Data-Informed Collaboration in Evaluating Design Alternatives

by

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Abstract

Evaluation of design ideas is an integral part of designing built environments. It involves multiple stakeholders with diverse backgrounds reviewing design solutions by studying their form and performance data. Although there are computational systems for supporting evaluation tasks, they are either highly specialized for designers or configured for a particular workflow with limited functions. I developed a Design Analytics method aiming at a collaborative and data-driven evaluation of alternatives in the design-evaluate-feedback cycle. Adopting this approach, I introduce D-ART as a prototype system composed of customizable Web interfaces for presenting design alternatives, enabling stakeholders to participate in data-informed discourse on alternatives and providing feedback to the design team. Its system design considers requirements gathered through literature review, critical analysis of the existing systems and collaboration with our industry partners. Finally, I assessed D-ART's design through an expert review evaluation, which generally reported positive results on the system's utility.

Keywords: collaborative visualization; design analytics; decision-making; participatory design

Dedication

To the child inside of me. We did it!
To my nephew Dhiyaa. Thank you for being yourself, a light!

Acknowledgements

I choose to be thankful! There is always a beautiful meaning that is waiting to be crafted by our perception. This journey of earning a master's degree had a lot of meanings for me. It taught me a lot about thinking like a designer, I had loving mentors, created new friendships, extended old ones, faced some dragons, and most importantly, started a new life in Canada!

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I thank my friend Ahmed for being together against all the odds!

I thank my friend Maher for teaching me how to have fun and care less.

I thank my friend Shehab for teaching me how to be a better programmer.

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Chapter 1

Introduction

Imagine you hire an architect to design your new home. After sharing your requirements and preferences, the architect determines and confirms with you the cost estimates, spatial needs, structure and material use, etc. A few days later, you receive a note from the architect asking you to visit a website to review the alternative design proposals for your project. The website includes plans, renderings, 3D models of the alternative designs, and the performance metrics of each alternative that are most related to your expectations. After comparing the alternatives with their form and performance metrics, you believe that Option-3—although a bit over your budget—is a better option with its large openings in the living room. On the same website, you add comments about the location of the back-door and the roof form for some options. Soon after, your family members see a notification of your comment on their smartphones. One of the family members reviews Option-3 and agrees with your comments; however, adds: "The large openings on the North sides of the living room create too much exposure to the street, not good for privacy." Furthermore, the family member asks for a new alternative with only one opening on the East side of the living room. The system notifies the architect of these comments, and the architect continues the discussion with your family using the website. After a few iterations, your family is happy with the design of your new home. Fast forward six months, you are enjoying a cup of coffee with your family on the sofa as the morning sun shines through your large windows in the living room.

Now imagine designing a massive building complex with residential, commercial, hospitality, and parking functions. Not only will there be far more stakeholders (i.e., persons who are interested in the outcome of the design), but you will also have far more complexity in the design performance data. There are more constraints and performance criteria, and the stakeholders' preferences might contradict. Also, the project may consist of several building functions that compete for the available space and the other allocated resources.

The complexity of design projects compounded with stakeholders' diversity can create serious bottlenecks in the design-evaluate-feedback cycle and design decision-making workflow[36, 47, 16]. These bottlenecks include the ambiguity of design information, lack of completeness of details or terms, unavailability or unfitness of means for information sharing, sequential discourse, etc.

1.1 Thesis Goal: What?

This thesis is about finding tool support to facilitate design stakeholders and designers continuously communicating design solutions, ideas, and suggestions. To address this concern, I propose designing and developing a platform-independent and online collaboration system that can support data-informed design decision-making using form and performance data. I also use this system for knowledge generation to understand how the design stakeholders and designers can interact within continuous cycles of propose-evaluate-negotiate-feedback. Developing such a system requires posing and addressing several research questions about the presentation of complex design data to stakeholders with variant interests and expertise levels, receiving their feedback, and finally presenting the feedback received to the designers. I propose a *design analytics* as an approach combining interactive visualizations of both form and performance data for making sense when exploring potential design alternatives [24].

There are various examples of systems for supporting the design stakeholders' involvement in design, e.g., for design review meetings [25], online design modelling [37], urban planning [32], etc. The majority of the existing systems are either highly specialized for designers or configured for a particular purpose or design workflow overlooking various stakeholder needs. The main question remains unaddressed: how can we facilitate sharing design information and receiving feedback into the design decision-making workflow considering the stakeholders' diversity and managing the design data's complexity.

My primary goal in this thesis is to explore how we can improve collaboration between the designers and design stakeholders. This research has three main objectives: (a) to enable data-informed design decision-making on alternative solutions starting as early as possible in the design process, (b) to identify the critical system features for supporting evaluating design alternatives, and (c) to explore and develop interactive online (platform-independent) interfaces for sharing alternative design form and performance and completing the feedback cycle as an integral part of design workflows.

1.2 Thesis Goal: How?

I relied on three different sources to achieve these objectives: research, existing systems, and continuous participation with industry partners. I surveyed the current research and systems that are aiming to address collaboration between various decision-makers and stakeholders. Parallel to these, our research group continuously worked with our industry partners to understand their workflows and system needs when they communicate their design ideas with design stakeholders. These three information sources let me develop a set of high-level system requirements that can guide the development of a data-informed collaborative decision-making system and using it as a means to better understand collaboration among stakeholders and designers. These requirements evolved over time in the process, and we called the prototypes developed as part of this thesis as Design Alternatives Reporting Tools, in short D-ART. The prototypes mainly seek to answer the research questions on how the potential design analytics interfaces can be composed for data presentation, feedback input, and feedback presentation. I conducted a formative evaluation of the D-ART's most current and minimally viable version to clarify and improve my understanding of the system requirements at several levels through an expert review study.

1.3 Thesis Goal: Why?

Developing a system for supporting collaboration between designers and their clients is an important goal for this thesis for several pragmatic and theoretical reasons. Collaborating through an asynchronous online system allows stakeholders to investigate designs more thoroughly. Further, it helps in starting an equal dialogue between stakeholders where each can share their opinion without having the dialogue dominated by some of the stakeholders as it usually happens in meetings, which have their overwhelming overheads and increasing costs [25]. One of the bottlenecks in successful collaboration between designers and their clients is the lack of collaboration support tools that can seamlessly integrate with current design workflows to engage the stakeholders in decision-making. This bottleneck may increase the cost and decrease the motivation for implementing new collaborative practices. Hence, I contend that for a collaborative tool to be widely adopted, it should be able to communicate with various CAD systems without any unnecessary friction. Low-cost integration will motivate more feedback cycles increasing stakeholders' engagement in design and leading to higher levels of satisfaction in the design outcome [6]. This thesis is an attempt to explore how these new systems can be developed and used in architectural design practices.

1.4 Thesis Structure

The thesis is divided into six chapters. The first is this introduction, followed by a background chapter where a survey of similar collaboration systems is introduced and the state of the art of design collaboration literature. The third chapter is a discussion of my research methodology and its expected outcomes. The fourth chapter is the chapter where I introduce the D-ART prototype design and implementation. The fifth chapter is the evaluation, where I present the methodology and results of evaluating D-ART with domain experts. Finally, I conclude with the sixth chapter outlining future work and concluding remarks.

Chapter 2

Background

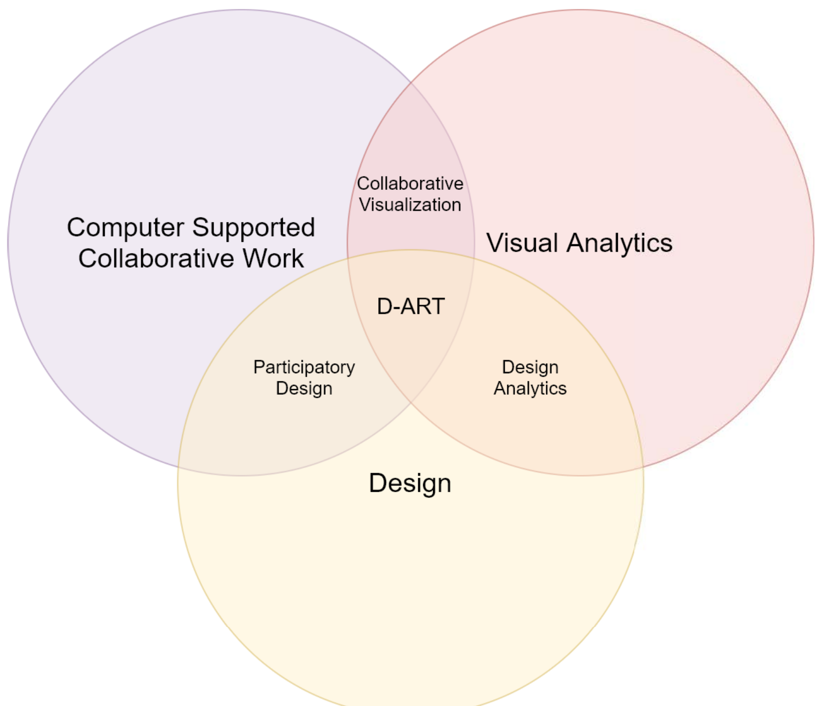

Figure 2.1: The fields of knowledge that this thesis is built around and on which the D-ART interfaces are developed.

This chapter presents the research that I surveyed to build a conceptual understanding of collaborative decision-making using data and explore how we can identify and support the data-informed collaboration tasks using interactive design-data visualizations. The three fields of knowledge that are central for this study include Design, Computer Supported Collaborative Work (CSCW), and Visual Analytics (VA) (Figure 2.1). In the intersection of these knowledge fields, I narrowed the focus in the background section on Design Analytics, Collaborative Visualization, and Participatory Design. Then I will conclude the chapter by introducing systems from literature and industry representing state of art.

2.1 Design Analytics

The use of data leads to better decisions in fields of science and engineering, likewise in design. While the designer's intuition is quite valuable in identifying aspects of design problems and in designing solutions, it remains limited when working with multi-criteria design problems that have conflicting design objectives [15]. Today's computational tools allow for incorporating performance analysis data in the early phases of design exploration [8]. For this, designers use parametric or non-parametric design tools with analysis tools, such as EnergyPlus [19], Radiance[3], Daysim[1], and OpenStudio[28]. This combination allows designers to estimate the design performance as early as possible. Moreover, design data is presented in a visual format that enhances cognition capabilities [41]. This visual format, combined with interactivity, allows designers to explore data more thoroughly and switch their attention to different objectives of the design.

D-ART is part of the *Design Analytics* research program investigating the use of interactive data visualizations in evaluating design alternatives starting in the early stages of design and throughout the rest of its life cycle. Design Analytics combines visual analytics and computational design methods and is used in parametric design [24, 22] and extended to non-parametric design in the project D-Flow [23]. D-ART started as an extension to D-Flow to understand how design alternatives can be shared with design stakeholders. So to better understand the context of D-ART, I will introduce D-Flow below.

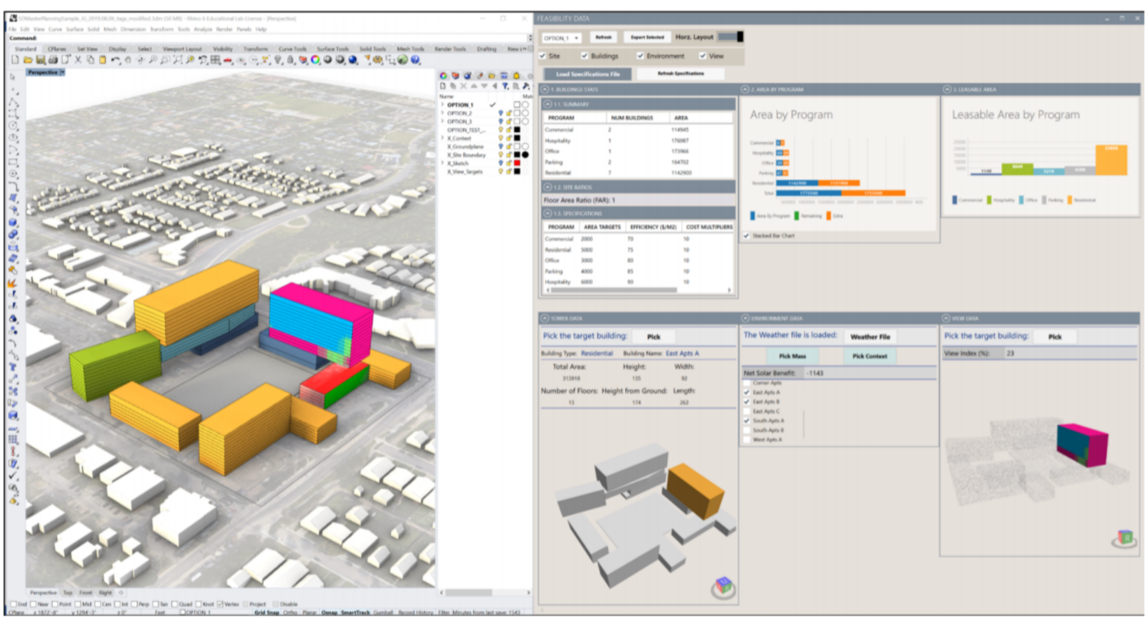

Figure 2.2: D-Flow Interface

D-Flow is a tool for performance-driven design and aims at mixed-use massing problems with interrelated objectives and constraints channelled through form-finding. D-Flow pro-

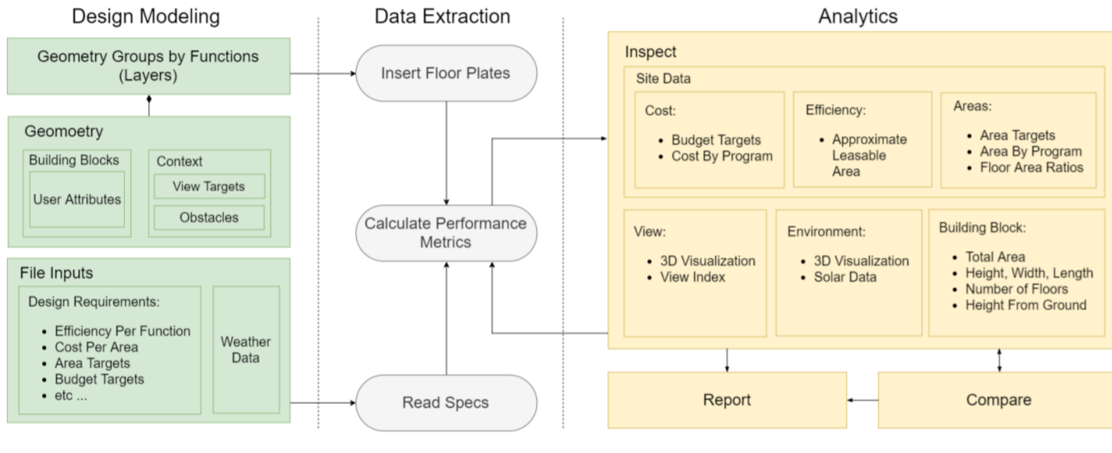

Figure 2.3: D-Flow System

vides immediate feedback about the performance of alternatives and enables comparison to design goals. The main components of the D-Flow interface are composed in the Data Analytics dashboard. They visualize the results of the performance calculation through textual and visual formats (Figure 2.2).

The literature, domain experts, and our investigations revealed critical concerns for the complexity of the design data when communicated to other stakeholders. We took this as an opportunity to develop a module responsible for the generation of design-data reports that supports communication between designers and stakeholders (c.f. "Report" module in Figure 2.3). While presenting design data in a visual form for expert designers is challenging, it becomes even more challenging to present design data to a non-expert audience with varying interests and concerns. This finding motivated the creation of D-ART, which later on grew to be an independent collaboration system capable of integrating with any design workflow or design data set.

2.2 Collaborative Visualization

Collaborative Visualization is an emerging field at the intersection of Computer-Supported Collaborative Work (CSCW) and Visual Analytics. Isenberg et al. [33] define collaborative visualization as: "The shared use of computer-supported, (interactive,) visual representations of data by more than one person with the common goal of contribution to joint information processing activities." This shared-use can be synchronous, i.e., accessed at the same time by different users, or asynchronous, i.e., accessed at different times by different users [13, 21] (Figure 2.4). The shared use can also differ on the space dimension by being co-located or distributed [13, 21]. Another category of looking at collaborative visualiza-

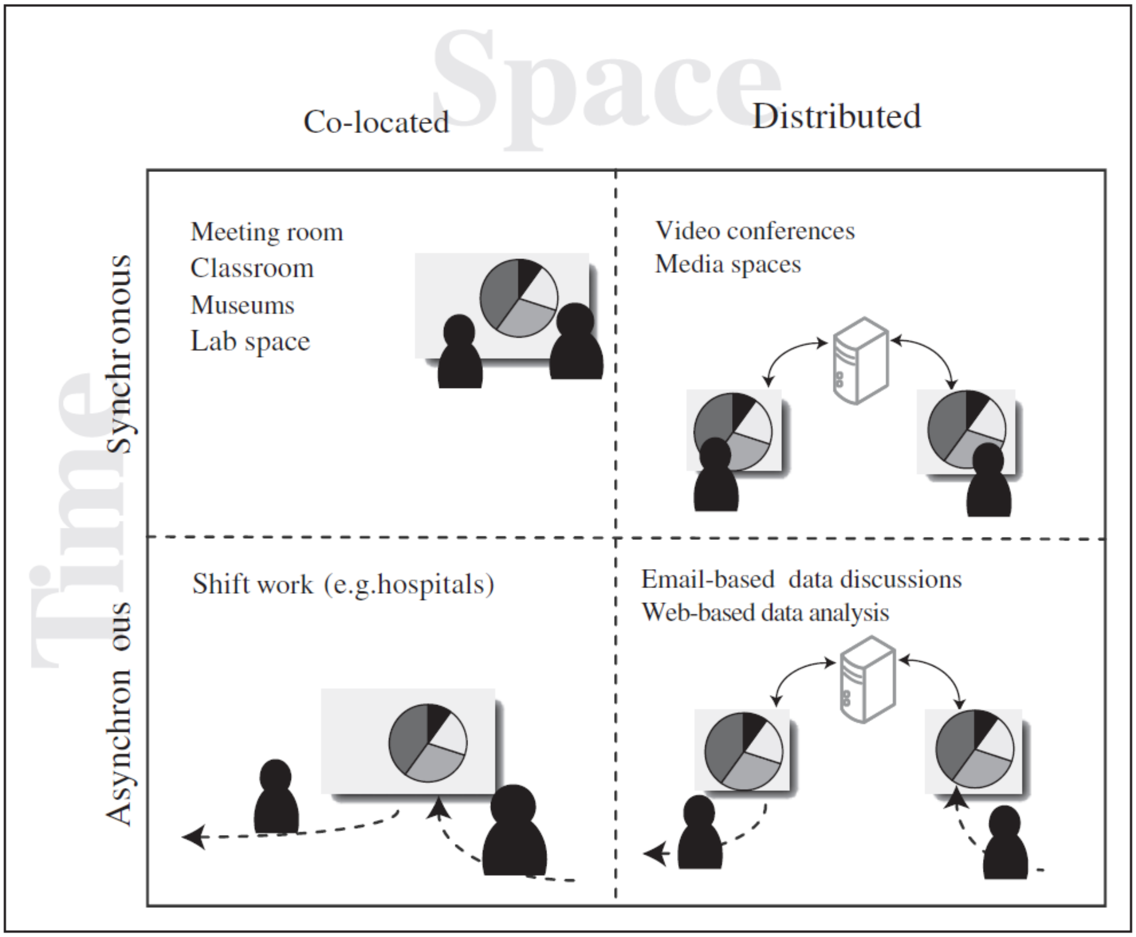

Figure 2.4: Time Space Matrix for Categories of Collaboration. Figure from [33]

tions is considering the users' level of engagement with the visualizations [57, 33]. Users can engage with visualizations at three levels:

- **Viewing:** Systems at this level can present static data to groups either in co-located settings such as the use of PowerPoint for presenting in classrooms or meetings or in a distributed setting such as the use of videoconferencing software or PDF reports. This level of engagement aims to present data to large groups of viewers in scenarios of teaching and learning or by summarizing information and presenting it to decision-makers to enhance their decisions.

- **Interacting/Exploring:** Users at this level of engagement can interact with the systems and make selections of the available data, and form visualizations. Discussions can happen through face-to-face conversations in co-located settings, or they can happen through chat, comment, and email in distributed settings. This level of engagement aims to allow the users to explore different aspects of the data and consider the different alternatives. In such scenarios, users can choose the data visualized from a larger set that the developers of the visualizations provide. In addition, the type of visualization can sometimes be chosen by the user among the possibilities that are provided. While in the "Viewing" category of engagement, the user plays a passive role, in this "Interact and Explore" level, the user plays an active role in raising awareness about the topics at hand.

- **Sharing/Creating:** Users at this level of engagement can create dashboards of visualizations using their data sets. Examples of these systems are Many Eyes[53] and Tableau[51]. In such systems, users can create, upload, and share new data sets and visualizations. This type of sharing is usually done with large communities to raise awareness about a particular issue.

There is evidence supporting the fact that asynchronous distributed collaborative analysis can result in higher quality outcomes, broader discussions, and more detailed reports compared to face-to-face collaboration [14]. However, most of the existing research in Collaborative Visualization focuses on the co-located synchronous collaborative analysis [5, 9, 17]. Both synchronous and asynchronous modes demand a system- support for *exploration and collaboration* [49]. The main challenge in developing an asynchronous distributed collaboration system is determining the design decisions leading to successful collaboration using visualization media. Heer and Agrawala [30] examined a set of distributed asynchronous web-based collaboration systems and listed a set of design considerations that can guide the development and study of future collaboration systems. I introduce a subset of these considerations that I believe are most important for my thesis in Table 2.1. I use these design considerations as guidelines in D-ART development, and I mention how they are applied in chapter four. While some of these considerations are practical and easy to materialize, some are less practical and not clear enough, making it challenging to interpret their meanings into functionalities.

A study conducted by [56] on how experts in the AEC industry reflect on collaboration identifies a set of principles necessary for successful collaboration. These principles include the involvement of all stakeholders as early as possible in the design decision-making, the development of common processes and tools, and the use of performance measurements for informed decision-making. Based on these principles, the systems aiming to support collaboration in the AEC projects must consider a data-driven approach, applicability in various design workflows and involvement of the design stakeholders with different interests in every phase of design. In particular, the last expectation poses the most difficult challenge. The interfaces should adapt to the stakeholder interests without demanding to operate on system-level settings and promote visualization of design form and data information at different abstraction levels.

Code	Design Consideration	Description
DC1	Modularity and granularity	Identify appropriately-scoped units of work that form basic analytic contributions.
DC2	Cost of integration	Synthesize work while attempting to lower integration costs and maintain quality.
DC3	Shared artifacts	Structure collaboration through shared, editable representations.
DC4	View sharing / bookmarking	Enable lightweight sharing of views across media with bookmarks (e.g., URLs)
DC5	Content export	Support embedding of annotated views in external media (e.g., email, blogs, and reports)
DC6	Discussion	Support commentary; consider implications of discussion model on common ground.
DC7	Notification	Support notification subscriptions for views, artifacts, people, and groups.
DC8	Action flags	Mark needed future actions: unanswered questions, need for evidence, etc.
DC9	Identity markers	Enable identification of collaborators in a contextually-appropriate manner.

Table 2.1: A subset of the 25 design considerations for asynchronous distributed collaborative visualizations systems. Adapted from [30]

2.3 Participatory Design

One of the most important goals for D-ART is increasing the involvement of stakeholders in the process of design. To understand the possibilities and methods for increasing involvement, I surveyed some of the works in *Participatory Design* field. Participatory design (a.k.a. co-design) focuses on involving design stakeholders such as clients, users, consultants, construction teams, etc in the design process. In general, the stakeholders' involvement is facilitated through project review meetings synchronously or reporting asynchronously [27]. The prior can be resource-intensive as they require the availability of most stakeholders at a specific time and place [29, 35]. Besides, the evaluation of design alternatives can be seriously hindered by the resource limitations [42]. The primary motivation behind this approach is to shift the focus from the object of design to the user of design [43]. Partici-

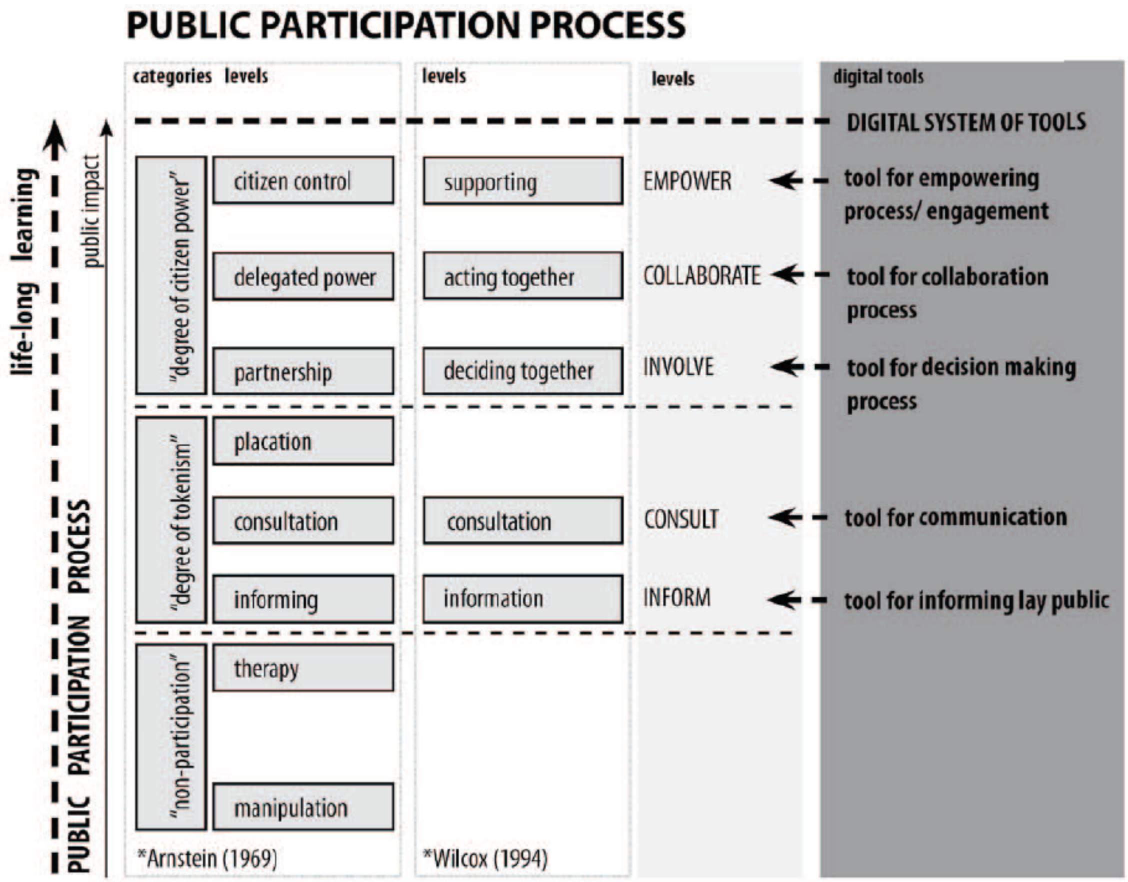

Figure 2.5: The levels of participation suggested by Arnstein and Wilcox [10, 54] and the digital tools needed to support each level suggested by Jutraz and Zupancic [34]. Figure from [34].

patory design aims for the empowerment of stakeholders and their continuous feedback to the design process [46, 20].

Participatory design approaches, particularly in the early stages, may help designers better understand their clients and lead to fewer disagreements and design changes [18]. Rinner and Bird [44, 39] suggests analytical and deliberative discourse components for successful public participation in the spatial design process. The analytical component is associated with decision-supporting tools such as visualizations and multi-criteria analysis. The deliberative component is about discussion and feedback tools such as online forums. Analytical and deliberative components complement each other in terms of helping the stakeholders understand the problem at hand and negotiate solutions. Hence, I believe a system's design should not tackle these two components separately; instead, it should be structured such that there is a system of tools that integrate seamlessly to support collaboration in the same context.

Identifying the tool needs to support stakeholders' involvement in design decision-making depends on understanding the stakeholders' participation and engagement levels. Figure 2.5 shows the different levels of participation suggested by Arnstein and Wilcox [10, 54] as well as the digital tools to support each level as suggested by Jutraz and Zupancic [34]. Arnstein defines three categories of participation: "Non-Participation", "Degree of Tokenism", and "Degree of Citizen Power". At Non-Participation, the objective is not to enable stakeholders to participate but to enable power-holders to influence stakeholders through manipulation. At Degree of Tokenism, stakeholders can voice their opinion and inform the power-holders of their input. However, this category of participation, compared to Degree of Citizen Power, lacks the tools and practices for ensuring that the participants' voices and opinions are heard and followed. Building on Arnstein's work, Wilcox defined five levels of participation. Degree of Tokenism has two levels of participation; "informing" and "consulting". Furthermore, Degree of Citizen Power has three levels of participation: "deciding together", "acting together", and "supporting".

The tool types for the digital collaboration systems can be studied considering the stakeholders' expected interaction with the content (Figure 2.5). For example, Jutraz and Zupancic [34] categorizes such tools considering the higher-level tasks performed at different levels of participation: tools for informing, tools for communication, tools for decision-making, tools for collaboration process, and tools for empowering process and engagement. While the tools for empowering stakeholders in decision-making give control to them, the tools for informing the public limit the feedback to be received from the citizens.

D-ART aims to provide supporting collaboration at different levels of participation. As a collaborative decision-making system, Its goal is to empower stakeholders with a "degree of citizen power" and help them in "deciding together" to reach an agreement. Hence, I decided that D-ART should integrate tools for informing (i.e., design data presentation), communication (i.e., feedback input), and decision making (i.e., design alternatives comparison) in Jutraz and Zupancic's terms [34]. The main challenge for realizing this decision was the design and integration of these tools to work together and not as independent tools. D-ART can be seen as an instance for such integration.

2.4 Similar Systems

This section presents three existing systems selected considering if they can support asynchronous distributed collaboration and are used in the AEC practices. The latter was difficult to satisfy as the adoption of collaboration systems in architectural design—especially in the AEC industry—is still in its early stages. Below, I present their capabilities and shortcomings. I added D-ART to the list for comparison by focusing on the main tasks it aims to support, i.e., presentation, comparison, and feedback of design information.

2.4.1 Modelo

Figure 2.6: Modelo 3D viewer. Screenshot by author.

Modelo [2] is an online commercial Web application for design assets management (Figure 2.6). It supports sharing and uploading a variety of design files including Rhino[40], Revit[12], SketchUp[52], 3DsMax[11], and some standard generic formats. Its presentation features include images, interactive 3D visualizations, and VR walkthroughs. It can also support feedback features, e.g., enabling 3D annotations and text comments. Although Modelo has quite powerful 3D presentation features, it lacks 2D visualizations and charts for presenting non-geometric data such as performance metrics and feedback given by the design stakeholders. In addition, comparing multiple design alternatives is not supported in Modelo, which I believe is necessary for better and informed design decision-making because every alternative reveals different aspects of the design problem at hand.

2.4.2 DesignLink

DesignLink is a decision-support environment that allows professionals from different backgrounds to share their data, make sense of shared data by different collaborators, and decide "trade-offs" based on performance results[31]. DesignLink combines data across different design systems into a set of customizable interfaces (Figure 2.7). DesignLink's data visualizations present different design aspects such as cost, physics, spatial design, etc. The users can evaluate design alternatives through 2D visualizations such as performance data in tabular form and form images. However, DesignLink does not offer feedback functionality as comments or discussions.

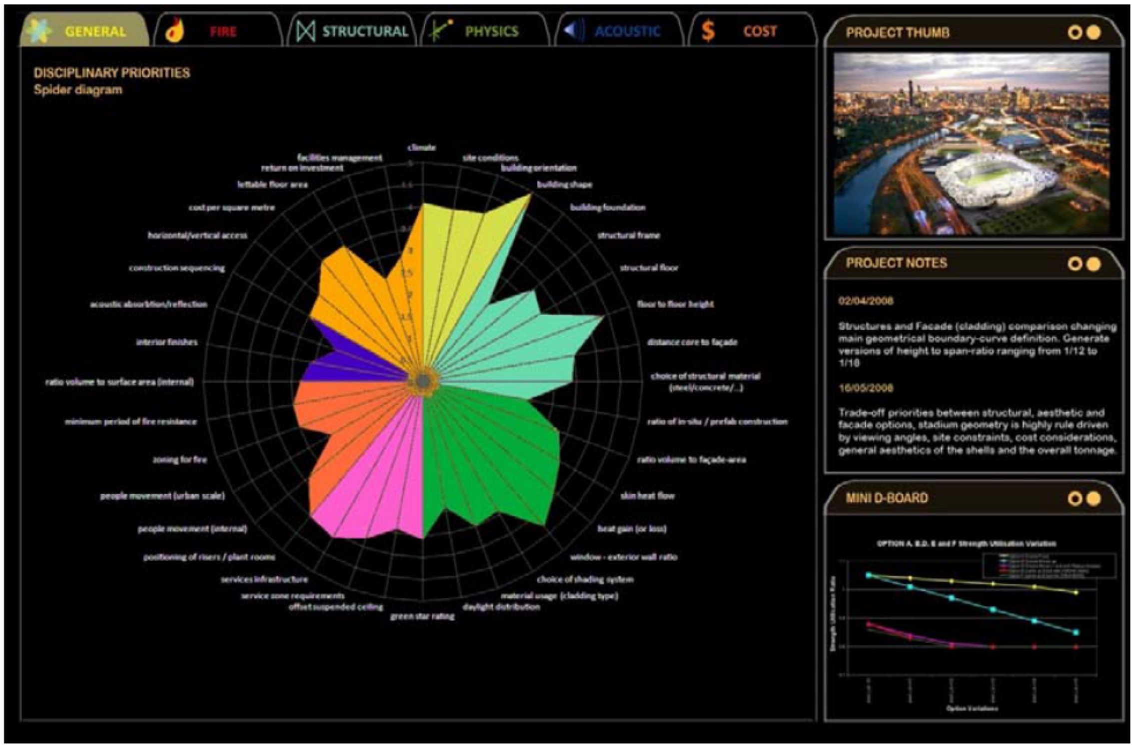

Figure 2.7: DesignLink interface. Figure from [31]

2.4.3 Koneiva et al.

Konica et al. [37] developed an online urban design system to facilitate communication between design stakeholders using an interface connected to a Grasshopper script running in a Rhino environment in the backend (Figure 2.8). The interface has controls that modify parameters in the Grasshopper script, allowing stakeholders to evaluate different combinations and view the results in the 3D viewer. In addition, users can hide and show different design layers to change the level of fidelity while evaluating. The system also displays analytical data about performances in the 3D view and the side panel. The system lacks feedback controls as well as comparison controls.

2.5 Systems Discussion

From my examination of the previous collaboration systems, we can see how collaboration is supported through three main high-level features:

- **Design Data Presentation:** The presentation of design alternatives on both dimensions form and performance as well as the presentation of associated stakeholder's feedback on the design data.

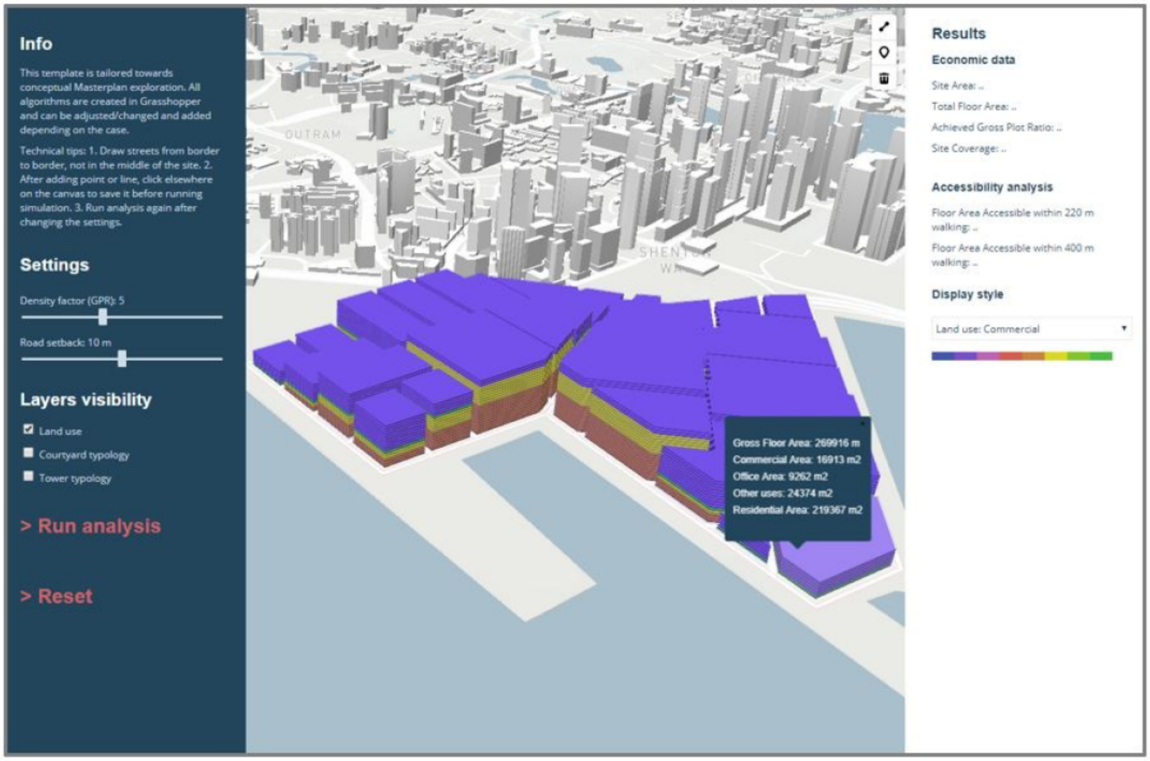

Figure 2.8: Koneiva et al system for urban design. Figure from [37]

- **Feedback Input:** The entry of stakeholder's feedback on the components of the form and the values of the performance. Also, the continuation of the discussions through replies and answers to the feedback.

- **Alternatives Comparison:** The comparison of design alternatives visual forms, how they perform, and comparison of the stakeholders' feedback and reaction to these design alternatives.

Each system of the systems I investigated supports only a subset of these three main features. In table 2.2, I show the features that each system support on the different dimensions of design data: form, performance, and feedback. While Modelio has strong form and feedback presentation features, it lacks support for presenting and comparing performance data. Meanwhile, DesignLink had minimum form presentation features using 2D images. It also combined performance data from different aspects allowing comparison of the design alternatives. However, it lacked any discussion and feedback features and would require additional software to enable discussions asynchronously. Finally, Koneiva et al. system gave its users an excellent level of control by allowing them to configure the input parameters and observe the changes to the form and performance. However, being a single-state system (i.e., users cannot see more than one design alternative simultaneously), it lacked

		Modelo	**DesignLink**	**Konieva et al.**	**D-ART**
Presentation	*Form*	Y	Y	Y	Y
	Performance		Y	Y	Y
	Feedback	Y			Y
Comparison	*Form*		Y		Y
	Performance		Y		Y
	Feedback				Y
Feedback Input	*Form*	Y			Y
	Performance				
	Feedback	Y			Y

Table 2.2: A comparison of the asynchronous AEC collaboration systems. (Y) is used to indicate that the system offer the corresponding feature. None of the systems offer the three features of presentation, comparison, and feedback except D-ART.

the comparison features. Further, it had no discussion and feedback capabilities to support asynchronous collaboration. This analysis leaves an interesting gap for a new system that supports features of design data presentation, feedback input, and design alternatives comparison simultaneously. D-ART aims to be the first high-fidelity prototype that fills this gap.

Chapter 3

Methodology

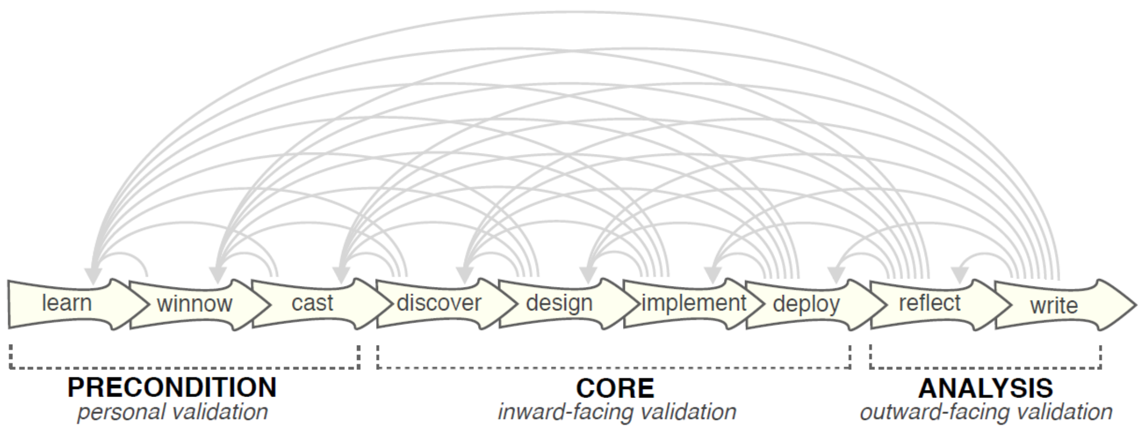

Figure 3.1: Design study method is divided into three phases: Precondition, Core, and Analysis; and it takes place in nine stages reflect the method's iterative approach. Figure from [48]

In my thesis, I choose to adopt the Research through Design (RtD) paradigm introduced by Frayling [26]. In RtD, "researchers generate new knowledge by understanding the current state and then suggesting an improved future state in the form of a design" [58]. I chose RtD for several practical reasons. First, the questions about design and collaboration I seek to answer in this thesis determined my choice of methodology. Design problems, in their nature, are "wicked" problems [45]: searching solutions through iterations is required to identify "satisficing" alternatives [50]. Alternatives are found after specifying, generating and evaluating a set of alternative solutions that can satisfy and suffice, sometimes conflicting, requirements. In each iteration, new knowledge about the problem at hand is discovered and used as feedback in the following iterations. Second, The RtD approach is consistent with my established workflow in the software development domain. Coming from a Software Engineering background, I am inclined to solve problems pragmatically and iteratively. I prefer having software prototypes shareable with others to have conversations about the ideas I explore through the research process. In my thesis, I developed software prototypes to explore ideas on supporting data-informed collaboration in design. Every prototype reveals a set of new aspects of this problem. The RtD provides a formalism for managing this process with some clear guidance. Third, the previous research with similar goals to my thesis in the Computational Design Lab demonstrated the utility of the RtD. These projects, e.g., D-Flow[23] and D-Sense[4], developed prototypes for generating knowledge about the domain problems they tackle as well as the prototypes themselves.

3.1 Design Study Method

In this thesis, I adapted the design study [48] as a problem-driven research method where iterative development and evaluation of designs is a key principle. The method involves *"analysis of a specific real-world problem faced by domain experts, designing a visualization system that supports solving this problem, validating the design, and reflecting about lessons learned in order to refine visualization design guidelines."* [48]. Its practical benefit is identifying solution features in iterations faster. A Design Study research has three main contributions:

- *Problem characterization and abstraction:* Characterizing a problem from the domain into high-level tasks.
- *Validated visualization design:* Developing a tool and validate its design through evaluation and supporting literature.
- *Reflection:* Retrospective analysis of the process, lessons learned, and comparison to related work.

While there is a value from having one strong area of contribution, in this thesis, I found following the entire processes of problem characterization, visualization design, and reflection enriching, engaging, and a good learning experience. It helped me create and validate solutions, raise questions, and grow better as a visualization designer. The following section describes the design study method and how I followed it in developing solutions for supporting collaborative decision-making for building design.

3.2 Design Study Stages

The design study method is divided into nine stages that are contained within three main phases. The first is the *Precondition* phase, and it contains three stages: learn, winnow, and cast (i.e., selecting collaborators). The next is the *Core* phase composed of four stages: discover, design, implement, and deploy. The final phase is Analysis which involves reflect and write stages. Each phase has its evaluation strategy, and every stage is connected to the other eight stages to reflect the iterative nature of the Design Study.

3.2.1 Precondition Phase

To develop D-ART, I studied the core works in data visualization literature and to be ready for implementation; I acquired skills in backend and frontend system development strategies, e.g., application of NoSQL databases. In the design study method, it is crucial to work with domain experts on a real-world problem. I made connections with collaborators from our industry partner organization and the Computational Design research lab, including my supervising committee. My main collaborator from the industry was a computational designer with substantial expertise in architectural design. I was hired as a funded intern in the initial parts of the project.

3.2.2 Core Phase

Building on a comprehensive literature review, analysis of multiple systems supporting collaborative work, and directly working with our industry partners, I incrementally and iteratively identified five high-level system requirements to be followed when developing D-ART prototypes or other systems with similar goals. These requirements guided the development of system features and were used in the formative evaluation of D-ART's versions.

DRQ1. Present each design alternative with customizable visualization of form and performance data along with the structured stakeholders' feedback.

DRQ2. Enable feedback as comments and questions on design form and performance data and responding to the other feedback.

DRQ3. Allow visual comparison of form, performance, and feedback on design alternatives.

DRQ4. Accessible online, independent from the design environments, workflows, and systems.

DRQ5. Provide adaptable interfaces to accommodate a variety of stakeholders with different interests and backgrounds.

In implementing D-ART, I used an agile software development [13] process of continuous feature requirements-research-development-evaluation cycles (Figure 3.2). The previous high-level requirements were decoded into lower-level requirements expressed as use-cases or scenarios e.g., developing bar chart visualization, developing comments replies feature, and developing email sharing feature. The process is supported through extensive research of literature review and studying other software systems supporting collaboration. We begin

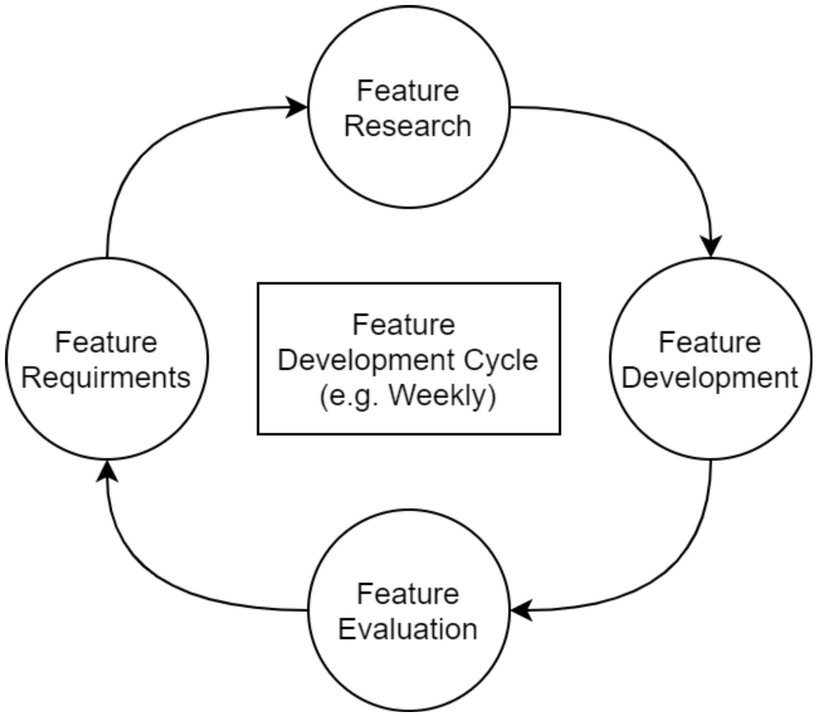

Figure 3.2: System Feature Development Cycle: In an iterative and incremental process, the feature development took place in small and rapid feature development cycles. This cycles usually completed weekly.

the development process by implementing a subset of solutions focusing system features use-case by use-case and backed by the literature research and weekly reviews with experts from the lab and the industry. In weekly meetings, I presented the developed features corresponding to use-cases agreed on realizing and received feedback. This presentation helped us plan the next feature development cycle and to assess the progress made quickly. The use-case realizations involved experimenting with several system design directions.

3.2.3 Analysis Phase

In this phase, there are two main stages: reflection and writing. Although reflection is a continuous process throughout the research, the majority of writing happens at the end. Reflecting on my selection of methodology, I am pretty happy with it! It is not too rigid to restrict the freedom of research, but it is also not too loose to not have a well-defined structure and guidance. The continuous evaluation that happens throughout the three phases solidifies the findings and enhances the validity. Writing the thesis was essential in not only communicating the research and its findings but also in discovering the findings and forming the arguments.

Chapter 4

System Description

D-ART adapts classical client-server Web application architecture to enable communication between the design data repository (database) and the D-ART's front-end interfaces, and visualization of data on browsers and collecting feedback from the stakeholders. Its system components consider the high-level tasks (defined in use-cases and scenarios during the system development) and corresponding interfaces that support these tasks.

4.1 High-level Tasks and Workflow

D-ART supports three high-level tasks: design data visualization and discussion, maintaining persistent design data models and receiving design data from CAD modelling tools (Figure 4.1). The D-ART interfaces facilitate the presentation of design form and performance information to design stakeholders and interactively reflect on the alternatives through commenting and discussions. D-ART's back-end component supports client-server communication and providing a dynamic and persistent repository of design data related to the curated design alternatives. The modeling environments connect with D-ART using a special plug-in responsible for enabling submission and updating design alternatives. Below we discuss the data and the tasks concerning the D-ART interfaces.

4.2 Design Data and D-ART Components

D-ART receives three different design data types: 1) design form, 2) performance metrics as categorical or numerical data, and 3) design objectives expressed as target data. The form is the geometrical representation of design data and can take multiple formats such as images or 3D interactive models. Performance data relates to how an alternative performs on a metric interest to the stakeholders, such as its cost, area, power consumption, etc. It can also be categorical such as program or function designation, e.g., residential, commercial, retail, etc. Targets are the anticipated values for the performance metrics to be achieved and set at the beginning of the design. The target values can change in the process as designers' and stakeholders' iterate on the solutions. Project targets and their units can be defined in

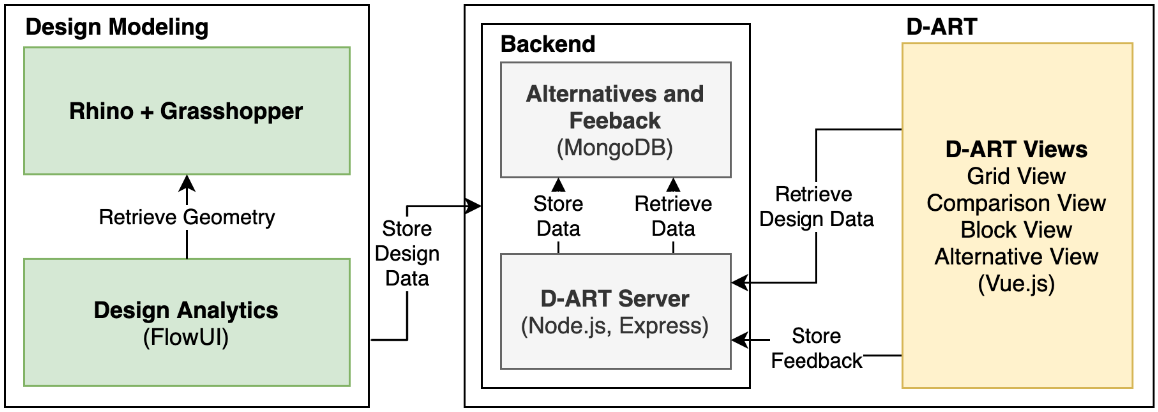

Figure 4.1: **System Overview.** System Architecture for D-ART Setup. The design modeling components are independent of the D-ART's architecture and can be of any modeling or data computing environment. It can be connected with D-ART either through a custom "adaptor" or components or directly pushing data in the design data repository in the D-ART server. The arrows direction indicate who initiates the function e.g., FlowUI design analytics system initiates storing design data in the server back-end.

the project creation interface (Figure 4.2). D-ART can receive an arbitrary quantity or type of performance data to accommodate the unique need of different projects. This gives the flexibility of reusing the tool with multiple collaboration problems or scenarios (DRQ4). In the D-ART repository, the stakeholders' comments, questions and suggestions are associated with the design data and persistently stored for retrieval and report generation.

4.3 D-ART Interface Composition

D-ART interfaces consist of five main views corresponding to the tasks associated with these views: Projects Browser, Grid View, Alternatives View, Building (Blocks) Components View, and Alternatives Comparison View. Below, I use the following annotation (DRQ*, DC*) to indicate how the design affirms the high-level requirements (DRQ) presented in section 3.2.2 and the collaborative visualization tools design considerations (DC) presented in section 2.2.

4.3.1 Projects Browser

The Project Browser interface displays all the projects accessible to the current user. A project is a set of design alternatives regarding one design problem (DC1). Each project is displayed in a box that shows its name and a thumbnail image. The project can be opened directly by clicking on the thumbnail. Extra details about the project can be displayed using the info button that appears when hovering at the right corner. Clicking on the info button, slide a panel from the right holding summary information about the project such

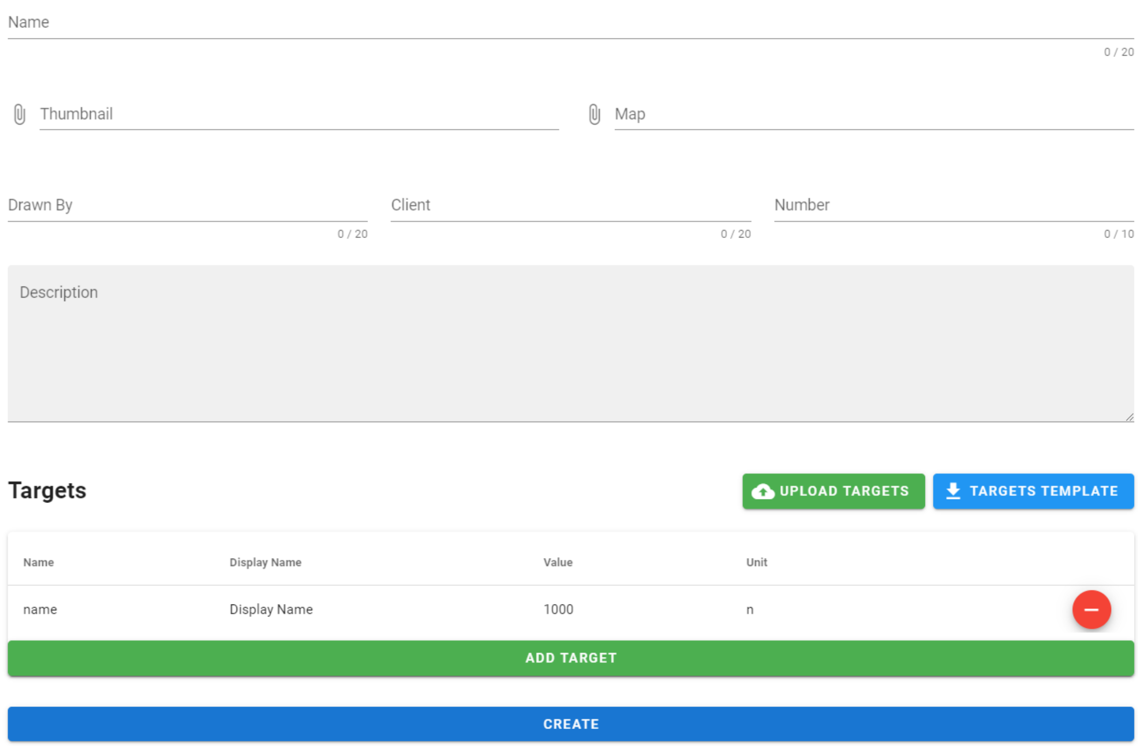

Figure 4.2: **Project creation.** The interface enables setting up a new project independent from any modeling environment. The curators can specify the project goals, performance metrics, form (2D and 3D) views either manually entering on this interface or importing from a spreadsheet.

as its creator, creation date, and last update date (Figure 4.3). From this panel, the project can be shared (Figure 4.4) with a particular stakeholder by entering his/her email (DC4, DC7).

4.3.2 Grid View

The Grid View presents an overview of all alternatives in juxtaposed images augmented with controls to access the other views (DRQ1) (Figure 4.5). Below each thumbnail image of an alternative, an expandable panel tabulates a summary of performance values. This view supports three tasks. First, the stakeholders can change the alternative thumbnail size to show more or less form details. The second task focuses on a rapid comparison of alternatives through side-by-side tabulated performance data (DRQ3). Finally, the Grid View is used as an entry point to access the Alternative Overview (Figure 4.6) interface or Building Components Overview (Figure 4.8) to examine each alternative in depth.

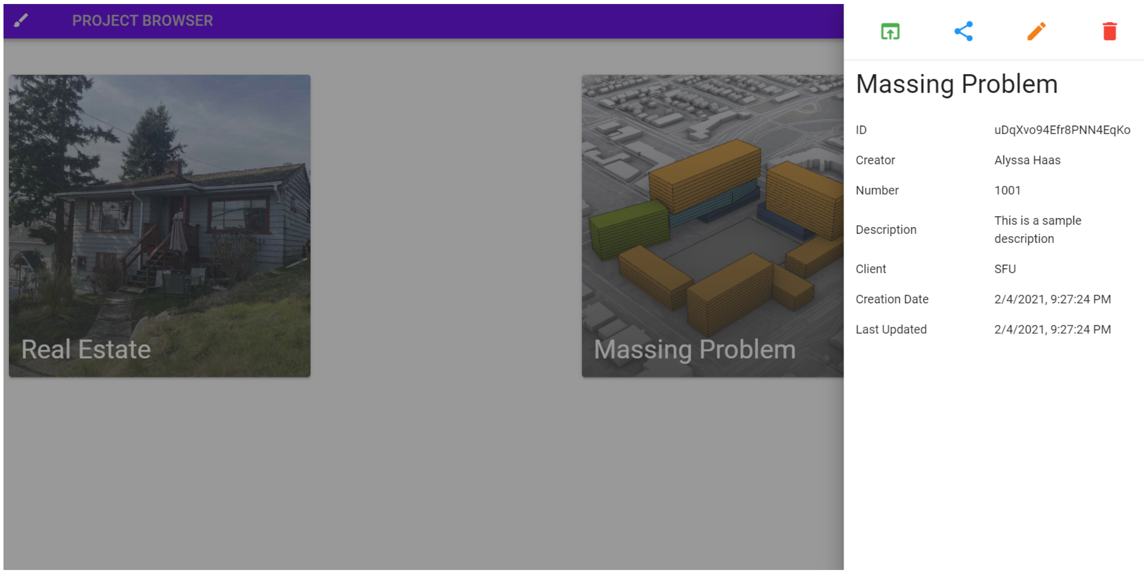

Figure 4.3: **Project browser.** The interface allows for browsing projects as well as a quick display of each project information. The project can be opened directly by clicking on the thumbnail. Extra details about the project can be displayed using the info button that appears when hovering at the right corner.

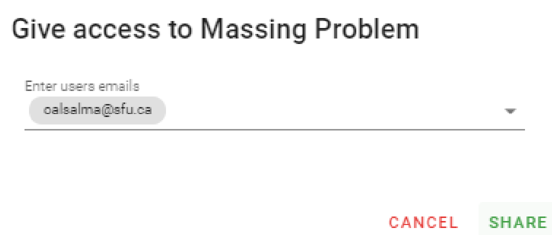

Figure 4.4: The user can share the project by entering the stakeholders' emails.

4.3.3 Alternative View

Alternative View supports inspection of a specific design alternative (DRQ1) through four main interfaces focusing on design data, form, charts, and stakeholders' feedback (Figure 4.6). The data view is a tabular visualization of the select performance metrics, their target values set in the design requirements, and how well each target is satisfied (as a percentage or real value) (DRQ5). Further, the tabular visualization indicates the level of performance achievement by colour coding. The form views include still images on a 2x2 grid as a placeholder for displaying images of the design or 3D model view. The designers choose the images at the time of curating the alternatives. The stakeholders can zoom in on any of the images in a larger view. In the 3D model view, the stakeholders can interact with a 3D model of the design to inspect the 3D form in its context by zooming, panning, and

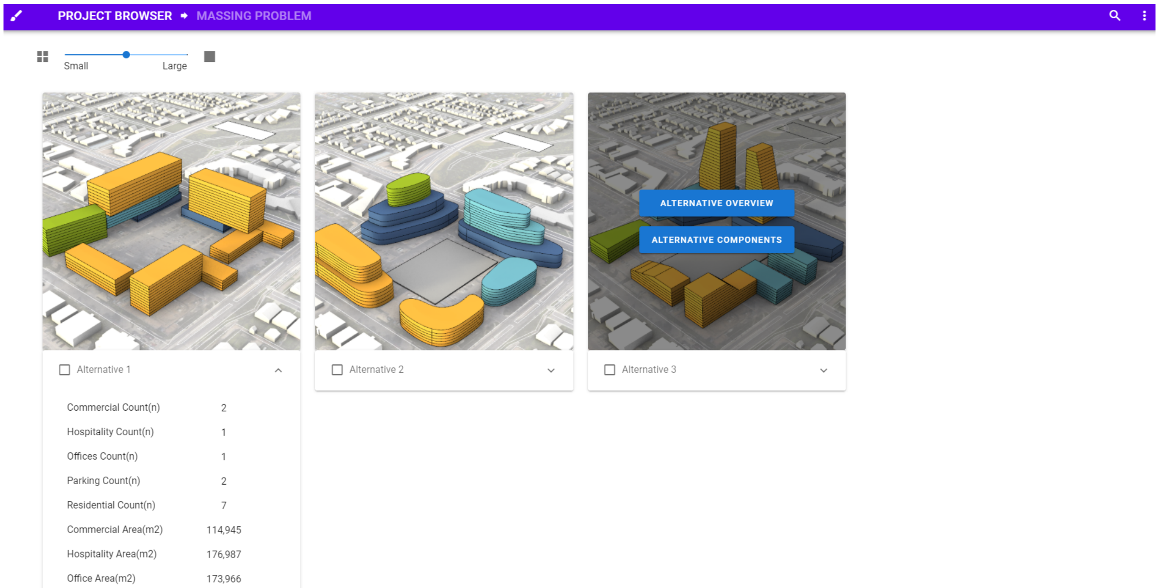

Figure 4.5: **Grid View.** Shows an overview of design alternatives. The arrow under each alternative thumbnail expands a tabular view of performance summaries. The figure shows only "Alternative 1" expanded.

rotating. In the charts view, the stakeholders create basic data visualizations like bar or line charts to understand better the relation between different performance metrics (DRQ5). The users can select any combination of performance values to display on charts against the target values. The interface for providing feedback is a dominant feature in D-ART to motivate discussion among the stakeholders [55]. In the feedback interface (Figure 4.7), the design stakeholders can express their opinions, ask questions, or request changes to the present alternative (DRQ2, DC6). This categorization aims to distinguish the stakeholders' concerns in the discourse and facilitate rich report generation (DC8). The stakeholders can review others' feedback and respond to them, such as in "online discussion systems" in threads (DC3). A resolve feature is added to inform the stakeholders that the feedback will be handled in the next iteration or an agreement is reached between the stakeholders. Comments are displayed with additional metadata that shows the creator of the comment and its creation date (DC9).

4.3.4 Building Components View

Building Components View supports inspecting the distinct components of an alternative in detail. A *component* in a design model can be any cluster of solid geometry designated with a particular architectural function (e.g., residential, commercial, hotel rooms, etc.) as in a massing problem. This view comprises a 3D Model View, Tabular data view, and Feedback interface (Figure 4.8). The tabular view lists each building component's perfor-

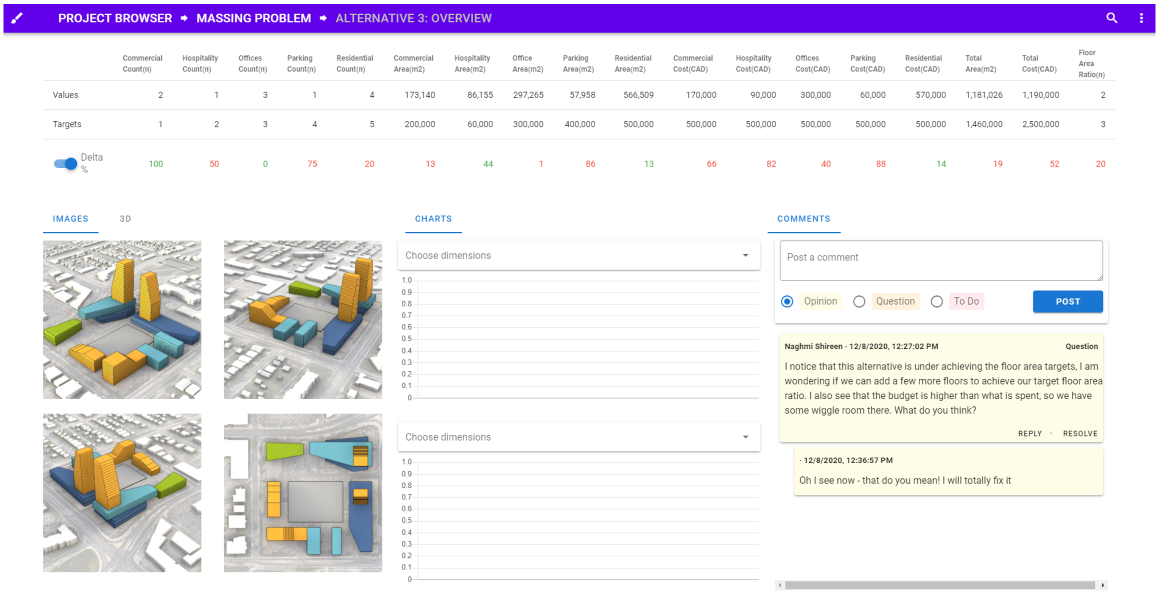

Figure 4.6: **Alternative View.** Deep inspection of one alternative performance, form, and feedback data.

mance. Selecting a row brushes and highlights the corresponding block on the model view or vice versa. The feedback interface works similarly in all D-ART interfaces. However, here it focuses on individual components (DRQ2).

4.3.5 Alternatives Comparison View

Alternatives Comparison View enables the stakeholders to compare multiple alternatives with each other (Figure 4.9). Presented in the Grid View, two or more alternatives can be selected, enabling a *compare* option in the menu. The stakeholders can visually compare form, performance data, and review feedback given to each alternative by other stakeholders (DRQ3). The performance metrics can be compared using the tabular view on the upper section of the interface. The stakeholders can create custom charts by selecting the performance values they are interested in. Side-by-side visualization of 3D models enables rotating views using synchronized camera angles. The URL of the comparison page preserves the selected alternatives for comparison, allowing sharing the current set with other stakeholders through comments (DC3, DC4).

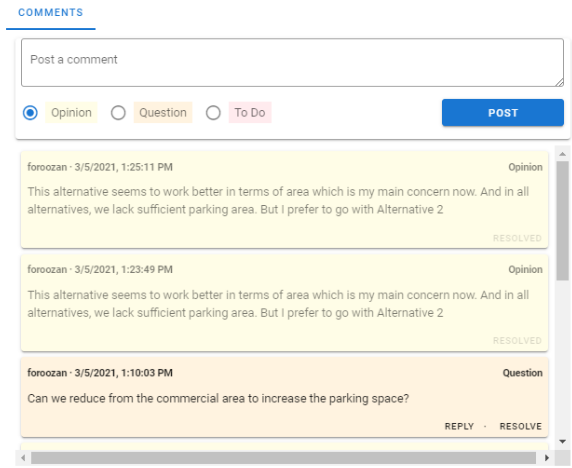

Figure 4.7: **The comments sub-view.** Users can create a new question, To Do, or opinion. They can also view other users' comments, reply to them, or mark them as resolved.

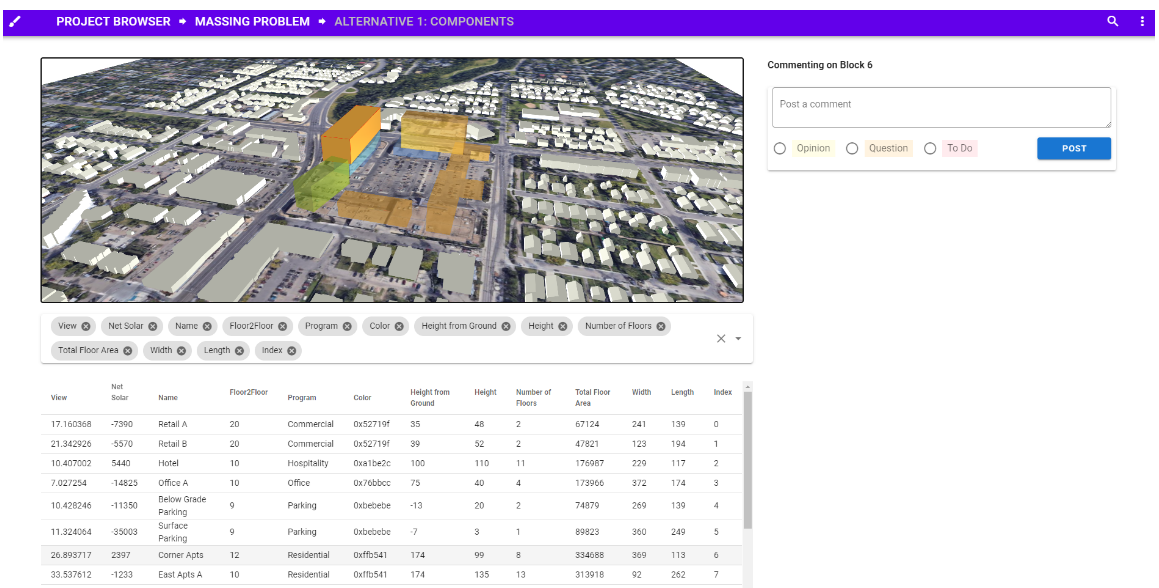

Figure 4.8: **Building Components View.** A block by block analysis of performance.

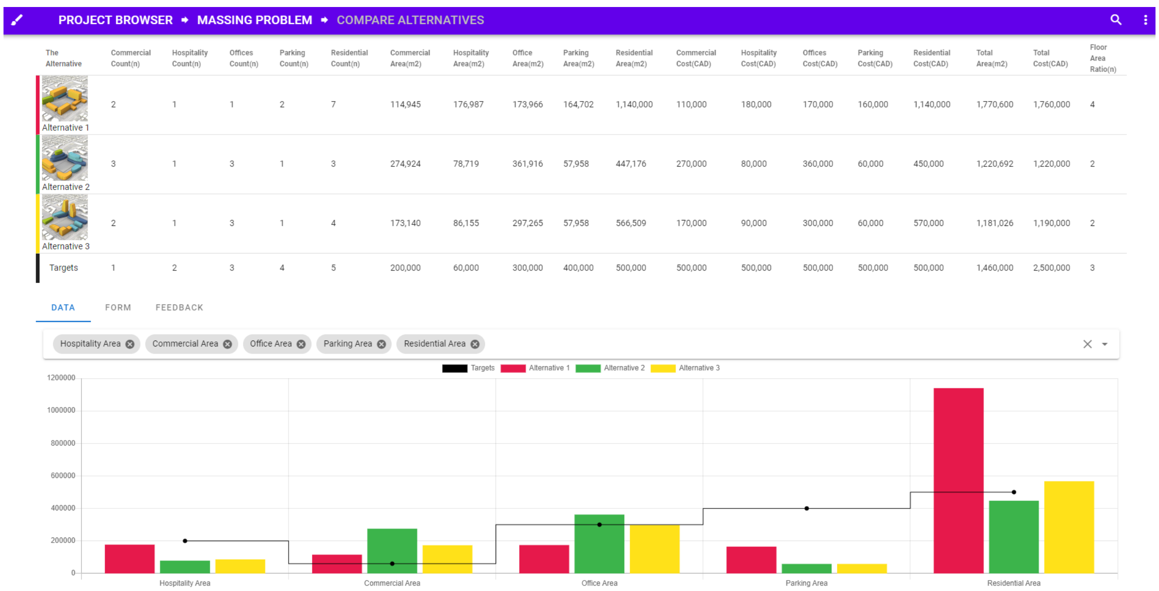

Figure 4.9: **Compare View.** Comparison of performance, form, and feedback of multiple design alternatives.

Chapter 5

Evaluation

To validate the design and requirements of D-ART, I performed an expert review evaluation. Lam et al. [38] provide seven case scenarios for evaluating visual analytics systems: Understanding Environments and Workplaces, Evaluating Visual Data Analysis and Reasoning, Evaluating Communication Through Visualization, Evaluating Collaborative Data Analysis, Evaluating User Performance, Evaluating User Experience, and Evaluating Visualization Algorithms. As a first evaluation, I used an expert review to understand how the domain experts react to the D-ART approach. As potential users of the system, the domain experts are asked to analyze the system's objectives and give feedback for its original goals. In the current and minimally-viable version of D-ART, I evaluated D-ART's objectives and its potential in practice; I leave the evaluation of D-ART with real-life stakeholders for future iteration where the prototypes are more refined for reduced "design confound" effect.

5.1 Participants

There are two categories of potential users for D-ART. First is designers and architects directly involved in the design and curating alternatives. Second is the stakeholders who have an interest in the design outcomes. In this expert review evaluation, I invited designers who have experience working in or with the AEC industry.

5.1.1 Recruitment

To find potential participants, I advertised for the study in social media and computational design chat groups. In the ad, I showed a short video as a simple introduction to the problem and the high-level goals of D-ART. I ended it by asking the potential participants to contact me through email. For those who contacted me, I sent them further instructions to get ready for the study, including a link to a short survey and an ethics consent form. The survey was intended to obtain information on participants' background and experience to contextualize their feedback better. It asked questions about their experience, positions in industry, familiarity with visualization systems, and their expectations of collaboration systems for designers and stakeholders. I aimed to find six participants as I wanted to get diverse yet manageable feedback.

5.1.2 The Experts

Seven experts joined the study, with one being the pilot. The pilot study helped me tune some of the variables, such as the expected duration and helped me test the online setup hosting D-ART. The pilot study also gave me insight into the results [7]. The participants (Five female and two male) (Table 5.1) had different roles in the industry, including architectural design, project management, construction management, interior design, BIM management, computational design, and research. Two-thirds of the participants had never used data visualization systems in AEC projects, and the rest had used tools such as Tableau, Excel, and Design Explorer. The majority of experts used physical meetings for communicating design data with stakeholders; however, one expert noted using PDF reports and their annotation features for feedback.

Expert Alias	**Expertise Area**	**Specialization**	**Experience Years**
Expert 1	Architect and Construction Manager	Construction	< 5
Expert 2	Architectural Designer	Construction	< 5
Expert 3	Architectural Designer	Interior Design	< 5
Expert 4	Computational Designer and Construction Supervisor	Construction	< 5
Expert 5	Architectural Designer and Project Manager	Construction	> 5
Expert 6	BIM Manager and Design technology Specialist	Construction	> 5

Table 5.1: Experts participated in the D-ART's evaluation.

5.1.3 Expectations

In the survey, the experts commented on the need for a different approach for presenting design information to stakeholders and receiving their feedback. Expert 6 believed that there is a need for better visualization tools and experts 2 and 5 commented on the need for system-level support for presenting data. Also, Expert 4 emphasized the gap between research and practice: *"Professional practice always falls behind the ongoing development in the field of design communication due to the fear of change"*. The experts had varying expectations about systems that support collaboration, such as real-time connectivity and feedback and the existence of annotation tools. However, experts 5 and 6 agreed that such a system would need a cloud-based database infrastructure for real-time connectivity. The experts suggested annotating the design data on visualizations, which has been on our agenda and is confirmed by the experts.

5.2 Evaluation Plan

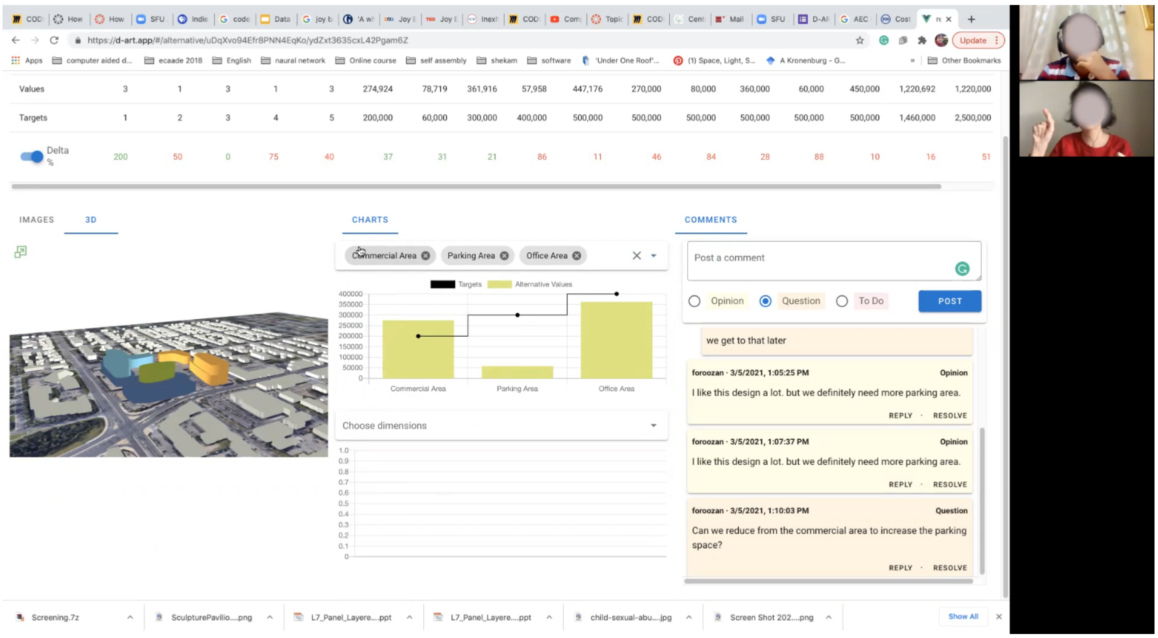

Figure 5.1: The evaluation employed Zoom online meetings where experts used D-ART while sharing their screen.

Due to COVID-19 concerns, the evaluation was done through individual one-hour online meetings with participants (Figure 5.1). Each meeting session included the following activities:

- Introduction of the same real-world case study (massing of a mixed-used building complex) in a short presentation.
- Walkthrough of the system features and tasks supported in D-ART.
- Presentation of a design-decision making scenario based on the case study.
- Evaluation of the given alternatives by focusing on form and performance data and the discussion-support features. Experts are asked to think aloud if and when possible.
- Interview with the experts about their experience with D-ART's design-data and feedback interfaces, the tasks they aim to support and corresponding system features.

5.2.1 Design Case-Study and Introduction of D-ART Interfaces

At the start of the meeting, I introduced the participants to the case study through a short slide presentation. Meanwhile, I shared my screen with the participants. I walked through D-ART's features and explained its interface. I also took questions from the participants to help clarify any misunderstanding they might have about the system or its features.

5.2.2 Roleplay Scenario

After finishing the introduction, the following roleplay scenario was narrated to the participants:

> As one of the stakeholders of a design project, you are asked to review and evaluate a given set of design alternatives; share your comments and questions with the other stakeholders, and give feedback to the design teams through the D-ART interfaces.
>
> The design team selects the design alternatives shown in D-ART for your review as potential solutions for a mixed-use building complex project that includes residential, commercial, retail functions with their related services. Each design consists of multiple building blocks accommodating one of the functions listed above.
>
> For each design alternative, D-ART presents "form" and "performance" data. It also shows the target performance values as given part of the architectural program. In your evaluation, consider the performance metrics with respect to their target values. Also, you can compare alternatives with each other by taking the performance metric as a reference.
>
> In your evaluation, use the D-ART views showing images and the 3D models to study design forms. Design forms can be evaluated subjectively considering their aesthetic and spatial composition, or objectively by evaluating how the building blocks respond to the context and the proposed spatial organization.

5.2.3 Evaluating Design Alternatives

As the experts acted in the roleplay scenario, I, along with another researcher, took notes of their interactions and behaviour. The evaluation session was also recorded to allow for analysis later in the process. The experts were asked to think aloud to capture further insights or clarify any misunderstandings.

5.2.4 Interview

To conclude the online meeting, I interviewed the experts asking the following questions:

- What do you think about the level of design data presentation in D-ART considering the stakeholders' different interests and expectations?
- What are your thoughts about the tools for sharing feedback that the interface currently supports?
- D-ART plans to complete the feedback cycle by compiling and presenting stakeholders' feedback on all alternatives back to designers. What are the possible tasks that you expect D-ART to support?
- What are your thoughts on the value of D-ART in real-world scenarios in the industry? What aspects of it may encourage or stop the industry from adopting it?
- How do you envision using D-ART in different domains? Do you think it can be used to help people solve other problems collaboratively?
- Do you have any further comments or suggestions on D-ART and the tasks it aims to support?

The first three questions are meant to directly validate D-ART's high-level requirements for design presentation, feedback input, and feedback presentation. The following two questions are to understand D-ART's value beyond its current context and its limitations. The last question is an open question to allow the expert to express any remaining feedback he or she might not have said earlier in the meeting.

5.3 Data Analysis

By the end of the meetings, I had three types of data ready for analysis:

- **Video Recording:** recording of the evaluation session where experts acted the role-play scenario and the following interview
- **Survey answers:** the answers to the survey sent to the experts before the online meeting.
- **Text notes:** notes taken by myself as well as another researcher from the Computational Design Lab as the experts were evaluating the design alternatives.

The primary analysis data was the video recordings. However, the other data were used to triangulate sources and contextualize the results. The video recordings were analyzed using a qualitative analysis software: MAXQDA (cite). The video analysis process consisted of the following steps:

Code System	Frequency
Code System	128
D-ART in Other Domains	7
Workflows Integration	6
Real-world Value	16
Other Systems	2
Compare Alternatives	8
Performance Comparision	3
Form Comparision	1
Feedback Presentation	13
Feedback Input	18
Sketching	2
Annotations	9
Data Presentation	11
Performance Values	10
Building Components	3
Alternatives Overview	2
Targets Achievement	2
Interactive 3D	2
Charts	10
Tables	3

Figure 5.2: Coding Scheme and the frequency of each code.

- **Developing the coding scheme:** The coding scheme was developed based on the high-level requirements of D-ART as well as the emerging patterns in the analysis process. In other words, before the coding process, I had some codes in mind, and after finishing the first iteration of the analysis, I completed the rest of the codes. The coding scheme was validated by having two researchers working on it. The scheme can be found in Figure 5.2.

- **Coding the data:** Coding the data was done using the MAXQDA video segmenting tool. The sections of the video were directly highlighted without the need for transcribing the data first. Using this method, I was able to complete several iterations of coding the videos relatively quickly. Two researchers also completed the coding process.

- **Analyzing the data:** After transcribing all the coded segments, I created summaries for each expert for each high-level code. These summaries can be found in Appendix A.

5.4 Results

I structured the results by the high-level themes that emerged during the coding of the findings. This presentation will highlight the most important results; however, the full results, i.e., summaries for each expert for each code, can be found in Appendix A.

5.4.1 Data Presentation

> *... How you give the flexibility to select each component, I think Its really a good tool*
> - Expert 6

The overall opinion of the experts about the data presentation features was positive. They were described as "very good" and "smooth". However, the experts faced some issues in their evaluation that could suggest improvements. First, Experts 1, 4, 5, and 6 asked about the meaning of some of the performance targets for the projects. For example, Expert 5 asked about the meaning of metric names: "This [commercial] count, what does it mean? Is it the number of floors?" and Expert 1 asked: "What is View [metric]?". This highlighted the need to establish a common ground for the stakeholders when understanding performance metrics. Further, when Experts 1 and 2 attempted to create performance charts in the Alternative View, the bar charts were not useful for comparing different units' values as the scale gap (i.e. the scale was is inappropriate for both variables) was too large to make the bar charts meaningful (Figure 5.3). Finally, Expert 4 noted that it is essential to help the stakeholders understand which targets are good to overachieve and which are good to underachieve. Moreover, the expert suggested the use of visual labels that identify ranges and their performance relatively. The expert exemplified for those labels with the energy efficiency cards (Figure 5.4) used worldwide to identify the performance of home appliances. In these cards, the consumer does not need to understand the units of measure and what constitutes a good value; however, the consumer can still make a good decision by understanding how two appliances relatively compare.

5.4.2 Feedback Input

All the experts agreed on the need for improvements for the feedback input features such as supporting annotations on images, 3D models, and charts. Experts 3, 5, and 6 suggested additional feedback input features. Expert 6 suggested supporting image attachments to comments for while "text comments would cover most of the clients' concerns", the addition of annotations and image sketches will support other edge cases. Expert 3 suggested using voice as a medium for commenting on design alternatives and presenting designs to stakeholders. The expert suggested that the use of voice could make the stakeholders feel closer to the designers and motivate them to express their opinions quickly. Expert 5 suggested

Figure 5.3: In the figure we can see the chart comparing the two metrics (Yellow Bars): "Residential Count" and "Commercial Cost against the targets (Black line)". Although the value of Residential Count is 7, however, the gap between it and the Commercial Cost makes the bar chart inefficient in reading the values.

using reactions such as "Like" and "Dislike" to motivate giving feedback. However, they indicated that these abstract reactions might be too vague to support decision-making as the reasons for Liking or Disliking an alternative are quite important to be known by the designers and the other stakeholders.

5.4.3 Feedback Presentation

The experts' feedback on this area was minimal because, as Expert 1 noted when asked about the features he imagined for feedback presentation: "This is not an easy question because we are not used to seeing such tools". However, experts 2, 5, and 6 suggested enhancements to the comments display, such as filtering by comment type, tracking To-Do tasks progress, and hiding resolved comments.

5.4.4 Alternatives Comparison

The experts described the comparison features as "pretty good", "handy", "gives clear information", and "nice". Expert 4 started evaluating designs by using the Compare View first and then decided to focus on one alternative. Expert 3 noted that the positive colour association of green and the negative colour association of red used in the Alternative View might cause biases when reused to identify different alternatives in the Compare View. Expert 1 did not remember how to access the Compare View because the "Compare" button was hidden and not activated until a selection is made in the Grid View.

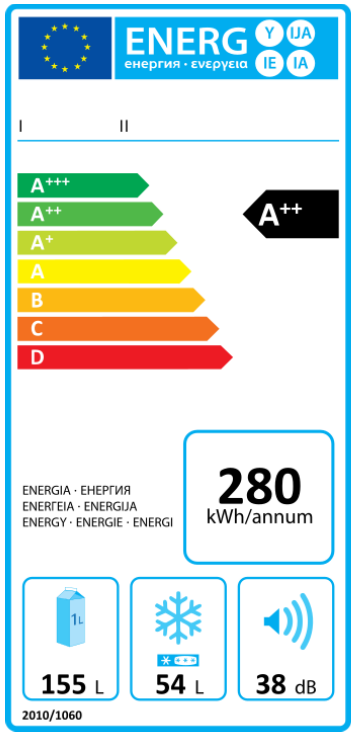

Figure 5.4: Energy Label Card used in European Union on Home Appliances.

5.4.5 Workflows Integration

> *You do not have to make this tool work for every design software. if it were limited to Rhino, it would also be good.*
>
> - Expert 6

While Expert 1 believed that D-ART real-world value would increase as it integrates with more design workflows, Expert 6 believed that there is still a great value in having the D-ART system customized to support one workflow. Further, the experts had some suggestions to enhance the workflow integration. Expert 5 suggested having an intermediate interface between the design system and D-ART to modify and select the level of design for stakeholders to leave their feedback. Expert 1 suggestion was to tightly couple file saves with cloud updates to achieve a real-time environment and keep stakeholders in the loop. Expert 1 disagrees with Expert 5, who believes that the designers should control the frequency of feedback cycles.

5.4.6 D-ART in Other Domains

> *I am not sure why it cannot be used for designing an engine or any other domain of design.*
>
> - Expert 1

Issue	Description	Category	Experts
IS1	Stakeholders not understanding the meaning of some of the performance targets	Data Presentation	1,4,5,6
IS2	Limitation of bar charts when working with multiple units' values	Data Presentation	1, 2
IS3	Limitation of numerical target values in communicating achievement levels	Data Presentation	4
IS4	Annotation system support for feedback input	Feedback Input	1,2,3,4,5,6
IS5	Image attachment support for feedback input	Feedback Input	6
IS6	Quick reactions to design data such as "Like" and "Dislike"	Feedback Input	5
IS7	Comments presentation features e.g. filtering by type and hiding resolved comments	Feedback Presentation	2,5,6
IS8	Color association bias when using "green" and "red" colors	Alternatives Comparison	3
IS9	Intermediate design data uploading interface	Workflows Integration	5
IS10	Supporting large files upload	D-ART in Other Domains	6

Table 5.2: A summary of the issues identified through the expert review evaluation, their category, and the experts that raised them.

There was an agreement from the experts that D-ART capabilities are transferable to other domains of designs such as web design, engine design, product design, interior design, etc. Expert 3 noted that D-ART is applicable in design domains where there is a comparison between the alternatives. Expert 6 highlighted one concern when working across domains, the cloud space and the fact that design files in some domains like engineering might be too large for the cloud to support.

5.5 Discussion on Findings

The overall response to D-ART was positive. The experts agreed that it supported collaboration through design data presentation, feedback input, and design alternatives comparison. To summarise the lessons learned, draw a plan of future development, and facilitate the discussion about the results in this section, I created a table of the issues identified by the experts (Table 5.2) from the results.

The misunderstanding facing the experts in IS1 is because they were not introduced to the different performance criteria and their meaning at the beginning of the project. While this understanding can be expected in real case projects, the complexity of design data would benefit from having permanent descriptors that act as reminders for the stakeholders and create a common ground for future discussions. They are also crucial for onboarding new stakeholders to the project. Further, when Expert 6 was asked about his opinion in having textual descriptions of performance criteria accessible on-demand, they reacted positively.

IS2 notes the limits of having one type of chart, i.e., bar charts. While bar charts are simple to understand and familiar with stakeholders due to their frequent use in media and education, they are limited in their presentation capabilities when working with multiple units. The gap between the values makes the comparison hard and, as Expert 1 put it: "meaningless". However, it remains necessary to consider different dimensions simultaneously when comparing design alternatives. That is why adding other kinds of charts to D-ART, such as Parallel Coordinates, can enhance the comparison capabilities. However, it is essential to note that adding new types of charts does not come without its difficulties, as it would become the responsibility of the designers to educate the stakeholders about their use and function.

Although one expert noted IS3, it remains an interesting technique that is worth discussing. Expert 4 highlighted that using single-value targets was not sufficient for stakeholders to know how much an alternative can overachieve and underachieve a target. While experts know what to consider as a good "energy use", stakeholders may not have the same level of knowledge. Comparing the energy use to a single-value target might be good in making stakeholders understand if the current design alternative is acceptable; however, it does not seem to be efficient when comparing multiple alternatives. Hence, Expert 4 suggested using labels to identify levels of energy use that hide its complexity, similar to the labels used for describing energy use on home appliances. The energy labels are required by law in many countries to describe an appliance's category of energy use (Figure 5.4). This helps consumers when comparing multiple alternatives, as they no longer need to understand the numerical values of their energy consumption. The consumers see the category letter assigned to each appliance and how it can compare to the other appliances. While this example was discussed on energy use, I do not see why it cannot be expanded to other performance criteria. An interesting challenge to consider when applying such labeling system is how the categories can be created. The first intuition is that the designers would solely create such labels; however, this assumes that the labels would be universal across projects which is not usually the case. What a stakeholder in a commercial construction project considers as efficient energy use is quite different from a stakeholder in a residential project. Nevertheless, I find the utility of these labels high in supporting decision-making, which makes this challenge worth tackling.

As expected from the literature review and consultation with our industry partners, the experts in IS4 agreed on the necessity of an annotation system in supporting feedback input. Such a system would highly assist in establishing a common ground between stakeholders and empowers their discussions. However, there is an interesting technical challenge in implementing such a system when working with multiple data dimensions. One approach would be to develop a data-agnostic annotation system that is screenshot-based. In such a system, stakeholders would take a screenshot of any component they want to annotate and attach their comments to the screenshot. While this would work with any data type, it lacks specialization benefits from the data-custom annotation system. For example, annotating 3D files would be based on selecting a 3D component (as it is currently the case in the building components view) and attaching a comment. Another example, annotating performance values, can be done through code references in the discussion forums. The positive that a data-agnostic annotation system has over data-custom is that it would integrate with any data type that D-ART might grow to support. However, going with data-custom annotations would make feedback input more refined and support the generation of more thorough reports that are useful when presenting feedback.

IS5 and IS6 highlight other potential enhancements for the feedback input that adapt to stakeholders' level of interest and experience. IS5 brings to light the importance of sketching in design alternatives exploration. Some advanced stakeholders might be interested in attaching reference images of designs they like or even basic drawings of how they imagine specific design components. On the other end, IS6 brings to light the importance of having quick interactions such as "Like" and "Dislike" to accommodate less interested stakeholders in expressing their opinion about a design alternative. While this has the negative of obscuring information of why and how they like and dislike an alternative, it positively motivates less-engaged stakeholders to participate in the discussion.

While the feedback regarding "Feedback Presentation" has been minimal (due to the novelty of the problem), IS7 sheds some light on its importance. I implemented this feature in a later version of D-ART (Figure 5.5). The original comment writing space was taking space from the comments display, and currently, it has been reduced to a button that expands into a comment box when attempting to add a new comment. Moreover, I added the option to filter resolved comments as they might clog the comment space unnecessarily. Finally, I added the feature to show only a subset of comments types to help in exploring the feedback.

In the Alternative View, I used green to indicate overachieving performance values and red to indicate underachieving performance values. Then, I reused these two colors along with other colors to identify alternatives in the comparison view (i.e., to associate them with the different bars in the bar charts). Expert 3 noted how this might cause some bias as alternatives associated with the color green would sound more favorable than ones associated with the color red. I removed these two colors; however, I aim to use visual patterns to identify alternatives as they are more accessible in future iterations.

The current integration workflow with Rhino requires some modifications to the Rhino files, increasing the friction of integration. IS9 highlights a potential solution where an

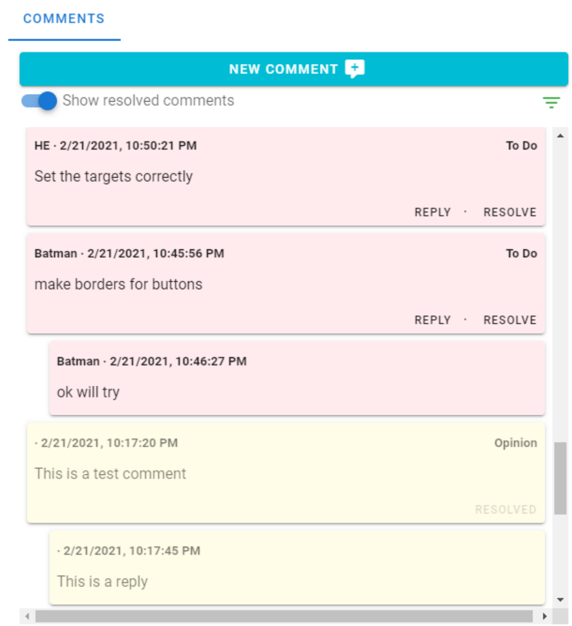

Figure 5.5: The new comments section where users can click on new comment to expand the writing box saving space when viewing comments. Further, users can hide resolved comments and filter by comments type

intermediate interface is introduced to control the data submitted to the cloud and its frequency. The interface would also mediate any necessary changes to the files before being updated to the cloud. Developing such an interface for all integration workflows would be challenging as each CAD software would have its own specifications and requirements. However, such an interface would remain necessary for reducing any friction resulting from integrating with existing workflows.

All the experts agreed on the utility of D-ART across design domains (e.g., web design, engine design, product design, interior design, etc). However, Expert 6 raised concerns about the possible difficulties when working with large models in large files and sharing them between designers. The expert noted that in the fields such as engine design, the 3D models are high fidelity. They usually have huge file sizes (i.e., exceeding 300MBs in some instances); this can cause a technical challenge for the cloud when managing such designs. Not only would they require more extended download and upload times, but they might also slow down the interfaces due to their rendering requirements. I see this as an important technical challenge but not necessarily directly questioning the design analytics approach. There could be various solutions for this problem, e.g., the models can be saved in lower resolution and decomposed into a set of smaller models that are accessed on demand. Such decomposition can be managed through the same intermediate interface discussed in the previous paragraph. This is an important concern and deserves to be studied further.

Chapter 6

Conclusion and Future Work

One of the essential activities in the process of design, regardless of its domain, is collaboration. Collaboration can happen between all sorts of groups: among designers, among stakeholders, and between designers and stakeholders. The latter is the concern of this thesis. Regardless of its mode, successful collaboration requires a system of tools that integrate seamlessly with the existing design tools. This thesis is an attempt to design such a system. As a Design Study thesis, there are three main contributions:

- *Collaboration between architects and stakeholders problem characterization and abstraction:* Based on literature and feedback from industry, I characterized the problem from the domain into high-level tasks defined in section 3.2.2.
- *D-ART validated visualization design:* I developed a tool and presented its design in Chapter 4. Then validated it through a formative expert review evaluation that I presented its results in Chapter 5.
- *Reflection:* I presented a retrospective analysis of the process in Chapter 3 and compared D-ART to related work in Chapter 2. Further, I provided my reflection and thoughts on results in Chapter 5.

Although I have implemented some of the feedback I received about D-ART interfaces in its latest version, such as adding filtering capabilities for comments and performance values, there are still other features and investigations that are planned for future work:

- *Annotations:* As literature and the experts noted, there is a need for a data annotation system that is compatible with different types of design data. Such a system is not only challenging because it needs to work with a variety of data types such as images, 3D forms, performance tables, etc., but it creates usability challenges when presented for non-expert users.
- *Feedback Presentation and Report Exportation:* While currently D-ART supports basic filtering operations on stakeholders' feedback, there is still room for improvement.

Complex feedback queries across alternatives and the generation of PDF reports are examples of potential features.

- *D-ART in other workflows:* D-ART works independently from design environments; however, I validated its integration with one design workflow (Rhino+Grasshopper) to test its generic design. More work is needed to test its integration with other design environments such as 3Ds Max, SketchUp, Revit, etc.

- *D-ART in other domains:* All the experts agreed that D-ART design is reusable in other domains of design. I started experimenting with D-ART in real estate; however, more work is needed to see the application of D-ART interfaces across other domains such as product design, interior design, etc.

In addition to the previously mentioned features and investigations, this work needs a more structured (task-based) evaluation of the current tool features, possibly by comparing it to other collaboration tools.

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Appendix A

Evaluation Summaries

The following is the list of summaries per expert per code for the formative expert review evaluation study I did.

Evaluation Summaries for each expert for each code

Code	Summary
D-ART in Other Domains	The expert believes D-ART can be used in any collaborative design field and gives an example of using it for engine design. The expert also highlights that D-ART's importance can increase with the emerging remote work trend as a potential tool for collaboration between the designers. "I am not sure why it cannot be used for designing an engine or any other domain of design." EX1
	The expert suggested that D-ART could help share progress with clients of software design projects such as websites. EX2
	The expert believes D-ART is applicable in any design domain where there is a comparison of alternatives. EX3
	The expert believes the tool can be used in other design domains since design problems have similar nature. EX4
	The expert agrees that D-ART can be used in other domains of design where there is a designer and client and exemplifies for product design EX5
	The expert believes that D-ART can be used in other design domains. However, it is vital to ensure that the cloud can support uploading detailed designs with large file sizes. EX6
Workflows Integration	The expert believes that the excellent integration with different design software would be an essential factor in encouraging D-ART usage in the industry. Moreover, the expert suggests associating the save command in CAD software to push data to D-ART to enhance the integration and keep the stakeholders updated. EX1
	The expert suggested that one of the essential features of successful integration is to make the designers control how frequently the design data is updated and when stakeholders are notified. EX5
	The expert believed that for this tool to support all design workflows and systems, it has to ensure that its cloud can support large file uploads and downloads because some

	design software files easily reach over 300 MBS. However, the expert also noted that "You do not have to make this tool work for every design software .. if it were limited to Rhino, it would also be good". Finally, the expert suggested having an intermediate stage in the workflow for uploading design data where designers can group a different set of components to determine the level of feedback that the stakeholders are going to give. EX6
Real-world Value	The expert saw a high potential for D-ART to be used in the industry. "I think it has a very high potential to be implemented in industry." EX1
	The expert suggested that D-ART could be valuable for real-world design projects for both the client and the designer. However, she noted that concerns of security and privacy of the data might hinder its adoption, such as design data theft. EX2
	The expert finds D-ART useful for industry, especially for presenting the second time after the first initial meeting. The expert believes using asynchronous collaboration tools such as D-ART, where stakeholders can inspect each alternative freely on their own time, could reduce the bias that happens when designers like an alternative and present it more favourably than the others. EX3
	The expert described the tool as "a great tool... It helps in answering lots of questions about numeric values for the project... It is easier for communication. It is really helpful." The expert noted that there is a gap between the understanding of designers and stakeholders for the latter get to focus on a limited set of performance criteria: "There might be ten criteria and the stakeholder only understands or focuses on two of them leading the client to choose an alternative that the designer will not agree with. The tool you are developing might shorten this gap". The expert also believed the current communication approaches between designers and clients are not practical and what makes this issue remain is that "Industry is never ok with introducing new tools". Finally, the expert noted that the input document from the stakeholders using the tool is better than verbal comments regarding accountability. EX4
	The expert believes D-ART value can be exploited as an advertising factor for design firms who care about integrating their clients in the design process. The expert believes D-ART

	is primarily beneficial, and if there is a shortcoming, it would be in the increasing usage of time as there will be more feedback cycles and more discussions back and forth. EX5
	"I do not know how easy it is to set up for designers, but from a client perspective, I think it is a really user-friendly tool." The expert believes the tool is quite helpful for the clients, but she is interested in seeing how the integration flow works. The expert believes that such a tool's adoption will not be possible unless it had designers' usability as a primary target. EX6
Other Systems	The expert mentioned a similar system to D-ART called OnShape, where it is possible to annotate geometry and post comments. EX1
	The expert tried working with a design collaboration tool from AutoDesk called A360, but they abandoned it due to the lousy annotation features. EX6
Compare Alternatives	The expert was satisfied with the performance comparison tools such as bar charts and described them as "pretty good" and "handy". However, the expert faced difficulty accessing the comparison view, noting that selecting two alternatives or more and then clicking on the appearing compare button is not adequate and might be harder to remember. The expert suggested an alternative is to keep the compare button visible before selection but to enable it once two alternatives or more are selected. EX1
	The expert found that the colour association with overachieving and underachieving targets (green and red) in the Alternative View is confusing since the same colours indicate different alternatives in the Compare View. The expert suggested using visual patterns as a replacement for colour to overcome the potential bias. Also, the expert noted that the Compare View could benefit from making the selection of alternatives to be compared mutable in the same interface compared to the current option of going back to the Alternatives View and then re-selecting the alternatives. This way, the user can remove alternatives they are no longer interested in or add new alternatives to see how they compare. Finally, the expert wanted to leave a comment on comparison and noted that they have to choose an alternative to leave the comment on; what they would have preferred is to leave a comment on all alternatives. Finally, the expert had to go back and forth between the compare

	bar charts and the comment sections as they were not visible at once: "I want to see the charts while I am giving feedback." This gives rise to the importance of annotations on charts as a potential solution. EX3
	The expert had no preference on the form so that's why the expert immeadiately started with the comparision view and focused on performance comparision. Since the expert ingored the other views in his analysis, the expert wanted a mechanisim to show the color asosicaition of programs at the Comparision View which can be currently done at the Block Components view. This gives an indication that the repetition onf information across different views might be necessary to accomidate different exploaration approaches and interests of the stakeholders. EX4
	The expert described the performance comparison in the compare view as both "gives clear information" and "nice". The expert had a minor comment about the colour association in the compare view, which currently uses bars to indicate the alternative colour in each alternative row. She suggested that the whole row can have a gradient of that colour to enforce the association better. EX5
Feedback Presentation	The expert highlights the importance of clarity in data presentation and indicates the difficulty of imagining feedback presentation features due to not seeing feedback presentation features in existing systems. EX1
	Regarding presenting feedback to the designers, the expert suggested that the designers be able to display all To-Do tasks and re-arrange them based on priorities and track the progress. EX2
	The expert believes statistics about the stakeholder's experience would be beneficial in informing the designer about their understanding of the design alternatives. Also, they can benefit from knowing which of the alternatives received more positive feedback to order their exploration of the alternatives. Finally, the expert favoured having some tools to support filtering comments by type across all alternatives and some searching capabilities. EX3
	Regarding the feedback on individual blocks, the expert found it suitable to present this feedback visually, especially the feedback of the To-Do category, so the designer can know which of the blocks needs modifications.

	EX4
	The expert suggested having searching and filtering by type capabilities for feedback presentation. EX5
	Since comments are left on different levels (alternatives and building components), the expert suggested merging and presenting these through unified interfaces where designers can filter the comments and search them. EX6
Feedback Input	The expert saw that the feedback features of D-ART require some improvements. First, the comment section was described as being "not smooth" due to the speed of posting comments as well as the speed of scrolling through. The expert also highlighted the importance of annotating performance values and posting associated comments. Finally, as a usability issue, the expert found that the highlight over the radio buttons selecting the comment type to indicate the colour can be better redesigned as a coloured border. EX1
	The expert suggested the use of general annotations and sketching features. EX2
	The expert found commenting on each alternative very helpful and gave feedback about improving the commenting experience, such as emptying the comment field after posting a comment and showing new comments first, similar to how commenting works in Instagram and other social media. The expert also suggested new commenting capabilities such as annotations that the expert believes suit the medium's visual nature and help illustrate and convey visual ideas faster than text. Another benefit of using annotations is increasing stakeholders' freedom in giving more understandable feedback by referencing images, charts and 3D files. The expert also suggested voice as a medium for feedback and data presentation. It could make the stakeholders feel closer to the designers and help them navigate the interface if needed. Finally, in the compare view, the expert suggested that the comparison of feedback section (comments side by side) should support leaving a comment on a set of alternatives instead of one by one as comments written in this view usually reference all the alternatives being compared. EX3
	The expert described the commenting features as "adequate" for the initial stages of design. However, at later stages of design, it might not be adequate as we would need

	lower levels of giving feedback (i.e. giving feedback on blocks will not be enough, but stakeholders would also need to give higher fidelity feedback such as windows, doors, etc.) The expert suggested supporting annotations to be able to reference and visually comment on multiple blocks. The expert believed that such annotation feedback mechanisms would reduce the misunderstanding gap between clients and designers. The expert also suggested having some sort of a feedback mechanism that allows stakeholders to rank the performance dimensions based on their importance. This feedback could help later in computing numeric values that help automate the comparison of the design alternatives. EX4
	The expert found that "text comments would cover most of the clients' concerns". However, the expert notes that the addition of annotations will support other edge cases. The expert also liked how the comments section took a prominent section of the interface and existed across all interfaces being a solid motivator for discussions. The expert also suggested having emotional reactions as feedback input such as Like, Dislike, Love, etc., as it would allow clients to give feedback when they cannot express in words or theorize their concerns. However, the expert noted that emotional reactions would require further investigation by the designers to communicate with their clients and understand their feedback. As a researcher, the expert believed that the stakeholders would love the feedback capabilities. However, from her industry perspective, the increase of feedback might be received negatively and hinder the design process! EX5
	The expert liked the commenting features and suggested having 3D annotations and the ability to attach images to comments to allow stakeholders to share sketches or send references. The expert also suggested supporting tagging stakeholders and designers to assign specific tasks similar to team task management software. EX6
Data Presentation	The expert was satisfied by D-ART's data presentation features, especially the interactive 3D view that he found "pretty cool". However, the expert faced some issues, such as knowing the meaning of one of the performance values, suggesting that target text descriptions could help stakeholders learn more about a performance value and its importance. Moreover, the expert noted that bar charts would not be efficient for comparing different units' values as the scale gap might be too large to make the bar charts meaningful. Hence, D-ART should support different types of charts that solve this issue, such as PCP. The expert also indicated the importance of controlling the presented data's

complexity across the interfaces by allowing the users to filter the performance criteria based on their interests.
EX1

The expert commented positively about the data presentation features and suggested presenting a separate category for design targets that shows the limits and regulations that the design cannot exceed. Also, as the expert was using the charts, she encountered an issue comparing performances of different units.
EX2

The expert found "The bar charts were really helpful and easy to comprehend". When dealing with charts in the Alternative View, the expert was initially confused about having two charts. Then the expert used them to compare vertically different categories of the performance data such as area and cost across all programs. That is why the expert also suggested having the ability to reorder the selected performance values in charts without unselecting everything and reselecting it again. In the Alternative View, the expert wanted to know the colour-coding used for programs and thought it would be better to know that in the same view instead of going to the Building Components View. Furthermore, in the table of performance values, targets, and their delta values, the expert thought that being able to sort for the delta values would make it easier to discover which of the alternative performance values are overachieving and which are underachieving. Finally, the expert also suggested voice as a new medium for feedback and data presentation. It could make the stakeholders feel closer to the designers and help them navigate the interface if needed.
EX3

The expert suggested several ideas for enhancing the stakeholders' understanding of the targets. First, a textual explanation of the performance target. Second, indicating visually which of the targets are good to overachieve and which are suitable to underachieve. Third, presenting a single numeric value for each alternative calculated based on each stakeholder's alternatives' weights or preferences. This, along with the categorical reference of a good value, will help stakeholders make better decisions. The expert mentioned a similar strategy used in Saudi Arabia to inform customers of the energy use of products where a label is placed on each product with a count of stars to indicate energy use. This way, consumers can choose products with higher star counts without understanding the units of energy use and what is good energy use. The expert also indicated that having ranges for targets at some performance values might be better than single target values.
EX4

	When starting her investigation, the expert's first question was "Where is north?" and suggested having some indicator preferably on the form. The expert described the data presentation capabilities as "understandable". The expert suggests further customization to simplify the data presented, like filtering the performance criteria across the interfaces. The expert was not sure about the meaning of some of the performance values and supported the idea of defining each performance value/target. The expert also faced some confusion about two charts in the Alternative View and whether they are similar. EX5
	The expert described the data presentation features as "really good and smooth". Also, she liked the flexibility of presentation tools supporting different data types. The expert suggested supporting overlaying design information over the interactive 3D form view, such as program type. The expert also suggested having textual definitions of performance criteria to explain design targets to stakeholders who might not understand them. The expert found the building components view helpful for the early stages of design, but the expert is unsure how it would look at later stages. EX6