

A Visualization Design Study for Hydrodynamic Connectivity Analysis in Marine
Aquaculture

by

Nazanin Shamshiri

B.Sc., Amirkabir University of Technology, 2020

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

in the Department of Computer Science

© Nazanin Shamshiri, 2026

University of Victoria

All rights reserved. This thesis may not be reproduced in whole or in part,
by photocopy or other means, without the permission of the author.

We acknowledge and respect the Lək̓ʷəŋən (Songhees and X̱wsep̓səm/Esquimalt) Peoples on whose
territory the university stands, and the Lək̓ʷəŋən and W̱SÁNEĆ Peoples whose historical
relationships with the land continue to this day.

A Visualization Design Study for Hydrodynamic Connectivity Analysis in Marine
Aquaculture

by

Nazanin Shamshiri

B.Sc., Amirkabir University of Technology, 2020

Supervisory Committee

Dr. Sean Chester , Supervisor
(Department of Computer Science)

Dr. Miguel Nacenta, Departmental Member
(Department of Computer Science)

Abstract

Hydrodynamic particle tracking simulations are used in the Fisheries and Oceans Canada study of connectivity between marine finfish aquaculture sites around Vancouver Island [1]. In this context, simulation outputs are summarized as connectivity matrices showing the percentage of particles released from one farm that arrive at another within selected time periods. Although these matrices are the main reporting artifact, domain experts often interpret them together with spatial context, temporal comparisons, and directional relationships. This makes interpretation, exploration, and communication difficult, especially when results must support discussion with non-specialist stakeholders.

This thesis presents a visualization design study conducted in collaboration with ocean scientists working on this aquaculture connectivity application. Through contextual inquiry, affinity-based task characterization, participatory co-design, low- and high-fidelity prototyping, and qualitative evaluation, the study investigates how interactive visualization can better support the interpretation and communication of farm-to-farm connectivity matrices derived from the particle simulations. As part of this process, the study identifies and stabilizes design requirements that capture key conditions for supporting these interpretation and communication tasks.

The resulting prototype combines an interactive connectivity map, a matrix view, temporal exploration controls, threshold filtering, and exploratory clustering. In connectivity exploration mode, coordination was achieved mainly through shared temporal and threshold controls that updated values and visual encodings across views. Stronger selection-based coordination was achieved in clustering mode. Evaluation findings suggest that the prototype supported spatial interpretation of farm-to-farm connectivity, plausibility checking against expected regional flow patterns, and exploratory comparison of candidate farm groupings, while also showing that familiar matrix-based representations remained important for user trust and verification.

Beyond the prototype, the thesis contributes design knowledge for interactive visualization of hydrodynamic connectivity matrices in the aquaculture management context, including

the value of combining spatial and matrix-based views, the importance of preserving familiar representations while introducing new analytical views, the need to frame clustering as an exploratory rather than authoritative result, and the importance of aligning interface terminology with the abstraction of aggregated connectivity data.

Contents

Supervisory Committee	ii
Abstract	iii
Table of Contents	v
List of Tables	ix
List of Figures	x
1 Context and Motivation	1
1.1 Motivation	1
1.2 Context and Problem Domain	3
1.3 Design Study Methodological Context	4
1.4 Research Questions and Contributions	5
2 Background and Related Work	7
2.1 Visualization and Scientific Decision-Making	7
2.2 Hydrodynamic Particle Simulations and Connectivity	8
2.3 Connectivity Matrices	9
2.4 Spatial Context of Farm Locations	10
2.5 Limitations of Static Connectivity Visualizations	11
2.6 Interactive Visualization Techniques	12
2.7 Visualization Techniques for Connectivity Analysis	13
2.8 Visualization Design Studies and Design Requirements	15
3 Design Study Process	18
3.1 Chapter Overview	18
3.2 Research Approach: Design Study and Participatory Design	18

3.3	Stakeholder Selection and Problem Scoping	21
3.3.1	Initial Contact and Early Exploration	21
3.3.2	Scoping Criteria and Practical Constraints	21
3.3.3	Stakeholders and Participants	22
3.3.4	Outcome of the Learn/Winnow Phase	22
3.3.5	Shift in Study Focus	23
3.4	Empathize: Domain Immersion and Problem Validation	23
3.4.1	Contextual Inquiry and Workflow Observation	24
3.4.2	Observation Summary and Traceability	25
3.4.3	Outputs of the Empathize Phase	26
3.5	Define: Task Characterization and Refinement	26
3.5.1	Method: Affinity Diagramming	26
3.5.2	Clustering and Mega Category Formation	27
3.5.3	Abstraction and Traceability	29
3.5.4	Resulting Task List (Verbatim)	30
3.6	Ideate: Co-design and Design Space Exploration	31
3.6.1	Participants and Setup	32
3.6.2	Session Structure	32
3.6.3	Initial Observations	32
3.7	Emerging Design Requirements	34
3.8	Prototype: Low-Fidelity Prototyping and Design Consolidation	34
3.8.1	Physical Paper Prototype	35
3.8.2	Paper-Prototype Walkthrough Interview	35
3.9	Stabilized Design Requirements	37
3.10	Prototype: High-Fidelity Digital Implementation	39
3.10.1	Data Scope and Feasibility	39
3.10.2	Implemented Components	39
3.11	Test: Evaluation Session and Feedback Collection	39
3.11.1	Evaluation Structure	40
3.11.2	Post-task Questionnaire and Evidence Collected	40
3.12	Chapter Summary	40
4	Tool Design and Implementation	44
4.1	Chapter Overview	44
4.2	Design Requirements as Design Drivers	44

4.3	Design Rationale	45
4.4	Spatial Connectivity Map	46
4.5	Connectivity Matrix	46
4.6	Temporal Exploration	47
4.7	Directional Semantics	48
4.8	Threshold-Based Emphasis	48
4.9	Coordinated Interaction	48
4.10	Exploratory Clustering View	49
4.11	Implementation Overview	49
4.12	Chapter Summary	50
5	Evaluation	52
5.1	Chapter Overview	52
5.2	Evaluation Goals	52
5.3	Participants	53
5.4	Procedure	53
5.4.1	Qualitative Evidence and Analysis Approach	53
5.5	Task Design	54
5.6	Quantitative Measures	54
5.7	Qualitative Findings	55
5.7.1	Spatial reasoning was supported, but navigation remained difficult	55
5.7.2	Threshold adjustment supported exploratory narrowing	55
5.7.3	Matrix interpretation was affected by the orientation inconsistency	56
5.7.4	Cross-view coordination was partial rather than uniform	56
5.7.5	Directional semantics were clearer for single-farm analysis than for group analysis	57
5.7.6	Two-way connectivity was not shown in the way participants expected	57
5.7.7	Task wording affected interpretation and ratings	58
5.7.8	The clustering view supported exploration, but required explanation	58
5.8	Summary of Findings	58
6	Design Knowledge, Limitations, and Conclusion	60
6.1	Design Knowledge	60
6.1.1	DK1: Spatial and relational views should be coordinated	60
6.1.2	DK2: Familiar representations support analytical trust	61

6.1.3	DK3: Algorithmic views require explanation and verification	61
6.1.4	DK4: Directional semantics depend on the reference frame	61
6.1.5	DK5: Terminology should match the data abstraction	62
6.1.6	DK6: Connectivity is understood as process but analyzed as aggregation	62
6.1.7	DK7: Progressive disclosure supports reasoning across scales	62
6.2	Limitations	62
6.2.1	Matrix orientation inconsistency	63
6.2.2	Directional terminology and semantics were unstable	63
6.2.3	Two-way connectivity was not represented as a distinct state	63
6.2.4	Spatial navigation was constrained by the interface layout	64
6.2.5	Cross-view coordination was useful but incomplete	64
6.2.6	Task wording did not always match the implemented abstraction . . .	65
6.2.7	Limited training and exploration affected some tasks	65
6.2.8	Questionnaire interpretation constraints	66
6.3	Future Work	66
6.4	Thesis Contributions	66
6.5	Conclusion	67

List of Tables

Table 3.1	Empathize phase themes	42
Table 3.2	Prototype feedback and requirement refinement	43

List of Figures

Figure 1.1	Annotated connectivity matrix	2
Figure 1.2	Example connectivity matrix	4
Figure 2.1	Connectivity matrix overview	9
Figure 2.2	Farm locations in the study region	10
Figure 2.3	Annotated matrix used in discussion	12
Figure 3.1	Design study process overview	20
Figure 3.2	Affinity diagram mega categories	28
Figure 3.3	Traceability from evidence to tasks	29
Figure 3.4	Representative co-design sketches	33
Figure 3.5	Low-fidelity paper prototype	35
Figure 4.1	Prototype overview	46
Figure 4.2	Directional connectivity map	47
Figure 4.3	Temporal connectivity comparison	47
Figure 4.4	Ingoing and outgoing connectivity	48
Figure 4.5	Threshold-based connectivity filtering	49
Figure 4.6	Clustering views	50
Figure 4.7	Cluster-aware connectivity exploration	51

Acknowledgements

I would first like to acknowledge the perseverance required to complete this thesis. Returning to graduate studies after a long interruption and continuing through a particularly demanding period of personal and family life required sustained effort and commitment. This work reflects not only academic progress, but also persistence and discipline during a time of uncertainty.

I am deeply grateful to my parents for their sacrifices, their trust, and their unwavering support. Their belief in me made it possible for me to pursue this path and continue my studies in Canada. I also wish to honour them with special respect through the name I carry on this thesis.

I would like to sincerely thank my supervisors for their continuous guidance, patience, and thoughtful feedback throughout this research and over the many years it took to complete this degree. Their support shaped both the direction and quality of this work.

I am especially grateful to the domain experts from Fisheries and Oceans Canada, who generously shared their time, expertise, and insights. Their collaboration made this study possible and grounded the work in real-world practice.

This research was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC) and by funding associated with a research project led by Dr. Charles Perin. I would also like to acknowledge Dr. Charles Perin for his contributions to the supervision and direction of this work.

I am profoundly grateful to my daughter, who has been a constant source of strength, purpose, and motivation throughout this journey. Her presence gave me the courage to continue through the most challenging moments and reminded me each day why striving for a better future matters.

Finally, I would like to thank my family and friends for their understanding, encouragement, and support throughout my graduate studies.

Dedication

To my daughter, who gave me strength beyond what I thought I had and who made every challenge worth facing. This thesis is for you, and for the better future your presence inspires me to keep building.

Chapter 1

Context and Motivation

1.1 Motivation

This thesis is motivated by the need to interpret and communicate particle connectivity results produced for aquaculture management around Vancouver Island. In the Fisheries and Oceans Canada (DFO) study of hydrodynamic connectivity between marine finfish aquaculture sites, particle tracking simulations were used to examine how particles released from one farm may later reach other farms over time [1]. These results were intended to support discussion of farm-to-farm connectivity in an area-based management context.

In this thesis, *hydrodynamic connectivity* refers to the simulated transport relationship between pairs of farms: particles released from one site may later be captured at another site within a selected time window. In the aquaculture setting, these pathways are important because they can indicate potential routes for the spread of sea lice, pathogens, or other contaminants between farms [1]. Interpreting these pathways therefore has practical consequences for how farm connections are understood and communicated in management settings.

In the DFO project, the main outputs reviewed by domain experts were static connectivity matrices and supporting figures [1]. During the early project meetings, the scientific team presented connectivity matrices together with maps and annotated slides used to support explanation. Figure 1.1 shows one example of a matrix that was manually marked during discussion to highlight possible groupings and connectivity patterns. These materials made the visualization opportunity visible: the matrix was clearly central to the scientific workflow, but interpretation also depended on added markings, cross-referencing with maps, and verbal explanation.

For a visualization researcher, these materials suggested an opportunity for design work.

Connectivity Matrices: West Coast

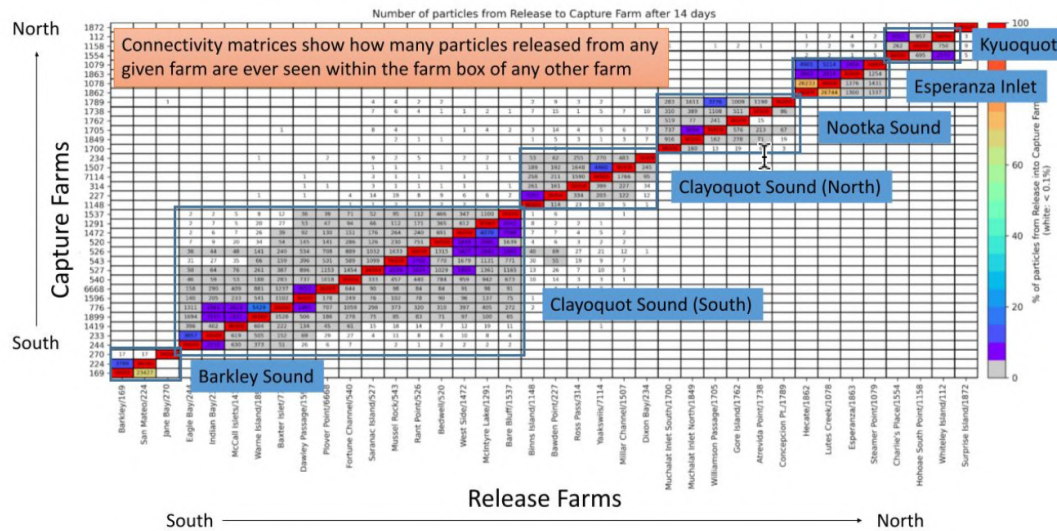


Figure 1.1: Annotated connectivity matrix from the DFO project. Manual markings were added during analysis and presentation to draw attention to possible groupings and connectivity patterns. This illustrates both the importance of the matrix as a project artifact and the interpretive effort required to explain the results.

The challenge in this setting was not only how to display simulation results, but how to represent them in a way that better supported the analytical and communication practices of the scientists working with them. In particular, the collaboration was motivated by the question of how interactive visualization might help scientists interpret farm-to-farm connectivity matrices together with spatial and temporal context.

Problem-driven visualization research argues that visualization design should begin with a concrete domain problem, the tasks of domain experts, and the practical setting in which analysis takes place, rather than with a preferred visualization technique [2]. This framing is appropriate for the present work because the goal was not to propose a general solution for ocean science, but to understand and improve the specific interpretation and communication challenges observed in this DFO application.

Accordingly, this thesis presents a design study conducted with scientists at Fisheries and Oceans Canada. The study characterizes domain tasks, explores design alternatives collaboratively, and develops an interactive visualization prototype grounded in observed workflows. A central outcome of the study is the identification and stabilization of design requirements for interpreting and communicating farm-to-farm connectivity matrices. Although the work is

specific to this application, the resulting requirements and design reflections may help inform future connectivity visualizations in related ocean science settings where scientists interpret aggregated connectivity matrices together with spatial and temporal context.

1.2 Context and Problem Domain

This research was conducted in collaboration with ocean scientists at Fisheries and Oceans Canada as part of a project examining hydrodynamic connectivity between marine finfish aquaculture sites around Vancouver Island [1]. The project used particle tracking simulations to estimate how particles released from one farm may later reach other farms over time. In the management context of the project, these simulated pathways were used to support discussion of farm-to-farm connectivity and potential transmission routes between aquaculture sites.

The simulation outputs were aggregated into connectivity matrices, which became the main artifacts used for analysis and reporting. In these matrices, each column represents a releasing farm and each row represents a receiving farm. Cell values encode the percentage of particles released from one farm that later arrive at another within a selected time window. This representation allowed scientists to review many pairwise relationships at once and to compare connectivity across farms and time horizons.

Figure 1.2 shows an example of a connectivity matrix from the project. The matrix provides a compact overview of farm-to-farm relationships and makes it possible to inspect which pairs are more strongly or weakly connected. At the same time, important aspects of interpretation remain difficult. Readers must mentally connect matrix rows and columns to farm locations, infer directionality from the row/column structure, and relate visible patterns to broader geographic context. Comparisons across multiple time horizons also require careful visual inspection.

In practice, scientists did not interpret these matrices in isolation. They also relied on maps, annotations, and discussion to explain possible groupings, directional relationships, and regional patterns. This made the Particle Project a useful setting for visualization research: the core representation was already established and scientifically meaningful, but its interpretation required substantial support. This context motivated a more systematic investigation of the tasks, reasoning practices, and visualization challenges involved in working with these connectivity results.

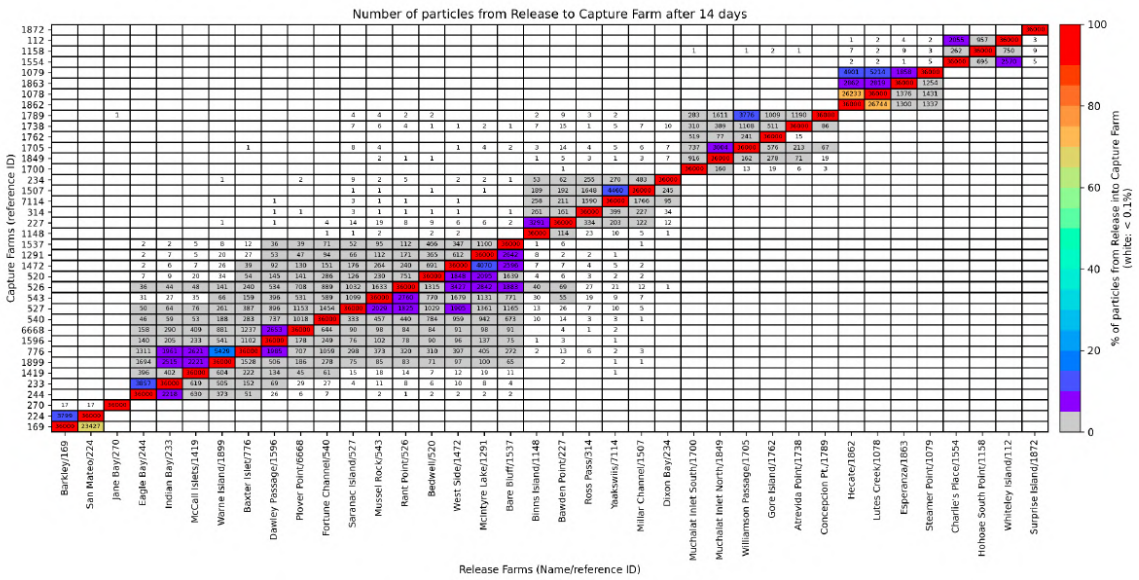


Figure 1.2: Example of a connectivity matrix from the DFO project. Columns represent releasing farms and rows represent receiving farms. Cell color encodes the percentage of released particles that arrive at another farm within a selected time window.

1.3 Design Study Methodological Context

This thesis follows the visualization design study methodology described by Sedlmair et al. [2]. Design studies emphasize close collaboration with domain experts and ground visualization design in real analytical problems and workflows. Rather than beginning with a specific visualization technique, the process starts with understanding domain practices and identifying the tasks that visualization should support.

In this methodology, the design process typically progresses through problem characterization, iterative design, and evaluation with domain experts. Observations from domain work are translated into task abstractions, which then inform visualization design. Iterative prototyping and feedback refine the design over time.

Several visualization design studies follow similar structures. Goodwin et al. [3] demonstrate a user-centered design process in which visualization tools are developed through close engagement with domain analysts. Meyer et al. [4] emphasize that rigorous design studies produce both a working system and generalizable design knowledge derived from the development process.

Later reflections on design study practice note that design requirements often emerge gradually rather than being fully specified at the start of a project [5]. Requirements may evolve through task analysis, design exploration, and prototyping. This iterative development process

is also compatible with participatory design approaches, in which domain experts contribute to shaping design ideas through co-design activities [6].

In this thesis, the design process combines elements of visualization design study methodology with participatory design practices. Domain workflows were examined through contextual inquiry, tasks were derived through affinity analysis, and design ideas were explored collaboratively during a co-design workshop. Low-fidelity prototypes were then used to refine the design before implementation and evaluation of the interactive prototype.

More broadly, this research follows a problem-driven design study conducted in close collaboration with domain experts. The study proceeds through domain immersion and contextual inquiry, task characterization, participatory co-design, iterative prototyping, and structured evaluation. The goal is not only to produce an interactive prototype, but also to generate design knowledge grounded in empirical observation. The approach therefore emphasizes traceability from raw observations to task characterization, design requirements, prototype design, and evaluation findings.

1.4 Research Questions and Contributions

Following a design study methodology, this thesis addresses four research questions spanning problem validation, task characterization, prototype design, and evaluation:

- **RQ1:** What visualization and communication challenges arise when ocean scientists interpret hydrodynamic connectivity results in the DFO aquaculture connectivity project?
- **RQ2:** How can the domain-specific tasks involved in interpreting farm-to-farm connectivity matrices be characterized to inform visualization design?
- **RQ3:** How does an interactive visualization prototype support key interpretation and communication tasks for these connectivity results?
- **RQ4:** What forms of reasoning, interpretation, and exploratory hypothesis generation emerge when experts explore connectivity data interactively?

The research questions in this thesis follow the stages of a visualization design study, progressing from problem validation to task characterization, design, and evaluation. In particular, RQ1 corresponds to the initial problem validation (winnow) phase, establishing that the interpretation and communication of connectivity matrices present a meaningful visualization

challenge in practice. As a result, not all research questions map directly to standalone contributions; instead, they structure the study process that leads to the contributions presented below.

- **C1: Empirically grounded problem and task characterization.**

This study documents how ocean scientists interpret hydrodynamic connectivity through spatial, relational, temporal, and directional reasoning practices. The task characterization was grounded in contextual inquiry, affinity analysis, and collaborative design activities.

- **C2: Requirement-driven visualization design.**

This work illustrates how visualization requirements can emerge and stabilize through iterative synthesis across domain immersion, co-design, low-fidelity prototyping, and evaluation. The study also shows that requirements continue to evolve when experts interact with concrete prototypes. A central outcome of the thesis is the identification and stabilization of design requirements for supporting the interpretation and communication of farm-to-farm connectivity matrices.

- **C3: Design knowledge for connectivity visualization.**

This thesis contributes design knowledge regarding coordination of spatial and relational views, trust in familiar analytical representations, the need for transparent framing of algorithmic views, the dependence of directional semantics on the reference frame, and the importance of matching terminology to data abstraction. Although these results arise from a specific aquaculture connectivity application, they may help inform future visualization work in related settings where scientists interpret aggregated connectivity matrices together with spatial and temporal context.

Chapter 2

Background and Related Work

This chapter reviews the background and prior work most relevant to this thesis. It first discusses the role of visualization in scientific analysis and decision-making. Next, it introduces hydrodynamic particle simulations and the connectivity matrices used in the DFO aquaculture connectivity project to summarize simulation results. The chapter then discusses why static connectivity visualizations can be difficult to interpret in this setting, especially when readers must relate matrix patterns to spatial context, directionality, and temporal change. It then reviews interactive visualization techniques that support exploratory analysis. Finally, it introduces visualization design study methodology and explains why it is appropriate for this thesis, including how its stages support the identification and stabilization of design requirements.

2.1 Visualization and Scientific Decision-Making

Visualization plays an important role in scientific analysis and communication because it helps people work with data that would be difficult to interpret in raw numerical form alone. Scientific datasets often contain many variables, long temporal spans, large numbers of relationships, or several possible levels of interpretation. In such settings, analysts need ways to compare cases, trace relationships, and connect local observations to broader context.

Information visualization research studies how visual representations support analytical reasoning. Chen describes visualization as a process that can support knowledge discovery by making patterns and relationships more evident than they are in raw numerical outputs [7, 8]. In practical terms, visualization can externalize relationships that would otherwise need to be computed, remembered, or inferred mentally. It may therefore support tasks such as

identifying clusters, comparing magnitudes, detecting outliers, or understanding how changes in one part of a dataset relate to others.

Visualization is also important in decision support. When decisions depend on understanding how different entities or conditions relate to one another, visual representations can help analysts compare alternatives and communicate findings more clearly [9]. In environmental science, this role is especially important because simulation outputs are often used not only for scientific interpretation but also for communication with managers, regulators, and other stakeholders.

In the present project, visualization mattered because the simulation results were intended to support discussion of connectivity among aquaculture farms. The issue was therefore not only whether a numerical summary could be produced, but whether the resulting representation supported interpretation, explanation, and communication in a practical management setting.

2.2 Hydrodynamic Particle Simulations and Connectivity

Hydrodynamic models simulate the movement of water masses through ocean circulation. Particle tracking simulations extend these models by releasing virtual particles at specified locations and following their movement through simulated currents over time.

In marine applications, such simulations are often used to study how material may move through a system. Depending on the application, particles may stand in for larvae, contaminants, pathogens, or other transported material. The resulting trajectories can therefore be used to reason about dispersal, exposure, and connectivity between sites.

In the DFO aquaculture connectivity project, particle tracking simulations were used to estimate possible transport pathways between marine finfish farms around Vancouver Island [1]. Particles released from one farm could later be captured at another farm, producing a simulated farm-to-farm connectivity relationship. In this thesis, *connectivity* refers to this modeled transport relationship between farms: material released from one site may later arrive at another site within a selected time window. This matters to ocean scientists because such relationships may indicate possible pathways for the spread of sea lice, pathogens, or other contaminants between farms [1]. As a result, interpreting connectivity is not only a technical modeling problem, but also part of understanding how sites may be related in a management context.

However, raw particle trajectories are difficult to work with directly. A simulation may involve many farms, many time steps, and very large numbers of particles. Even when the

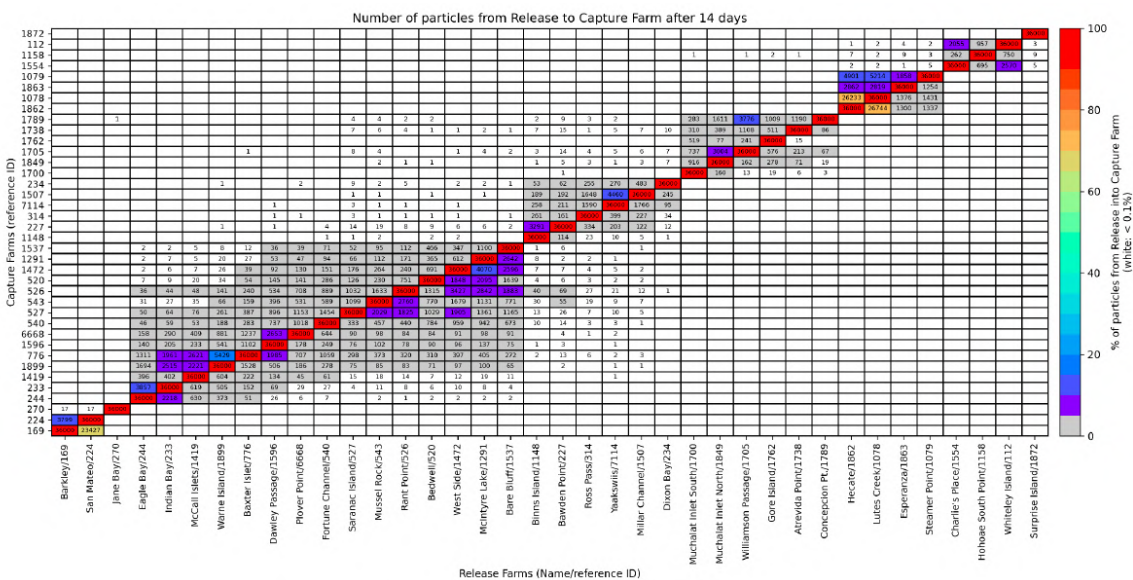


Figure 2.1: Connectivity matrix summarizing particle transport between aquaculture farms. Columns represent releasing farms and rows represent receiving farms. Cell color encodes the proportion of particles released from one farm that reach another farm within the selected time window.

underlying trajectories are available, direct inspection does not easily support comparison across all farm pairs or across multiple time horizons. For this reason, simulation outputs were aggregated into more compact summary representations.

2.3 Connectivity Matrices

A central summary representation in the DFO project was the connectivity matrix. Connectivity matrices summarize the relationships between particle release locations and particle arrival locations.

In the project matrices, each column represents a releasing farm and each row represents a receiving farm. Cell values encode the proportion of particles released from one farm that arrive at another within a selected time window.

This representation is useful because it provides a compact overview of many farm-to-farm relationships at once. Analysts can inspect stronger and weaker connections, compare asymmetries between pairs, and look for regions of denser interaction that may suggest possible groupings.

At the same time, the representation is not self-explanatory. Interpreting a connectivity matrix requires readers to understand what rows and columns mean, to infer directionality

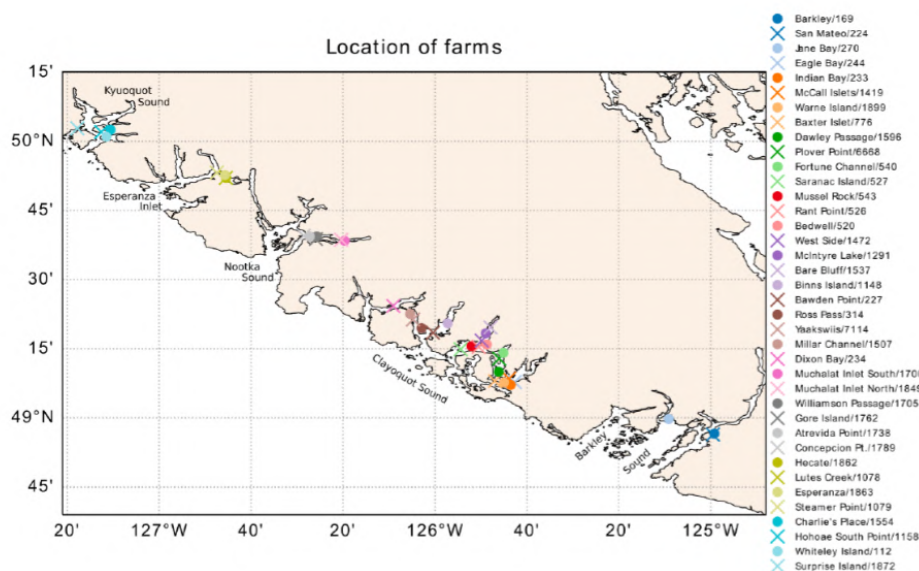


Figure 2.2: Geographic distribution of aquaculture farms included in the hydrodynamic connectivity simulations. Each point represents a farm location used as both a particle release site and a receiving site in the connectivity analysis.

from matrix position, and to relate visible patterns to the geographic arrangement of farms. The matrix can therefore support precise comparison, but it may not make broader spatial meaning immediately apparent. In addition, comparisons across multiple time windows require careful inspection or repeated switching between separate figures.

In the DFO project, the matrix was also the main reporting artifact. Maps and other visual materials were used mainly to support explanation of the matrix rather than to replace it. This made the matrix both analytically central and practically unavoidable in the workflow.

2.4 Spatial Context of Farm Locations

Connectivity patterns are strongly shaped by the geographic distribution of farms and the surrounding ocean circulation. Farms located in the same inlet, channel, or coastal region may exhibit stronger connectivity because they are influenced by similar current structures, while farms that are farther apart may show weaker or more asymmetric relationships.

Maps therefore provide important spatial context for interpreting connectivity results. A map makes farm locations visible and allows readers to relate patterns to coastlines, regional structure, and distance.

For the DFO project, this spatial context was important because the scientists did not interpret matrix values in isolation. They often wanted to know whether a visible pattern in the matrix corresponded to farms in the same region, farms connected along a plausible flow path, or farms separated by geographic features that might affect transport.

Maps, however, do not solve the whole problem. A simple location map does not directly show the strength or direction of connectivity between all pairs of farms. In the present context, strength refers to how much modeled exchange exists between two farms, while direction refers to whether particles move from farm A to farm B, from farm B to farm A, or in both directions over the selected time period. These questions matter because ocean scientists are not only interested in whether farms are connected, but also in how strongly they are connected, in which direction, and whether the pattern is plausible given regional geography and ocean dynamics. A map alone does not make all of this visible, so scientists must connect spatial positions with relationships encoded in the matrix. This interpretive burden was one of the central motivations for the present work.

2.5 Limitations of Static Connectivity Visualizations

In the DFO project, connectivity matrices and maps were commonly used in static reports and presentations [1]. These materials were scientifically useful, but their interpretation often required additional effort.

One limitation of static matrices is that they require readers to perform several tasks mentally. A reader may need to identify a farm in the matrix, determine whether the relevant value is in the row or the column, compare it against many other cells, and then relate the resulting pattern back to a geographic location. This becomes more difficult when the number of farms is large, when values vary across several orders of magnitude, or when multiple time windows need to be compared.

A second limitation is that interpretation often depends on additional explanation. During project discussions, scientists manually annotated matrices to highlight possible groups of farms or notable patterns.

These annotations show that the matrix itself was central, but not always sufficient. Important patterns were often made visible through added boxes, arrows, or verbal explanation. Such interpretation work is reasonable in collaborative scientific practice, but it also suggests that the representation could be better supported.

A third limitation is that static figures make interactive comparison difficult. Thresholds, time windows, and directional relationships cannot be adjusted dynamically. Instead, each

Connectivity Matrices: West Coast

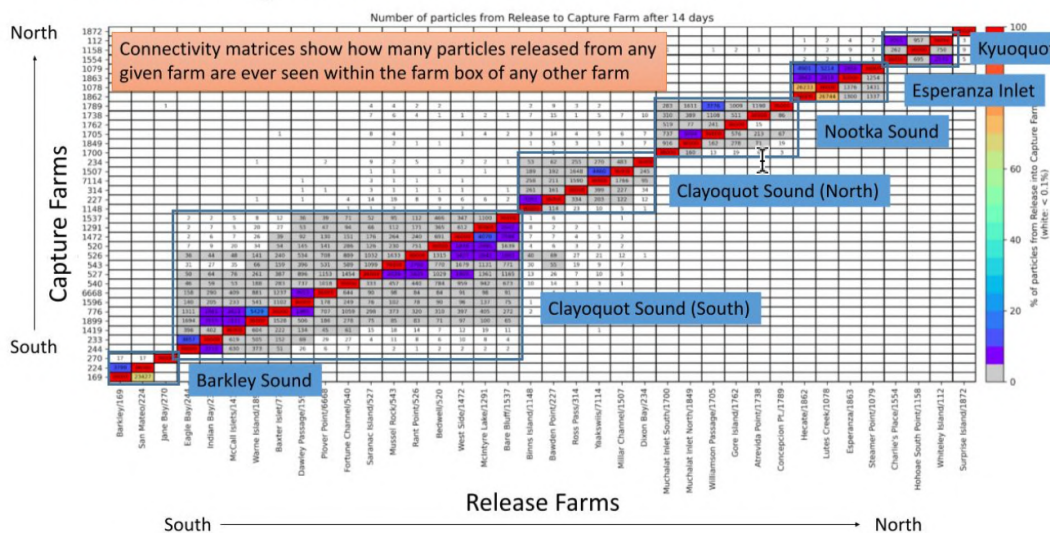


Figure 2.3: Connectivity matrix annotated during project discussions. Scientists manually highlighted groups of farms and connectivity patterns to support interpretation and communication of results.

variation must be prepared separately or inferred indirectly. In practice, scientists working with these materials often had to move back and forth between a matrix, a map, and spoken explanation in order to understand how a pattern in the grid related to a real group of farms in space. This was not simply a matter of inconvenience. It meant that some of the work of interpretation remained outside the visualization itself and had to be reconstructed by the analyst.

Taken together, these limitations suggest that the challenge in this project was not the absence of a meaningful summary representation. The connectivity matrix was meaningful and necessary. The challenge was that its interpretation required substantial cross-referencing, annotation, and explanation.

2.6 Interactive Visualization Techniques

Interactive visualization systems allow analysts to explore data dynamically through filtering, selection, and comparison. A common analysis workflow is described by Shneiderman's visual information seeking mantra: overview first, zoom and filter, then details on demand [10]. This pattern is relevant to the present work because connectivity analysis also involves movement

between broad structure and focused inspection of specific farm relationships.

One important idea in interactive visualization is the use of multiple coordinated views. Different representations can show different aspects of the same data, while shared controls or linked interactions help analysts move between them. Coordination may be achieved through linked highlighting, shared parameter changes, or synchronized filtering. These mechanisms can reduce manual cross-referencing and help users compare spatial, relational, and temporal information more directly.

Guidelines for coordinated multiple views have been described by Baldonado et al. [11] and Roberts [12]. Systems such as Snap-Together Visualization demonstrate how linked views can support interactive construction and comparison of related representations [13].

Interactive filtering is also relevant in scientific analysis. Filtering allows users to reduce visual complexity and focus on subsets of interest. In the connectivity setting, this could mean adjusting a threshold so that weaker links are suppressed while stronger ones remain visible. Such interactions are not only visual conveniences; they can function as analytical controls that shape what relationships become salient.

Heer and Shneiderman describe how interactive dynamics support iterative visual reasoning during exploratory analysis [14]. This perspective is especially relevant here because the scientists in the DFO project did not simply read fixed outputs. They compared, explained, questioned, and refined their interpretations through discussion and repeated examination of different project materials.

These techniques are relevant to the present thesis because they point toward possible ways of supporting the kinds of tasks later formalized in the study, including relating matrix structure to geography, adjusting thresholds, comparing across time, and exploring possible groupings. At the same time, the literature also suggests that interaction alone is not enough. The success of an interactive system depends on whether the design supports the actual reasoning practices of its users and whether the resulting representations remain interpretable and trustworthy.

2.7 Visualization Techniques for Connectivity Analysis

Understanding hydrodynamic connectivity requires reasoning about relationships between spatially distributed locations over time. From a visualization perspective, this type of problem combines relational structure, geographic context, and changing values across time. Several visualization techniques are relevant to this setting, including node-link diagrams, matrix representations, spatial connection maps, and coordinated multiple views. Each offers differ-

ent advantages and limitations for the Particle Project context.

A common way to represent relationships between entities is through node-link diagrams, where nodes represent entities and edges represent connections between them. Such representations can make paths, clusters, and overall network structure visually intuitive, especially when the number of nodes and edges is relatively small. However, as relational data become denser, node-link diagrams often become hard to read because of overlapping links, crossings, and clutter. In the Particle Project context, where many farms may be connected with different strengths, a pure node-link representation would make precise comparison difficult, especially when weak and strong connections appear together.

Matrix-based representations provide an alternative that scales better for dense relational data. Adjacency matrices encode pairwise relationships in a structured grid, supporting value comparison and pattern inspection without edge crossings. This is particularly relevant here because connectivity matrices were already the main analytical artifact used by the ocean scientists in the original workflow. The matrix therefore supports continuity with domain practice, and it provides a compact summary of connectivity strengths between all pairs of farms. At the same time, matrix representations do not directly show geographic structure. Analysts must still relate rows and columns to real farm locations and surrounding coastal features.

Spatial representations embed connectivity in geographic space by placing entities according to their real-world locations and drawing connections between them. In this project, such a view is useful because connectivity is interpreted partly through geography. Analysts reason about channels, inlets, regional proximity, and expected flow patterns when judging whether connections appear plausible. A spatial view therefore supports interpretation and communication in ways that a matrix alone cannot. However, spatial representations are weaker for precise pairwise comparison, especially when multiple connections overlap or when connection strengths differ by small amounts.

These trade-offs motivate the use of coordinated multiple views. Coordinated view systems combine complementary representations and allow interaction in one view to affect others [11, 12]. This approach is especially relevant when no single representation is sufficient for the analytical task. In the Particle Project, the scientists already used maps and matrices together, but they used them separately and had to mentally translate between them. Coordinated interaction can reduce that burden by allowing analysts to move between spatial and relational reasoning more directly. More broadly, interactive filtering, selection, and dynamic updates support iterative analysis by helping users move from overview to focused inspection [14].

These visualization techniques are directly relevant to the design of this thesis. The existing workflow already established the value of the connectivity matrix, but it also exposed the need for stronger spatial grounding and better support for comparison across changing analytical conditions. For this reason, the reviewed techniques were not treated as alternatives from which one would be chosen. Instead, they motivated the combination of complementary views in the prototype. More importantly, they helped clarify the design requirements that structure the rest of the thesis. The importance of geographic views supports **R1** (spatial reasoning), the continued role of the matrix supports **R2** (preserve the matrix as a familiar analytical reference), interaction across different time horizons supports **R3** (cumulative and interval-based temporal exploration), directional representations support **R4** (directional interpretation), filtering and visual emphasis support **R5** (threshold-based emphasis), and the combination of map and matrix through shared interaction supports **R6** (coordination across views). Finally, because dense connectivity patterns may also suggest groups of related farms, the literature on relational representations and interactive exploration also motivates **R7** (exploratory grouping while preserving interpretability). In this sense, the visualization literature does not simply provide background; it helps explain why the stabilized design requirements in this thesis are appropriate for this specific application.

2.8 Visualization Design Studies and Design Requirements

Visualization design studies focus on solving real-world problems through collaboration with domain experts. Rather than starting with a predefined visualization technique, design studies begin by understanding domain workflows, analytical tasks, and practical constraints.

Sedlmair et al. [2] describe a design study methodology that includes problem characterization, iterative design, and evaluation with domain experts. The outcome of a design study is typically both a visualization system and design knowledge derived from the development process.

Later reflections on design study practice note that design requirements often emerge gradually rather than being fully specified at the start of a project [5]. In this thesis, *design requirements* refer to the design conditions that a visualization must satisfy in order to support the tasks and reasoning practices identified in the domain. They are important because they provide the bridge between observed domain challenges and concrete design decisions. Rather than moving directly from observations to an interface, the study uses requirement formulation to stabilize what the prototype should actually support.

Participatory design methods may also be incorporated into design studies. Co-design

approaches involve domain experts directly in the design process, allowing them to contribute ideas and evaluate design alternatives collaboratively [6, 15]. This is relevant to the present thesis because the DFO scientists were not only users to be evaluated at the end of the project; they also helped shape task understanding and design direction during the study.

Design study methodology is therefore well suited to this work. First, it provides a structured way to move from initial problem characterization to task understanding. In this thesis, that stage supported the identification of challenges in interpreting and communicating connectivity matrices in the DFO aquaculture project. Second, it emphasizes iterative design and prototyping, which were necessary because the appropriate visual response was not known in advance. Third, it provides a process through which design requirements can be stabilized over time. Early observations, co-design ideas, and prototype feedback do not all carry equal weight, and the study needed a way to refine provisional ideas into requirements stable enough to guide implementation. Finally, the methodology supports evaluation in context, which was important here because the goal was not only to build an interface, but to understand how the resulting prototype aligned with the reasoning practices of the scientists working with the connectivity results.

For a reader unfamiliar with the design study process, the key stages can be summarized as follows. Problem characterization identifies the domain setting, the users, the artifacts already in use, and the practical challenges that make visualization support worthwhile. Task characterization translates domain observations into a clearer understanding of what users need to accomplish. Ideation and prototyping explore alternative responses to those tasks. Requirement stabilization identifies which design directions remain important and feasible after repeated feedback. Evaluation then examines how well the resulting prototype supports the target practices and where it falls short. In the present thesis, these stages were important not only for structuring the research process, but for making the design requirements themselves a central outcome of the work.

This framing also clarifies the direction of the remainder of the thesis. The challenge in the DFO project was not simply that particle tracking simulations produced large amounts of data. The more specific problem was that the main project artifacts—connectivity matrices—were scientifically meaningful but difficult to interpret in isolation. Scientists therefore relied on maps, annotations, and discussion to relate matrix structure to geography, directionality, and possible groupings. These conditions made the project well suited to a design study, because the key research need was to identify the design requirements that could better support interpretation and communication of farm-to-farm connectivity matrices.

This emphasis on design requirements is especially important for the present thesis. The

main contribution is not simply that a prototype was built for one ocean science project. Rather, the study identifies and stabilizes design requirements for interpreting and communicating farm-to-farm connectivity matrices in this application. The prototype and the later evaluation are important in part because they make those requirements concrete and allow them to be examined in practice. The following chapters therefore move from problem understanding to task characterization, design requirement stabilization, prototype development, and evaluation.

Chapter 3

Design Study Process

3.1 Chapter Overview

This chapter describes the design study process used to move from an initial domain collaboration to a tested visualization prototype. Building on the background and methodological framing presented in Chapter 2, the study followed an iterative visualization design study approach informed by design thinking and participatory design principles.

The chapter documents how the study progressed through six interconnected activities: (1) scoping the collaboration and stakeholders, (2) domain immersion through contextual inquiry, (3) task characterization and abstraction, (4) co-design exploration, (5) iterative prototyping and requirement stabilization, and (6) preparation for evaluation.

Rather than presenting these activities as a strictly linear pipeline, this chapter shows how understanding of tasks, design directions, and requirements evolved through repeated interaction with domain experts. The primary outcomes of this process are a refined task characterization and a set of stabilized design requirements that later informed the prototype design described in Chapter 4.

3.2 Research Approach: Design Study and Participatory Design

This thesis follows a visualization design study conducted in collaboration with ocean scientists involved in the Particle Project. Design studies are problem-driven investigations that combine domain understanding, visualization design, and situated evaluation to address real-world analytical challenges [2].

The study was guided by a design thinking framework consisting of the phases *empathize*, *define*, *ideate*, *prototype*, and *test* [16]. In practice, these phases were iterative and overlapping rather than strictly sequential. Insights gained during later activities frequently required revisiting earlier assumptions about tasks, representations, and design priorities.

Consistent with prior visualization design studies, problem understanding, design exploration, and requirement formulation co-evolved throughout the process. Requirements were not fixed immediately after task abstraction. Instead, they emerged and stabilized through iterative cycles of co-design, low-fidelity prototyping, and feedback [4, 2, 5].

Accordingly, the design requirements reported in this thesis represent *stabilized design directions* synthesized from multiple phases of the study rather than predefined specifications or fully realized interface capabilities.

Before formal task characterization, an initial learning and scoping phase was conducted to evaluate the suitability of the collaboration, following the learn/winnow stage recommended in design study methodology [2]. This phase included early meetings with domain experts, review of existing visual materials, and assessment of practical constraints such as data availability and stakeholder engagement (Section 3.3).

Participatory design principles were adopted throughout the study, positioning domain experts as active contributors to both problem framing and solution development rather than only evaluators [6]. Co-design activities enabled participants to externalize domain reasoning and explore alternative visualization concepts, expanding the design space through mixed expertise collaboration [17].

Figure 3.1 summarizes the overall design study process followed in this research. Although several activities informed one another iteratively, the process can be understood chronologically as follows. First, the collaboration was scoped and the domain problem was examined through contextual inquiry. Second, observations from this formative stage were organized through affinity diagramming and abstracted into task characterizations. Third, these task characterizations informed a co-design workshop, whose sketches were reviewed and synthesized into a paper prototype. Fourth, feedback from the paper-prototype walkthrough was used to refine and stabilize design requirements. These requirements then guided implementation of the digital prototype, which was subsequently evaluated with domain experts. The dashed arrows in the figure indicate points where later stages informed refinement of earlier design directions, especially during low-fidelity prototyping and after evaluation.

In this sequence, sketch analysis refers specifically to the review and synthesis of ideas produced during the co-design workshop. To support this synthesis, the sketch ideas were organized using the dimensions of purpose, appearance, and action. This coding helped iden-

tify which representations and interactions appeared most relevant to the task intents identified earlier, and it functioned as an analytic bridge between open-ended workshop sketches and the construction of the low-fidelity paper prototype. The later digital prototype was not a direct one-to-one implementation of this coding. Instead, it was developed after the paper-prototype walkthrough had clarified which design directions should be carried forward.

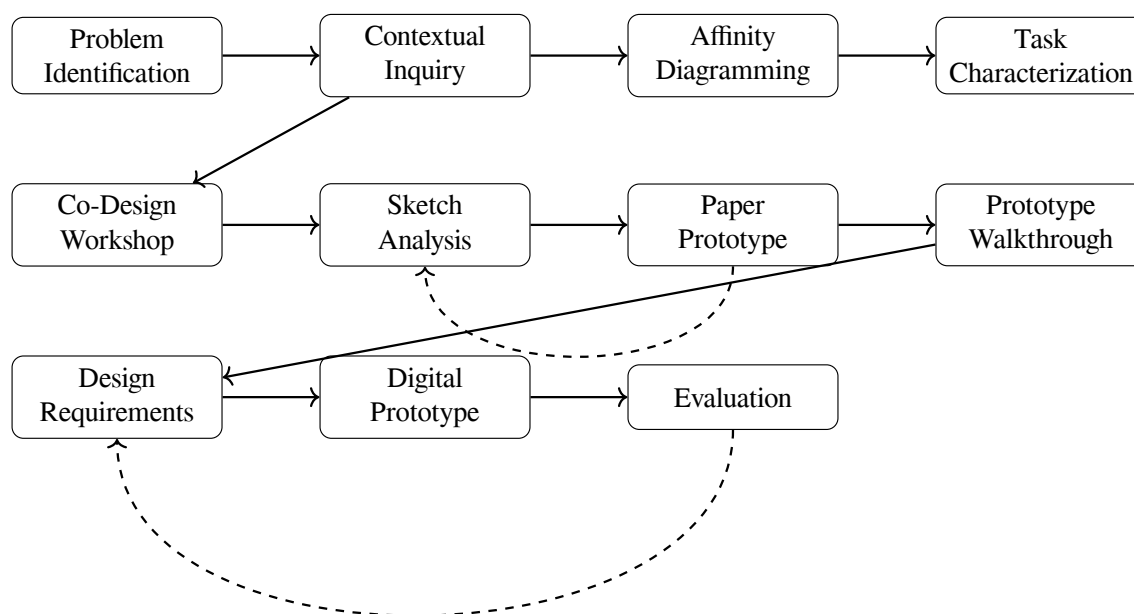


Figure 3.1: Visualization design study process showing the progression from problem identification to evaluation. The diagram illustrates the flow from contextual inquiry to task characterization, co-design, prototyping, and requirement stabilization. Dashed arrows indicate iterative feedback loops where later stages informed refinement of earlier design decisions.

This study received approval from the University of Victoria Human Research Ethics Board (HREB) (Protocol No. 21-0592-03). Participants were informed of the purpose of the study, the voluntary nature of participation, and their right to withdraw at any time without consequence. The study involved minimal risk, primarily related to time commitment and, at the time of data collection, potential exposure to COVID-19 during in-person sessions. No additional risks were associated with the procedures. Participants were informed of potential benefits, including contributing to the design of a visualization system to support their workflow, improving communication of ocean simulation outputs, and enabling new insights into connectivity patterns. Data were anonymized where possible and stored securely in accordance with university policies.

3.3 Stakeholder Selection and Problem Scoping

Design study methodology recommends spending time early to learn the domain, identify promising directions, and narrow the scope before committing to design and implementation [2]. This early phase is sometimes described as a *winning* process. The goal is to select a collaboration that is both feasible and scientifically interesting. In our case, this phase helped determine whether the Particle Project contained a visualization problem worth studying and whether the required resources were available.

3.3.1 Initial Contact and Early Exploration

The collaboration began after one researcher attended a presentation by two ocean scientists from Fisheries and Oceans Canada (DFO) about the Particle Project. During this presentation, the scientists shared the visual materials used in their analysis and reporting workflow.

These materials primarily consisted of static connectivity matrices and maps. Representative examples of these artifacts are included in Chapter 2, including a connectivity matrix deliverable, farm location maps, and presentation materials that use manual annotations to support communication.

The scientists explained that connectivity matrices were the primary project deliverables for management. Maps and other visuals were supplementary and used mainly to support explanation during presentations.

These early observations revealed two issues. First, connectivity matrices required substantial interpretation and cross-referencing with maps to understand spatial patterns. Second, grouping and threshold decisions were often explored visually and informally rather than through structured interactive tools.

These limitations motivated a deeper investigation of task needs and possible interactive support, described in the following sections.

3.3.2 Scoping Criteria and Practical Constraints

The goal of these early interactions was to evaluate feasibility and define a starting scope. We focused on the following questions:

- **Data access:** What data exists, and in what form is it available to us?
- **Stakeholder commitment:** Are domain experts available for repeated sessions?

- **Timeline:** Can we schedule participatory sessions within the study period?
- **Stakeholders and audience:** Who uses the results, and for whom are decisions made?
- **Contribution:** What kind of visualization contribution would be useful?

These criteria helped narrow the collaboration toward a realistic visualization goal that could be addressed through iterative design.

3.3.3 Stakeholders and Participants

The Particle Project includes multiple stakeholder groups. Based on early discussions, the main stakeholders were (1) scientists, (2) management, and (3) the aquaculture industry. In this thesis, we primarily collaborated with two DFO scientists who led the Particle Project. They participated in multiple sessions approved by the institutional ethics process.

Management was a major stakeholder because they were the main recipient of the project results and used the outcomes to support area-based management decisions. However, management did not participate directly in our design sessions due to limited availability and because the Particle Project reporting was already complete at the time of this study. As a result, management needs were mostly understood indirectly through the scientists' descriptions of reporting requirements and decision-making context.

Industry stakeholders were not directly involved in the study. Limited access and weak connections made it difficult to form a collaboration with this group. For this reason, the design process focused on supporting the scientists' analysis and communication needs, while remaining aware that the results may later be used by other audiences.

3.3.4 Outcome of the Learn/Winnow Phase

At the end of this phase, we concluded that the collaboration was feasible and that the Particle Project contained a visualization challenge worth investigating. We also identified constraints that shaped the remainder of the study, including limited stakeholder availability, the central role of derived connectivity matrices, and the need to support communication beyond the research team. These outcomes motivated deeper domain immersion and task characterization, described next.

3.3.5 Shift in Study Focus

The study initially began with the intention of exploring improvements to the visualization artifacts used in the Particle Project, particularly the connectivity matrices and supporting map-based representations observed during early presentations.

However, during the learn/winnow phase and the contextual inquiry, it became clear that the visualization challenge was embedded within a broader analytical workflow. Participants demonstrated that producing connectivity results involved multiple stages, including running particle simulations, aggregating results into connectivity matrices, selecting thresholds, manually identifying patterns, and creating supplementary visualizations for communication. The matrices themselves were the primary deliverables requested by management, while maps, arrows, and animations were created as supporting artifacts to explain those results.

These observations indicated that the challenge was not limited to improving a single visualization artifact. Instead, interpretation depended on how multiple representations, parameters, and manual steps were combined within the workflow. For example, participants experimented with threshold values to determine connectivity, manually identified clusters from matrix patterns, and constructed map-based representations through separate tools to communicate results.

As a result, the focus of the study shifted from optimizing or directly improving individual visualizations toward understanding how domain experts construct, interpret, and communicate connectivity results. The study therefore adopted a task- and workflow-centered design approach, where the primary goal became the identification of task requirements and the derivation of design knowledge.

Participants were informed that subsequent sessions focused on understanding their workflows and exploring design directions collaboratively, rather than producing a finalized or optimized tool.

3.4 Empathize: Domain Immersion and Problem Validation

The goal of the Empathize phase was to develop a grounded understanding of the Particle Project domain, the participants' workflows, and the context in which simulation results are produced and communicated. This phase focused on goals, decisions, constraints, and practices, rather than proposing visualization solutions. This approach follows design thinking and design study methodology, which emphasize deep domain immersion before formal problem

formulation [16, 2].

Although Empathize is presented here as a distinct phase, empathizing occurred throughout the study. Insights gained during later phases occasionally required revisiting assumptions about users, tasks, and goals. These iterations are referenced where relevant in subsequent sections.

3.4.1 Contextual Inquiry and Workflow Observation

To move beyond surface-level impressions from early presentations, we conducted a contextual inquiry session with two DFO ocean scientists who were primary contributors to the Particle Project. The session was conducted in a university research setting rather than in the participants' regular workplace. For this reason, the session should be understood as a guided reconstruction of a relevant workflow, rather than a direct observation of day-to-day work in its natural setting.

The focus of the session was the workflow used to produce and explain the connectivity visualizations previously introduced to the research team during preliminary meetings and seminars. Participants were asked to walk through the process of creating or interpreting one of these visualizations as if teaching it to someone unfamiliar with the workflow. This included describing the data sources, intermediate processing steps, decisions about thresholds and visual encodings, and the intended audience for each artifact.

The session followed a semi-structured master–apprentice interview model [18, 19]. The participants acted as domain experts and led the explanation, while the research team took the role of learners. We asked clarification questions when participants' actions, terminology, or assumptions were unclear, and probed moments where our initial understanding differed from the participants' explanations. This format allowed the session to remain focused on the participants' own reasoning while still giving the research team opportunities to validate or revise emerging assumptions.

The objective was not to evaluate a visualization tool at this stage. Instead, the session aimed to understand how connectivity results were constructed, interpreted, and communicated in the Particle Project, and to identify task needs that could later inform design. Because the workflow was reconstructed in a study setting and focused on selected visualization artifacts, the observations are treated as evidence of participants' reported and demonstrated practices for this project, rather than as a complete account of all aspects of their scientific work.

During the session, participants demonstrated how particle tracking outputs are processed

into aggregated connectivity summaries and reported through daily matrices for each model configuration. Participants emphasized that connectivity matrices were the primary required outputs, while other visual materials, such as maps, arrows, and animations, were created mainly to support explanation:

“Truly the grid ones were the deliverables and what we were asked to produce. Everything else was supplementary, usually used for presentations to help people understand what those grids mean.” [P1]

Participants also described that visualization parameters were often tuned for visual clarity and comparability. For example, threshold values were explored through trial and comparison, and participants preferred using consistent thresholds across regions to support comparison:

“I tried it with 0.1, 0.2 and 0.05. I liked 0.1.” [P2]

A recurring theme was that the matrix supported precise comparison, but did not provide geographic grounding. As a result, participants manually created supplementary map-based views, including arrows and region markings, to explain spatial patterns and directionality (one-way versus two-way connectivity). These practices indicated that interpretation and communication challenges were not only due to visual encodings, but also due to workflow needs such as selecting farms, inspecting directionality, adjusting the perceptual salience of weak connections, and communicating results to non-expert audiences.

The session was video-recorded to capture verbal explanations and interaction sequences, and was supplemented by researcher notes and artifact review. These materials were later transformed into discrete observation notes for affinity diagramming.

3.4.2 Observation Summary and Traceability

The contextual inquiry generated a substantial set of discrete observations about workflow procedures, parameter selection, data processing routines, and interpretive practices. Observations were transcribed into individual notes and subsequently analyzed using affinity diagramming. Table 3.1 summarizes the dominant themes identified during the Empathize phase. The complete observation dataset is provided in the online appendix repository to support traceability from raw evidence to higher-level themes.

During analysis, observations were systematically coded according to source using a pre-defined color scheme. Notes in pink corresponded to observations recorded directly by the researchers during the contextual inquiry session. Gray notes represented input provided by

the session facilitator during the same session. Blue notes denoted insights derived from subsequent review of video recordings. Yellow notes captured prior knowledge of participant workflows obtained from presentations, meetings, and seminars.

This structured coding approach supported group discussion and maintained traceability between raw observations and the thematic categories derived from analysis.

3.4.3 Outputs of the Empathize Phase

The Empathize phase produced the following outputs:

- a grounded understanding of the Particle Project workflow and constraints,
- evidence that connectivity matrices are central deliverables,
- identification of recurring interpretation and communication challenges, especially the need to connect matrix patterns to geographic context,
- recognition of multiple audiences with different needs (scientists, management, public).

These outputs informed the task characterization process described next.

3.5 Define: Task Characterization and Refinement

The Define phase transforms insights gained during Empathize into a structured characterization of domain tasks. In design thinking, this phase articulates what users need to accomplish rather than how existing tools support those needs [16]. Design study methodology similarly emphasizes task characterization as a necessary step before proposing visualization solutions [2].

In this study, the Define phase addresses **RQ2**: *How can the problem domain and domain-specific tasks of the Particle Project be characterized to inform visualization design?* Task characterization was grounded in empirical observations from contextual inquiry and earlier domain interactions and refined through iterative engagement with these materials.

3.5.1 Method: Affinity Diagramming

Affinity diagramming was used to synthesize qualitative observations into structured thematic groupings. All observation notes used in the affinity session were directly generated from

a structured observation table prepared by the author. Each row in the table represented a single atomic idea (action, goal, constraint, or interpretation). The table was printed and cut into individual notes, which were physically arranged on a large board during collaborative analysis. No additional data were introduced during clustering.

The observation table was used to print and cut the notes for the affinity session; therefore, the table and the physical notes contain the same observation content.

To preserve traceability, each note retained its source label and was color-coded before clustering:

- **Pink:** Researcher observations during contextual inquiry
- **Gray:** Facilitator input during contextual inquiry
- **Blue:** Insights derived from video analysis
- **Yellow:** Prior workflow knowledge from meetings and presentations

Because the notes were directly derived from the observation table, there is a one-to-one correspondence between the observation table provided in the online appendix repository and the physical notes. This ensures traceability from raw evidence to thematic grouping.

3.5.2 Clustering and Mega Category Formation

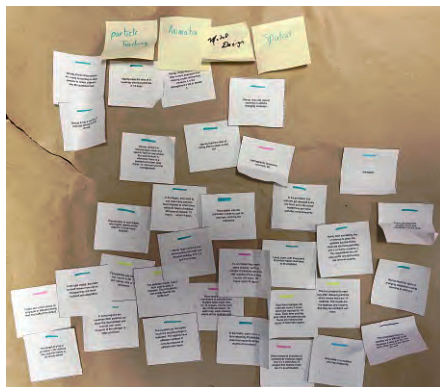
Notes were grouped based on semantic similarity and shared analytical intent. Clustering was iterative and required multiple passes before stable groupings emerged. The process emphasized task orientation rather than frequency of occurrence.

Across the board, a total of 158 observation notes were organized into intermediate thematic clusters. These clusters were subsequently abstracted into higher-level groupings referred to as *mega categories*.

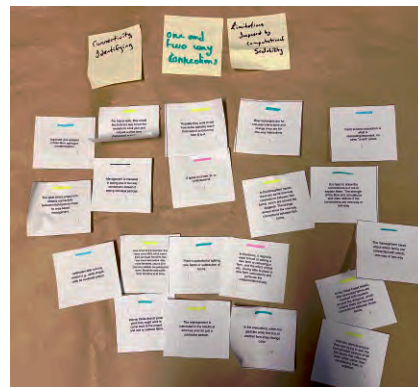
Figure 3.2 shows the refined affinity structure. Observations were reassigned and labeled during abstraction. Three categories were identified as task-centered and were used to structure task formulation. Two additional categories emerged from observations that did not directly correspond to task definition but were retained to inform later ideation.

The three task-centered mega categories were:

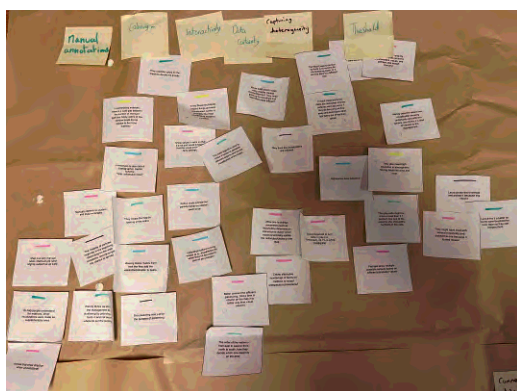
- **MC1:** Compare particle movement at different spatio-temporal scales
- **MC2:** Observe or identify connectivity between farms



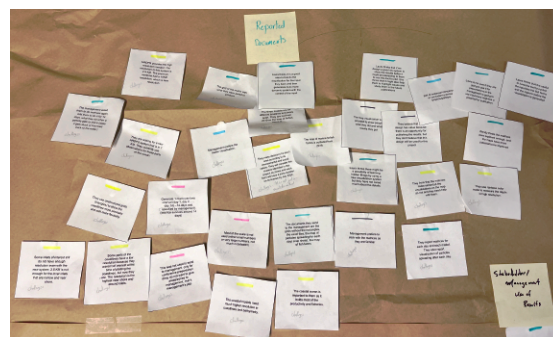
(a) MC1: Compare particle movement at different spatio-temporal scales



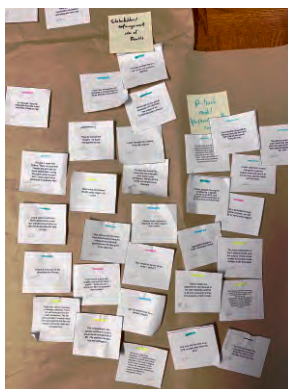
(b) MC2: Observe or identify connectivity between farms



(c) MC3: Improve confidence in (validate) the model and results



(d) Workflow-related observations



(e) Challenges and opportunities for contribution

Figure 3.2: Refined affinity diagram organized into three task-centered mega categories (MC1–MC3) and two additional categories (“Workflow” and “Challenges”). Observations were reassigned and labeled during abstraction. Each note corresponds to one entry in the observation table provided in the online appendix repository.

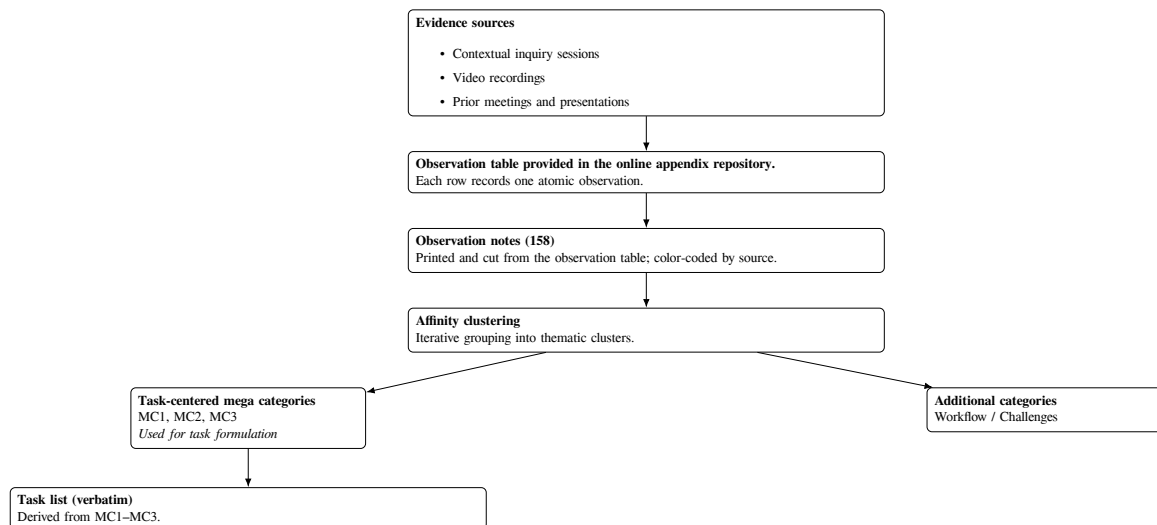


Figure 3.3: Abstraction and traceability from qualitative evidence to task characterization.

- **MC3:** Improve confidence in (validate) the spatio-temporal model and results

Two additional categories were identified:

- **Workflow:** Observations related to workflow constraints and features to retain
- **Challenges:** Observations indicating limitations or opportunities for contribution

The Workflow and Challenges categories informed the ideation phase but were not used to define task statements.

3.5.3 Abstraction and Traceability

The abstraction process followed a structured progression:

raw observation (table row) → affinity cluster → mega category → task statement

Figure 3.3 illustrates this traceability structure. The observation table provided the source material for clustering; observations were converted into individual notes and organized through affinity clustering. This process produced task-centered mega categories (MC1–MC3), which were then used to formulate the preliminary task list. This task list subsequently guided co-design activities, prototype scoping, and evaluation planning.

3.5.4 Resulting Task List (Verbatim)

The task list below is reported **verbatim** as produced during analysis. Preserving wording maintains traceability to domain language and avoids post-hoc reinterpretation. Some tasks overlap or vary in granularity; this reflects domain complexity and differing levels of abstraction used by participants. As later evaluation showed, some verbatim terms (e.g., *movement*, *spread*) did not map cleanly onto the aggregated connectivity abstractions implemented in the prototype, but they are retained here to preserve the original language of task elicitation. This mismatch between task wording and data abstraction later became an explicit finding during evaluation, where participants distinguished between trajectory-based interpretations and aggregated connectivity summaries.

MC1: Compare Particle Movement at Different Spatio-Temporal Scales

- Observe the progression of particles over time for a given farm (given the large number of particles)
- Compare particle spread at different time points for each farm with respect to a time granularity
- Have particles' pattern of movement as the final result after 14 days for each farm
- See the dominant flows and streams (circulations) to justify particle movement patterns
- See different levels of detail on contextual info (such as regions, landmarks, inlets, and channels) to aid analysis of movements
- See the distance the particles travel with respect to a time granularity
- See the progression of connectivity matrices over time

MC2: Observe or Identify Connectivity Between Farms

- Capture connection patterns between farms to support area-based management
- Compare patterns of particle movements within a group of farms
- Identify connected farms in case of contamination
- Differentiate between one-way and two-way connections

- Compare the strength of connections between farms
- Add or remove farms to change scale
- Compare directional strength between two farms
- Explain connections with respect to circulations and tides
- Notice when particles reach farm boundaries

MC3: Improve Confidence in (Validate) the Spatio-Temporal Model and Results

- Show interpretations based on the grid representation
- See percentages of particles spreading within a time period
- Manually group farms to define zones
- Compare alternative clustering side by side
- Compare received particle percentages across farms or models
- Show the simulation timeline when multiple runs exist

Consistent with prior design studies, requirements were derived through iterative synthesis rather than predefined specification, reflecting the progressive clarification of analytical needs observed during collaborative design [4, 5].

3.6 Ideate: Co-design and Design Space Exploration

The Ideate phase explored possible visualization responses to the task characterization developed in Section 3.5. Ideation was conducted through a structured co-design workshop involving domain experts and members of the research team. This approach aligns with participatory and co-design methods in which stakeholders actively contribute to shaping design directions rather than only evaluating finished systems [20, 15, 21].

3.6.1 Participants and Setup

The co-design workshop involved five participants: the facilitator (first author), a computer scientist, a designer, and two ocean scientists from DFO. The session was conducted around a shared work surface using printed maps and sketching materials. These artifacts supported collaborative discussion and allowed participants to externalize ideas through quick drawings and annotations.

3.6.2 Session Structure

The workshop was organized into three rounds corresponding to the three task-centered mega categories identified during the Define phase (MC1–MC3). Each round followed a sketch–share–refine cycle. Participants sketched potential solutions individually, presented them to the group, and revised ideas based on discussion.

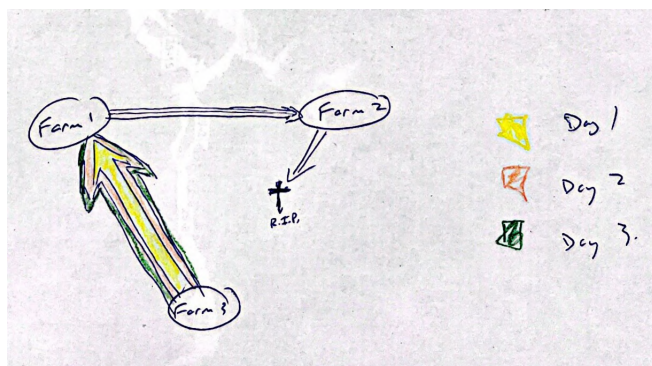
During the co-design workshop, participants produced a large number of sketches exploring possible ways to represent particle movement, connectivity between farms, and interactions with simulation results. Rather than representing a single proposed interface, the sketches illustrate different design directions considered during early ideation.

Figure 3.4 shows representative examples from the session. The selected sketches illustrate four recurring design themes observed during the workshop: spatial representations of connectivity, grouping of farms based on connectivity relationships, conceptual representations of particle movement, and potential interface layouts combining multiple views. These sketches served as inputs for the later synthesis stage and informed the development of the paper prototype described in Section 3.8.

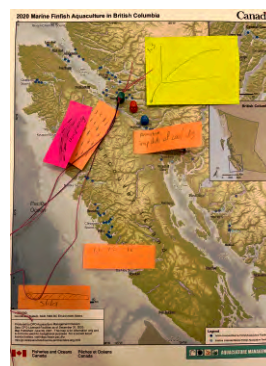
Several ideas explored in these sketches later informed stabilized design requirements such as spatial reasoning (R1), directional connectivity (R4), and coordinated multi-view interaction (R6).

3.6.3 Initial Observations

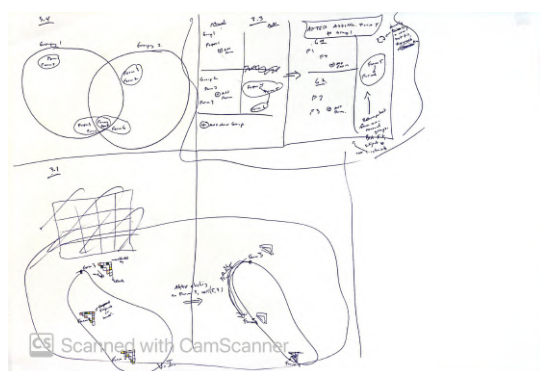
The sketches revealed several recurring design ideas. Participants frequently suggested combining geographic maps with relational representations such as connectivity matrices or graphs. Interaction concepts commonly involved selecting one or more farms to reveal incoming or outgoing connections, adjusting time ranges to explore particle spread, and filtering connections based on particle concentration thresholds.



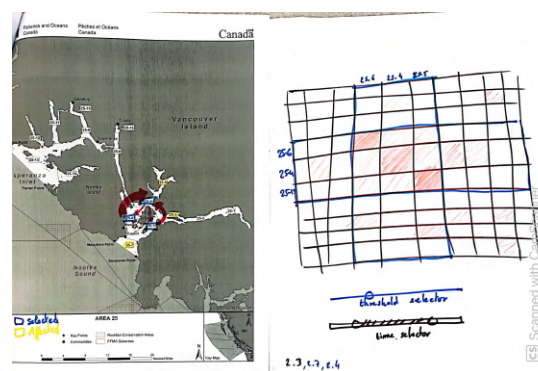
(a) Sketch exploring spatial representations of directional connectivity between farms.



(b) Conceptual sketch illustrating particle progression and spatial spread over time.



(c) Sketch exploring grouping of farms based on connectivity relationships.



(d) Sketch exploring coordinated layout of map, matrix, and control elements.

Figure 3.4: Representative sketches produced during the co-design workshop. The selected sketches illustrate four recurring design directions explored during early ideation: spatial representations of connectivity, grouping of farms based on connectivity patterns, particle movement and spread over time, and coordinated interface layouts combining multiple views. These sketches were later synthesized into the paper prototype.

Discussions also revealed variation in how participants interpreted terms such as *progression*, *spread*, and *movement pattern*. At this stage, these terms appeared reasonable within the broader domain discussion, but later evaluation showed that they did not always align with the aggregated connectivity abstraction implemented in the prototype. These differences later informed refinement of evaluation task wording and clarification of interface terminology for directional connectivity.

All sketches were photographed and workshop discussions were recorded and transcribed to support later analysis.

3.7 Emerging Design Requirements

The Define and Ideate phases produced a set of *emerging* design requirements. These requirements were not treated as a finalized specification. Instead, they captured provisional design directions inferred from (i) recurring task intents identified through affinity analysis and (ii) early solution ideas expressed during co-design.

At this stage, requirements remained deliberately broad and occasionally competing (e.g., adding richer contextual layers versus maintaining visual simplicity). The purpose of articulating emerging requirements was to guide prototype construction and to provide hypotheses that could be challenged and refined through discussion around concrete interface artifacts.

Because requirements were refined through later evaluation of the paper prototype, the emerging set differs slightly from the stabilized set reported in Chapter 4. In particular, some directions were merged, reworded, or deprioritized once participants reacted to trade-offs and interpretability constraints during prototype discussion.

3.8 Prototype: Low-Fidelity Prototyping and Design Consolidation

Following the co-design workshop, the sketches and recorded discussion were analyzed to identify recurring design directions. Rather than treating each sketch as a standalone proposal, we focused on the reasoning behind each idea and the intended analytical scenario.

To support this synthesis, ideas were organized using three complementary dimensions:

- **Purpose** — the analytical goal participants wanted to achieve
- **Appearance** — the visual representation proposed to support that goal
- **Action** — the interaction used to perform that goal

This coding structure was used to examine which representations and interactions appeared most relevant to the task intents identified in Section 3.5.4. The coding did not define the final prototype directly. Instead, it supported early design synthesis by helping identify which ideas were central to connectivity reasoning and which were feasible enough to carry forward into a low-fidelity paper prototype.



Figure 3.5: Low-fidelity paper prototype used as a shared artifact during expert walkthrough. The board aggregated candidate components (map, matrix, time and threshold controls, and alternative encodings) to support comparison of design directions before implementation.

3.8.1 Physical Paper Prototype

Coded ideas were consolidated into a physical low-fidelity prototype assembled from paper components on a board. This format enabled rapid comparison of design alternatives without committing to implementation details. The board integrated the most frequently recurring components across sketches, including a spatial map view, a connectivity matrix, temporal controls, and threshold controls. Alternative visual encodings for similar tasks were placed side-by-side to preserve options during discussion.

3.8.2 Paper-Prototype Walkthrough Interview

We conducted a structured walkthrough interview with the two domain experts using the prototype board as the primary discussion artifact. The goal was to elicit feedback on (1) which components supported realistic analysis and communication scenarios, (2) which al-

ternatives created confusion or unnecessary complexity, and (3) which interaction semantics best matched how connectivity results are interpreted in practice.

The session followed a component-by-component format. For each component, the facilitator briefly introduced the alternatives (e.g., connection map vs. graph, manual vs. automatic grouping, cumulative time controls, directional modes), then prompted participants to reason through concrete tasks such as identifying high-risk connections from a selected farm, comparing strength and directionality, and interpreting patterns for communication to management audiences.

Participants consistently emphasized that spatial grounding was essential for interpretation and presentation, while the matrix remained the authoritative reference for precise comparison. For example, one participant described the map as filling a key gap in the matrix by providing geographic context, while still treating the matrix as informative but less intuitive for non-expert audiences.

The walkthrough also clarified temporal semantics. Participants highlighted that project results were interpreted as *cumulative time since release* (e.g., Day 3 includes all arrivals up to Day 3), which informed how time controls should be framed. In addition, participants discussed thresholding as a practical method for reducing clutter and focusing on meaningful connections.

Importantly, the walkthrough acted as a *winning step* for design ideas: several sketch-inspired concepts (e.g., particle trajectory animations and velocity-focused encodings) were considered appealing for explanation but were treated as lower priority for connectivity decision-making given data scale and implementation effort. This feedback directly informed which requirements were carried forward into implementation. Several of these requirements were carried forward as design goals, although later evaluation showed that some were only partially realized in the digital prototype.

To summarize how prototype discussion narrowed the design space, Table 3.2 links major prototype components, key expert feedback, and the resulting design requirements.

Feedback during the walkthrough reinforced several design directions that later became stabilized requirements. Participants repeatedly emphasized the importance of spatial context for interpreting connectivity patterns. As one participant explained:

“I’m a map person. The map shows what is missing in the matrix, which is the geographical location. The matrix is informative but not intuitive.”

This comment illustrates how spatial context complements matrix-based analysis by supporting geographic interpretation and communication of connectivity results.

Participants also clarified how simulation time should be interpreted in the visualization. In the Particle Project workflow, connectivity results are treated cumulatively rather than as independent time intervals:

“The time slider should be based on 14 days meaning day 3 includes all particles released throughout the first three days because the data is cumulative.”

This clarification informed the design of temporal controls and reinforced the need for cumulative temporal exploration in the final prototype.

3.9 Stabilized Design Requirements

Requirements in this study did not emerge as a fixed specification after task analysis. Instead, they evolved through iterative synthesis of affinity analysis, co-design sketches, and feedback obtained during the paper-prototype walkthrough interview (Section 3.8.2). The requirements below represent the subset of design directions that remained consistent across these stages and were therefore carried forward into the high-fidelity prototype described in Chapter 4.

- **R1 – Support spatial reasoning about connectivity.**

Connectivity interpretation relies heavily on geographic context such as coastlines, inlets, and relative farm locations. During the prototype walkthrough, participants emphasized that spatial context complements the connectivity matrix and makes patterns easier to interpret and communicate. This observation aligns with tasks in MC1 and MC2 that involve understanding particle movement and connectivity patterns in geographic space.

- **R2 – Preserve the connectivity matrix as a familiar analytical reference.**

Despite the value of spatial representations, participants consistently treated the connectivity matrix as the primary analytical artifact used in existing workflows. The matrix enables precise comparison of connection strengths between farms and therefore needed to remain part of the visualization system rather than being replaced by alternative representations.

- **R3 – Support cumulative and interval-based temporal exploration.**

Connectivity results are interpreted cumulatively in the Particle Project, meaning that arrival counts represent particles accumulated up to a given day. Participants clarified

this interpretation during the prototype walkthrough, which informed the design of time controls supporting comparison across cumulative time horizons and intervals derived from cumulative matrices.

- **R4 – Support directional interpretation of connectivity.**

Experts frequently reason about connectivity relative to a selected farm, distinguishing between outgoing and incoming particle transport. Prototype discussion also highlighted the need to represent both one-way and two-way connections to support risk assessment scenarios such as tracing contamination pathways, while making the directional reference explicit enough to avoid later ambiguity in the interface.

- **R5 – Support threshold-based visual emphasis.**

Connectivity values vary across several orders of magnitude, and participants commonly apply thresholds during analysis to focus on meaningful relationships. During the walkthrough session, thresholding was repeatedly discussed as a mechanism for reducing clutter and highlighting stronger connections in both maps and matrices.

- **R6 – Support coordination across views through linked interaction.**

Participants described analysis workflows that involve moving repeatedly between spatial and relational representations. Prototype feedback suggested that selections in one representation should, where feasible, be reflected in others to reduce manual cross-referencing and support validation of interpretations. This requirement therefore expressed a design goal for linked interaction, even though later implementation realized this coordination only partially across interaction modes.

- **R7 – Support exploratory grouping while preserving interpretability.**

Affinity analysis and co-design sketches revealed interest in grouping farms based on connectivity patterns. However, participants expressed caution about fully automatic clustering and emphasized the need to validate groupings through familiar spatial and matrix views. The prototype should therefore support exploratory grouping while maintaining interpretability.

These stabilized requirements guided the design of the high-fidelity prototype presented in Chapter 4. That chapter describes how each requirement was translated into specific visual representations and interaction mechanisms.

3.10 Prototype: High-Fidelity Digital Implementation

Following the low-fidelity phase, we developed a high-fidelity interactive visualization prototype to support realistic evaluation. This stage operationalized the most stable visual representations and interaction patterns from the paper prototype. It did not aim for feature completeness; instead, it aimed to support a representative subset of high-priority tasks sufficiently for evaluation [2, 16].

3.10.1 Data Scope and Feasibility

Although early ideas included views based on raw particle trajectories, the first digital version focused on aggregated connectivity data that was already familiar to participants. This choice was driven by file size, processing constraints, and the goal of evaluating connectivity interpretation rather than ocean model reconfiguration.

3.10.2 Implemented Components

The digital prototype centered on three main components: (1) interactive map views for connectivity patterns, (2) a connectivity matrix, and (3) a control panel for selecting simulation, time range, and threshold. Interaction supported map panning and zooming, farm selection, and partial coordination across views. More consistent cross-view highlighting was achieved in some modes, especially clustering mode, than in others.

After the digital prototype had been implemented, a separate internal review was conducted to assess which prioritized tasks were supported by the available features and which remained unsupported. This review did not repeat the earlier sketch coding. Instead, it was used as a prototype coverage check to judge whether the implemented prototype supported a sufficient subset of important tasks to justify proceeding to evaluation.

3.11 Test: Evaluation Session and Feedback Collection

The Test phase evaluated the high-fidelity prototype with participants to collect feedback and assess task support [16, 2]. This section documents the evaluation as a study activity (what was done and what was collected). Chapter 5 presents the full evaluation methodology, results, and analysis.

3.11.1 Evaluation Structure

Each evaluation session followed four parts: (1) consent review, (2) brief training, (3) task performance with post-task questionnaires, and (4) open exploration with interview discussion. Sessions were screen-recorded and accompanied by facilitator notes. Participants were encouraged to think aloud.

3.11.2 Post-task Questionnaire and Evidence Collected

Tasks were selected from the task characterization and matched to prototype capabilities. After each task, participants rated five statements on a 0–4 scale: task meaningfulness, interface usefulness, ease relative to existing tools, confidence, and whether the interface produced the expected result. We also recorded task completion times, interpreted cautiously due to learning effects and exploratory behaviour, and collected qualitative evidence from comments and exploration behaviour.

One task in the final sequence was repetitive, which reduced the number of distinct questionnaire responses. In addition, some task prompts used wording that participants interpreted differently from the intended connectivity-focused meaning. These issues are considered in Chapter 5 when interpreting the evaluation results.

3.12 Chapter Summary

This chapter described the iterative design study process used to move from an initial collaboration to a tested visualization prototype. Following design study methodology [2] and a design thinking framework [16], we conducted a sequence of phases combining domain immersion, task characterization, participatory ideation, and iterative prototyping.

The main outcomes of this chapter are:

- **Validated domain context and scope:** early learn/winnow activities established feasibility, constraints, stakeholders, and the role of communication artifacts in the Particle Project.
- **Empirical workflow understanding:** contextual inquiry documented how connectivity results are produced, interpreted, and communicated, including the central role of connectivity matrices and the use of thresholds for visual comparison.

- **Task characterization:** affinity diagramming produced a task list organized into three mega categories, directly addressing **RQ2**.
- **Design requirements:** synthesis of contextual inquiry, co-design, and prototyping yielded a stable set of requirements that guided the prototype design.
- **Prototyping and evaluation preparation:** co-design outcomes were synthesized into low- and high-fidelity prototypes, and a later prototype coverage check was used to confirm that the implemented features supported a sufficient subset of prioritized tasks for task-based evaluation.

The next chapter (Chapter 4) describes the resulting prototype design and implementation in detail, including the main components, interaction mechanisms, and data representations.

Table 3.1: Summary of dominant themes from the Empathize phase. Source tags correspond to the color coding used during analysis (CI-R = researcher observation; CI-F = facilitator input; CI-V = video-derived insight; Prior = prior workflow knowledge). Full observation table is provided in the online appendix repository.

Theme	Source(s)	Representative observations
Role of matrices as deliverables	CI-R CI-V	Connectivity matrices were the primary required outputs. Other visual materials were supplementary and mainly used for explanation to management or non-expert audiences.
Threshold tuning and comparability	CI-R CI-V	Threshold values were selected through iterative trial and comparison for visual clarity. Participants also preferred consistent thresholds and percentage-based reporting to compare across regions and simulation spans.
Spatial context gap	CI-R Prior	Matrices enabled pairwise comparison but lacked geographic grounding. Maps were used to provide spatial context for interpretation and communication.
Workflow transformation	CI-R CI-V Prior	Raw model outputs were processed into aggregated connectivity summaries before reporting. Intermediate scripts and manual steps were part of this transformation.
Manual grouping and directionality cues	CI-R CI-F	Farm ordering and visual annotations (e.g., rectangles and arrows) were used during communication to suggest possible groupings and to distinguish one-way vs. two-way connectivity. These annotations were not formal zoning results.
Validation through domain knowledge	CI-R CI-V	Participants cross-checked connectivity patterns against expected ocean dynamics (e.g., tides, circulations) and discussed plausibility when patterns appeared unexpected.

Table 3.2: Summary of how feedback from the paper-prototype walkthrough informed the refinement and stabilization of design requirements. The table links key prototype components to participant observations and shows how these observations contributed to shaping requirements R1–R7.

Prototype Component	Key Feedback from Walkthrough	Implications for Design Requirements
Connectivity Map	Participants emphasized that geographic context was essential for interpreting connectivity patterns and communicating results to non-expert audiences. Map-based visualization was considered more intuitive than abstract graph representations, though edge clutter needed to be managed.	Confirmed the importance of spatial grounding and threshold filtering. → Supports R1 (spatial reasoning) and R5 (threshold emphasis) .
Connectivity Matrix	Experts stressed that the matrix remained the authoritative analytical reference used in current workflows. While maps help interpretation, the matrix provides precise comparison of pairwise connectivity values.	Matrix should remain a central coordinated view rather than being replaced. → Supports R2 (preserve matrix representation) and R6 (coordinated views) .
Temporal Controls	Participants clarified that simulation outputs are interpreted cumulatively (e.g., arrivals up to Day 3). They emphasized comparing connectivity across cumulative time horizons rather than isolated time intervals.	Temporal exploration should support cumulative ranges consistent with domain interpretation. → Supports R3 (cumulative and interval-based temporal exploration) .
Directional Connectivity	Experts discussed interpreting connectivity relative to a reference farm and distinguishing incoming versus outgoing relationships. They also noted that two-way connectivity can be understood as overlapping directional links.	Directional relationships must be explicit and interpretable relative to farm selection. → Supports R4 (directional interpretation) .
Clustering / Grouping	Participants showed interest in grouping farms with strong connectivity but emphasized the need to validate clusters using familiar spatial and matrix views. Automatic clustering alone was viewed cautiously.	Grouping should support exploratory analysis while preserving interpretability. → Supports R7 (exploratory grouping) and R6 (linked views) .
Particle Trajectory / Density Concepts	Ideas involving raw particle trajectories and animations were considered useful for explanation but less central to connectivity decision-making due to data scale and modeling constraints.	Trajectory-focused ideas were deprioritized in favor of aggregated connectivity views. → Helped narrow the design scope and focus on requirements R1–R6.

Chapter 4

Tool Design and Implementation

4.1 Chapter Overview

This chapter presents the visualization prototype developed to operationalize the design requirements derived through the design study process (Chapter 3). Rather than describing the prototype as a collection of interface features, the chapter explains how design decisions translate domain tasks and stabilized requirements (R1–R7) into visual representations and interactions.

The goal of the prototype is not to replace existing scientific workflows, but to support exploratory reasoning about hydrodynamic connectivity by integrating spatial, relational, and temporal perspectives within a single interactive environment. Design decisions are therefore described in terms of analytical intent and domain reasoning rather than implementation detail.

4.2 Design Requirements as Design Drivers

Following task characterization and early ideation (Chapter 3), design requirements were refined through iterative narrowing during co-design and paper-prototype walkthrough sessions. These activities clarified which design directions consistently supported domain reasoning and which introduced unnecessary complexity.

The stabilized requirements guiding implementation were:

- **R1 – Support spatial reasoning about connectivity.**
- **R2 – Preserve the connectivity matrix as a familiar analytical reference.**

- **R3 – Support cumulative and interval-based temporal exploration.**
- **R4 – Support directional interpretation of connectivity.**
- **R5 – Support threshold-based visual emphasis.**
- **R6 – Support coordination across views through linked interaction.**
- **R7 – Support exploratory grouping while preserving interpretability.**

The implemented prototype should therefore be understood as a selective realization of these stabilized requirements rather than as a direct implementation of all earlier co-design ideas.

4.3 Design Rationale

Observations from contextual inquiry showed that domain experts continuously shift between two complementary reasoning modes:

1. **Relational reasoning** using connectivity matrices.
2. **Spatial reasoning** using geographic context.

The prototype adopts a coordinated multi-view design combining:

- a spatial connectivity map,
- a connectivity matrix,
- shared temporal and threshold controls,
- an exploratory clustering view.

Analytical meaning emerges through coordination across views rather than from any single representation. Coordination, however, differs between interaction modes.

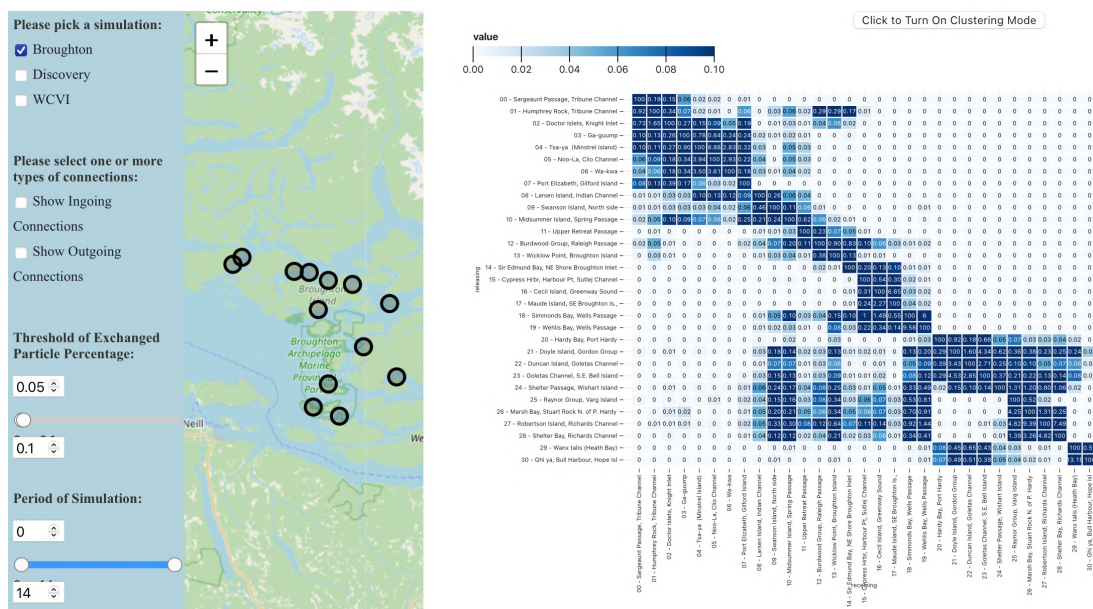


Figure 4.1: Overview of the prototype showing the control panel, spatial map, and connectivity matrix in the default connectivity mode. No farm is selected in this state.

4.4 Spatial Connectivity Map

Addresses R1, R4

The spatial map provides geographic grounding for connectivity relationships. Farms are represented as spatial points, while directed links encode particle exchange between farms above a user-defined threshold.

Selecting a farm reveals filtered connectivity pathways relative to the selected site. These patterns support reasoning about transport routes and regional coupling.

4.5 Connectivity Matrix

Addresses R2, R5

The connectivity matrix preserves the primary analytical artifact used in the Particle Project workflow.

Rows and columns encode relationships between releasing and receiving farms. Each cell represents the percentage of particles exchanged within the selected temporal range.

Visual encoding adapts dynamically to the current temporal and threshold context, allowing relative differences to remain visible under changing conditions.

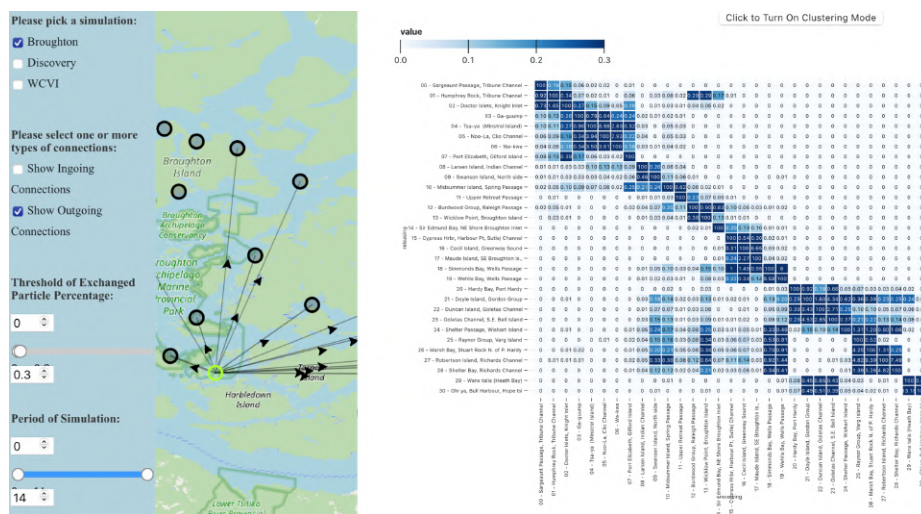
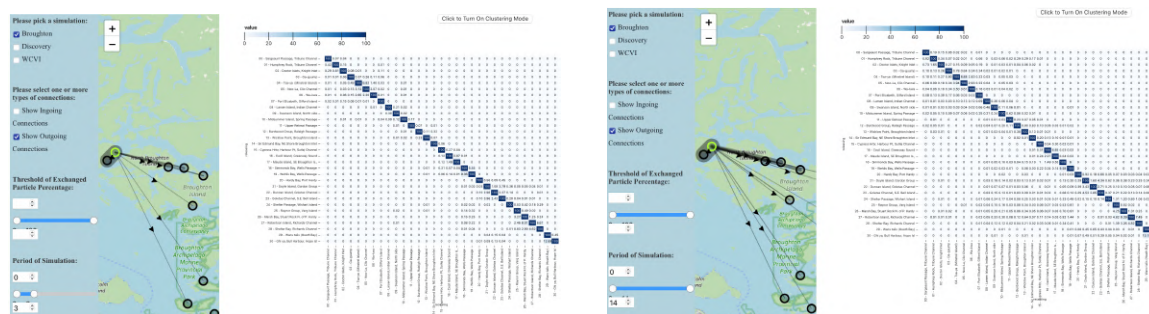


Figure 4.2: Spatial connectivity view for a selected farm in outgoing mode. Directed links above the active threshold are shown relative to the selected farm, supporting geographic interpretation of connectivity patterns.



(a) Earlier cumulative connectivity. (b) Later cumulative connectivity.

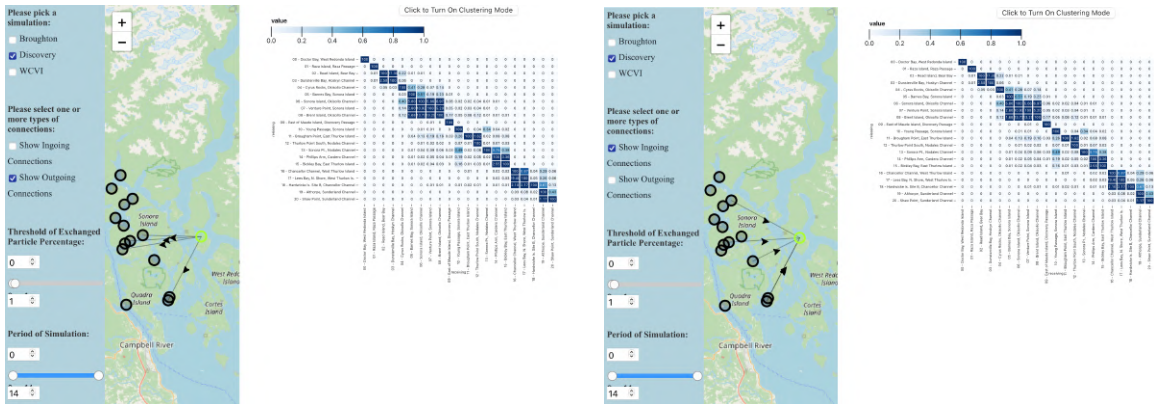
Figure 4.3: Temporal exploration of connectivity for a selected farm. Comparing earlier and later cumulative periods shows how visible connectivity relationships expand over time.

4.6 Temporal Exploration

Addresses R3

Connectivity is organized by cumulative arrival time. A temporal slider allows users to explore connectivity across different time horizons.

Intervals are computed as differences between cumulative states, supporting comparison across selected time ranges.



(a) Outgoing connectivity from the selected farm. (b) Ingoing connectivity to the selected farm.

Figure 4.4: Directional interpretation of connectivity relative to a selected farm using the prototype’s ingoing and outgoing modes.

4.7 Directional Semantics

Addresses R4

The prototype used the interface labels *ingoing* and *outgoing* to represent directional connectivity. Directional connectivity was interpreted relative to selection:

Single selection:

- Outgoing shows farms receiving particles from the selected farm.
- Ingoing shows farms contributing particles to the selected farm.

Multiple selection: Direction filters connectivity across selected farms.

No selection: Direction filters global connectivity patterns.

4.8 Threshold-Based Emphasis

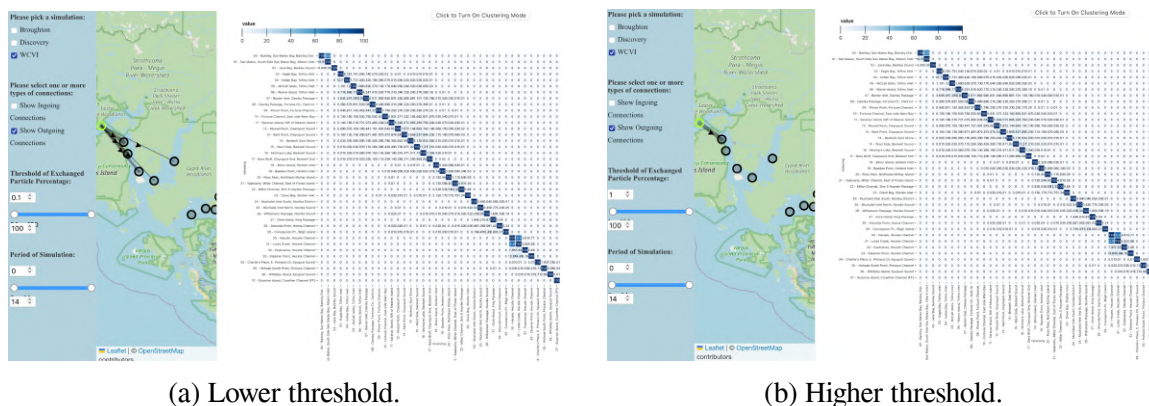
Addresses R5

The threshold control filters connections below a user-defined percentage.

4.9 Coordinated Interaction

Addresses R1–R6

Coordination is achieved in two ways:



(a) Lower threshold.

(b) Higher threshold.

Figure 4.5: Lower thresholds reveal more connections, while higher thresholds emphasize stronger relationships.

- shared parameter updates (time and threshold),
- selection-based interaction.

In connectivity mode, coordination is driven mainly by shared parameter updates.

In clustering mode, coordination is stronger and includes selection and group-based interaction. Connectivity highlighting in this mode is interpreted relative to the active cluster assignments. Rather than showing connectivity in the same way as connectivity mode, displayed links are constrained by the current cluster grouping, supporting inspection of within-cluster connectivity relationships.

4.10 Exploratory Clustering View

Addresses R7

A scatterplot groups farms based on connectivity similarity. Clusters can be defined manually or generated automatically.

4.11 Implementation Overview

The prototype was implemented in Observable using D3-based interaction. The focus was on enabling responsive updates and coordinated visual representations.

The implementation should be understood as a research prototype intended to support exploratory analysis and evaluation.

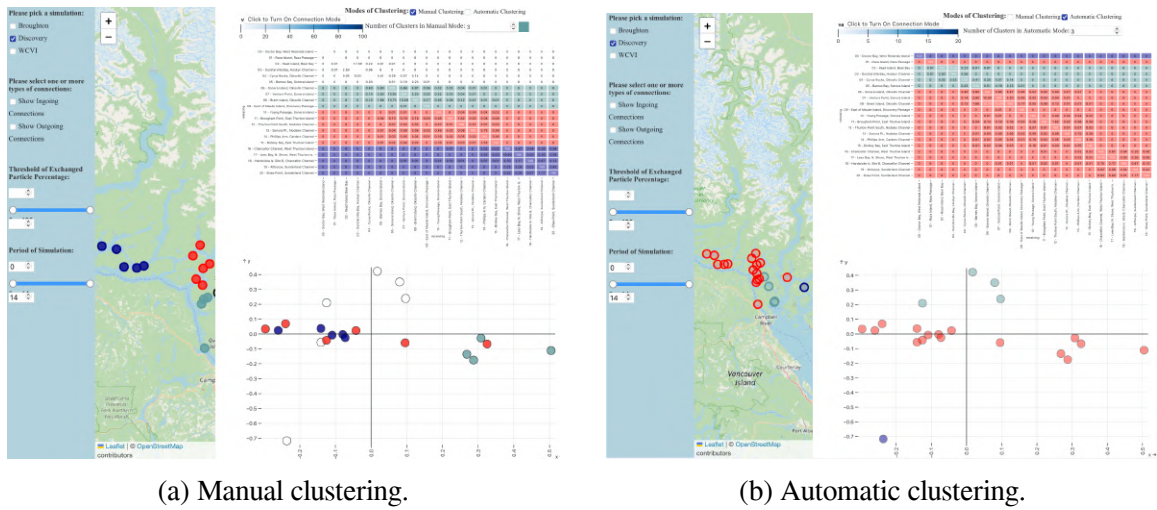


Figure 4.6: Comparison of manual and automatic clustering approaches across coordinated views.

4.12 Chapter Summary

This chapter described how design requirements were translated into a visualization prototype integrating spatial, relational, and temporal perspectives.

The prototype supports coordinated exploration across multiple views, with different interaction modes enabling different forms of analysis. Connectivity mode emphasizes parameter-driven exploration, while clustering mode introduces group-aware interaction and constrained connectivity interpretation.

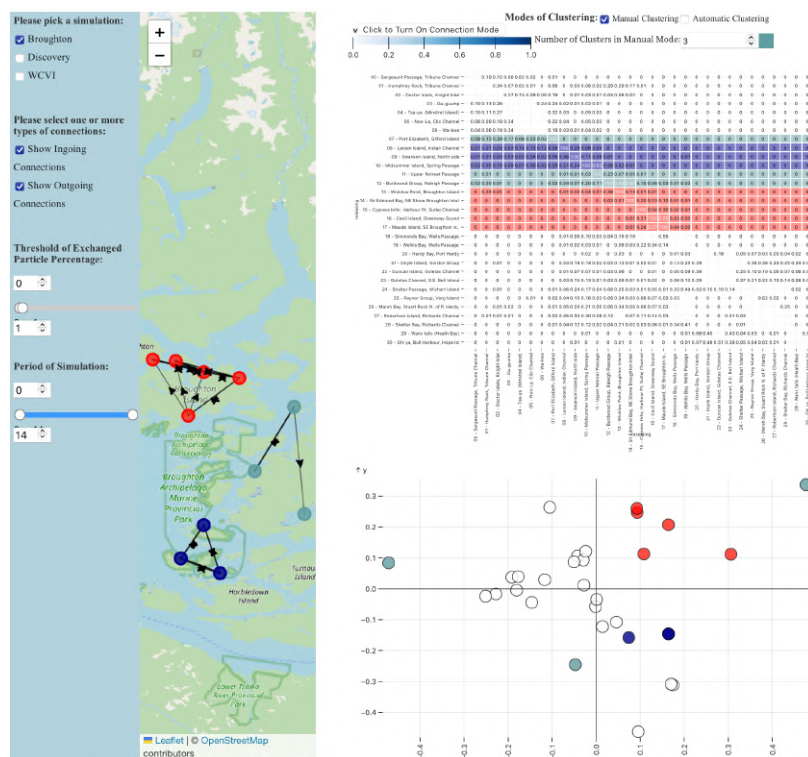


Figure 4.7: Cluster-aware connectivity exploration in manual clustering mode. Colored farm groups are shown across views, while directional links are restricted by the active cluster assignments to support inspection of within-cluster connectivity patterns.

Chapter 5

Evaluation

5.1 Chapter Overview

This chapter evaluates how the prototype supported analytical reasoning about hydrodynamic connectivity. The evaluation focused on how domain experts interpreted connectivity relationships, how they used the interface during realistic analytical tasks, and which aspects of the design supported or hindered task performance.

The goal of the evaluation was not to measure efficiency in isolation, but to understand how the prototype functioned as a research tool for exploratory analysis and communication. The chapter therefore presents both quantitative indicators from post-task questionnaires and qualitative findings derived from think-aloud observations and post-session interviews.

5.2 Evaluation Goals

The evaluation addressed three main questions:

- How effectively did the prototype support spatial and relational reasoning about connectivity?
- How did interaction mechanisms such as threshold adjustment, farm selection, and clustering influence analytical understanding, interpretation, and exploratory reasoning?
- What usability, interpretability, and representation issues emerged when domain experts used the prototype?

These questions reflect the broader design study goal of assessing how visualization supports real-world analytical reasoning rather than isolated task efficiency.

5.3 Participants

Two ocean scientists involved in the Particle Project participated in the evaluation sessions. Both participants had prior experience interpreting connectivity matrices and communicating simulation results to management. Their familiarity with the domain enabled evaluation of analytical usefulness rather than basic domain comprehension.

For reporting purposes, the participants are referred to as **P1** and **P2**.

5.4 Procedure

Each evaluation session consisted of four stages:

1. consent review and study overview,
2. brief prototype training,
3. task-based interaction with post-task questionnaires,
4. open exploration and semi-structured interview discussion.

Participants were encouraged to think aloud while interacting with the prototype. Sessions were screen-recorded and accompanied by facilitator notes to capture interaction behaviour, interpretation strategies, and points of confusion.

5.4.1 Qualitative Evidence and Analysis Approach

The evaluation drew on multiple forms of qualitative evidence, including think-aloud verbalizations, post-task comments, interview responses, screen recordings, and facilitator notes. Screen recordings were reviewed to capture interaction behaviours that were relevant to interpretation but not always stated explicitly by participants, such as repeated zooming and panning, searching for farms, switching between views, and hesitation after control changes.

These materials were interpreted qualitatively to identify recurring patterns related to task difficulty, navigation, coordination across views, and interface limitations. The study did not attempt a formal micro-analysis of cursor trajectories. Instead, screen-recording observations were used as supporting evidence for broader behavioural patterns visible during use.

5.5 Task Design

Evaluation tasks were derived from the task characterization presented in Chapter 3. The tasks were intended to reflect realistic analytical scenarios, including:

- identifying incoming or outgoing connectivity for a selected farm,
- comparing connectivity across cumulative time horizons and selected intervals,
- examining directional relationships,
- exploring candidate groups of connected farms.

Tasks were open-ended enough to allow variation in strategy, but specific enough to ground comparison across sessions.

In retrospect, task wording affected interpretation for several tasks. Some task prompts used language such as *movement*, *progression*, and *spread*, whereas the prototype displayed aggregated connectivity relationships rather than raw particle trajectories or density fields. This mismatch is important for interpreting both task performance and questionnaire responses.

5.6 Quantitative Measures

After each task, participants rated five statements on a 0–4 Likert scale, where 0 indicated *not at all* and 4 indicated *completely*:

- this task is meaningful/useful to me,
- the interface is useful to complete the task,
- it is easier to complete this task than with my existing tool(s),
- I was confident while performing the task,
- I think the interface is giving me the result I expected to get.

Task completion times were also recorded. However, timing results were interpreted cautiously because the sessions included learning effects, navigation overhead, and exploratory behaviour.

The questionnaire results should also be interpreted with caution for two additional reasons. First, one task in the final task set was repetitive, which reduced the number of distinct

questionnaire responses. Second, some tasks were rated poorly partly because their wording did not match the connectivity abstraction implemented in the prototype. In those cases, lower ratings may reflect ambiguity in task framing rather than only limitations of the interface.

5.7 Qualitative Findings

Qualitative analysis focused on how participants reasoned with the map, matrix, controls, and clustering view, and on what kinds of problems became visible during use.

5.7.1 Spatial reasoning was supported, but navigation remained difficult

Both participants relied heavily on the map to interpret connectivity in geographic context. The map helped them connect farm relationships to coastline structure, local geography, and plausible circulation patterns. This made the map particularly useful for explanation and communication.

At the same time, the map was difficult to navigate efficiently. Participants spent substantial time zooming and panning to locate named farms. Farm labels were not always fully visible, and the narrow map panel reduced the ability to maintain regional context while searching. P1 stated that the map was too narrow and that she had to zoom out too far to retain context. P2 similarly noted that a larger map would make the region easier to interpret.

These observations suggest that spatial context was valuable, but the interface layout limited how effectively the map could support task performance.

5.7.2 Threshold adjustment supported exploratory narrowing

Threshold filtering played an important role in how participants explored connectivity. Both participants used threshold changes to move between broad patterns and more selective relationships. Lower thresholds were used to inspect wider connectivity structure, while higher thresholds were used to focus on stronger links.

This behaviour matched domain practices observed during contextual inquiry. Participants did not treat thresholding as a purely visual option. Instead, they used it as an analytical control for deciding which relationships were meaningful enough to inspect.

However, participants also noted practical limitations. Very small threshold values were difficult to set precisely, and in some cases changing threshold values disrupted the current

selection state.

5.7.3 Matrix interpretation was affected by the orientation inconsistency

The matrix remained an important reference during evaluation, especially for confirming connection strength and comparing farm pairs. However, the matrix also introduced a major interpretability problem.

In the original DFO materials, rows represented receiving farms and columns represented releasing farms. In the evaluated prototype, this convention was unintentionally reversed. As a result, the prototype matrix corresponded to the transpose of the domain-standard representation. This inconsistency affected directional interpretation and contributed to confusion when participants compared matrix patterns with map directions and familiar regional flow behaviour.

P2 identified this issue explicitly during exploration when she noticed that expected flow directions appeared reversed. This should therefore be understood as a prototype implementation problem rather than a domain finding.

Apart from the orientation issue, participants also tended to use the matrix more for confirmation than for initial discovery. The matrix was useful once a candidate relationship had been identified, but it was not always the first point of entry into analysis.

5.7.4 Cross-view coordination was partial rather than uniform

The prototype did provide coordination across views, but the strength and type of that coordination varied by mode.

In connectivity exploration mode, coordination was achieved mainly through shared parameter updates. Temporal and threshold controls updated matrix values, matrix color encoding and legend context, visible map links, and map line thickness together. However, selection-based coordination was limited in this mode. Selecting a farm affected the map clearly, but support for linked matrix highlighting remained limited.

In clustering mode, coordination was stronger in a different sense. Selecting farms or assigning them to clusters produced clearer simultaneous highlighting across map, matrix, and scatterplot views. In addition, connectivity arrows in this mode were no longer shown in the same way as in connectivity exploration mode. Instead, displayed links were interpreted relative to the active cluster assignments and were limited to farms treated as members of the

same cluster grouping. Participants were therefore sometimes able to use clustering mode as an indirect way to obtain the cross-view highlighting and focused group-level exploration they expected during connectivity analysis.

These findings suggest that the design direction of coordinated views was useful, but only partially realized in the evaluated prototype.

5.7.5 Directional semantics were clearer for single-farm analysis than for group analysis

Participants generally understood directional filtering when one farm was selected. In that context, incoming and outgoing corresponded reasonably well to common analytical questions, such as which farms receive particles from a selected site and which farms contribute to it.

However, directional semantics became less clear when more than one farm was selected. For two farms, incoming for one farm is also outgoing for the other. For larger groups, the same problem becomes more pronounced. P1 explicitly noted that with two farms the incoming/outgoing distinction loses much of its meaning.

Participants also questioned the label *ingoing*. P2 suggested that *incoming* would be clearer, and further suggested that *receiving* and *releasing* would align more closely with the matrix semantics.

This finding suggests that directional filtering was useful for single-farm reasoning, but the terminology and model were not robust enough for multi-farm reasoning.

5.7.6 Two-way connectivity was not shown in the way participants expected

The prototype did not provide a dedicated two-way connectivity mode. Instead, users could enable both directional filters simultaneously. From an implementation perspective, this exposed both incoming and outgoing links. From an analytical perspective, however, participants expected a view showing only reciprocal links.

This mismatch caused some confusion. Participants expected a more direct answer to the question “which farms are connected in both directions?” rather than a combined display of all incoming and outgoing edges. When both directions were shown together, overlapping lines could produce extra visual complexity and make interpretation harder.

This result indicates that reciprocal connectivity should be represented explicitly rather than approximated through combined directional filters.

5.7.7 Task wording affected interpretation and ratings

Several tasks used terms such as *progression of particles*, *movement pattern*, and *spread*. Participants interpreted these as referring to particle trajectories, animations, or density views rather than aggregated connectivity summaries.

P1 stated that “progression of particles” suggested “a movie like moving particles.” P2 similarly noted that the wording referred to movement rather than connectivity. This mismatch influenced both task performance and questionnaire responses. In some cases, participants rated a task poorly not because the interface failed to perform its actual function, but because the wording suggested a different type of representation than the prototype provided.

This issue is important when interpreting the quantitative ratings. Some lower scores reflect task ambiguity in addition to interface limitations.

5.7.8 The clustering view supported exploration, but required explanation

The clustering view was one of the most exploratory parts of the prototype. Participants used it to identify candidate groups of farms, compare manual and automatic groupings, and question whether clustered farms also appeared close in the map and matrix.

At the same time, participants wanted more explanation of what the scatterplot meant and how the clustering had been computed. P1 described the scatterplot as interesting and potentially useful, but also said that she would want to understand the mathematics behind it before relying on it. P2 made a similar point and asked for clearer explanation of the clustering assumptions.

These responses suggest that the clustering view had exploratory value, but that its interpretation depended on stronger explanatory support and better integration with direct interaction across the other views.

5.8 Summary of Findings

The evaluation showed that the prototype supported several meaningful forms of analytical reasoning. In particular, the map supported spatial interpretation and communication, threshold adjustment supported progressive narrowing of the analysis space, and the clustering view supported exploratory comparison of candidate groups.

At the same time, the evaluation exposed important limitations. The matrix orientation

inconsistency affected interpretation of direction. Cross-view coordination was only partially realized, with stronger linking and more cluster-aware interaction in clustering mode than in connectivity exploration mode. Directional semantics were useful for single-farm reasoning but weak for multi-farm analysis. Two-way connectivity was not represented as a distinct analytical state. In addition, some task ratings were affected by wording mismatches and by the inclusion of a repetitive task in the questionnaire sequence.

Overall, the findings support the general value of combining spatial, relational, and exploratory views, but they also show that the final prototype did not fully achieve the level of coordination and semantic clarity originally intended. These issues are examined further in Chapter 6. This study does not aim to optimize or quantitatively evaluate a final visualization system in terms of performance, efficiency, or accuracy. Instead, the goal is to understand domain workflows, identify task requirements, and derive design knowledge through iterative design and qualitative evaluation.

The prototype developed in this work serves as a research instrument for exploring how different representations and interactions support interpretation, rather than as a finalized or optimized tool.

Chapter 6

Design Knowledge, Limitations, and Conclusion

6.1 Design Knowledge

Visualization design studies rarely proceed in a strictly linear way. Design rationale often becomes clearer through iterative development, evaluation, and reflection [5]. This study followed that pattern.

Beyond the development of a prototype, this work produced a set of design insights for the analysis and communication of hydrodynamic connectivity. These observations are grounded in contextual inquiry, co-design, prototyping, and evaluation with domain experts. They are not presented as universal rules, but as lessons that may inform visualization design in related spatio-temporal connectivity domains.

6.1.1 DK1: Spatial and relational views should be coordinated

Connectivity analysis requires both geographic context and precise pairwise comparison. During evaluation, participants repeatedly moved between the map and the connectivity matrix. The matrix supported detailed inspection of pairwise values, while the map supported geographic interpretation and plausibility checking.

These observations suggest that spatial and relational reasoning play complementary roles. When the two representations are separated, analysts must mentally translate between them. Coordination across views can reduce this burden, whether it is achieved through shared parameter controls, linked selection, or both.

In connectivity domains, spatial and relational representations should therefore be integrated rather than treated as alternatives.

6.1.2 DK2: Familiar representations support analytical trust

Participants consistently treated the connectivity matrix as the main analytical reference because it matched established reporting practice. Map-based views were described as more intuitive and more useful for communication, but not sufficient on their own for precise analysis.

This suggests that new visualizations should augment familiar representations rather than replace them entirely. Familiar views support trust, validation, and adoption in scientific workflows.

6.1.3 DK3: Algorithmic views require explanation and verification

The clustering scatterplot generated interest and supported exploration, but participants also wanted more explanation of how the result was produced. In particular, they wanted to understand the mathematical basis of the clustering and how it related to recognizable connectivity patterns in the matrix and map.

This suggests that algorithmic views should be framed as exploratory aids rather than self-evident analytical outputs. In scientific contexts, users need opportunities to verify algorithmic patterns against familiar representations before relying on them.

6.1.4 DK4: Directional semantics depend on the reference frame

Directional concepts such as incoming and outgoing were easier to interpret when analysis was anchored to a single selected farm, where direction could be understood relative to a clear reference point. In that case, direction corresponded clearly to domain questions such as which farms receive material from a selected site and which farms contribute material to it.

However, direction became less meaningful when multiple farms were selected. For two farms, an incoming connection for one farm is also an outgoing connection for the other. For clusters of farms, the same problem becomes more pronounced. This suggests that directional encodings are most effective for single-entity reasoning, while group-level analysis may require different representations emphasizing mutual connectivity rather than direction alone.

6.1.5 DK5: Terminology should match the data abstraction

Evaluation showed that some task and interface terms did not align well with the abstraction implemented in the prototype. Terms such as *movement*, *progression*, and *spread* were interpreted by participants as particle trajectories, animations, or density distributions. The prototype, however, showed aggregated connectivity relationships derived from simulation outputs.

This mismatch introduced avoidable confusion. Interfaces for simulation-derived data should distinguish clearly between process-level representations and aggregated analytical summaries.

6.1.6 DK6: Connectivity is understood as process but analyzed as aggregation

Early design discussions frequently referenced moving particles, circulation, and dynamic flow, reflecting a process-oriented mental model of the domain. In contrast, the main project deliverables were aggregated connectivity matrices summarizing cumulative outcomes.

This suggests that visualization systems in simulation domains may need to explicitly bridge process understanding and aggregated reporting. Some representations may support explanation of dynamics, while others support analysis of summarized outcomes.

6.1.7 DK7: Progressive disclosure supports reasoning across scales

Participants moved between overview and detail throughout the evaluation. They used broad patterns to identify candidate areas of interest, then used the matrix and farm selection to inspect specific relationships. This behaviour occurred across spatial, relational, and temporal scales.

Connectivity visualization systems should therefore support progressive disclosure. Users should be able to move from overview to focused inspection without losing context.

6.2 Limitations

The evaluation revealed both implementation limitations and deeper design limitations in the final prototype. Some issues affected usability directly, while others exposed conceptual problems in how connectivity was represented. These limitations do not invalidate the prototype,

but they qualify the interpretation of the evaluation results and help clarify what should be supported in future work.

6.2.1 Matrix orientation inconsistency

A major limitation of the evaluated prototype was the unintended reversal of the matrix row/column convention relative to the original DFO matrices. This implementation inconsistency affected directional interpretation and made some patterns appear opposite to participants' expectations based on prior domain knowledge.

Because this issue influenced how users related the matrix to the map, it should be understood as a prototype implementation error rather than as a finding about the usefulness of the matrix representation itself. The result also shows how strongly expert interpretation depends on consistency with established analytical conventions.

6.2.2 Directional terminology and semantics were unstable

The directional terms used in the interface were not fully aligned with participant expectations or with matrix semantics. Participants found *ingoing* less natural than *incoming*, and also suggested that *receiving* and *releasing* would better match the matrix labels and domain interpretation. P2 explicitly proposed this change during evaluation.

More importantly, directional semantics were not stable across analysis contexts. For a single selected farm, incoming and outgoing links were generally understandable. However, when multiple farms were selected, or when users compared two farms directly, the meaning of direction became less useful. In these cases, an incoming connection for one farm is simultaneously an outgoing connection for another. P1 explicitly noted that with two farms the distinction loses meaning.

This limitation suggests that the directional model was appropriate for single-farm reasoning, but under-specified for multi-farm and cluster-level analysis.

6.2.3 Two-way connectivity was not represented as a distinct state

The prototype did not implement reciprocal connectivity as a separate analytical mode. Instead, two-way connectivity was approximated by allowing users to enable both directional filters at the same time. Although this exposed both incoming and outgoing links, it did not correspond to users' expectation of a view showing only mutually connected farm pairs.

In practice, this approach sometimes introduced overlapping lines and visual ambiguity. Participants expected a more explicit representation of reciprocal links. P2 stated that a two-way view should show only the connections that exist in both directions, rather than a combined display of all incoming and outgoing connections.

This limitation indicates that reciprocal connectivity should be treated as a first-class analytical state rather than a by-product of enabling two separate filters.

6.2.4 Spatial navigation was constrained by the interface layout

A further limitation concerned the spatial layout of the interface. The map panel was too narrow to support efficient navigation, especially when participants needed to locate specific farms by name while maintaining awareness of surrounding context. Both participants spent substantial time zooming and panning to find farms. Labels were often hard to read, partially clipped, or extended beyond the visible map area.

P1 stated that the map was too narrow and that she had to zoom out too far to retain context. P2 similarly stated that the map should be larger so that more farms in a region could be seen at once.

These issues affected task performance directly. They increased search time, reduced map readability, and limited the map's usefulness as an entry point for analysis. The results therefore suggest that the prototype needed either a larger map area, more compact controls, or a farm search mechanism.

6.2.5 Cross-view coordination was useful but incomplete

The prototype demonstrated the value of coordination across views, but this coordination was not uniform. In connectivity mode, map and matrix were coordinated mainly through shared temporal and threshold controls. These controls updated matrix values, matrix color encoding and legend context, and map link visibility and thickness together. However, participants also expected stronger selection-based coordination, especially direct highlighting of corresponding rows or columns in the matrix when farms were selected on the map.

Stronger linked highlighting was available in clustering mode, where selected or assigned farms were reflected more directly across map, matrix, and scatterplot views. In addition, connectivity visualization in clustering mode was constrained by cluster membership, such that links were shown only between farms belonging to the same cluster. While this supported focused inspection of within-group relationships, it also introduced a mode-dependent

interpretation of connectivity that differed from the global view in connectivity mode. Participants nevertheless encountered interaction inconsistencies across modes, and some control changes disrupted their analytical flow.

This limitation is important because coordination across views was a central design direction in the prototype. The evaluation suggests that the overall direction was useful, but the implementation did not yet provide the interaction stability and consistency needed for fluid expert use.

6.2.6 Task wording did not always match the implemented abstraction

A further limitation concerned the evaluation tasks themselves. Several tasks used language such as *progression of particles*, *movement pattern*, and *spread*. Participants interpreted these terms as referring to raw particle movement, animated trajectories, or density-based visualizations. The prototype, however, operated on aggregated connectivity summaries.

This mismatch affected task interpretation. P1 stated that *progression of particles* suggested “a movie like moving particles,” and P2 similarly noted that the task wording referred to movement rather than connectivity. In these cases, lower task clarity did not necessarily reflect only interface weakness; it also reflected a mismatch between the wording of the task and the abstraction supported by the prototype.

This issue should therefore be considered when interpreting the evaluation results. Some task difficulty arose from wording and framing, not only from interaction design.

6.2.7 Limited training and exploration affected some tasks

The evaluation sessions included a brief training period followed by task performance. In retrospect, some of the later tasks, especially those involving clustering and cross-view comparison, would likely have been easier if participants had more time to explore the tool before performing structured tasks.

This limitation does not invalidate the evaluation, but it likely affected performance on tasks that depended on discovering interaction patterns. Participants often became faster and more confident later in the session as they learned how the interface behaved. The results therefore reflect both the strengths and weaknesses of the prototype and the cost of learning a new interactive system.

6.2.8 Questionnaire interpretation constraints

The post-task questionnaire results should be interpreted with caution. One task in the final task set was repetitive, which reduced the number of distinct questionnaire responses. In addition, some tasks used wording that participants interpreted differently from the intended connectivity-focused meaning. As a result, lower ratings may reflect task ambiguity as well as interface limitations.

6.3 Future Work

Future work can build on these findings in several directions.

First, the prototype should be corrected and refined at the representation level. This includes restoring the matrix to the domain-standard row/column orientation, improving directional labels, and implementing reciprocal connectivity as an explicit analytical state. The role of cluster-constrained connectivity should also be revisited, including whether cluster-based filtering should be optional or integrated more consistently with global connectivity exploration.

Second, the coordination among views should be strengthened. Selection, highlighting, and filtering should remain stable across map, matrix, and scatterplot views. All major visual components should support direct interaction where possible.

Third, spatial navigation should be supported. A revised interface should provide more space for the map, better label handling, and search or lookup tools for locating farms by name.

Fourth, the clustering view should be made more interpretable. Users should be able to select scatterplot points directly, inspect the mathematical basis of the clustering more clearly, and compare manual and automatic groupings without losing supporting visual context in the matrix.

Finally, future evaluations should distinguish more clearly between tasks involving aggregated connectivity and tasks involving particle movement. Longer exploration time before task performance may also produce a more stable assessment of advanced features.

6.4 Thesis Contributions

This thesis makes three primary contributions.

- **C1: Empirically grounded problem and task characterization.**

This study documents how ocean scientists interpret hydrodynamic connectivity through spatial, relational, temporal, and directional reasoning practices. The task characterization was grounded in contextual inquiry, affinity analysis, and collaborative design activities.

- **C2: Requirement-driven visualization design.**

This work illustrates how visualization requirements can emerge and stabilize through iterative synthesis across domain immersion, co-design, low-fidelity prototyping, and evaluation. The study also suggests that requirements continue to evolve when experts interact with concrete prototypes. A central outcome of the thesis is the identification and stabilization of design requirements for supporting the interpretation and communication of farm-to-farm connectivity matrices.

- **C3: Design knowledge for connectivity visualization.**

This thesis contributes context-specific design knowledge regarding coordination of spatial and relational views through shared controls and linked representations, the need for transparent framing of algorithmic views, the dependence of directional semantics on the reference frame, and the importance of matching terminology to data abstraction.

6.5 Conclusion

This thesis presented a visualization design study aimed at improving the analysis and communication of hydrodynamic connectivity.

Through domain immersion, participatory design, iterative prototyping, and evaluation with domain experts, the study developed and assessed an interactive visualization prototype for connectivity analysis. The results suggest that combining map, matrix, and clustering views supported exploratory reasoning and communication for the participants in this study, especially when shared controls coordinated the views and familiar analytical representations were preserved.

At the same time, the evaluation revealed important limitations in the final prototype. These included a matrix orientation inconsistency, unstable directional semantics across analysis contexts, weak support for reciprocal connectivity, limited spatial navigation, incomplete cross-view coordination, and mismatches between some task wording and the implemented

abstraction. These limitations helped clarify both what the prototype achieved and what remains unresolved. The prototype should therefore be understood as a research artifact used to generate design insights, rather than a finalized system intended to outperform existing tools.

Overall, the thesis contributes both a concrete design study case and a set of design lessons for future visualization work on spatio-temporal connectivity data. These findings are grounded in a small number of domain experts working within a specific project context. As such, they should be interpreted as context-specific design insights rather than generalizable conclusions, although they may inform similar visualization challenges involving spatio-temporal connectivity data.

Appendix Note

Supplementary appendix materials, including selected study artifacts, transcripts, and supporting documents, will be organized in an online repository for final archival submission:

<https://github.com/naxaninsh/msc-thesis-appendix>

Bibliography

- [1] Fisheries and Oceans Canada, “Hydrodynamic connectivity between marine finfish aquaculture facilities in british columbia: In support of an area based management approach,” Canadian Science Advisory Secretariat, Fisheries and Oceans Canada, Tech. Rep. 2021/042, Jan. 2022, Pacific Region. Catalogue no. Fs70-7/2021-042E-PDF.
- [2] M. Sedlmair, M. Meyer, and T. Munzner, “Design study methodology: Reflections from the trenches and the stacks,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 18, no. 12, pp. 2431–2440, 2012. DOI: 10.1109/TVCG.2012.213.
- [3] S. Goodwin et al., “Creative user-centered visualization design for energy analysts and modelers,” in *IEEE Conference on Information Visualization (IV)*, IEEE, 2013, pp. 1–8.
- [4] M. Meyer, M. Sedlmair, and T. Munzner, “Criteria for rigor in visualization design study,” *IEEE TVCG*, 2012.
- [5] e. a. Goodwin, “Reflections on visualization design study methodology,” *IEEE Computer Graphics and Applications*, 2019.
- [6] E. B.-N. Sanders and P. J. Stappers, “Co-creation and the new landscapes of design,” *CoDesign*, vol. 4, no. 1, pp. 5–18, 2008. DOI: 10.1080/15710880701875068.
- [7] C. Chen, *Information Visualization: Beyond the Horizon*. London: Springer London, 2004, ISBN: 978-1-85233-789-6. DOI: 10.1007/1-84628-579-8.
- [8] C. Chen, “Information visualization,” *Wiley Interdisciplinary Reviews: Computational Statistics*, vol. 2, no. 4, pp. 387–403, 2010. DOI: 10.1002/wics.89.
- [9] A. Comai, “Decision-making support: The role of data visualization in analyzing complex systems,” *World Futures Review*, vol. 6, no. 4, pp. 477–484, 2014. DOI: 10.1177/1946756715569233.
- [10] B. Shneiderman, “The eyes have it: A task by data type taxonomy for information visualizations,” in *Proceedings of the IEEE Symposium on Visual Languages*, 1996, pp. 336–343.

- [11] M. Q. W. Baldonado, A. Woodruff, and A. Kuchinsky, “Guidelines for using multiple views in information visualization,” in *Proceedings of the Conference on Advanced Visual Interfaces (AVI)*, 2000, pp. 110–119.
- [12] J. C. Roberts, “State of the art: Coordinated & multiple views in exploratory visualization,” in *Proceedings of the International Conference on Coordinated and Multiple Views in Exploratory Visualization (CMV)*, 2007, pp. 61–71.
- [13] C. North and B. Shneiderman, “Snap-together visualization: Can users construct and operate coordinated visualizations?” *International Journal of Human-Computer Studies*, vol. 53, no. 5, pp. 715–739, 2000.
- [14] J. Heer and B. Shneiderman, “Interactive dynamics for visual analysis,” *Communications of the ACM*, vol. 55, no. 4, pp. 45–54, 2012.
- [15] M. Steen, “Co-design as a process of joint inquiry and imagination,” *Design Issues*, vol. 29, no. 2, pp. 16–28, 2013.
- [16] R. Wolniak, “The design thinking method and its stages,” *Systemy Wspomagania w Inżynierii Produkcji*, vol. 6, no. 6, pp. 247–255, 2017.
- [17] M. Kang, P. Choo, and C. E. Watters, “Design for experiencing: Participatory design approach with multidisciplinary perspectives,” *Procedia - Social and Behavioral Sciences*, vol. 174, pp. 830–833, 2015. doi: 10.1016/j.sbspro.2015.01.676.
- [18] K. Holtzblatt and S. Jones, “Contextual inquiry: A participatory technique for system design,” in *Participatory Design: Principles and Practice*, D. Schuler and A. Namioka, Eds., Hillsdale, NJ: Lawrence Erlbaum Associates, 1993, pp. 177–210.
- [19] H. Beyer and K. Holtzblatt, *Contextual Design: Defining Customer-Centered Systems*. San Francisco, CA: Morgan Kaufmann, 1998, ISBN: 978-1558604117.
- [20] Y. Lee, “Design participation tactics: The challenges and new roles for designers in the co-design process,” *CoDesign*, vol. 4, no. 1, pp. 31–50, 2008.
- [21] M. Kleinsmann, R. Valkenburg, and J. Sluijs, “Benefits of co-design in service design projects,” *International Journal of Design*, vol. 11, no. 2, pp. 1–14, 2017.