DOI: 10.1111/cgf.14312
Eurographics Conference on Visualization (EuroVis) 2021
R. Borgo, G. E. Marai, and T. von Landesberger
(Guest Editors)

Volume 40 (2021), Number 3

Boundary Objects in Design Studies: Reflections on the Collaborative Creation of Isochrone Maps

R. Vuillemot[1,3], P. Rivière[3,4], A. Beignon[2,3], and A. Tabard[2,3]

[1]École Centrale de Lyon
[2]Université Claude Bernard Lyon 1
[3]LIRIS, CNRS UMR5205, F-69621, France
[4]https://visionscarto.net/

Figure 1: *Sample of boundary objects used is the study. (1) A mood board, (2) a paper prototype, (3) a concept illustration in vector graphics, and (4) a parametric interactive notebook.*

Abstract

We propose to take an artifact-centric approach to design studies by leveraging the concept of boundary object. Design studies typically focus on processes and articulate design decisions in a project-specific context with a goal of transferability. We argue that design studies could benefit from paying attention to the material conditions in which teams collaborate to reach design outcomes. We report on a design study of isochrone maps following cartographic generalization principles. Focusing on boundary objects enables us to characterize five categories of artifacts and tools that facilitated collaboration between actors involved in the design process (structured collections, structuring artifacts, process-centric artifacts, generative artifacts, and bridging artifacts). We found that artifacts such as layered maps and map collections played a unifying role for our inter-disciplinary team. We discuss how such artifacts can be pivotal in the design process. Finally, we discuss how considering boundary objects could improve the transferability of design study results, and support reflection on inter-disciplinary collaboration in the domain of Information Visualization.

1. Introduction

Design studies are widely used in Information Visualization (InfoVis) research. They often lead to reflection on design outcomes, design processes, and validation methods. Despite efforts to define best practices [Mun09], design studies have been controversial for their lack of reproducibility, raising questions about rigor, validity, and contribution to the field. In response, a growing body of work argues for valuing the situated knowledge they produce. Such knowledge should be assessed on whether it can be transferable to other contexts [SMM12], and judged on rigor criteria [MD20].

In this paper, we focus on the material aspects of design studies. We are especially interested in how design artifacts are involved in collaborations in a visualization context. We ground our work in the Science and Technology Studies (STS) scholarship around the concept of *boundary object* i. e. artifacts that support work and communication within and across different communities of practice [SG89]. This concept is useful for identifying artifacts of relevance in collaborative activities and analyzing how actors with different backgrounds work together. We argue that boundary objects can help us look beyond processes and designs, to better articulate how tools and collaborative artifacts shape design outcomes. This opens up the potential to improve the transferability and rigor of design studies.

We ground our discussion in a design study of isochrone maps, illustrating how some tools and artifacts served as collaboration anchors within an interdisciplinary team. We draw on a project seeking to support spatial analysis tasks, especially for answering reachability-related questions such as *where can I go in 15 min with a bus?* To tackle those issues, we leveraged *cartographic generalization* principles. They provide transformation guidelines to improve map readability and combine data sources. However, despite many studies and a proposed visual semiotic [Bru86,BM91,MS92], generalization remains a manual process or task-specific process [KAB*10], and there has been few successes to automate it.

We first discuss the role of artifacts in design studies and introduce boundary objects. We then discuss our application domain, our application domain geo-spatial analysis and approach (cartographic generalization), and the context of our design study. We present the maps we built, but also unpack our design process using boundary objects [SG89] as a novel perspective to analyze visualization research by looking at the tools and artifacts we used systematically. We generalize from this study by characterizing five categories of re-occurring artifacts: structured collections, structuring artifacts, process-centric artifacts, generative artifacts, and bridging artifacts. We conclude on the usefulness of considering transient artifacts used to better account for the collaborative dynamics of the design process, and suggest how to better capture and reflect on boundary objects beyond our application domain.

2. Related Work

2.1. Design Studies

Design studies are a widely used methodology in InfoVis research. By describing projects from problem framing to final outcomes, they seek to contextualize visualization questions and contributions, with an attention to processes and the knowledge of domain experts [SMM12]. More importantly, design studies emphasize critical *reflection* on the process itself [BDFM14], and eventually identifying guidelines (e. g., [MBW11]) or transferable outcomes.

We are particularly interested in the way design artifacts are used and discussed in design studies. This relates to the discussion on *tactics* [SMM12] in design studies, e.g., using paper or rapid code prototypes. However, besides prototypes, key collaborative artifacts are rarely discussed, despite the important role they play in setting the stage and defining collaboration protocols [Lee05].

In this article, we reflect on the use of tools and artifacts, e.g. mood boards†, process books, paper-based explorations, alongside digital sketches and code prototypes, and the associated design activities we conducted to develop an isochrone maps generalization. Such artifact-centric *retrospectives* have been identified as promising in the software engineering literature [PPV00, BBVB*01, LB03].

Design study methods, like action research, emphasize transferability over replicability as the main project outcome [SMM12]. We argue that a focus on artifacts in collaboration can complement the current focus on actors, processes, and prototypes in improving transferability. Moreover, recent discussions on Design Studies tackled the issue of rigor. Being more attentive to the artifacts, could improve transparency and enrich reflection on processes, two rigor criteria discussed by Meyer and Dykes [MD20].

† Design mood boards "consist of a collection of visually stimulating images and related materials" [Luc12]

2.2. Boundary Objects

Science and Technology Study scholars have developed the concept of boundary object [BS00] to describe artifacts that move and support communication across different communities of practice. Maps and other graphical representations are canonical examples of such boundary objects. Based on their analysis of inter-disciplinary research collaborations Star [SG89] defines it as (quoting):

> "Objects which are both plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. They are weakly structured in common use, and become strongly structured in individual-site use."

The most noted property of boundary objects is their *interpretive flexibility*, i.e., the same object can be understood and used differently by different groups of people [Sta10]. Griesemer and Star give the example of a map used to locate a place of recreation by one group, or animal habitats by another [SG89].

While flexibility is key, and boundary objects allow groups to work together without consensus, this does not mean a complete lack of structure. To become boundary objects, an arrangement on how to operate and collaborate must be established. Groups can work on common objects locally, making them more tailored to their local use and needs, i. e. something that is not interdisciplinary, and then share it back in a way that works across the various groups. The capacity to move back and forth between local specialized work and common share-able objects is constitutive of boundary objects, but it is also dynamic and negotiated.

Star emphasizes two criteria, scale and scope, to delineate what is not a boundary object. In respect to scope, or granularity, Star suggests boundary objects are most useful at the organizational level [Sta10]. Regarding scope, boundary objects are most useful when analyzing work arrangements of objects that can be built, manipulated, or distributed.

While not an exhaustive list, Star proposes four types of boundary objects that are developed by communities of practice over time [SG89]:

- **Repositories** are collections of objects, or *piles*, that are indexed in a standardized way. Through indexing and standardization, repositories help manage problems of different lenses or units of analysis.
- **Ideal Type** are objects that are abstract or vague enough to be adaptable. They do not accurately describe details, but it is "good enough" for collaboration and coordination work.
- **Coincident Boundaries** are objects that define the scope. "They have the same boundaries but different internal contents". Coincident Boundaries are especially relevant when work is conducted remotely and autonomously, as they help define a shared referent.

Figure 2: *Example of isochrone map: a central location with peripheral areas that are reachable according to multiple time steps: 5min, 10min, and 15min (each visible with a different red color gradient).*

Standardized Forms are standardized indices that have no ambiguity as to what they refer to. Star refers to Latour "immutable mobiles", i. e. "objects which can be transported over a long distance and convey unchanging information". Standardized forms are especially useful to communicate across distributed work groups, and remove uncertainty.

Although many scholars used the boundary concepts as is, and reused Star's categories. Some explored other types of collaborative situations and proposed other categories [Lee05]. This has been the case notably by the Computer Supporter Cooperative Work community, with a focus on digital artifacts. For instance, Lee proposes to consider boundary negotiating artifacts rather than boundary objects, arguing that some artifacts are there either to negotiate roles, responsibilities, and agency in collaborative settings. She defines five types of boundary negotiating artifacts: (1) self-explanation, (2) inclusion, (3) compilation, (4) structuring, and (5) borrowing [Lee07]. In the domain of Information Systems [DM12], scholars have studied how boundary objects can help coordinate stakeholders in terms of knowledge and power gaps within complex design ecologies [MLB07].

We will draw on the concept, the body of work surrounding it, and reflect on how it applies to visualization research in a multidisciplinary context. We will focus on a specific project centering around the visualization and design of novel isochrone maps.

2.3. Geo-spatial Analysis and Isochrone Maps

To ground our discussion, we turn to a project focused on supporting geo-spatial analysis with Isochrone Maps. We sought to offer urban planners and citizens better *geo-spatial analysis* tools, to make more informed decisions. For instance, exploring how reachable areas can be using one or multiple transport modes. Solving such problem often requires relying upon various layers of information (basemaps for context, road and network, and eventually points of interest. Resulting reachability maps are often designed using *isochrone maps*, which are overlays that convey time using shapes. Figure 2 illustrates a typical isochrone map where the red color gradient indicates which part of the city is reachable from an origin in different time intervals. Isochrone maps are featured on many websites and have been applied to many application domains in mobility [EGL*13,ZFA*14,OG15], but there has been little attempt to visually improve them except at the algorithmic level (e. g., [MG10, GBCI11]). The closest work to improve isochrones visual appearance is IsoScope [GKvN14] that conveys time variability by animating isochrones over different times of the day, or lens-based visualizations blending detailed networks views, with isochrones for context [LTD19].

2.4. Cartographic Generalization

In this project, we drew on principles of cartographic generalization. Generalization is the process of abstracting maps by either adding, removing or transforming existing elements. Such a process is useful to improve map readability and is for instance currently used to render different maps at different zoom levels. Generalization roots back to paper cartography [Bru86, BM91, MS92], and there is still some active work to achieve if automatically in a digital environment [BDM14], but is not automatically achievable or is dedicated to a specific domain (e. g., taxi routes [KAB*10] or touristic maps [BMWW14]). Generalization can be summarized using the following [Zhi13] dimensions such as: SELECTION to remove eliminate elements by category (e. g., roads or labels); SIMPLIFICATION to remove details (e. g., apply filtering on curves); SMOOTHING to reduce sharp shapes (e. g., angles); EXAGGERATION to enlarge elements while keeping the geometry constraint; COMBINATION to combine different elements while keeping their individual semantic; DISPLACEMENT to change the position of elements; finally, AGGREGATION to represent groups of objects differently; ENHANCEMENT combines the EXAGGERATION and the SMOOTHING properties (mostly on geometry) process.

Applying generalization principles to isochrone maps consists in following the former principles to both the basemap as well as all overlays, including the isochrone one. However, as the isochrone shapes are data-driven, they require a strong knowledge of the underlying isochrone generation processes from experts in GIS (GeoGraphical Information Systems) and cartography.

3. Case study context

This work was conducted with the M2I PROJECT, a 4-year, nationally funded project to improve urban mobility. We closely worked with domain experts in mobility to build visualizations for citizens and decision-makers. We discuss here work conducted within a specific work package that aims at building better reachability maps for decision-makers and urban planners.

3.1. Actors and Resources

We gathered an inter-disciplinary [Ste91] team of 5 **actors** in this project with skills that match the needs we identified prior to star our design study:

- **DES** (Designer) is part-time Interaction Design student, with a background in graphics design;
- **GIS** (Geographic Information Systems post-doc) is full-time GIS Expert, with a background in geography;

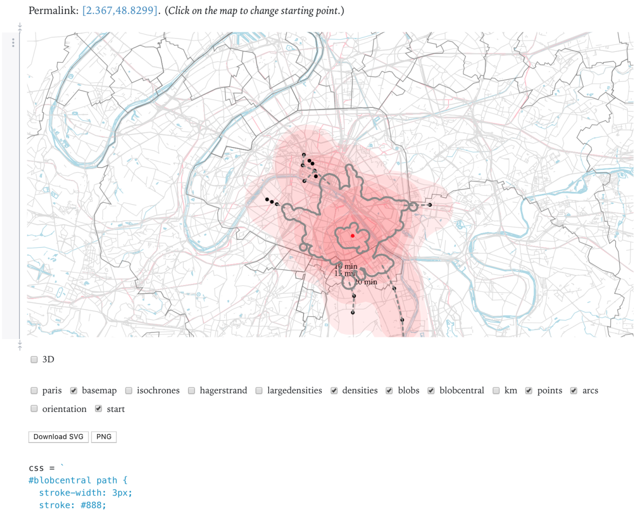

Figure 3: *Screenshot of our interactive notebook generating parametric isochrones maps. It is based on an ObservableHQ notebook and exposes its design parameters as widgets (e. g., check-boxes) or code (e. g., CSS).*

- **MAP** (Cartograph) is a freelance Cartographer with D3js [BOH11] and ObservableHQ notebooks [Bos20] expertise, and a background in mathematics and journalism;
- **VIS** (InfoVis researcher) is Assistant Professor splitting time between this research project, teaching and administrative duties;
- **HCI** (Human-Computer Interaction researcher): Assistant Professor also splitting time between research projects, teaching and administrative duties.

The actors have different backgrounds and expertise: they belong to different communities of practice [Wen99]. In our case, we are situated within a funded project with deliverables and industry partners, a university research group, a computer science laboratory, informal research networks for academics, or professional networks for freelancers, engineers, and designers. Both **VIS** and **HCI** act as co-PIs of the project and are leads writing this article. They also were responsible for the early design study stages (*pre-condition* ones [SMM12]) and lead the structure of the *analysis* part.

3.2. Requirements

Isochrone maps can become rather complex, and it may be difficult to grasp details as some fairly complex areas. Moreover integrating variability and uncertainty as underlying data is often inaccurate (e. g., bus schedule is theoretic) and varies over time (e. g., bus frequency during day or nights). The straightforward solution of adding such information directly on the map would provide visual clutter. Building upon the cartographic generalization principles we introduced in the related work, we defined a set of requirements:

R1 keep geo-layers consistent
R2 convey underlying structural information
R3 simplify the visual complexity of isochrones
R4 convey accessibility at varying travel durations

R1 is motivated by the need to add more layers of information to the maps. While space-deformation techniques such as cartograms [Tob04] are quite popular to encode quantities spatially, they make it more complex to align layers and are harder to understand for non-experts. Even techniques that seek to limit deformation [BDD*16, HKYA14], are can lead to confusion. With **R1**, all layers should use the same location, but also the same projection coordinate system, we did not consider the DISPLACEMENT generalization dimension. Nonetheless, we considered that minor displacement could be acceptable, e. g., using simplified or enhanced shapes.

Previous (unpublished) laboratory experiments with isochrones, as well as discussions with project stakeholders and users, showed us that dendrites and isolated accessible spots were hard to reason about. This motivated **R2** and **R3**. We tackled the *simplification* requirement by using the SELECTION generalization dimension that removes elements, as well as SIMPLIFICATION and SMOOTHING dimensions. Showing *underlying structure* (**R2**) and *varying travel durations* (**R4**) can be addressed with COMBINATION.

R4 is motivated by the variable nature of isochrone maps underlying information, such as the location of departure, travel date, mode, and duration. Thus reachability should reflect different types of reachability, e. g., for different travel times.

3.3. Documentation method

We conducted the design study over a period of 15 weeks within the scope of the larger M2I PROJECT (other sub-projects happened in parallel within and outside this project, all related to urban mobility). We tracked all interactions within the team by turning on the history features of our digital tools, to date and identify authors of the changes. We gathered a corpus that is representative of most interactions (except informal face-to-face discussions). We focus our reporting in the next sections on the:

1. **lifecycle** of tools and artifacts we organized as a timeline
2. **main artifacts** produced and used during the project
3. **final outcome** we presented to our external project partners

While we provide transparency in our reporting for those elements (and provide some of them as supplemental material), internal and detailed working documents (Google Documents, Calendars) cannot be shared for privacy and disclosure agreement reasons. The final result of this implementation is illustrated on figure 1 (right) and is detailed in section 6. In the next section, we present the tools we used, analyze their role, and how they contributed to the final outcomes.

4. Lifecycle of Tools and Artifacts

We identified 12 main *moments* in the design process (see figure 4), and 18 formal meetings. Each moment corresponded to interactions within the team geared towards a specific goal and leveraging artifacts. The moments could be short, e.g., a 2-hour workshop, or span over several weeks. The work intensity could also vary from being a background activity of the team to being full-time work for several actors at once. In our description, we signal boundary objects with the same box used in figure 4, e.g. the output of the meetings were captured in a shared document of meeting notes.

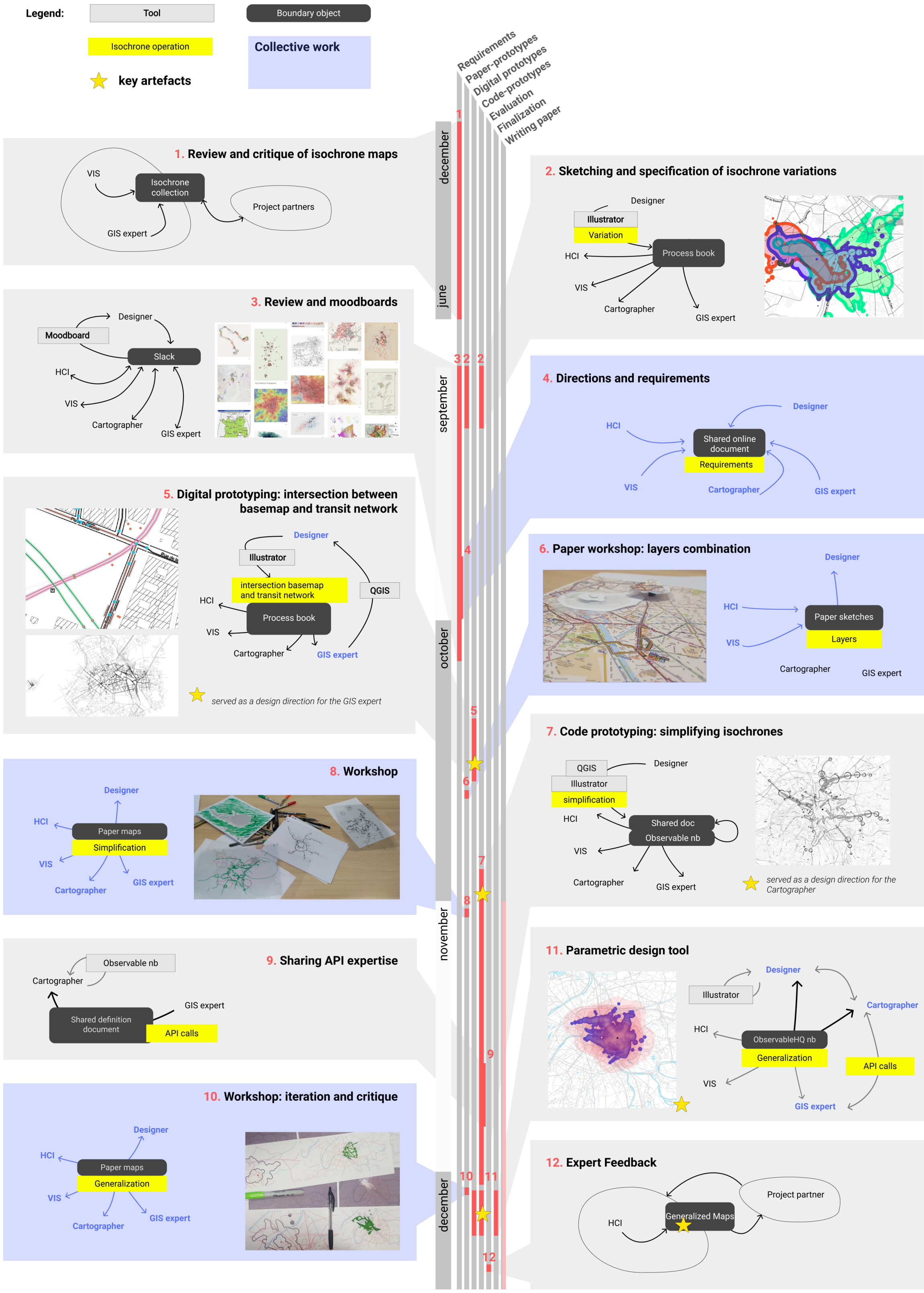

Figure 4: *Collaboration timeline of the design study (top is the beginning, the bottom is the end)*

Design space of isochrone maps (1)
We started the project by collecting existing isochrones examples, either from personal collections, found on the web or in the literature. We structured this isochrone map collection in a shared spreadsheet that allowed anybody to contribute and discover the collection `https://goo.gl/GV7Urg`. We kept a total of 32 isochrone maps [VLRT18].

Digital sketching of maps (2)
When the designer joined the team, she started familiarizing herself with the domain space, by sketching strategies to overlap isochrone maps and display variations in Adobe Illustrator. The work was shared using as a process book, in a shared online document, which supported exchanges around different maps between the **HCI**, **VIS** and **DES** actors.

Map mood boards (3)
In parallel, the designer created two mood boards: a broad visual collection of accessibility maps, and a collection of basemaps. **DES** used Pinterest (`http://pinterest.com/anaellebeignon/plan/`), which is widely adopted by the design community, for collecting and assembling visual material into collections, and **DES** felt it was more appropriate for the task at hand.

Design directions (4)
After initial explorations, the team reflected on previous projects and ongoing explorations to define a new direction. The focus on generalization was not precisely articulated yet but centered on expressing isochrones variation, and better integrating basemaps, transit networks, and isochrones. These directions were captured as a list of requirements and mainly framed by the assistant professors, in the shared online document containing meeting notes.

Rapid prototypes → data-based designs (5)
The designer experienced well-known limits [BDFM14] of data binding using graphics editing tools (mainly vector operations in Adobe Illustrator, and sometimes shifting to Photoshop for complex masking or raster operations that were doable but costly to execute in Illustrator). Isochrones are highly complex data structures that blend itinerary calculation with geometric shapes, making it hard to manipulate design parameters, while being faithful to data (especially when injecting new ones to convey time or structure **R4**, **R2**). This is reinforced in our case because of **R1** which requires consistency between layers so if an isochrone is drawn on one layer, then it should match others (e. g., annotations, POIs, etc.). This led **DES** to learn how to use QGIS from the **GIS** expert, to create data-driven SVG shapes that could be imported into Illustrator to simulate isochrone style information directly, treating network layers differently, or applying masks. The resulting maps were shared in an online process book, and discussed during team meetings to define new design directions, and identifying the corresponding cartographic data that would be required.

Design workshops (6, 8, 10)
We conducted 3 design workshops involving the team at different stages of the project using paper-based designs. They aimed at exploring design variations for the various layers. The first workshop was very open-ended and explored the material properties of paper in combining map layers. The second workshop focused on variability and simplification (**R3**). The third workshop balanced between a design review and a generative workshop focusing on incremental improvements. In all the workshops, we sketched paper maps with our own perspectives, critiqued them, and captured them for later reviews.

Designs → static tool (7, 9)
MAP built a tool that implemented the layers-based design, previously created. One isochrone map created with QGIS and Illustrator by the designer (displayed in figure 4, phase 7) served as the main design direction. Unlike a classical isochrone, this design did not obfuscate the basemap, while providing more explanations on why distant zones around transit stations were easily reachable.

This map and tool enabled us to 1) to explore rapidly design variations that took hours or days to create with QGIS and Illustrator, and 2) inject realistic isochrones datasets to geo-reachability scenarios. We could confront design ideas to realistic datasets, and for instance notice that some design elements did not have corresponding, e. g., the direction of a transit line.

At this stage, we picked a capital city which was familiar to the team and set a zoom level that allowed to have the city fit within the page (no need to zoom). The city was also well-known by the project's partner who has independently built isochrones for this city as well. The tool was built with ObservableHQ [Bos20] using D3 [BOH11], and querying the Navitia.io API. This led **MAP** to use API calls provided by **GIS** to gather the appropriate data (phase 9).

Static tool → parametric tool (11)
The longest phase was to code custom interactive design tools. Both the **GIS** and **MAP** built one and the prototypes enabled us to quickly explore data and design variations. **GIS** mostly tested data fetching through transit APIs and simplification algorithms. The **MAP** prototype used Web technologies and became shared within the team with minimal UI exposing *parameters* we carried along from the design space identification and which were refined during previous steps. As we did not want to have too many parameters, **MAP** only activated the ones related to layers visibility or level of details (e. g., tiles map scale level). When some parameters were too complex to expose using widgets, the code section of the notebook exposed variables that could be changed in-place through JavaScript or CSS. The selected parameter combinations were dynamically saved through the URL so that **DES** could easily share design explorations.

The parametric tool is an ObservableHQ notebook (`https://observablehq.com/@romsson/isochrone`) so all team members could look at the maps it produced and tweak the code. Towards the end of the design process, **DES** edited CSS properties directly in ObservableHQ for more precise and faster design iterations. We present the final design choices in section 6.

Expert Feedback. One of the co-PIs presented the final designs to an external project coordinator related to the reachability maps design sub-project. We remotely presented 6 techniques in a slideshow of Generalized Maps screenshots.

The expert provided feedback while discussing the differences with the ones they generated in their company. The discussion centered on: 1) the relevance of layers: transit and road networks, mobility strategies (bike, car, scooters, transit), points of interest, real-

Figure 5: *Illustration of one of the paper-based workshops we organized. One can see the various possibilities paper layers have to offer, from creating overlays (right) to flipbooks with transparent layers (middle).*

estate. On our side the discussion centered on their integration especially aligning them (**R1**), and how to display temporal progression **R4**. 2) the strategy to reveal the underlying structure, while we aimed at displaying it outside the highly connected center **R2**, the partner chose to display the journey from the center when a point was clicked on the map. 3) the accuracy of the maps produced; this discussion centered on various locations around PARIS, FR, and the shape of isochrones one should expect. Related to the accuracy, we discussed the complexity of the underlying computations to offer results in interactive times, and strategies to simplify the presentation **R3**.

5. An Artifact-Centric Retrospective

We now revisit the artifacts used by reflecting on their nature and their impact on the project. As encouraged by both Star [Sta10] and Lee [Lee07], we extend and propose new categories of artifacts, when existing ones do not fit. It should be noted that the status of a given artifact can change over time, as its status is defined by the way it is used. A paper sketch can be *generative* during a creative workshop and become *structuring* if it is the one picked to be implemented.

5.1. Structured Collections

We created several collections of maps, i. e. an isochrone map collections, and two mood boards. But only the collection can be considered as a boundary object. The designer created the mood boards primarily for personal use as an inspiration source. They were loosely structured and contained elements that were not maps, but inspirational shapes or color compositions. They would fall in the self-explanation artifacts category [Lee07].

The construction of the design space is an instance of the repository definition [Sta10]. Like all repositories, it had limits, and elements that we had to leave out because they were hard to characterize. For instance, the visual signature of isochrones (e. g., branches/dendrites, the organicity of the shapes,...) The main benefit of the design space is that it allowed us to identify and discuss isochrone properties. It also helped frame what should be considered an isochrone, *align everybody on the project*, both internally but also with our project partners, and *define the degrees of freedom for prototyping*. The designer joined the project after it was created and it helped frame her understanding.

5.2. Structuring Artifacts

Our requirement list was the primary structuring artifact [Lee07]. It guided our initial explorations and helped us negotiate a common direction: the team members shared limitations they found to isochrones and directions they thought could lead to better designs.

The other structuring artifacts we identified were two maps created by **DES** and which served as the main development direction for **MAP** and **GIS** (maps with stars on figure 4, moments 5 and 7). The code prototypes did not implement 100% of the map designs because of technical limitations or changes in the design direction as the project evolved. The whole team referred to these map images when discussing progress and iterations on the prototypes.

These structuring artifacts had two properties: 1) they were pivotal in the project i. e. setting design parameters and narrowing the design space, and 2) we came back to them at a different instance of the project to decide to check whether the design choices we were discussing were in line with these artifacts, as representations of the direction we had set.

5.3. Process-centric Artifacts

Process-centric artifacts are close to what Henderson calls conscription devices: process-related artifacts that enlist group participation and capture created knowledge [Hen99]. In our case, standup notes, meeting notes, and process books were the main process-centric artifacts. Meeting and standup notes are shared online documents that are captured by the team and that help capture progress, todos, and blocking problems.

The process books of **DES**, who also shared online documents, served a different role as she was the only one filling them with maps. But they were reviewed by the team members, who could comment on the various maps produced and guide asynchronously the process.

We came back to these documents for writing the article, but during the project, they rather acted as *an externalization* of the team's ongoing thoughts and activities, and as *a short-term memory*. We came back much more often to content that was less than a week or 10 days old.

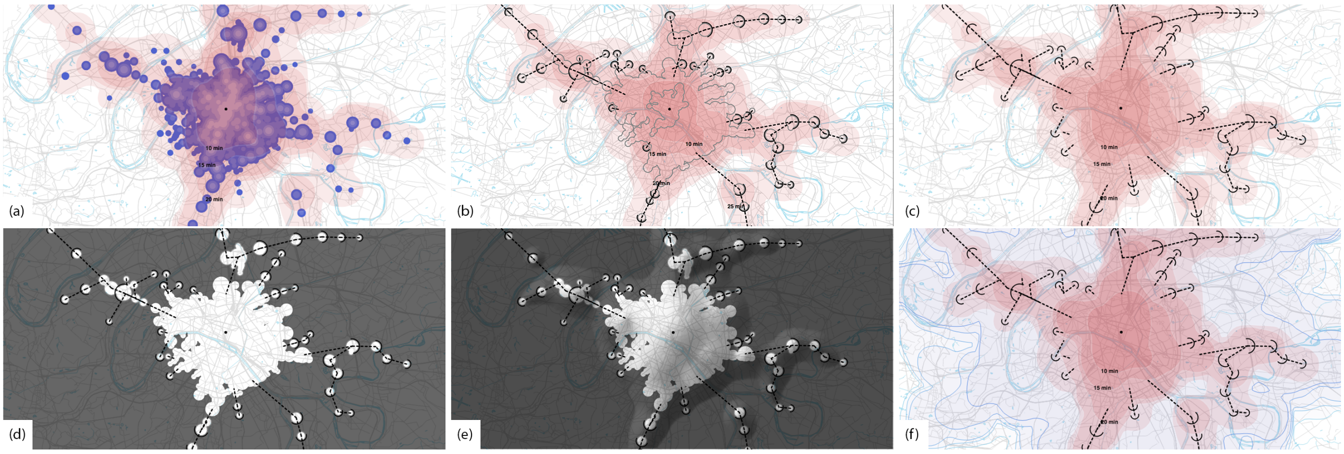

Figure 6: *Illustration of the* 6 *techniques* **DES** *selected using the interactive code-based prototype. (a)* ISOCHRONE*, (b)* DETAILED*, (c)* SIMPLIFIED*, (d)* MASK*, (e)* SHADING*, (f)* CONTINUOUS.

5.4. Generative Artifacts

Two types of artifacts, paper maps, and ObservableHQ notebooks served generative purposes. The inclusion artifacts from Lee [Lee07] and the Ideal Type objects from Star [SG89] serve a similar purpose, but are static. Whereas the artifacts discussed here are dynamic, they can be manipulated, shared, or remixed.

Paper maps supported exploration, especially through their material properties: use of layers, opacity, and transparency, color combinations, drawing and inking strategies, paper types, cutting and stacking layers. In workshops, exploration strategies that would have been difficult or impossible with digital tools became possible with paper, e.g. complex cuts, or dynamic opacity (figure 5 shows generative artifacts co-created during a workshop).

These generative artifacts did not serve directly as specifications. They were not using realistic or coherent data e. g., transit network from one city and isochrone shape from another but enabled us to explore and generate ideas through layer operations and drawing.

The final parametric ObservableHQ notebook can also be considered as a generative artifact: it supports design explorations, through interactive parametric controls, but also direct code modifications. Towards the end of the project, **DES** would directly modify CSS from the notebook to get faster and more realistic feedback on design choices.

We also observed a back and forth between paper and ObservableHQ notebooks: We used printed maps generated with the parametric notebooks in the last workshop, and **MAP**introduced some suggestions from paper sketches as parameters in the notebook.

One challenge with these generative artifacts has been scoping the exploration. The freedom of paper also created challenges and long discussions about the faithfulness of the sketches to the data. With the notebook, many parameters were tied to each other or redundant. Finding interesting combinations became difficult as the expressiveness of the tool increased.

5.5. Bridging Artifacts

The paper, digital, and code prototypes, can be considered as bridging artifacts. While most of the artifacts presented before were co-created by the team. The prototypes were developed by one actor, who then presented his/her work as a manifestation of the prototype, either through screenshots or a link to a notebook. In any case, these artifacts were directed from one person to the rest of the team, expecting feedback, but no direct involvement in the prototype development.

As the development progressed, **DES** and **MAP** iterated upon design choices, and fixing technical problems. This process was often conversational, with team members reflecting on screenshots or examples, with the overall project in mind. It is only in the latest stage of development of the ObservableHQ notebook, when it moved to be a tool that could be used, that its status changed to become generative.

Another type of bridging artifacts was the paper prototypes after they were created. Considered as generative artifacts during workshops, the most interesting instances were captured as collections of maps and displayed as a mini-exhibit on an empty desk (figure 5 right). The output of **DES**'s material explorations of paper maps was also stuck on walls. This was especially useful to trigger conversations within the team but also with colleagues, or visitors, making the project much easier to convey to an external audience.

One of the co-PIs also assembled maps created with the parametric tool into a slide-show, to share the team progress with project partners, and gather feedback on the designs. This is another instance of a bridging artifact with actors outside the team.

Many of the bridging artifacts also served as snapshots of progress, that could be shared in-process books, or through direct communication channels.

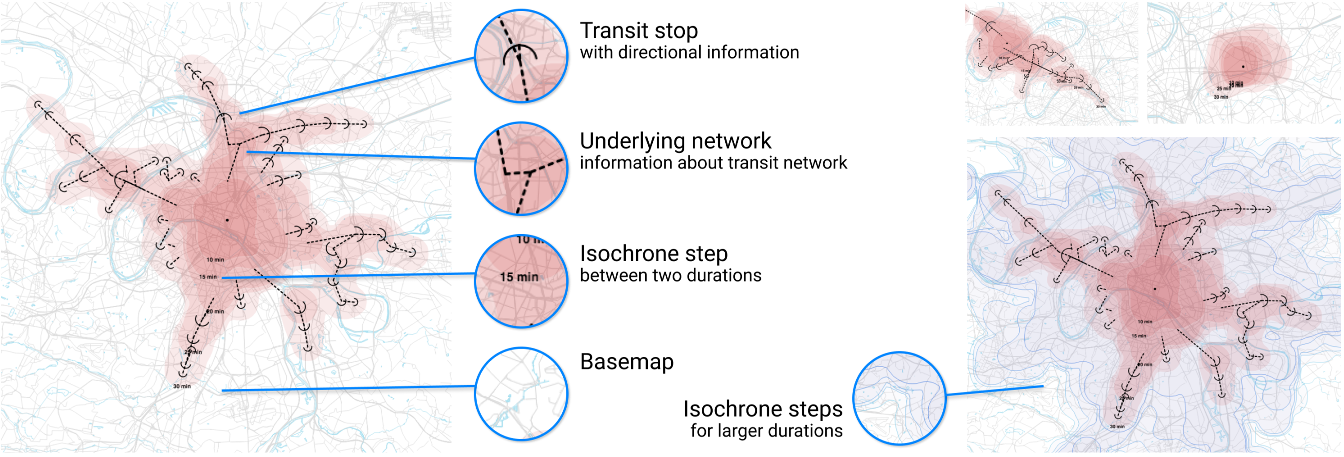

Figure 7: *Isochrone maps examples of* PARIS, FR *to characterize the reachability of different locations: highly connected to the transportation network one (left) ; isolated one (top right), external location with transportation mostly towards the center of the city (top center) ; and isochrone that display further information about reachability of distant locations. Click on text for the live interactive version.*

6. Project outcomes

The final outcome of our process is an ObservableHQ notebook and a set of techniques generated with it and illustrated both on figure 1 (right), figure 6 and 7.

An Interactive notebook. The main result is the code-based prototype developed during the study: **MAP**'s ObservableHQ notebook (figure 3). While this UI is restricted to the notebook capabilities, it was sufficient to expose the main parameters or the code to tweak during the feedback sessions we organized. This tool was used to generate all the isochrone illustrations in this paper We also used this tool to identify specific techniques we discuss next. Note that this tool was not intended to be part of our deliverables, but it reached such a level of expressiveness and interactivity that we decided to share it.

Techniques. As **DES** used the notebook to re-recreate static prototypes and test variations, it started converging towards one main technique (figure 7 left) we considered the final result and ended the *core phase* of the design study [SMM12]. This design display transit lines in the dendrites, to explain their construction, and the transit flows/network structure. This is displayed outside the isochrone core where displaying network information would be too dense. We used 5 minutes steps with a color gradient, and transparency to ensure the base map would remain visible.

Other techniques (figure 6) show interesting points in the design space that were either candidate to the best technique, or interesting variations that would need further investigation:

ISOCHRONE (figure 6-a) is an isochrone map using 5-minute distance steps. A central darker layer of simplified bounding shapes account for variability, and for improving visual continuity (**R1**, **R4**).

DETAILED (figure 6-b) the isochrone central dark filling is removed to make the basemap more visible, a new layer with structuring transit routes outside the densely connected center conveys information about the underlying network (COMBINATION). Half-circle around stations convey the travel direction (SIMPLIFICATION), and give temporal cues on reachability from each of those stations (**R1**, **R2**, **R4**).

SIMPLIFIED (figure 6-c) is similar to DETAILED, but the isochrone layer is completely removed (SELECTION) and only simplified contours remain (**R1**, **R2**, **R3**, **R4**).

MASK (figure 6-d) emphasizes the basemap of the accessible parts, while connecting the dendrites with transit lines, and half-circle directions (**R1**,**R2**, **R3**).

SHADING (figure 6-e) emphasizes accessibility through an hill-shading effect (EXAGGERATION), the isochrones lines provide precise information, while the *hills* provide a simpler and more continuous read of the accessibility (**R1**, **R2**, **R3**, **R4**).

CONTINUOUS (figure 6-f) extends the DETAILED technique by providing more time steps (in light blue), covering the whole map (**R1**, **R2**, **R3**, **R4**).

7. Discussions and Limits

Through this project, we created interactive isochrone designs that comply with cartographic generalization rules. We identified interesting techniques variations and insights using our parametric tool (figure 7), and received positive feedback from our partners. Reflections on boundary objects in our process allowed us to retrospectively classify them into 5 categories. This section discusses the limits of our study methodology.

Following modern software development practices—such as Agile retrospectives [BBVB*01]—we discussed our process during frequent meetings where each participant explained *What worked well*, *What didn't work well* and *Next steps* or *Actions*. Some form of reflective activities were already implemented but mostly focused on improving communication and coordination. We also had stand-ups meeting every second day and structured our process around shared documents and code repositories. The list of requirements was always discussed and updated during those meetings.

Working with rapid iterations had the setback of discarding ambitious, yet complex experiments. For instance, geometric simplification (e. g., using Peucker's algorithm) was investigated as a treatment on the geometry of the central blob. But since preliminary results were not satisfactory, as those experiments were time-boxed, we sought alternatives to such technique. The same happened as we moved away from a skeleton-based approach that were better performing than the simplification we used.

On a methodological level, we did not *define anchor moments upfront*. Defining such moments, regardless of progress, could ensure incremental documentation and *foster dedicated moments for reflection*. Along the same lines, we managed to maintain stand-up and meeting notes, but only **DES** maintained a process book, which could have been extended to the whole team to better capture interactions and global progress. The fact that **MAP** worked remotely and that PIs had multiple offices on campus both facilitated and forced us to *shift to online channels of communication and work*, leading to more capture and documentation than may happen in smaller or co-located projects. This proved extremely beneficial to our retrospective process.

Looking back at our design process, we noticed that some of the artifacts categories were better supported (e. g., to manage or capture them) than others. This opens up opportunities for the development of collaborative tools that support InfoVis design processes:

- The creation of structured collections was well supported, we used an online spreadsheet and Exhibit [MG10], but other tools such as SurVis [BKW16] are already available to the community.
- Managing framing artifacts was straightforward since their quantity was limited. One question is whether we could have improved them by applying more structure to them, or whether moving from map images to specification lists could have improved our discussions and the resulting prototypes.
- We captured generative artifacts mostly through screenshots and photos. This was quite limiting, animation effects were difficult to convey and capture. Another challenge we encountered was collaborating around these artifacts remotely. Tools such as DoDoc [GGED16] that support the capture of workshop activities could be extended to better support remote collaboration.
- Process-centric artifacts were the least supported. Different threads of design explorations were explored in parallel creating a classical tension between a chronological structure and a thematic one on the design side. On the code side, it was much more challenging to capture and share progress. In both situations commenting on the content of the process-centric artifacts was challenging, for instance, the documents only supported comment on an image level, and commenting on Jupyter or ObservableHQ notebooks is still not well supported. Finally, although code can be versioned, most of the intermediary code prototypes are not accessible anymore, which means that we cannot reproduce intermediary results that we could find interesting in retrospect.
- Bridging artifacts were mostly used informally to support discussions. Under such conditions, they were not captured, except if they were added to a process-centric artifact.

Finally, maps or other visual representations should not only be considered as the final artifact and end-result of cartographic or visualization research. They supported cooperative work throughout the design process, being discussed and iterated upon. While visualization design tools could better support interdisciplinary work and collaboration, in becoming more stable, they will likely codify how collaborations between disciplines should happen.

This is an avenue for future work on design studies: investigating when boundary objects reach a stable stage and become "standards", or whether such standards already exist in industry or academia. This is discussed implicitly in the literature around design sheets, survey platforms, and other side outcomes of projects. But it is rarely articulated as such. Moreover, our work centered mostly on internal collaboration, yet many projects involve more loosely tied collaboration and exchanges with external stakeholders. This calls for further attention to artifacts that support collaborations within and outside project teams. Science and Technology Studies also suggest that paying attention to power and political dynamics in larger projects and organizations, as they also shape the tools used, the value put in various design artifacts, and final outcomes.

8. Summary and Perspectives

We took an artifact-centric approach to discuss our design process, by using *boundary objects* as an analytical lens. We reflected on our work and on the collaboration within an inter-disciplinary team developing novel visualizations. Our team had actors commonly involved in visualization research projects: PIs, researchers, designers, and engineers, with various areas of expertise, career paths, and belonging to different communities of practice. Our processes and tools of choice were different and had to be aligned to collaborate. The 5 artifacts categories we introduced (structured collections, structuring artifacts, process-centric artifacts, generative artifacts, and bridging artifacts) structured our work, tied it together, and supported everyday collaboration. While some framing artifacts had an even stronger role and clearly shaped the project outcome. We structured our transcription of the design process around a *collaboration timeline*, with the evolution of the maps at each stage of the process. Our approach enabled us to present the end results— novel isochrone maps using cartographic generalization— but also intermediary collections, tools, and artifacts, that were used for personal but also inter-personal cooperation.

This paper demonstrated the benefits to complement the structure of design studies [SMM12] with an attention to collaboration artifacts. It may enable the InfoVis community to go beyond the narratives of controlled design processes that can be replicated regardless of the context in which they unfold. An artifact-centric approach can capture design practices that could be transferred and reused in other contexts, e.g. as tools and recipes that can be incrementally incorporated in projects, rather than as a whole design process.

9. Acknowledgments

We thank Thomas Leysens for his technical contribution. This project was partially supported by the M2i project on Urban Mobility funded by French Agency for Ecological Transition (ADEME) `https://projet.liris.cnrs.fr/mi2/`.

Supplementary materials

https://github.com/sical/boundary-objects-design-studies/

References

[BBVB*01] BECK K., BEEDLE M., VAN BENNEKUM A., COCKBURN A., CUNNINGHAM W., FOWLER M., GRENNING J., HIGHSMITH J., HUNT A., JEFFRIES R.: Manifesto for agile software development.

[BDD*16] BOUTS Q. W., DWYER T., DYKES J., SPECKMANN B., GOODWIN S., RICHE N. H., CARPENDALE S., LIEBMAN A.: Visual Encoding of Dissimilarity Data via Topology-Preserving Map Deformation. *IEEE Transactions on Visualization and Computer Graphics 22*, 9 (Sept. 2016), 2200–2213. doi:10.1109/TVCG.2015.2500225.

[BDFM14] BIGELOW A., DRUCKER S., FISHER D., MEYER M.: Reflections on How Designers Design with Data. In *Proceedings of the 2014 International Working Conference on Advanced Visual Interfaces* (New York, NY, USA, 2014), AVI '14, ACM, pp. 17–24. doi:10.1145/2598153.2598175.

[BDM14] BURGHARDT D., DUCHÊNE C., MACKANESS W.: *Abstracting Geographic Information in a Data Rich World: Methodologies and Applications of Map Generalisation*. Springer, July 2014.

[BKW16] BECK F., KOCH S., WEISKOPF D.: Visual Analysis and Dissemination of Scientific Literature Collections with SurVis. *IEEE Transactions on Visualization and Computer Graphics 22*, 1 (Jan. 2016), 180–189. doi:10.1109/TVCG.2015.2467757.

[BM91] BUTTENFIELD B. P., MCMASTER R. B.: *Map Generalization: Making Rules for Knowledge Representation*. Longman Scientific & Technical New York, 1991.

[BMWW14] BIRSAK M., MUSIALSKI P., WONKA P., WIMMER M.: Automatic generation of tourist brochures. *Computer Graphics Forum 33*, 2 (2014), 449–458. doi:10.1111/cgf.12333.

[BOH11] BOSTOCK M., OGIEVETSKY V., HEER J.: D3; Data-Driven Documents. *IEEE Transactions on Visualization and Computer Graphics 17*, 12 (Dec. 2011), 2301–2309. doi:10.1109/TVCG.2011.185.

[Bos20] BOSTOCK M.: Observable. https://observablehq.com/, Dec. 2020.

[Bru86] BRUNET R.: La carte-modèle et les chorèmes. *Mappemonde 86*, 4 (1986), 2–6.

[BS00] BOWKER G. C., STAR S. L.: *Sorting Things Out: Classification and Its Consequences*. MIT Press, Aug. 2000.

[DM12] DOOLIN B., MCLEOD L.: Sociomateriality and boundary objects in information systems development. *European Journal of Information Systems 21*, 5 (Sept. 2012), 570–586. doi:10.1057/ejis.2012.20.

[EGL*13] EFENTAKIS A., GRIVAS N., LAMPRIANIDIS G., MAGENSCHAB G., PFOSER D.: Isochrones, Traffic and DEMOgraphics. In *Proceedings of the 21st ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems* (New York, NY, USA, 2013), SIGSPATIAL'13, ACM, pp. 548–551. doi:10.1145/2525314.2525325.

[GBCI11] GAMPER J., BÖHLEN M. H., COMETTI W., INNEREBNER M.: Defining isochrones in multimodal spatial networks. In *Proceedings of the 20th ACM Conference on Information and Knowledge Management, CIKM 2011, Glasgow, United Kingdom, October 24-28, 2011* (2011), Macdonald C., Ounis I., Ruthven I., (Eds.), ACM, pp. 2381–2384. doi:10.1145/2063576.2063972.

[GGED16] GOURLET P., GARCIN S., EVEILLARD L., DERVIEUX F.: DoDoc: A Composite Interface That Supports Reflection-in-Action. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (New York, NY, USA, 2016), TEI '16, ACM, pp. 316–323. doi:10.1145/2839462.2839506.

[GKvN14] GORTANA F., KAIM S., VON LUPIN M., NAGEL T.: Isoscope-Visualizing temporal mobility variance with isochrone maps. *Poster Abstracts of IEEE VIS 2014* (2014).

[Hen99] HENDERSON K.: *On Line and on Paper: Visual Representations, Visual Culture, and Computer Graphics in Design Engineering*. MIT Press, Jan. 1999.

[HKYA14] HONG S. R., KIM Y.-S., YOON J.-C., ARAGON C. R.: Traffigram: Distortion for clarification via isochronal cartography. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2014), CHI '14, Association for Computing Machinery, pp. 907–916. doi:10.1145/2556288.2557224.

[KAB*10] KOPF J., AGRAWALA M., BARGERON D., SALESIN D., COHEN M.: Automatic Generation of Destination Maps. In *ACM SIGGRAPH Asia 2010 Papers* (New York, NY, USA, 2010), SIGGRAPH ASIA '10, ACM, pp. 158:1–158:12. doi:10.1145/1866158.1866184.

[LB03] LARMAN C., BASILI V. R.: Iterative and incremental developments. a brief history. *Computer 36*, 6 (June 2003), 47–56. doi:10.1109/MC.2003.1204375.

[Lee05] LEE C. P.: Between Chaos and Routine: Boundary Negotiating Artifacts in Collaboration. In *ECSCW 2005* (2005), Gellersen H., Schmidt K., Beaudouin-Lafon M., Mackay W., (Eds.), Springer Netherlands, pp. 387–406.

[Lee07] LEE C. P.: Boundary Negotiating Artifacts: Unbinding the Routine of Boundary Objects and Embracing Chaos in Collaborative Work. *Computer Supported Cooperative Work (CSCW) 16*, 3 (June 2007), 307–339. doi:10.1007/s10606-007-9044-5.

[LTD19] LISTEMANN M., TRAPP M., DÖLLNE J.: Lens-based Focus+Context Visualization Techniques for Interactive Exploration of Web-based Reachability Maps. *Journal of WSCG 27*, 2 (2019). doi:10.24132/JWSCG.2019.27.2.1.

[Luc12] LUCERO A.: Framing, aligning, paradoxing, abstracting, and directing: How design mood boards work. In *Proceedings of the Designing Interactive Systems Conference on - DIS '12* (Newcastle Upon Tyne, United Kingdom, 2012), ACM Press, p. 438. doi:10.1145/2317956.2318021.

[MBW11] MUNZNER T., BARSKY A., WILLIAMS M.: Reflections on QuestVis: A Visualization System for an Environmental Sustainability Model. In *Scientific Visualization: Interactions, Features, Metaphors*, Hagen H., (Ed.), vol. 2 of *Dagstuhl Follow-Ups*. Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, Dagstuhl, Germany, 2011, pp. 240–259. doi:10.4230/DFU.Vol2.SciViz.2011.240.

[MD20] MEYER M., DYKES J.: Criteria for Rigor in Visualization Design Study. *IEEE Transactions on Visualization and Computer Graphics 26*, 1 (Jan. 2020), 87–97. doi:10.1109/TVCG.2019.2934539.

[MG10] MARCIUSKA S., GAMPER J.: Determining Objects within Isochrones in Spatial Network Databases. In *Advances in Databases and Information Systems* (Sept. 2010), Lecture Notes in Computer Science, Springer, Berlin, Heidelberg, pp. 392–405. doi:10.1007/978-3-642-15576-5_30.

[MLB07] MARK G., LYYTINEN K., BERGMAN M.: Boundary Objects in Design: An Ecological View of Design Artifacts. *Journal of the Association for Information Systems 8*, 11 (Nov. 2007), 546–568. doi:10.17705/1jais.00144.

[MS92] MCMASTER R. B., SHEA K. S.: Generalization in digital cartography. Association of American Geographers Washington, DC.

[Mun09] MUNZNER T.: A nested model for visualization design and validation. *Visualization and Computer Graphics, IEEE Transactions on 15*, 6 (2009), 921–928.

[OG15] OTAMENDI F. J., GARCÍA-HEREDIA D.: Isochrones as Indicators of the Influence of Traffic in Public Health: A Visual Simulation Application in Ávila, Spain. *International Journal of Environmental Research and Public Health 12*, 10 (Oct. 2015), 12556–12576. doi:10.3390/ijerph121012556.

[PPV00] PERRY D. E., PORTER A. A., VOTTA L. G.: Empirical Studies of Software Engineering: A Roadmap. In *Proceedings of the Conference on The Future of Software Engineering* (New York, NY, USA, 2000), ICSE '00, ACM, pp. 345–355. doi:10.1145/336512.336586.

[SG89] STAR S. L., GRIESEMER J. R.: Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science 19*, 3 (Aug. 1989), 387–420. doi:10.1177/030631289019003001.

[SMM12] SEDLMAIR M., MEYER M., MUNZNER T.: Design Study Methodology: Reflections from the Trenches and the Stacks. *IEEE Transactions on Visualization and Computer Graphics 18*, 12 (2012), 2431–2440. doi:10.1109/TVCG.2012.213.

[Sta10] STAR S. L.: This is Not a Boundary Object: Reflections on the Origin of a Concept. *Science, Technology, & Human Values 35*, 5 (Sept. 2010), 601–617. doi:10.1177/0162243910377624.

[Ste91] STEMBER M.: Advancing the social sciences through the interdisciplinary enterprise. *The Social Science Journal 28*, 1 (Jan. 1991), 1–14. doi:10.1016/0362-3319(91)90040-B.

[Tob04] TOBLER W.: Thirty Five Years of Computer Cartograms. *Annals of the Association of American Geographers 94*, 1 (Mar. 2004), 58–73. doi:10.1111/j.1467-8306.2004.09401004.x.

[VLRT18] VUILLEMOT R., LEYSENS T., RIVIÈRE P., TABARD A.: An Online Corpus of Isochrone Maps. In *CityVis – Urban Data Visualization* (Berlin, Germany, 2018).

[Wen99] WENGER E.: *Communities of Practice: Learning, Meaning, and Identity*. Cambridge University Press, Sept. 1999.

[ZFA*14] ZENG W., FU C. W., ARISONA S. M., ERATH A., QU H.: Visualizing Mobility of Public Transportation System. *IEEE Transactions on Visualization and Computer Graphics 20*, 12 (Dec. 2014), 1833–1842. doi:10.1109/TVCG.2014.2346893.

[Zhi13] ZHILIN L.: Digital Map Generalization at the Age of Enlightenment: A Review of the First Forty Years: The Cartographic Journal: Vol 44, No 1. https://www.tandfonline.com/doi/abs/10.1179/000870407X173913, Nov. 2013.