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Co-creation with carbon data: Reframing the designer's role in the decarbonization of the built environment

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Abstract: Cross-scale, multidisciplinary design projects such as station area redevelopment are inherently complex, with many stakeholders and vast amounts of data relevant to decision-making. In the Netherlands, these projects face a dual challenge: meeting housing demands while reducing the embodied carbon emissions associated with construction. Early integration of carbon data is essential, yet the abundance and heterogeneity of supporting datasets required for Life-Cycle Assessment beyond the building scale can hinder progress. This paper presents a collaborative workshop method that enables a data-supported design process for informed decision-making. Sessions with station architects, urban designers, railway operators, and carbon specialists co-create a curated data inventory for low-carbon station design. Using analogue data-cards in a constrained deck turns digital data opulence into a structured, tangible, face-to-face procedure based on a shared language, making tacit choices explicit and traceable. Findings underscore the architect's new digital-era role as a knowledge integrator.

Keywords: Design Tools and Methods, Integrated Knowledge, Data-Supported Design, Role of the Architect

1. Introduction

Complex projects, such as the development of station areas, sit at the interface of architecture and urban design, where many actors, competing agendas, and heterogeneous, multi-scale datasets converge. In the Dutch context, these projects face a dual challenge: meeting housing demands while reducing the embodied carbon emissions associated with construction. Early integration of carbon data is essential, yet the abundance and heterogeneity of supporting datasets required for Life-Cycle Assessment beyond the building scale can stall progress. This paper presents a workshop method that enables a data-supported design process for informed decision-making, by converting digital data opulence (Carpo, 2017) into a structured, tangible, face-to-face procedure based on a shared language, making tacit (design) choices explicit and traceable.

The study is situated within a PhD research on Carbon Data as Design Material, at Delft University of Technology (TU Delft), which investigates the integration of embodied carbon data across the design scales of Architecture and Urban Design. It adopts the Rotterdam Lombardijen train station as a case study for cross-scale carbon assessment, experimenting with the extension of Building Life-Cycle Assessment (LCA) into urban design (station precinct) applications. While this research is developed through the specific case of train station precincts, the method is intended to inform other complex redevelopment projects that require cross-scale coordination, heterogeneous data curation, and multi-stakeholder decision-making.

2. Workshop method as research approach

Named "CARDS" - Carbon-Aware Research for Data-Supported Design, this research develops a case study through mixed methods, starting with desk research for theoretical background and contextualization, followed by an auto-ethnographic research-by-design experiment and workshop with experts for strengthening and validation. This study demanded diverse stakeholder knowledge as the problems of mobility, carbon assessment, station design and neighbourhood design demand expertise on usually siloed disciplines.

Desk research reviewed workshop-based and practice-led precedents to base the co-creation method, material design, and data-collection approach. Hemstock et al. support the use of workshops as a format for learning, knowledge exchange, creative problem-solving, and innovation around a domain-specific issue (Hemstock et al., 2022). By noting the limits of online sessions, Hemstock et al. reinforce the decision this present study makes for in-person observations. Davis et al. frame co-design as a way of engaging diverse stakeholders in complex problem-setting, aligning with Sanders and Stappers' view of co-design not only as a method or tool, but also as a mindset, with the workshop functioning as a space in which generative processes can unfold (Davis et al., 2022; Sanders & Stappers, 2014). Aflatoony et al. show the methodological value of rich visual-tactile data in the format of game cards, and how they can be interpreted by participants, providing insights and informing design requirements for architects. Building on this background work, the present study develops an in-person co-design workshop using game cards to curate carbon-related data for integration in early-stage architecture and urban design processes.

Desk research also involved reviewing planning documents and previous urban studies about the site (Meijel et al., 2008; Schaasberg & Tjokrokoesoemo, 2021; Wijngaarden & Hooykaas, 2016; Wijtsma, 2016). In "People Oriented Sustainable Design: Renovation of Post-War social housing in Rotterdam Lombardijen", Derk Wijtsma presents an approach for material inference based on visual observations of the buildings on Spinozaweg, a main mobility axis crossing the Lombardijen station site, p.27 (Wijtsma, 2016). Although Wijtsma does not study decarbonization, this approach inspired the CARDS method to initiate the creation of a georeferenced data inventory for precinct-scale LCA, based on site visit photos (Figure 1).

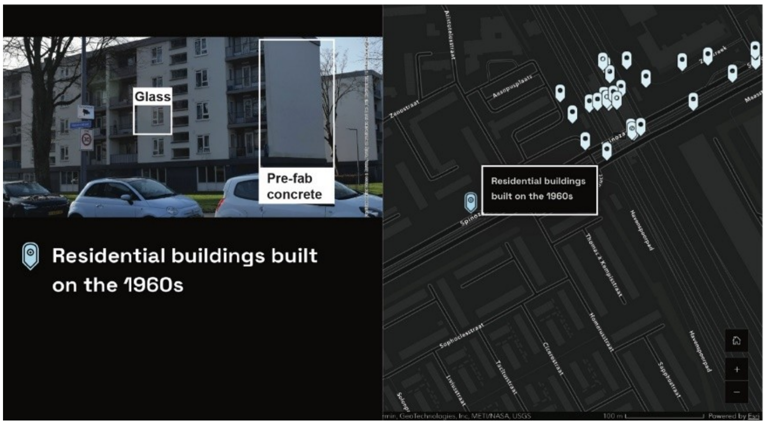

Figure 1 Georeferenced site photo with material inference annotation. By Halina Veloso e Zárate, 2024.

This inventory is a key starting point for extending LCA to urban design applications, because the standard LCA methods for buildings are based on the quantity of materials used in construction (ISO 14040/44; EN 15804/15978). LCA uses material databases certified through Environmental Product Declarations (EPD) and attributes a carbon impact value to each construction material in a building – the Global Warming Potential (GWP), in KgCO2 equivalent per square meter, for example. Building Information Modeling (BIM) facilitates the production of Bills of Quantities (BOQ), which lists the construction materials used and the quantities of each. This facilitates the application of LCA methods through BIM-based plug-in tools such as OneClickLCA. However, at the urban/precinct scale, assets go beyond the building envelope, including transportation infrastructure and landscape components. This demands the creation of a tailor-made material inventory, constructed from site observations and ground-truthed with supplementary data. The CARDS methodology performs an analysis of archival construction drawings, point-cloud data, satellite imagery, maps in Geographic Information Systems (GIS), and other sources to strengthen the material inference identified in the initial observations.

Similarly, construction materials from landscape assets such as a lawn or a permeable paver sidewalk are not always available in open access material databases such as ÖKOBAUDAT. In response, the CARDS research identifies material benchmark GWP values in alternative data sources, such as the "Climate Positive Design" web app (*Climate Positive Design App*, 2023). It also seeks reference benchmark values linked to building typology in scientific papers, such as Kayaçetin and Tanyer's 2019 "Embodied carbon assessment of residential housing at urban scale" (Kayaçetin & Tanyer, 2019), and practice-led studies, as seen in Paris Proof Stations (Spoorbeeld, 2024). This way, CARDS produces a curated database of reference for precinct-scale LCA application.

Extending LCA methods gains complexity when moving away building envelope boundaries and encompass negotiable (ill-defined) boundaries (e.g., based on catchment areas, or ownership interfaces) (Talen, 2011). To define the system boundary, CARDS draws from the methodology described by Talen in "The Geospatial Dimension in Urban Design" to perform a multi-factor geospatial analysis including factors such as walkability, property ownership, and building age. Within the defined system boundary, project data about the built environment assets is crucial for quantifying how much area of a given material, but is not always available. For instance, when existing, architectural 3D models or 2D drawings of ancillary buildings are owned by various parties, and rarely public. The area of sidewalks and roads, or parks can be publicly accessible through PDOK geospatial data, which requires processing using Geographic Information Systems (GIS) - not always easily interoperable with BIM software. Furthermore, allocation risks (double counting, shared infrastructure) are high. In response, the CARDS research re-creates a schematic precinct-scale digital 3D model based on 3D BAG data, complemented and validated with supplementary data. To recreate elements not originally available in 3DBAG, archival 2D architectural drawings, PDOK data, point cloud data, satellite imagery, street view imagery and photos from site visits are also applicable in the construction of this station area model. As this was a process driven by the main researcher (first author), the workshop as a co-creation method becomes relevant to mitigate bias and strengthen the methodology with varied knowledge and data.

The primary conclusions of this investigation regard how methods, datasets, and conventions for LCA are still being developed for its application at precinct scale. To validate the methodological steps and data described above, the exploratory research method addressed in the paper includes a series of workshops involving experts to co-create a methodological framework (CARDS framework) (Figure 2).

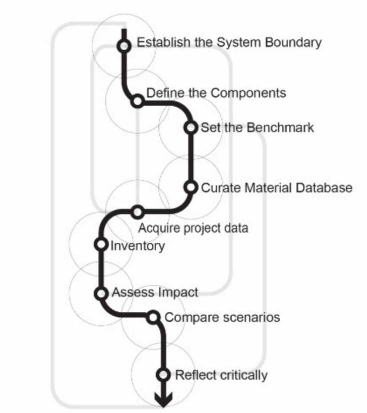

Figure 2 The CARDS Framework. The workshop method described here addressed data related to the steps "Establish the system boundary", "Define the Components', and "Acquire Project Data". Illustration by Halina Veloso e Zárate.

The first and main workshop was held in March 2024, at TU Delft, counting with approximately 55 designers: architects, urban designers, city planners, railway station operators, carbon experts, data-scientist. Through their engagement, the CARDS framework is developed with its intended users. Following Sanders & Stappers' co-creation perspective (Sanders & Stappers, 2008), the workshop treated architects and collaborating experts as co-designers of both the method and its data vocabulary. It also created a setting in which participants' judgments and justifications could be observed, helping to surface forms of tacit knowledge about design problem-solving that often remain unspoken (Cross, 2006; Schrijver, 2021).

The format of the workshop was tested in four iterations, with slight variations of the tasks and experts involved. On its multiple iterations (Table 1), the workshop brought forward the value of co-creation as a triangulation method for research-by-design and case study, surfacing findings beyond the data-inventory initially wanted.

Table 1 Low-Carbon Stations Workshop Iterations.

Iteration	Participants	Expertise
#1 "Low Carbon Stations Workshop" (TU Delft) March 12th, 2024	55	design, railway/station architecture, urban design/planning, circular construction, software development, urban data-sciences, mobility consultants, carbon-design specialists, ~20 architecture students
#2 AMS Institute "Reinventing the City" Conference (AMS) April 23rd, 2024	7	Architecture, AI workflows and computational methods, urban energy systems, project management, urban planning, railway/station architecture, low carbon design, 2 architecture students
#3 Mobility Congres Groene Metropool Regio Arnhem-Nijmegen June 6th, 2024	8	Sustainable mobility strategy and policy, traffic engineering, 1 industrial design student
#4 AI & de digitale transformatie in het Ruimtelijk Ontwerp Gemente Groningen June 13th, 20204	29	Urban design/planning, traffic engineering, civil engineering, landscape architecture, Geoinformation Data management, policy

3. Co-creation with carbon data

While data-supported methods enhance environmental accountability from the moment projects are conceived, they also increase complexity, multiplying sources, metrics, formats. The data abundance in CARDS leads to inquiries such as "What constitutes 'data' in the process of designing low-carbon stations?", or "which data is relevant to support fulfilling each step of the CARDS framework?". Such inquiries necessitate new modes of coordination in design contexts of increased datafication (Vrachliotis, 2022), redirecting focus from data quantity to the value each dataset adds to design and carbon assessment.

This study therefore aims to validate both the CARDS framework and the supporting data applied in the Rotterdam Lombardijen station case. Following Schön, it understands problem setting as distinct from problem solving: a process in which practitioners "name the things to which we will attend and frame the context in which we will attend to them", p. 40 (Schön, 1982). In the proposed workshop, this problem-setting process takes place collectively through the selection of system boundaries, components, and datasets for early-stage carbon assessment. Accordingly, the study translates these practical concerns into the following research question: **"**How can carbon-related data be operationalized as a collaborative instrument for cross-scale and multidisciplinary knowledge integration?"

The workshop method responds by transforming heterogeneous carbon datasets into game cards, which serve as negotiable shared artifacts that can be interpreted and utilized by multiple actors from distinct perspectives, yet still facilitate coordination among collaborators because their meaning remains stable enough across disciplines. The data-card is a piece of paper printed in A5 format that comprises representations of multiple digital data pieces, relative to the steps on the CARDS framework (Figure 3). They feature both curated data (pre-selected and prepared) from multiple sources and formats, as well as blank data-cards to collect data suggestions. The data-cards included datasets in the form of photos (site pictures taken by the first author), diagrammatic analysis of materials (Adobe Photoshop, Illustrator), digitized construction drawings from public or private archives, geospatial data (3DBAG, PDOK, Kadaster), numeric values of Global Warming Potential (GWP) of materials (ÖKOBAUDAT, Climate Positive Design/CarbonSpace), schematic diagrams based on construction details for material composites, and 3D model of the station and station area reconstructed using 3DBAG and PDOK data processed in QGIS and Rhino/Grasshopper (CityJSON).

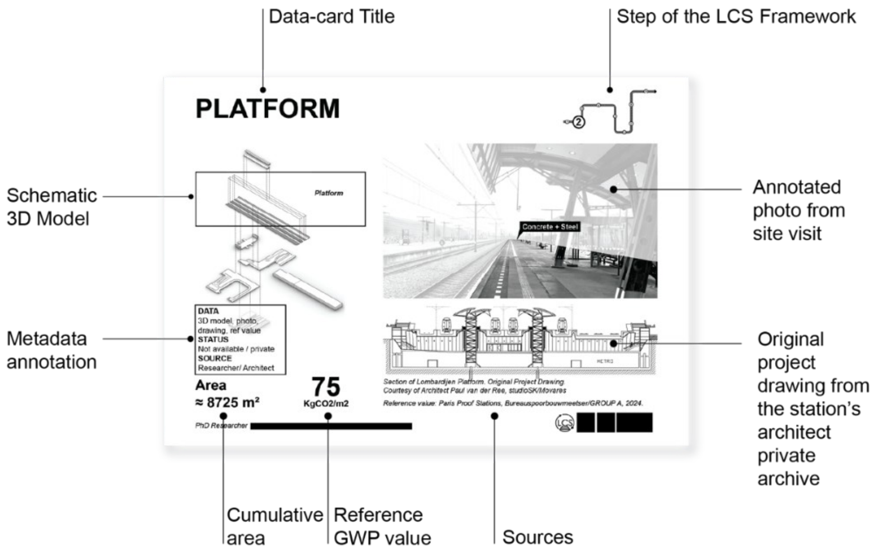

Figure 3 Data-card example, featuring data relevant to step 2 of the CARDS framework: Define the components. In this case, the component featured is the station platform. This data-card was used as represented above in the Workshop at TU Delft, in March 2024. For the other workshop iterations, simplified data-cards were used, as explained in 3.1 Iterations. Created and illustrated by Halina Veloso e Zárate.

The analogic data-cards are a constant, standardized empirical material that form the basis of comparative analysis. Given the constraints of a limited deck (to manage data abundance), the workshop provided a structured, tangible, and face-to-face procedure (Figure 4). The adoption of this expert co-creation session for early-stage data curation provides the occasion to perform an empirical research method loosely inspired by protocol analysis's (Ericsson & Simon, 1993), described by Cross as a way "to bring out into the open the somewhat mysterious cognitive abilities of designers" p.77 (Cross, 2006). The researcher asks participants to work on a shared problem while verbalizing their thoughts. The data-cards provide a common topic for discussion, aiding participants in speaking out-loud their judgments, negotiating trade-offs, and leaving auditable traces. As experts discuss about data-cards, their reflections and tacit knowledge is made explicit in-action, when justifying choices - aligning with Schön's view of design as a reflective conversation with the situation.

Figure 4 The workshop iterations, 2024. Photos by Inès Zaid and Halina Veloso e Zárate.

Analyzing the workshop method, particularly the data cards supporting carbon assessment of the station and station area, positions design as an activity that extends beyond artifact production. By treating design as a process, a shared language, and a platform for addressing urgent societal challenges, this research aligns with contemporary views of design as both process and instrument of social impact (Moreau et al., 2024). The workshop further reveals the designer's role as an integrator and conciliator of conflicting briefs, heterogeneous data and tools, and the tension between scientific precision and practical applicability. In this sense, the designer frames problems as operable systems (Oxman, 2006), while their "instruments of service" (Christoforetti & Reidel, 2025) include curating data, orchestrating interactions between human and digital matter, mediating across scales and disciplines, and assigning value to raw datasets.

4. Preparation – data and materials

A deck of thirty-five data-cards represented datasets supporting three main steps of the methodological framework for carbon assessment: Establishing the System Boundary (ESB), Defining the Components (DC) and Acquiring Project Data (APD). The data-cards provided received a name, described the datasets used in the data-card, indicated datasets status - if this data already existed or needed to be created, and if it is of open access or not-, and indicating data sources and tools utilized (Appendix Table 1).

Besides the data-cards, described in *2. Co-creation with Carbon Data* other materials were prepared to support the workshop (Figure 5). An informed consent was prepared to collect signatures from participants, for the use of photos and annotations from the workshop in publications related to the first author's PhD research. Task-cards, printed on A5 format, gave clear instructions on "what to do". These task-cards were only used in the first workshop iteration, which had three tasks. For the follow-up workshop iterations, participants only had one task, briefed in the introductory slide-show, but no task-cards.

Printed basemaps on A2 format featured the Lombardijen station area and served as a board for annotation, sketching and sticking notes justifying choices along the activity. On the first workshop, basemaps portrayed 2 design scales: station building (architectural scale), and the precinct urban scale of approximately 800m around the station (typically considered a

10-minute walk). The basemap was an overlay of satellite imagery and BGT (Basisregistratie Grootschalige Topografie, in English, Large-scale topography basic registration) data, featuring buildings, roads, water, and railway lines, from Kadaster, obtained through Publieke Dienstverlening Op de Kaart (PDOK). In addition to basemaps, questionnaire-cards on A5 format were provided to collect notes and track data curation. The short questionnaire-cards were created to record selections, rationales, and gaps discussed in each group. Sticky-note pads and pens enabled direct annotation on basemaps and data-cards.

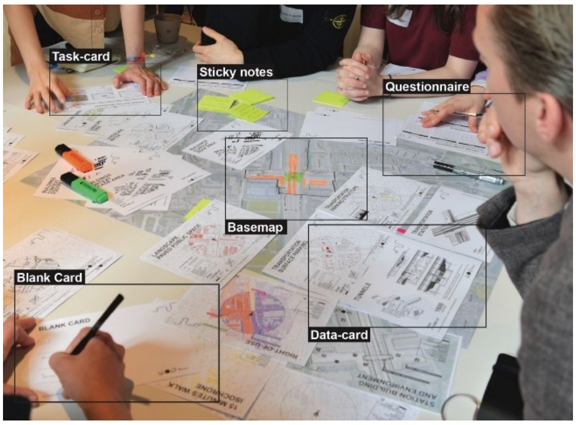

Figure 5 Materials provided at the Workshop at TU Delft. Illustration by Halina Veloso e Zárate.

A large panel representing the proposed framework served as a mind-board for participants to gather around and share thoughts in a plenary session. The color-coded sticky notes were categorized by the framework step they related to and added to the panel. The filled-in questionnaires were also added to the panel, creating one collective output (Figure 6).

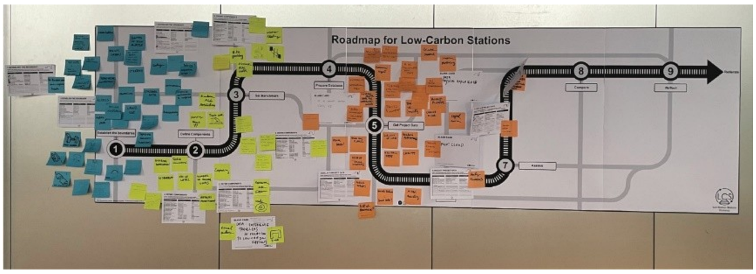

Figure 6 Panel collecting sticky-notes from participants. Photo by Halina Veloso e Zárate.

The collection of analogue material was useful to constrain the "data opulence" designers deal with in their workflows when dealing with digital formats. While the data-cards offered a shared language for discussion, the questionnaires, marked basemaps, and sticky-note panel produced an auditable data inventory and a map of missing data relevant to the carbon assessment of low-carbon stations.

5. The workshop process

The CARDS workshop opened with a brief lecture to establish a common baseline on scope and embodied carbon, followed by a step-by-step exercise briefing, so all participants clearly understood the data-curation tasks. In the first Iteration, participants were seated in large tables with ten seats around them, deliberately composed so that each group contained at least one representative from each knowledge field. The tasks asked from the participants were:

- **Establish the System Boundaries:** To delineate the physical boundary of the functional "station area" for their scenario – what is the extent of the carbon assessment system. Then, to select data-cards that supported the proposal, or propose on blank-cards; draw the boundary on the basemap; annotate considerations on sticky notes. Participants would conclude by filling in the questionnaire: tick used data-cards; list missing data, and annotate source, and status of the suggested data.
- **Define components:** To identify which components – from the data-card deck – are relevant to embodied-carbon assessment (e.g., station roof, platforms, façade systems, street segments, parking, landscape systems). Select data-cards, dismiss data-cards that "do not fit" the scope, or propose new ones; note reasoning and, on the questionnaire, record chosen data-cards and unavailable data.
- **Collect project data:** Teams selected what types of data about the station development project would be crucial for carbon assessment (e.g., archive drawings, site photos, bills of quantities, geospatial data in the form of maps, 3D models, etc). The task was to prioritize data-cards for carbon assessment at early-stage design, note reasoning, and, on the questionnaire, record chosen data-cards and unavailable data.

A central timer paced the activities in three rounds of 15 minutes; facilitators circulated to ensure even participation and documentation of the process, capturing oral remarks that may not have been annotated in the material given (Figure 7).

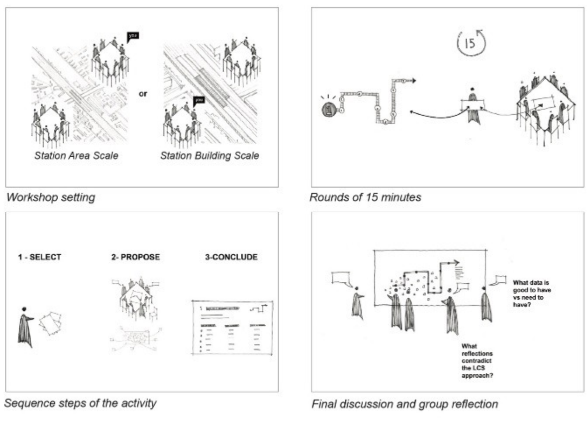

Figure 7 Workshop Process. Illustration by Mark Caruana and Halina Veloso e Zárate, 2024.

Inputs were collected in four synchronized forms: (i) marked basemaps (boundaries/components), (ii) checked which data-cards were used and proposed (dismissed cards were not taken in consideration unless justified in annotations), (iii) free-text sticky-notes (rationales, uncertainties, sketches), transferred to the large panel, and (iv) completed questionnaires (structured metadata: data, source, status).

5.1 Iterations of the workshops – findings beyond the initial inquiry

At each iteration of the workshop, slight adjustments were made to the data, materials and process, based on participant feedback. Workshop participants from the first session shared thoughts about the data-cards effectiveness as an interdisciplinary artifact for collaboration: some found them eye-opening regarding the amount of datasets behind a data-card, some considered it presented too much information in one go. Designers and carbon experts expressed interest in knowing more details about the workflow behind the creation of carbon-related data - i.e. station building components, station 3D model, construction materials -, especially when it comes to curbing inexistent or inaccessible datasets. For the participants from a computer science or software engineering background, a single data-card presented enough elements for the 15 minutes round of discussion, leaving little time to discuss many data-cards. Therefore, the authors took in the suggestion of simplifying the data-cards and tested their receptiveness on other workshop iterations. New data-cards were designed featuring minimum information – however, one data-card often hides a nesting of datasets, and deconstructing a data-card was like opening a *matrioshka* doll (Figure 8). For example, a single *Platform/Station Roof (Canopy)* data-card contains: photos and text (descriptive evidence), 3D models (geometry and parts), deductions based on point cloud data, although not illustrated (as-built capture), and GIS/BGT layers (context and extents). Each of these datasets can be further subdivided into sub-datasets (component breakdowns, material libraries, EPD factors, versions, etc.). Participants noted that this nesting mixes scales of design, sources, and purposes of analysis in one single object of assessment. Following this example, the same data on *Platform/Station Roof (Canopy)* is read differently when used for different purposes: to scope a precinct, quantify materials, or verify as-built conditions. Based on this feedback, the method unpacked the nested data-card into several data-cards with less information, each representing one dataset type with minimal fields (source and status). The data-card re-design increased the deck size, but made curation more granular and dynamic, prompting deeper discussion on data quality, acquisition, and fit-for-purpose while keeping the function of an interdisciplinary artifact for collaboration clear.

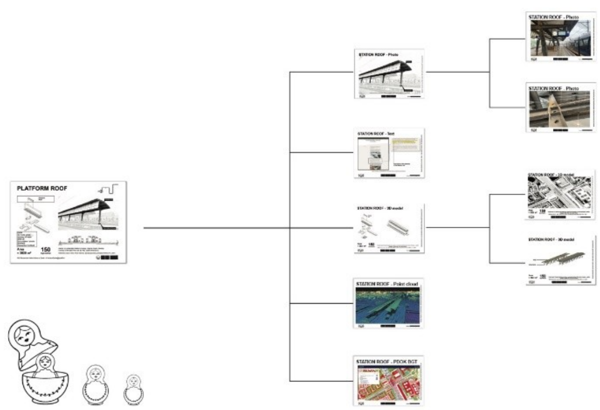

Figure 8 Example of a data-card that originated several other data-cards, with less datasets. Created and illustrated by Halina Veloso e Zárate.

Across sessions, participants consistently identified a **precinct-scale data-gap**: a missing data aggregation level between what was found in city-level GIS overviews (coarse, aggregated) and building/BIM detail (fine, component-level). This data needs to be created by the Designer-researcher, if it is to be included in the proposed low-carbon stations framework – which can be too time consuming in practice. Such a gap hinders the adaptation of LCA to cross-scale application, and data-supported design methods at early-stage design.

Addressing this insight, the following workshop iterations used three basemap boards (instead of two). One, featuring the station building architectural drawings (courtesy of the architect who designed the station renovation from 2006, Paul van der Ree, from Studio SK and Movares), and two basemaps at precinct scale of approximately 100m from the station and 800m from station (Figure 9). These basemaps were generated using MapTiler in QGIS. The participants were prompted to sort the data-cards according to the scale of assessment. A color-coded round sticker represented each of the scales of design and carbon assessment. This way, data-cards that were a good fit for multiple scales received multiple stickers.

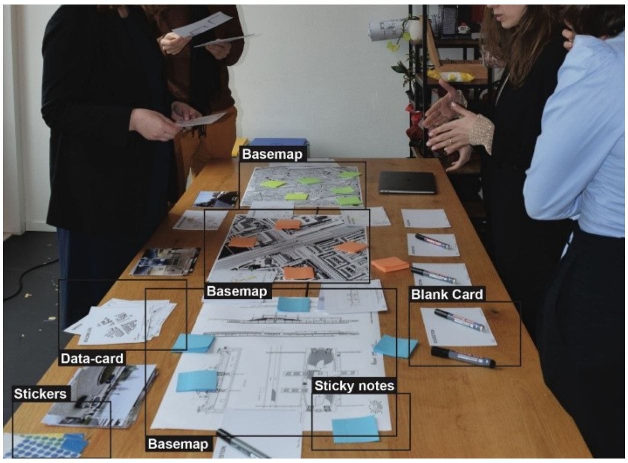

Figure 9 Workshp at AMS Institute, simplified data-cards and basemaps with three design scales. Illustration by Halina Veloso e Zárate.

Putting the data-cards through a scale exercise (building ↔ precinct ↔ city) made the relevance of data resolution visible. Many data-cards earned multiple stickers, showing cross-scale relevance, yet teams quickly saw that unmodified data-cards were not directly adequate for applicability at the precinct scale: attributes had to be disaggregated to avoid double counting, for example in the case of the station environment boundaries. Only after this manual adjustment, urban data becomes useful for precinct-level LCA.

One interesting suggestion from participants regarded redefining station design scales – city, district, area (precinct), (station) building and (building) detail (Figure 10). At city scale, design and planning relies on coarse, aggregated datasets, such as "land ownership" data. These datasets are better suitable for strategy, but too blunt for "establishing the system boundary" on their own, and useless for other LCA-related goals such as material quantification. At the district scale, data must capture networked elements (streets, landscape systems, ancillary buildings) with enough specificity to "define the components" and establish a clear physical boundary for the LCA system – yet remaining far less granular than building models. The area (precinct) scale is the "in-between", which would be best represented by a schematic urban 3D model or digital twin, with granularity closer to building models used for LCA assessment. At the (station) building scale, BIM provides fine geometry and bill of quantities, linked to material data, enabling seamless LCA through software plug-in such as OneClick LCA. At detail scale, real-time information could be used to detect components in need of maintenance (using sensors, cameras) and unlock a more detailed whole-life LCA for stations. In that sense, this reflection confirms that the data produced for this workshop, at precinct scale, is fit-for-purpose for LCA at precinct scale, for early-stage design.

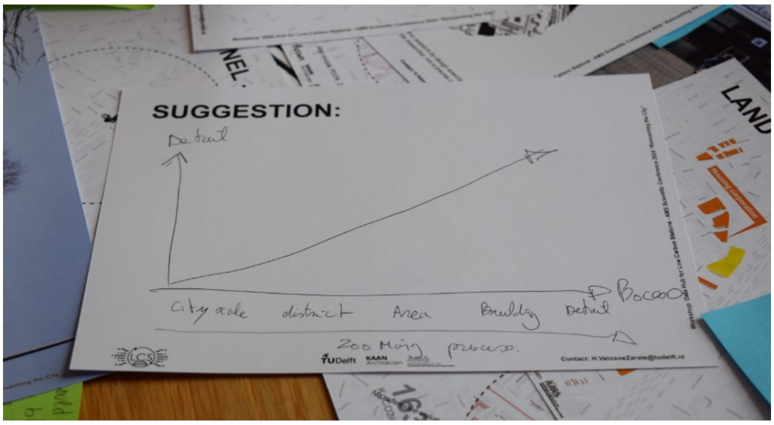

Figure 10 Low-Carbon Stations - suggested station design scales, where data resolution increases as the scale of design (and scope of LCA assessment) becomes more detailed. Photo Halina Veloso e Zárate.

6. Results

6.1 An extended data inventory

Amongst the suggestions of which data to include or exclude from the CARDS framework and workflow, a few deserve closer attention. In “Establishing the System boundary”, the data-cards supporting this step included circular buffers, isochrones and human-centric evidence on walkability from station. Some participants expressed the suggestion to exclude circular buffers as a data-card, as it is an oversimplified manner of considering walkability, and generate a physical boundary that is too bound to a deterministic geometry. After some consideration, the researchers decided to maintain buffers in the final inventory. A 400m or 800m circular buffer is a fast, transparent dataset, suitable for early scoping and rough checks; it creates a consistent baseline when little is known. The CARDS frameworks resort to buffers as part of a practical sequence: start with a buffer (set the study envelope), refine with isochrones (traffic, crossings, barriers, slopes), then add a layer of human-centric evidence from fieldwork to adjust boundaries and priorities. This staged approach provides teams with speed and fidelity, while avoiding false precision in early-stage design, and still converges on a defensible precinct boundary for design and LCA.

In “defining the components”, participants suggested the data-card on station tracks to be excluded from the assessment of the station building. The suggestion was to consider only the building and covered passenger domains, excluding rails, overhead lines, track beds, switches etc. The track infrastructure is typically viewed by railway and station designers as belonging to the broader railway network or the railway junction rather than the station building itself. For LCA assessment, having the tracks factored in complicates assessment at early stage due to its longer lifespan and networked effect. Despite not being included in this assessment, further investigation is needed to consider the tracks for a holistic analysis and more precision in more advanced phases of low-carbon station design.

Appendix Table 2 depicts the data-cards participants suggested to add to the CARDS inventory.

As expected, when inviting broad participation, the workshop resulted in expanding the original inventory rather than narrowing it down. In a data-rich design culture, experts tend to incorporate considerations such as soundscapes, existing building as-built (BIM) detail structure audit data, social perceptions of bio-based materials (e.g., gentrification risk vs. premium attractiveness), and more. These inputs are valuable to the CARDS Framework, but they also confirm the workshop strategy: constrain the initial deck and use the session to debate data quality and fitness-for-purpose. If more data were provided in the data deck, even more data would be added to the initial inventory, on an endless feedback loop. In practice, very few data-cards were discarded; instead, teams clarified how each dataset should be adapted by scale and decision. The researchers perceived that some of the not-ticked data-cards in the questionnaires were not a result of deliberate elimination, but due to the lack of time to discuss and reach consensus on them – a limitation of the workshop setting.

The exercise underscored that there is no single "correct" weighting of low-carbon design datasets: station design entails trade-offs (e.g., a frugal, low-material solution may reduce embodied carbon while compromising comfort or experience). Data does not drive the process; it makes consequences legible, allowing designers to prioritize transparently what matters for that station intervention project: carbon reduction, accessibility, resilience, or user delight? The workshop thus functions as an instrument for the architect-integrator to surface tacit judgments, capture expert reasoning, and identify competing aims to consider when designing coherent, accountable choices.

6.2 Summary of Findings

This study observes that methods, datasets, and conventions for LCA are still being developed for its application at precinct scale. Reference studies from scientific background on the application of urban LCA are still in a experimental level (Herfray et al., 2011; Kayaçetin & Tanyer, 2019; Moisio et al., 2024). Great insight has been brought from practice-led research, in constituting reference benchmarks for boundary setting, component definition and GWP range values per building typology. However, most practice-led research encountered in this investigation is limited to the LCA applied to buildings, with exception of Christian Oettinger's masters study in partnership with Henning Larsen and Ramboll (Oettinger, 2023). This finding sheds light in the timely relevance for deeper research on urban scale LCA applications, specially making explicit the intrinsic steps of the design process, not only its results.

It is important to note that, in the preparation of the data and materials for this research, a gap surfaces regarding the **lack of existing/open data.** Approximately 50% of the data-cards featured datasets that were not available or of open access at the time of the research. This is especially the case **in the scale of the station building and its immediate surroundings**. Approximately 30% of the datasets can only be processed using software that requires a paid license, raising questions about the replicability of methods, and inclusivity – who can afford adopting a low-carbon design workflow using these datasets? To bridge this gap, the designer-researcher resorted to abduction reasoning based on the architect's tacit knowledge to determine the components, their materiality and their physical boundary. At early stages of design, the heuristic data resulting from design-thinking to solve data-gaps suffices to enable an initial carbon assessment. This resulted in original datasets that are a combination of existing data of high accuracy, from reliable sources, and created data, from low accuracy, from assumptions or intuitive determinations.

The workshop iterations on cross-scale data application showed that the same dataset can support different decisions across scales, but only when its granularity is appropriately adjusted. Precinct-scale carbon assessment, for example, requires precinct-level data, which is still largely absent from the Dutch and European repositories consulted in this research. This points to a broader methodological need: not only for better data availability, but also for design methods that help practitioners collectively interpret and negotiate carbon information across scales.

7. Discussion on limitations and next steps

Although this specific workshop method was not tested in an education setting, it shows potential for academic implementation, building on educational experiments conducted through TU Delft research projects such as WALK-IN[1] and CARB-HUB[2], that investigate decision-making through serious gaming. While developed for station-area design, the method may also be transferable to other urban typologies involving cross-scale environmental decision-making, such as residential retrofits or green infrastructure opening directions for further research beyond the scope of this study. Future work could also define readiness criteria to help practitioners and municipalities identify which multidisciplinary projects are most likely to benefit from this approach. Future research could also define readiness criteria to help practitioners and municipalities identify which multidisciplinary projects are most likely to benefit from this approach.

Emerging from participants manifested interest in accessing the datasets curated for this workshop, the author created an online Data-Hub (Figure 11). A web-based platform built in ArcGIS StoryMaps, it functions as an interactive report and information portal. Users can browse the event documentation and navigate the Lombardijen case data layers in interactive maps and 3D city models. The interface foreground traceability – the data-cards,

[1] **WALK-IN (Widening sustAinable mobiLity networKs: Impact on Nodes)** was a one-year NWO-funded KIEM GoCI project developed by the Complex Projects group at TU Delft with public and private partners, focusing on sustainable mobility and station-area design in Rotterdam South. The project contributed in education through a workshop-based format, where students used a serious card game to explore stakeholder negotiation, shared ambitions, and design interventions for mobility hubs and their surrounding urban areas. More information: https://www.nwo.nl/en/projects/gocikiem01045

[2] **CARB-HUB (Climate-Adaptive Resilient and Balanced Mobility Hubs)** is a follow-up project that combines the co-creation and mobility-hub design approaches developed in WALK-IN with the present PhD research on carbon data as design material. It translates these combined insights into methods and tools for low-carbon, climate-adaptive station-area development. More information: https://www.nwo.nl/projecten/sbrex58302

workshop program and photos, and written explanations about the CARDS framework steps (at that time, named the Low-Carbon Stations - LCS roadmap).

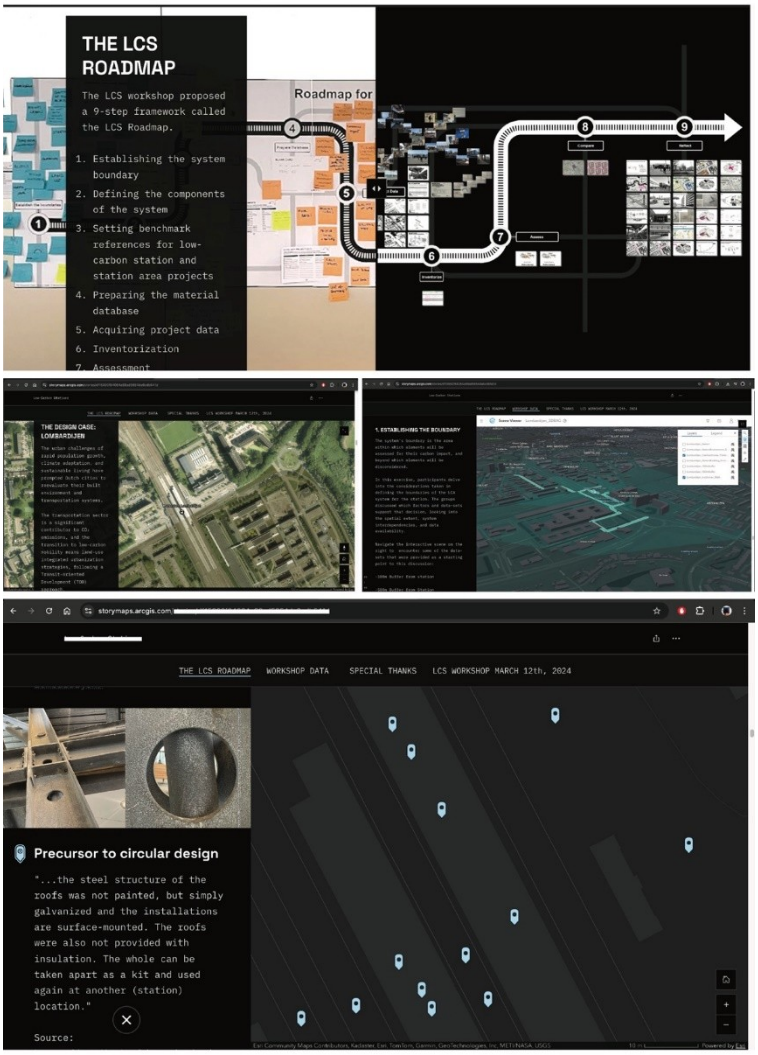

Figure 11 The Data-hub. Created by Halina Veloso e Zárate.

The data-hub is an ongoing effort with clear ambitions for the next steps: (1) publish downloadable versions for precinct-scale datasets via a trusted digital repository (the hub will link to DOIs), (2) develop a replicable precedent so curation can scale to the ~400 stations in the Netherlands, and (3) creating a repository for station and station area photos, with annotation on material inference and with metadata, to enable future use for machine learning and artificial intelligence training, facilitating scalability of the CARDS framework.

8. Conclusion

This workshop series creates a new perspective on stations not only as a building or a transport node, but a live database that aggregates heterogeneous records across scales and times: buildings, transportation and landscape components, construction materials, carbon factors, user experience, mobility, and much more. Treating the station “as a database” reframes design from drawing the station as an iconic architectural object, moving towards integration schemas - defining fields (what counts), provenance (where it comes from), resolution (at what scale), and permissions (who stewards it). This view exposes both the promise and the risk of today's data opulence: without governance and curation, datasets become noisy, redundant, or unusable for cross-scale tasks like precinct-level LCA. The workshop and the Data-hub respond by turning data into interdisciplinary artifacts for collaboration with shared metadata (scale, source, confidence, actionability), making the database legible and negotiable in early design.

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10. Appendix

Table 1 Data-card Inventory - in grey the data-cards containing datasets that were not existing and accessible at the time of the research.

Count	Step	Data-Card	Datasets	Status	Sources
1	ESB	100m Buffer	Basemap, Point data - station, polygon data - buffer	Existing / Open	PDOK, geoprocessing QGIS
2	ESB	500m buffer	Basemap, Point data - station, polygon data - buffer	Existing / Open	PDOK, geoprocessing QGIS
3	ESB	5min isochrone	Basemap, Point data - station, polygon data - buffer	Existing / Open	PDOK, Open Route Service
4	ESB	10min isochrone	Basemap, Point data - station, polygon data - isochrone	Existing / Open	PDOK, Open Route Service
5	ESB	15min isochrone	Basemap, Point data - station, polygon data - isochrone	Existing / Open	PDOK, Open Route Service
6	ESB	15min mission isochrone	Basemap, Point data - station, polygon data - isochrone	Created / Closed	Designer-Researcher
7	ESB	Station building and environment	Basemap, Line data – user trajectory	Existing / Open	MapTiler, PDOK, Designer-Researcher
8	ESB	Property Ownership	BGT pand – land ownership	Existing / Closed	Gemeente Rotterdam
9	ESB	Right of use	Cadastral Data – right of use	Existing / Fee	Kadaster
10	ESB	Building age	Pand – year built	Existing / Open	3D BAG
11	DC + APD	(Buildings) Building Footprint	Ground Surface, cumulative area	Existing / Open	3D BAG, processed in Rhinoceros 3D using RhinoCityJSON plugin for Grasshopper
12	DC + APD	(Buildings) Number of Floors	Number of Floors, cumulative area	Created / Closed	Designer-Researcher, 3D BAG, processed in Rhinoceros 3D using Grasshopper
13	DC + APD	(Buildings) Facade Area	Wall surface, cumulative area	Existing / Open	3D BAG, processed in Rhinoceros 3D using RhinoCityJSON plugin for Grasshopper
14	DC + APD	(Buildings) Roof Area	Roof surface, cumulative area	Existing / Open	3D BAG, processed in Rhinoceros 3D using RhinoCityJSON plugin for Grasshopper
15	DC + APD	(Transportation)	Schematic 3D Model, cumulative	Created /	Designer-Researcher

		Station Building	area (GFA)	Closed	
16	DC + APD	(Transportation) Station Platform Canopy	Schematic 3D Model, Site photo, Archival architectural drawing, Reference GWP value, cumulative area	Created / Closed	Designer-Researcher, Station Architect private archive, Paris Proof Stations 2024.
17	DC + APD	(Transportation) Station Platform	Schematic 3D Model, Site photo, Archival architectural drawing, Reference GWP value, cumulative area	Created / Closed	Designer-Researcher, Station Architect private archive, Paris Proof Stations 2024.
18	DC + APD	(Transportation) Station Tracks	Schematic 3D Model, Site photo, Archival architectural drawing, Reference GWP value, cumulative area	Created / Closed	Designer-Researcher, Station Architect private archive, Lokesh et. al, 2022.
19	DC + APD	(Transportation) Station Hall	Schematic 3D Model, Site photo, Archival architectural drawing, Reference GWP value, cumulative area	Created / Closed	Designer-Researcher, Station Architect private archive, Paris Proof Stations 2024.
20	DC + APD	(Transportation) Station Parking Structure	Schematic 3D Model, Site photo, Reference GWP value, schematic diagram, cumulative area	Created / Closed	Designer-Researcher, Paris Proof Stations 2024.
21	DC + APD	(Transportation) Station Environment	Schematic 3D Model, Site photos, Reference GWP value, cumulative area	Created / Closed	Designer-Researcher, ClimatePositive and CarbonSpace.
22	DC + APD	(Transportation) Station Tunnels	BGT tunneldeel, Schematic 3D Model, Site photo, Archival architectural drawing, Reference GWP value, cumulative area	Created / Closed	PDOK, Designer-Researcher, Station Architect private archive, Paris Proof Stations 2024.
23	DC + APD	(Transportation) Station Bike Parking	Schematic 3D Model, Site photo, schematic section detail, Reference GWP value, cumulative area	Created / Closed	Designer-Researcher, Station Architect private archive, Paris Proof Stations 2024.
24	DC + APD	(Transportation) Bike Path	BGT wegdeel, Bike path, 500m buffer, schematic section detail, cumulative area, Reference GWP Value	Existing / Open	PDOK, geoprocessing QGIS, Designer-Researcher
25	DC + APD	(Transportation) Pedestrian path	BGT wegdeel, Pedestrian path, 500m buffer, schematic section detail, cumulative area, Reference GWP Value	Existing / Open	PDOK, geoprocessing QGIS, Designer-Researcher
26	DC + APD	(Transportation) Surface parking	BGT wegdeel, Surface Parking, 500m buffer, schematic section detail, cumulative area, Reference GWP Value	Existing / Open	PDOK, geoprocessing QGIS, Designer-Researcher, ClimatePositive.
27	DC + APD	(Transportation) Streets	Road, 500m buffer, schematic section detail, cumulative area, Reference GWP Value	Existing / Open	PDOK, geoprocessing QGIS, Designer-Researcher
28	DC + APD	(Landscape) Grass	Grass and Bush, 500m buffer,	Existing /	PDOK, geoprocessing QGIS,

			schematic section detail, cumulative area, Reference GWP Value	Open	Designer-Researcher, ClimatePositive
29	DC + APD	(Landscape) Trees	Tree point data, 500m buffer, Reference GWP Value	Existing / Open	PDOK, ClimatePositive
30	DC + APD	(Landscape) Paved Open Space	BGT Open Space, 500m buffer, schematic section detail, Reference GWP Value	Existing / Open	PDOK, ClimatePositive
31	DC + APD	(Landscape) Water	BGT Waterdeel, 500m buffer, schematic section detail, cumulative area, Reference GWP Value	Existing / Open	PDOK, geoprocessing QGIS, ClimatePositive
32	APD	Site photos	Photos	Created / Closed	Designer-Researcher
33	APD	Archival Architectural Drawings - station	Site plan, Floorplans, Sections, Elevations, construction details, bill of quantities, text documentation	Existing / Open	Stadsarchief Rotterdam
34	APD	Archival Architectural Drawings – surrounding buildings	Site plan, Floorplans, Sections, Elevations, construction details, text documentation	Existing / Closed	Private Archive
35	APD	List - Project Inventory	Building, Transportation and landscape elements - area, material and GWP value	Created / Closed	Designer-Researcher

Table 2 Suggested data, to add to the initial inventory.

Count	Step	Data-Card	Datasets	Status	Sources
1	ESB	Urban Density	Floor-scape Index (FSI)	Existing / Open	RUDIFUN
2	ESB	Function Mixing	Mixed-use Index (MXI)	Existing / Open	RUDIFUN
3	ESB	Compactness	Open-scape Ratio (OSR)	Existing / Open	RUDIFUN
4	ESB	15min biking isochrone	Basemap, line data - bikepath, polygon data - isochrone	Existing / Open	PDOK, Open Route Service
5	ESB	Soundscape	Noise pollution	Existing / Open	Atlas Leefomgeving, DCMR GIS Portal
6	ESB	Infrastructure safety (explosives)	Explosieaandachtsgebieden	Existing / Open	Atlas Leefomgeving
7	EDB	Point Cloud (as built)	Puntenvolken	Existing / Open	AHN
8	ESB	Traffic	verkeersgegevens	Existing / Open	RVMK
9	ESB	Number of Housing Units	Cadastral data	Existing/ Fee	Kadaster

10	ESB	Pedestrian Flow	-	-	-
11	ESB	Land Use	Bestemmingsplan	Existing/ Open	PDOK
12	ESB	Station Are Development perimeter	-	-	Municipality, Developers
13	ESB	Persona-based isochrone	-	Not existing	Designer-Researcher
14	ESB	Biodiversity	-	-	-
15	DC	How travellers experience low-carbon stations (i.e. biobased materials)	-	Not Existing	-
16	DC	Flooding	Kans op een overstrooming vanuit zee, meer or rivier	Existing / Open	Atlas Leefomgeving
17	DC	Building Foundation	-	-	-
18	APD	Amenities and Services	Point Of Interest	Existing / Open	Open Street Map
19	APD	Existing Buildings – Floorplans (as built)	-	-	-
20	APD	Existing Buildings – BIM Models (as built)	-	-	-
21	APD	Existing Structure Audit	-	-	-
22	APD	Accessibility for mobility and visual impairment	-	-	-
23	APD	Station Precinct 3D Model for LCA	-	-	Designer-researcher
24	APD	“AI X-ray” to detect materials, floor plans and sections	-	-	-
25	APD	Open site visit Photo repository (Google Street View does not offer open data)	-	-	-