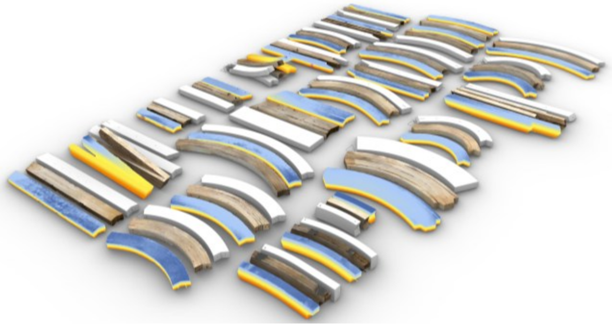
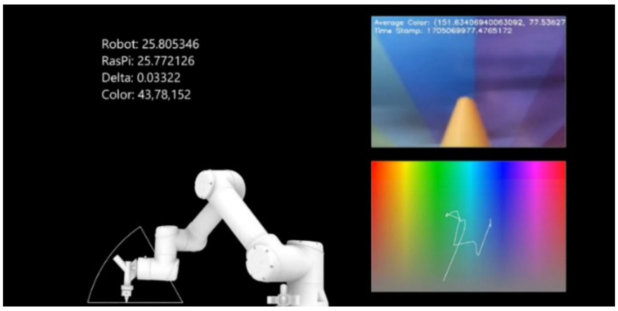


Figure 2: Data from the History Stack is used to assess deviations of stored Glulam elements from the original fabrication data – enabling their reuse in ReShelter.

Time-based data with hourly or minute increments is captured in the Bio-polymer experiments. The Rig and the Observatory are equipped with sensors including an Azure Kinect depth camera which was programmed to automatically document the panels at 7-hour intervals (Tamke et al., 2024). Other data sources included a camera and environmental sensors (Fig. 3).

Figure 3: The EMA monitoring Rig follows the behaviour of BioPol panels over time.

During isolated events such as fabrication, data may be captured even in sub-second increments. In order to analyse and improve 3D printing of gradient biopolymers a color tracking device was developed to record the average RGB value of the printed material in real-time, while it was being printed. The resulting timeseries data contains colors and spatial coordinates with timestamps just milliseconds apart, rather than minutes or days, demonstrating the flexibility of the "increment" in our incremental approach. This data was furthermore coalesced into a single, colored point cloud with one unified timestamp for ease of comparison with other panels at the object level (Fig. 4).



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Robot: 25.805346
RasPi: 25.772126
Delta: 0.03322
Color: 43,78,152
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Average Color: (151.63406940063092, 77.53627
Time Stamp: 1705069977.4765172
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Figure 4: Validation of the color-tracking apparatus, correlating RGB colors with a timestamp and a point in space extrapolated from robot joint positions.

Semantic links

Once these data are compiled in the History Stack, semantic links relate different datapoints and models to one another. In the History Stack, datapoints are stored as fields grouped within models, where any datapoint always has a "timestamp" field, and often also fields specifying a building component and its position/orientation (Fig. 5). The History stack integrates different types of data and data storage. In our prototypical tests, we use semantic web architecture, as e.g. the use of rdf and ontologies, to integrate simple data storages, where multitude of files at different moments of time, with the timestamp being the main representative and a file directory as means to access, container formats (HDF5), as well as timeseries databases (influxDB).

For example, a model in the History Stack for the BioPol Rig contains data fields for humidity, temperature, panel weight, and the filename of an associated 3D scan, among others; all referencing a particular panel on the rig, at a certain offset from the rig's base orientation frame, and all recorded at a particular date and time. Leveraging the three fields common to all entries, semantic links typically fall into one of three categories: *temporal links, spatial links, and object links.*

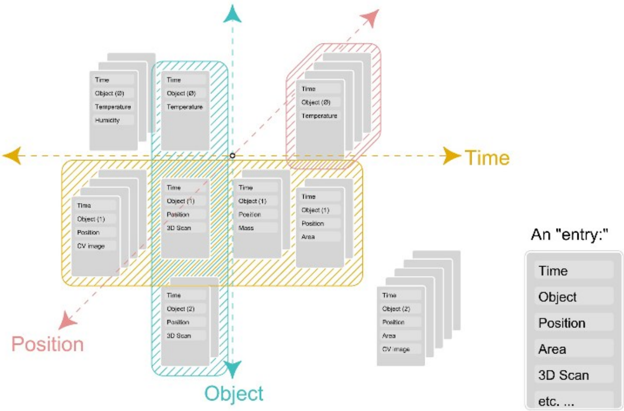

Figure 5: Models in the History Stack are naturally organized according to three primary kinds of semantic link, but each entry can contain various fields of different formats according to the context it references.

Temporal links relate datapoints from different models based on their proximity in time; for example, allowing one to retrieve the humidity or a component's weight at the time a particular 3D scan was captured (Rossi, 2021). In the case of the biopolymer temporal links were established between weather events, such as precipitation, freezing temperatures or periods of high humidity, and the 3D scans recorded immediately before and after those events. In this way the team could narrow down when the most dramatic material deformations occurred (Fig. 6).

Spatial links associate data that is grouped by spatial distance, such as aligning multiple point clouds, captured with different techniques or at different times, in the same coordinate space. In the case studies described above, this has been accomplished using oriented bounding box (OBB) and spatial transformation algorithms (Fig. 3) (Tamke et al., 2023) to align 3D data of an object captured from different viewpoints. Here the detected camera position and parameters becomes an important datapoint enabling spatial semantic links between disparate data, just as timestamps enable temporal semantic links.

Object links associate individual objects or assemblies. In our case study, some 3D scans of the BioPol panels are stored as surface meshes, and others as raw point clouds.

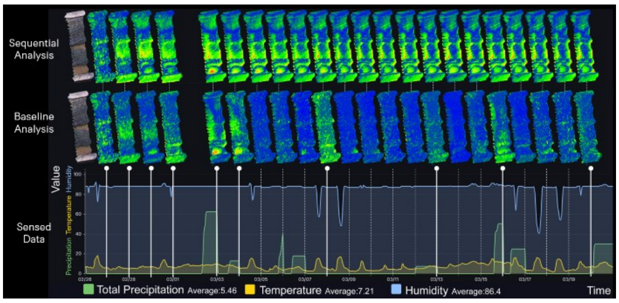

Figure 6: Incremental monitoring allows to understand the impact of weather events on biopolymer panels through sequential analysis.

Furthermore, many scans only capture the panels' outer surfaces, omitting internal details like thickness and porosity. We can more easily combine the most useful parts of these different data formats (e.g. combining the interior detail of one model with the as-built accuracy of another) when we are able to query the datapoints belonging to a particular building component. We semantically "group" these together when they represent the same object, even though their specific formats or capture methods differ. Object links can also be used to declare sub-objects and hierarchies, as in the case of the 2D images of the timber samples from RawLam captured using a linear photo scanner. Each of these is associated with the distinct faces of a single wooden component (Fig. 2). They are then used to texture a 3D surface model reconstructed from a LiDAR scan. In this way the History Stack supports the organization of complex multi-part structures.

Difference Analysis & Visualization

Semantic links help form a basis for comparison of pairs or series of entries in the History Stack. Temporal, spatial and object links can be used in unison to discover correlations between diverse datasets. For the BioPol project we have developed a digital user interface that presents in parallel camera images, environmental data, and two- and three-dimensional analysis of panels. The data is linked by timestamps and, in this prototype, stored in an Influx DB database. This approach allows users to track trends and filter data to find interdependencies between e.g. weather and material behavior (Fig. 7).

Insights into the temporal behaviour of buildings is gained via "difference analysis." Such analysis can form new datapoints or series. For example, we store global values representing the extremes, average, or variance of a series of scalar datapoints grouped by a given semantic link, such as the maximum temperature reached in a specific 24-hour period. The differences between values in a timeseries are extrapolated as an estimate of that value's rate of change, for any point in time.

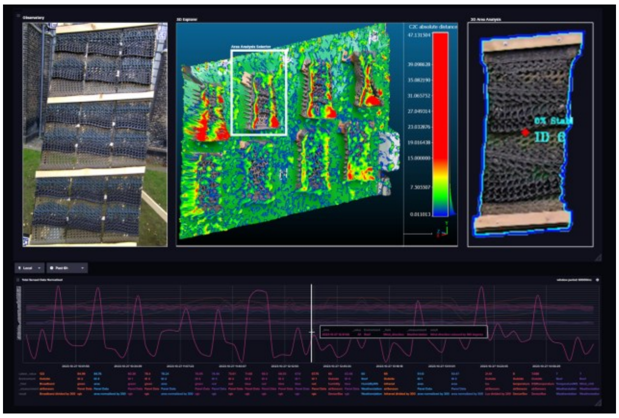

Figure 7: A online dashboard enables access to historic and current models in the form of raw, processed (interpolated), and interpreted data (e.g. analysis of panel shrinkage).The screenshot shows work in progress of the dashboard that will be used in an installation in May 2025 in Copenhagen.

This technique was used to track material deformation of the panels on the Observatory demonstrator by detecting the panel's contour using computer vision and then tracking changes in the contour's area over time (Tamke et al., 2023) (Fig. 8).

Difference analysis may be purely quantitative and automatically calculated, or qualitative. This approach is especially helpful, when the system's behavior is not yet fully understood, as it can serve as an explorative tool and uncover motivations for further, quantitative analysis. Simple stop-motion animations of the point cloud scans of the observatory were useful to highlight otherwise obscure changes by simulating accelerated time (Fig. 8). Visualisations can be augmented by analysis. For example, coloring one point cloud according to its pointwise distance from a second one permits easy assessment of millions of individual differences at a glance.

Figure 8: An image segmentation tools allow to track and quantify the deformation of each BioPol panel over time. In the screenshots from a stop motion animation the shrinkage of the nine biopolymer panels is visible from left to right.

This technique was used to understand the depth cameras' time-varying accuracy in the Rig and Observatory demonstrators (Fig. 7).

Triggers

The History Stack extends the notion of a database by incorporating reactive protocols in the form of "triggers" and "actions". Triggers are conditions on the data that can be evaluated to Boolean values, and thus form a subclass of difference analysis. The action to follow the activation of a trigger can be automatic or manual.

One trigger-action pair employed in BioPol involves analysing the daily 3D images of the panels. Here computer vision algorithms are used to isolate the individual panels on the observatory and calculate their area dimensions. If these areas fall below a threshold the monitoring framework sends a message and triggers inspection and eventual repair actions (Tamke, Shahriar Akbari, et al., 2024). Another uses real-time weather data to determine the optimal time within a 6 hour window for recording the panels' 3D scans. (Tamke et al., 2024).

Actions

The workflow of automatically monitoring for damage and triggering repairs has been developed in parallel with the History Stack and is particularly suited to its methodology. For the goal of automatic material monitoring and repair, one must be able to extrapolate that a failure has or is about to occur; assess what kinds of repair are appropriate; and determine what historical data are necessary for specifying the repair, as well as any conversions necessary to translate the historical data into the present context.

Repairing the 3D printed panels requires printing conformally onto the damaged material, which in turn requires an accurate updated 3D model of its outer surface (Fig. 9). While the 3D scans taken outdoors with the Kinect camera give enough resolution to detect whether a trigger threshold has been reached, it was found this was not sufficiently accurate for printing, with a margin of error of up to 4mm (Tamke, Akbari, et al., 2024). Therefore, an additional scan is conducted on the panel after it is taken into the workshop with the 3D printing robotic arm refitted with a single-point laser distance sensor, creating a more accurate datapoint that can directly inform robotic repair (Chiujdea et al., 2024).

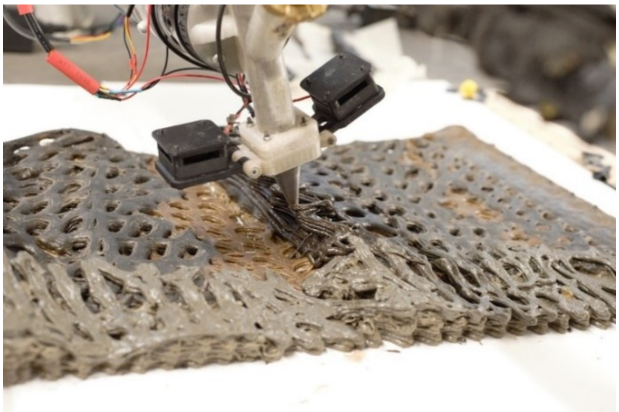

Figure 9: Repair practice with 3D printed biopolymer panels.

Discussion

The key features of the History Stack which depart from existing approaches to BIM and digital twins are its incremental and non-relational (i.e. nontabular and asymmetric) natures.

Incrementally adding to the History Stack ensures datapoints are closer to one another in time, improving modeling of time-varying behavior for prediction and better understanding of conditions leading to discontinuous behaviors like sudden failure. In the BioPol track, automatic incremental scan data allows for transitive point cloud feature matching. Matching global position and orientation, or individual extracted feature points, from an initial to a final model may be difficult or impossible if the object has undergone significant warping, but if only two subsequent datapoints are compared at a time, and these matchings are then compounded in time, this difficulty can be ameliorated. The less time between recorded datapoints, the greater the confidence of the overall feature matching (Tamke, Akbari, et al., 2024).

All entries in the History Stack contain a timestamp. In this way, regardless of the kinds of data therein, any two entries can be compared in one linear, monotonic axis: time. Enforcing timestamps ensures that temporal phenomena like longevity, rate of change, or state at failure can be easily inferred for other data streams. This requirement is crucial to the material monitoring workflow for which this architecture was designed.

At the same time, the History Stack's nontabular architecture aptly handles asymmetric data. It is easy to adjust the rate at which data is recorded; to record simultaneous streams of data at different rates; or to incorporate historical data that may have been recorded in another rate. This flexibility applies to format as well as rate of data capture. As such, the History Stack is easily extended, which is an advantage in a circular building paradigm where each new use of a component might necessitate new kinds of data, or during handoffs between different entities each using their own unique collection methods. Enforcing a set of semantic links (timestamp, position, object ID etc.) makes the data in the history stack reusable and encourages data retention following best practice (Lindlar2014). This allows future access and analysis of data, when new questions and tools emerge and avoids todays data dumps of inextensible data architecture.

The asymmetric nature of the History Stack also implies that data can be recorded once at high resolution, often at the beginning of a structure's life as is already common practice in BIM; and then subsequent monitoring may be performed incompletely or at a lower resolution, whether for cost-saving or practical reasons.

An example where all the above features of the History Stack come into play is in the print path generation for the repair of the BioPol panels. The daily scans of the panels in BioPol are sufficient for some analyses but not accurate enough for the purposes of print path generation. When these panels are taken down from the Observatory for repairs, they must be scanned again with a more accurate laser distance sensor. The History Stack gives a framework for associating these different scans. The timeseries of scans are not only different in resolution, but also they show the panel in different states of decay. Spatial and component semantic links establish a basis for translating between them. An advanced application of the History Stack uses radial basis functions to develop a smooth spatial displacement map from the idealized model of a panel--dating from the time of its fabrication and represented by hairline toolpath curves in 3D space--to the final distorted model, for which only the surface is captured as a colored 3D point cloud. This example leverages the History Stack's ability to adapt various datatypes (curves, point clouds) to new contexts, and to extrapolate new information by combining them, thanks to its emphasis on temporal ordering and incremental capture.

Conclusions

Our work with the concept of the History Stack proved to be beneficial for our practices of maintenance and repair of bio-based materials. The framework allowed us to reuse historic data and develop practices of correlation, comparison and synthesis of models from different paradigms and resolutions.

Of central importance here are the introduction of temporal, spatial, and object links. These links are in most cases given in the metadata of data entries and allow for easy establishment of connections between the diverse range of models in use.

In this way the History Stack was indeed operational, supporting actions and creating immediate benefits, thus taking a different trajectory from other data preservation efforts in AEC such as the material passport. Whereas the data within the material passport is only potentially valorized at the end of a building's lifetime when the building's usefulness to the owner is limited, the History Stack sets out to be an active asset, as it allows to trigger and steer actions that help to preserve and adapt a built structure continuously.

The History Stack is currently in a conceptual state and its architecture is not fixed. The exposure of it to the demands of our use cases shall ensure its adaptability and resilience and is understood as a step towards a more sustainable data practice in AEC. As such it is understood as an input to e.g. ongoing European research project on digital building logbooks (DBLs), as it shows the potential and need for open ended and expandable data infrastructures to achieve the aims of the circular economy. Here data cannot be understood only from a data conservation point, that serves a future end of life scenario, but one of constant flow and update, where the costs of data use and (automated) update proves its utility in building operation, maintenance and reuse.

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