Hydrogen Station Location Planning via Geodesign in Connecticut: Comparing Optimization Models and Structured Stakeholder Collaboration

Pre-publication accepted version

Oscar Lopez Jaramillo [1]*, Joel Rinebold[2], Michael Kuby[3], Scott Kelley[4], Darren Ruddell[5], Rhian Stotts[6], Aimee Krafft[7], Elizabeth Wentz[3].

[1] Arizona State University, Ph.D. Student, School of Geographical Sciences and Urban Planning *Corresponding author: oglj@asu.edu
[2] Connecticut Hydrogen Fuel Cell Coalition, Director
[3] Arizona State University, Professor, School of Geographical Sciences and Urban Planning
[4] University of Nevada, Reno, Assistant Professor, Department of Geography
[5] University of Southern California, Associate Professor, Spatial Sciences Institute
[6] Arizona State University, Lecturer, School of Human Evolution and Social Change
[7] University of Nevada, Reno, Masters Student, Department of Geography

Abstract: Geodesign is a participatory planning approach in which stakeholders use geographic information systems to develop and vet alternative design scenarios in a collaborative and iterative process. This study is based on a 2019 geodesign workshop in which 17 participants from industry, government, university, and non-profit sectors worked together to design an initial network of hydrogen refueling stations in the Hartford, Connecticut metropolitan area. The workshop involved identifying relevant location factors, rapid prototyping of station network designs, and developing consensus on a final design. The geodesign platform, which was designed specifically for facility location problems, enables breakout groups to add or delete stations with a simple point and click, view and overlay different map layers, compute performance metrics, and compare their designs to those of other groups. Using these sources of information and their own expert local knowledge, participants recommended six locations for hydrogen refueling stations over two distinct phases of station installation. We quantitatively and qualitatively compare the workshop recommendations to solutions of three optimal station location models that have been used to recommend station locations, which minimize travel times from stations to population and traffic or maximize trips that can be refueled on origin-destination routes. In a post-workshop survey, participants rated the workshop highly for facilitating mutual understanding and information-sharing among stakeholders. To our knowledge, this workshop represents the first application of geodesign to hydrogen refueling station infrastructure planning.

Keywords: hydrogen fuel cell vehicle; FCEV; stakeholder engagement; collaborative planning; geodesign; station network design; optimization models; refueling station

1. Introduction

Governing bodies throughout the world have developed mandates to curtail greenhouse gas (GHG) emissions to mitigate environmental impacts [1]. Transportation accounts for 21% of global GHG emissions [2]. Some markets have embraced fuel cell electric vehicles (FCEVs) as one means of lessening GHG emissions. FCEVs combine gaseous hydrogen (H_2) and oxygen (O_2) to produce electricity, which powers an electric motor, and water, which the vehicle emits. Limited access to H_2 refueling stations (HRSs) inhibits uptake of FCEVs, which in turn hinders demand for HRS fueling. This "chicken-and-egg problem" inhibits the formation of a hydrogen ecosystem [3].

Governance can help resolve the chicken-and-egg problem by facilitating collaboration between various actors in the public and private sectors and by providing subsidies that incentivize HRS construction to break the stalemate [4,5]. [6]. To ensure that subsidies are used most economically, or—in markets where no subsidies exist—to ensure that HRS network development constitutes a viable business venture, HRS developers must carefully locate their stations to reduce the costs and increase the revenues [7].

Various methods for locating stations to encourage alternative fuel vehicle (AFV) diffusion have been developed by industrial, civil, and electrical engineers, management scientists, and geographers. Hundreds of papers have specifically addressed the question of where to optimally locate AFV refueling or recharging stations using operations research models [8–12], which are able to solve combinatorial optimization problems in which the number of possible combinations of station locations is exceedingly large. Decision-makers and stakeholders, however, often consider a wide variety of location factors and goals that are difficult to include in optimization models. To date, there have been limited efforts in understanding some of the key differences between station locations selected by optimization models and locations recommended by stakeholders from the public and private sectors. This paper therefore asks: how does a set of HRSs that was negotiated, vetted, and ultimately selected by a group of stakeholders in a collaborative workshop setting compare to the arrangements produced by optimization methods in a region actively interested in facilitating FCEV and HRS diffusion?

This study addresses this question by using the geodesign framework—a planning method that leverages the geographic and design sciences to support stakeholder-centered decision-making about the built environment [13–21]. We collaborated with the Connecticut Hydrogen Fuel Cell Coalition (CHFCC) to convene stakeholders representing government, industry, non-governmental research and H_2 advocacy groups, and academia at a workshop. Participants generated multiple designs for an HRS network in the Hartford, Connecticut (CT), USA metropolitan region, ultimately agreeing on a rollout strategy for six new stations in the region. We compare model performance and the spatial distribution of this set of stations to the solutions generated using three well-known HRS optimization models: the p-median [22], fuel-travel-back [23], and flow refueling location models [24]. We also compare the design process that stakeholders used to generate those stations to the conceptual underpinnings of the models, as well as to the rollout strategies that HRS developers have actually used in deploying HRSs to various markets.

1.1 Literature Review

1.1.1 Geodesign

Geodesign stems from the disciplines of architecture, cartography, civil engineering, geography, urban planning, and computer science. Geodesign refers to the use of geographic information systems (GIS) to support stakeholders and decision-makers in collaborative and iterative design of the built environment. Geodesign entails four components: local stakeholders, geoscientists, information technology, and design professionals [21]. Local stakeholders identify problems, provide the quantitative and qualitative data that inform the geodesign process, review the design solutions generated by the geodesign process, and make the ultimate decisions on which solution to recommend. Geoscientists model the study area's physical, ecological, and social systems and how interventions may change the area. Information technologies map the study area, run the geoscientists' models, compare results, and facilitate communication among stakeholders and specialists. Design professionals work with stakeholders and geoscientists to design, assess, interpret, and improve the model results. These four components often overlap, and individuals involved in a geodesign study might fill several roles.

Given geodesign's openness toward diverse and interdisciplinary methods, tools, and epistemologies, there is no standard way of doing geodesign. While the actual method developed by the geodesign research team will vary with each project, most use a meta-planning framework that guides the development of a plan for improving the built environment [14]. Geodesign frameworks solicit needs, observations, concerns, and ideas from stakeholders via a planning support system or spatial decision support system that integrates GIS, models and multi-criteria analysis in a digital platform. Steinitz [21] developed a framework (Fig 1) for systematically planning changes to the built environment via geodesign. The geodesign team works in three phases: understanding the scope of the project, planning the workshop, and conducting the workshop [25]. Each phase uses a series of models and technologies to understand facets of the built environment, the stakeholders, and relationships between the two, and to produce outputs that evaluate the impacts of proposed changes. Representation models describe the study, its contextual setting, and its composite systems; the team can then identify factors that will impact negotiations and decision-making between stakeholders. Process models simulate the study area's future without any intervention. Evaluation models assess challenges and opportunities for change. Change models assess alternative futures for the study area. Impact models determine the social, economic, and environmental impacts of those changes. Decision models support negotiation processes by which decision-makers select a course of action. Although Figure 1 presents the framework linearly, in practice it need not be linear, sequential, nor inclusive of every step. Many geodesign scholars have adopted this framework for conducting geodesign [14,21,26–28].

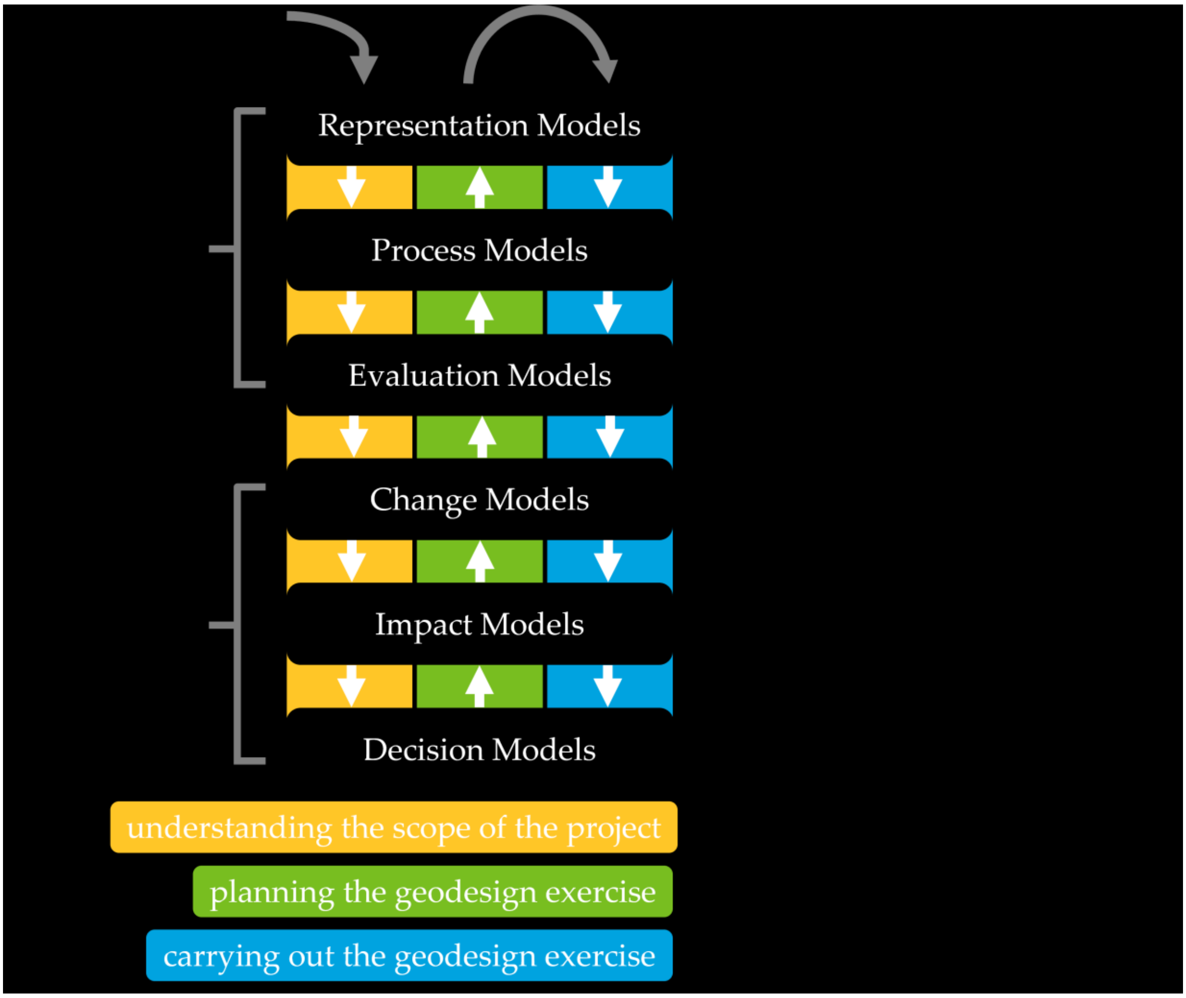


Figure 1. This visual aid—adapted from Steinitz [21]—represents a framework for geodesign. Each vertical column of arrows represents one of three phases: understanding the scope of the geodesign exercise, planning the geodesign exercise, and carrying out the geodesign exercise [25].

1.1.2 Methods for Locating Hydrogen Refueling Stations on a Network

There are two main approaches to planning a network of facilities in a given region: spatial overlay analysis conducted in geographical information systems (GIS), and spatial optimization models—although significant overlap exists between the two [29]. The literature includes models originally developed for other kinds of facilities or fuel stations that have been adapted to siting HRSs, as well as models originally designed for HRSs.

1.1.2.1 Spatial Overlay Analysis

The GIS approach to facility location creates, collects, and analyzes spatial data to develop a spatial plan for facility locations. The process varies depending on the team members, methods, data, resources available , and project goals. Some commonalities include using multiple layers of georeferenced data that represent particular geographic phenomena important to understanding a study area's spatial context, combining and superimposing those layers to help identify locations suitable to site location, stepwise site selection, and using maps to visualize and communicate spatial information and outputs [30]. GIS methods excel in fulfilling Church and Murray's [29] second law of location science—namely, that spatial context impacts the efficacy of facility locations—due to GIS' flexibility in incorporating a variety of spatial data during analysis.

The California Highway Infrastructure Tool (CHIT) exemplifies the use of GIS for HRS location planning [31]. CHIT assesses past, present, and projected supply and demand for FCEVs and for H_2 throughout California, identifies gaps in the existing HRS network, and recommends new station locations to fill gaps where projected future demand is high and HRS supply is low [32]. CHIT users can alter analysis variables and datasets to explore alternative scenarios. CHIT does not provide exact recommendations for station locations; it is designed to inform the choices made by decision-makers [7].

Muratori et al. [3] describe the scenario evaluation and regional analysis (SERA) model, which maximizes station utility by prioritizing regional markets with high densities of potential early adopters, then by maximizing the overall coverage of stations within each region. The SERA model uses a probabilistic approach to provide final locations for stations and thereby accounts for variability in local conditions.

1.1.2.2 Optimization Models

Spatial optimization models define problems mathematically with an objective(s) and constraints and apply exact or heuristic techniques to solve them [33]. Operations researchers collaborate with relevant subject matter experts to: understand the problem objectives and parameters; translate those criteria into a workable objective function; validate the solution; and update the solution over time [33]. Most models for optimizing refueling station locations represent demand using one of three approaches—as points on a network, arcs on a network, or trips or paths between origins and destinations.

1.1.2.2.1 Point-Based Models

Point-based models represent demand as nodes with demand weights (e.g., population). The classic p-median model locates a number (p) of facilities and allocates each node to its closest facility to minimize the total distance or travel time experienced by customers [34]. This modeling approach is widely used for locating public facilities such as libraries, where accessibility is important but there is no strict maximum distance or travel time [28]. Nicholas et al. [35] were first to apply the p-median model to HRS location at the urban scale in California. Many others have followed, including Itaoka et al. [36], whose results comprise the blueprint for Japan's national HRS network development plan [37].

Other popular point-based models include the set cover and max cover models, which apply a maximum distance or travel time for covering a demand [38,39], and have been widely used for emergency response facilities, cell towers, warning sirens, and others with accepted standards for closeness [28]. Applications to electric vehicle (EV) charging include Frade et al. [40] in Portugal and Tu et al. [41] in Shenzhen. He, Kuo, and Wu [42] produced charging station location recommendations using each of the three point-based models in Beijing.

1.1.2.2.2 Arc-Based Models

A second approach, developed specifically for locating fuel stations, views traffic on network arcs as exerting the demand for fuel stations [43,44]. The fuel-travel-back (FTB) model [23] represents demand as arcs with annual average daily traffic (AADT) values, and solves a p-median model using the midpoint of each arc as the nodes and vehicle-miles traveled (VMT=AADT*arc length) as the weights. It was initially applied to locating HRSs in Southern California.

1.1.2.2.3 Trip-Based Models

The third general approach defines demands as origin-destination (O-D) trip volumes on their shortest/fastest paths. The flow-capturing location model maximizes the number of O-D trips that can be intercepted by any facility located on their shortest path, and has been applied to facilities for impulse purchasing or vehicle interception [45]. Kuby and Lim [24] extended this model to HRS location by assuming that drivers stop along their way to refuel and by adding a driving range of vehicles. Their flow refueling location model (FRLM) maximizes the number of O-D trips for which one or more stations along the path enable vehicles to complete a round trip without running out of fuel or charge. Kuby et al. [46] applied the FRLM to statewide and metropolitan HRSs for the Florida Hydrogen Initiative. The FRLM has since been extended and applied to Level 2 and DC fast EV charging, battery switching, wireless charging, natural gas, and HRSs in many countries, especially for long-distance travel and trucks [47–49].

The three categories of station optimization models have been combined and compared with each other and with cost minimization. Brey et al. 2016 combined maximum VMT capture with the p-median model in a multiobjective model for Sevilla, Spain, while Stephens-Romero et al. [50] combined VMT capture with set covering in Irvine, California—both for HRSs. Badri-Koohi and Tavakkoli-Mghaddam [51] combined the FRLM and p-median approaches for Tehran. Honma and Kuby [52] compared the effectiveness of node- and path-based models in terms of coverage and convenience on the same networks. Other models reduce the risk to station developers by locating stations to serve both fleet operators and consumers [53,54].

2. Materials and Methods

2.1 Study Area

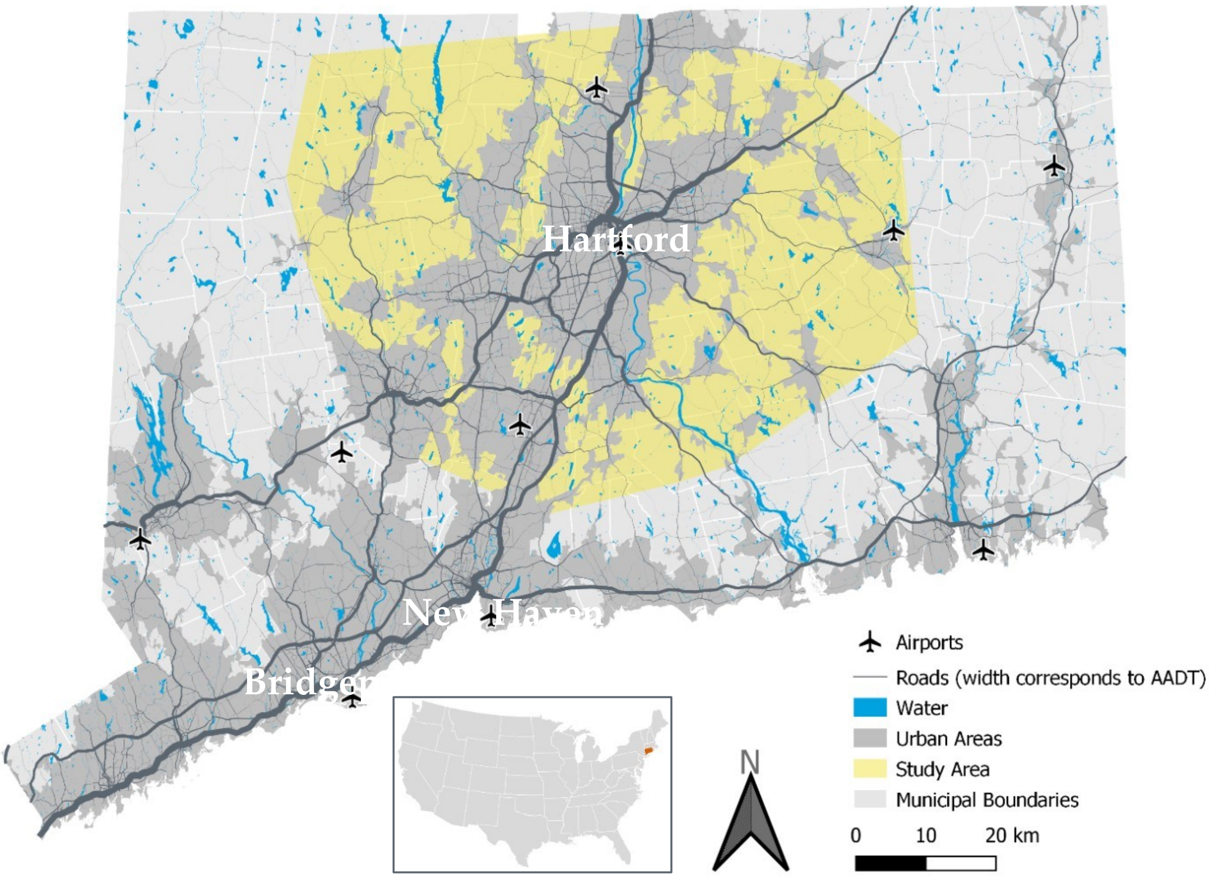


Figure 2. Connecticut, highlighted in red in the inset map, lies in the New England region of the Unites States. The city of Hartford occupies a central position within the state of Connecticut. Highways carry interstate traffic between Boston, Massachusetts (to the northeast) and New York, New York (to the southwest).

Hartford is the capital of the state of Connecticut (CT) with a metropolitan area population of 1.5 million and densities of 180 to 7150 people per mi^2 [55]. The Hartford area contains ~3,000 of Connecticut's ~15,000 miles of roadway and accounts for 1.8 million of the state's 7.7 million daily vehicle-miles traveled (VMT) [56]. Half of all CT residents live within 10 miles of their workplace, and 86% commute by automobile. About 91% of households own a vehicle and 60% own two or more. Electric vehicles accounted for 11,600 (0.88%) of Connecticut's 1.3 million registered automobiles in 2018 and 2% of new car sales in 2019 [57]. Hartford lies roughly halfway between Boston, Massachusetts and New York, New York along several interstate highways.

One publicly accessible hydrogen station exists at the NEL Hydrogen facility in Wallingford CT south of Hartford near I-91. Another station is planned near the Liebert Road exit of I-91, just north of downtown Hartford near a city bus depot and an auto-mall [58]. Both stations are located to serve local refueling demand as well as travel between New York and Boston. Connecticut and the surrounding northeast states represent the next region in the United States after California to actively explore FCEV and HRS diffusion.

Understanding how local stakeholders navigate the decision of where to place stations in central Connecticut serves to ensure future success of refueling infrastructure in the region and provide a template for other regions that may follow suit.

2.2 Geodesign Workshop

The geodesign workshop took place on Monday, October 7th, 2019 at the Connecticut Center for Advanced Technology, which is the headquarters of the CHFCC. Knowing that it would be challenging to attract experts to a 7-hour workshop, we invited over 50 individuals with different types of expertise related to the "business ecosystem" of hydrogen [59] in Connecticut. Invitees included national and local hydrogen and fuel cell experts—including members of the CHFCC—and other local stakeholders with related expertise in transportation, energy, planning, air quality, finance, engineering, and real estate. Seventeen participants attended, including several from outside of Connecticut, representing 14 different organizations that we grouped together as: Academia (7 participants); Government (4 participants); Industry (3 participants); and Hydrogen Research and Advocacy (HRA) (3 participants). We seated participants at four tables—one for each group—with one laptop and one large monitor at each table.

Steinitz [21] describes nine distinct change models that can generate potential futures; we combine the participatory and optimization change models for the purpose of this study. The "participatory change" workshop resembles a charette. Participants use GIS tools to apply changes to the study area, explore the impacts of those changes, and negotiate priorities, and explore the impacts [60–62]. The "optimization change" model uses optimization models to generate and explore potential changes to the study area [21]. Consistent with this general framework, we developed representation, process, and evaluation models (Figure 1) for the stakeholders to use during workshop deliberation [63,64], and included them in our Collablocation platform. We developed an agenda that included tasks to complete at each stage, and time limits for doing so (Table 1).

Table 1. The workshop agenda lists the goals of each phase of the workshop, the activities we used to accomplish those goals, and the times allocated to those activities.

9:00	**Introduction**	
	Tasks	• Provide brief introduction of workshop organizers • List key organizations represented • Introduce overview of Geodesign concept and process
	Outcomes	• Show and distribute Geodesign process diagram • Clarify that final goal as a group is to: **produce an agreed-upon, negotiated plan for a network of ten (10) H_2 stations for Hartford region**
9:15	**Moderated Panel**	
	Tasks	• Invite representatives from stakeholder groups to speak to all participants in panel format • A moderator will prompt stakeholder group representatives to articulate considerations that all workshop participants should be aware of when recommending stations

	Outcomes	• Produce a comprehensive list – visible to all workshop participants throughout the day – of **constraints**, **concerns**, and **criteria** that should be considered when recommending stations locations
10:15	Break	
10:30	**Collablocation Demonstration**	
	Tasks	• Workshop organizers provide demonstration to orient all participants to the software interface
	Outcomes	• Participants see a directed example of how to identify and select station sites, save a layout, and generate performance metrics
10:50	**Breakout Groups Stage 1, Part 1**	
	Tasks	• Divide workshop participants into **four (4)** groups, each of which represents a particular stakeholder group (e.g., industry, government, academia) • For each group, produce an initial map using the Collablocation tool – agreed upon *within* your group – of the top **ten (10)** station locations in the region. • List these 10 stations in order of importance
	Outcomes	• Across workshop participants, complete four (4) different station layouts: one (1) each for the four groups, each of which are saved and can be compared using the Collablocation tool
11:30	**Breakout Groups Stage 1, Part 2**	
	Tasks	• Choose one representative from your group to give no more than a **five (5) minute presentation** to the rest of the workshop participants • For your presentation, share the map and describe the priorities and variable rankings within your group
	Outcomes	• Communication to all workshop participants of the various recommended networks of ten (10) H_2 stations for the Hartford region • Identify initial points of agreement and disagreement for station locations between groups
12:00	**Assign Groups for Stage 2**	
	Tasks	• Draw a 4x4 correspondence matrix on board in front of room • Each group ranks how likely they would be to partner with other groups for next stage • Based on responses in the correspondence matrix, consolidate into two groups
	Outcomes	• Identify the two working breakout groups for Stage 2 of workshop
12:15	Lunch	
13:00	**Breakout Groups Stage 2, Part 1**	
	Tasks	• Move into the **two (2)** groups produced from correspondence matrix • Each group produces a new map using the Collablocation tool – agreed upon *within* your group – of the top **ten (10)** station locations in the region. • List these 10 stations in order of importance
	Outcomes	• Across workshop participants, complete two (2) new station layouts: one (1) each for the two groups, each of which are saved and can be compared using the Collablocation tool
13:45	**Breakout Groups Stage 2, Part 2**	
	Tasks	• Choose one representative from your group to give no more than a five (5) minute presentation to the rest of the workshop participants • After these are complete, all workshop participants discuss and negotiate the two plans
	Outcomes	• Communication to all workshop participants of the updated recommended networks of ten (10) H_2 stations for the Hartford region • Identify current points of agreement and disagreement between groups

14:15	Break		
14:30	**Stage 3**		
	Tasks	• Complete any final negotiations and discussions • All workshop participants – as one group - create a map that shows the top ten (10) stations in the Hartford region. • List these 10 stations in order of importance	
	Outcomes	• Complete one new, final station layout, saved in the Collablocation tool	
15:00	**Workshop Wrap-up**		
	Tasks	• Review final recommended station layout • Discuss/identify key near-term next steps that would need to be completed to realize the recommended station layout • Discuss/identify key long-term next steps that would need to be completed to realize the recommended station layout	
	Outcomes	• Share final map with all workshop participants • Summarize key comments that emerged from group discussions • Produce a list of short-term and long-term next steps that would need to be accomplished to produce recommended station layout	
16:00	Close		

We followed Steinitz's recommendation that participants carry out the design process for at least three stages so that they have sufficient opportunity to improve on previous designs (Figure 3). In the first part of the first stage, the four stakeholder groups worked separately using the Collablocation tool to design several versions ("iterations") of HRS network plans before agreeing on a preferred one within their group. In the second part, a representative from each group presented their group's design iteration to the other groups. At the end of Stage 1, the facilitator engaged groups in a short exercise to determine whether they were "very compatible," "incompatible," or "very incompatible" with each other group. The resultant matrix informed the pairing of stakeholder groups for the second stage, in which the two merged groups designed several new infrastructure iterations, presented their preferred alternative to the other group, and discussed their strengths and weaknesses with the aid of the facilitator. In the third and final stage, all participants merged into one large group using the room's main screen to converge toward a consensus station network design by the end of the workshop.

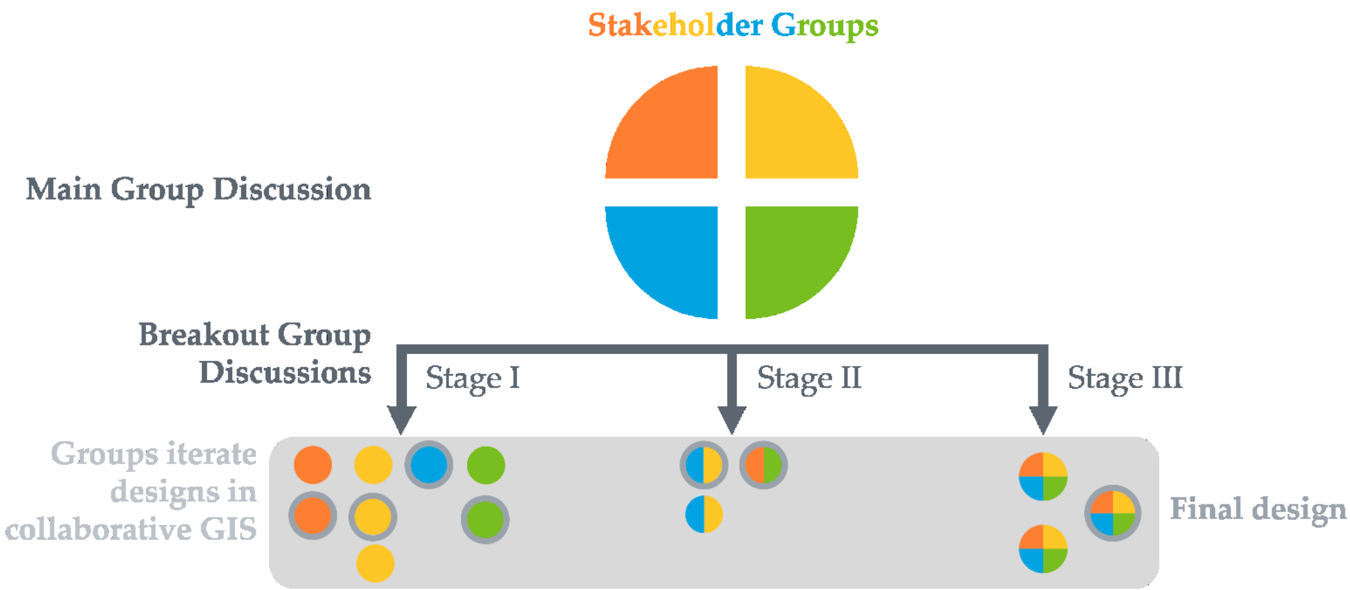


Figure 3. This schematic exemplifies the geodesign workshop structure. Stakeholder groups collaboratively generate one or more design iterations and select one to present to the main group. In successive stages, stakeholder groups increasingly work together to achieve a final design.

To study the collaborative geodesign process, we drafted a set of factors or themes for note-takers to observe and record group discussions (Table 2). At least one member of our research team sat with each stakeholder group at each stage to take qualitative notes about the group's activities related to these themes. We recorded audio of the main group discussion sessions at the end of each stage and reviewed them afterwards. Finally, we concluded the workshop with a quantitative survey to gauge participant satisfaction with the workshop.[1]

Table 2. Themes considered by groups and captured by note-takers during the Hartford geodesign workshop

Theme (consideration by group during design activity)
Map layers
Station and iteration metrics
Pre-packaged optimization solutions
Designs by other groups in earlier stage
Previous solutions by same group
Outside knowledge (not visible in any map layer or performance metric)
Other—tool, scale, supporting long-distance travel, etc.
Final decision

2.3 Collablocation

[1] The Arizona State University Office of Research Integrity and Assurance approved all procedures for studying participants under code STUDY00005048.

Collablocation is an open-source geodesign platform designed specifically for locating point-based infrastructure facilities. Locating point-based infrastructure facilities on a transportation network contrasts with assigning land uses to polygons, which has been the predominant aim of geodesign studies to date. Kuby et al. [65] originally developed Collablocation for a geodesign workshop for locating a network of compressed natural gas (CNG) refueling facilities for long-distance truck travel in the US southwest. In this paper, we adapted the Collablocation platform to the task of locating HRSs at the metropolitan scale in Hartford and included the layers described in Table 3.

Table 3. Spatial Data Layers in the Collablocation Platform

Layer	Source	Description
H_2 Stations	DOE Alternative Fuels Data Center	Existing or planned stations with fuel for retail to the public
Candidate sites	Google Maps	Existing gas stations in the Hartford metropolitan area
Annual average daily traffic (AADT)	CT Department of Transportation	AADT, separated into interstate, other freeway, major arterial, and minor arterial sub-layers
Population	CRCOG	2015 populations for aggregated traffic analysis zones
Trips (to or from)	CRCOG	Number of trips originating from or terminating at traffic analysis zones
Optimization model results	Optimized by our team for this paper using dataset from Zhao et al. (2019)	6 sublayers depicting locations of additional 3 or 8 HRSs as determined by p-Median, FRLM, and FTB models
Opportunity zones	US Dept. of the Treasury	Economically distressed communities where new investments, under certain conditions, may be eligible for preferential tax treatment
Natural gas pipelines	US Energy Information Association	Natural gas pipelines in CT
Existing points of H_2 demand	CHFCC; Google Maps	Sublayers representing auto dealers, warehouses, cold-storage facilities, food processing facilities, metal finish shops, transit companies, truck parking, and wholesale retailers—all of which present opportunities for HRS co-location

2.4 Optimization models

Prior to the workshop, we applied three optimization models to generate networks of 5 and 10 HRSs in metropolitan Hartford, and added them as map layers in the geodesign tool for stakeholders to consider—if they chose to do so. The mathematical formulation of each model is given in Table 4, using consistent notation to the extent possible. In the formulations, the index *j* refers consistently to candidate site locations. The indices *i*, *a*, and *q* refer to the fuel demands at residential nodes (*i*), arc centroids (*a*), and O-D round-trip paths (*q*). X_j always refers to a 0-1 decision variable whether to open a station at *j* or not, and *Y* variables always refer to some type of 0-1 demand allocation or coverage variable.

Table 4. HRS Optimization Model Formulations

p-Median Problem (PMP)	Fuel Travel Back Model (FTB)	Flow Refueling Location Model (FRLM)
$Min \sum_i \sum_j a_i t_{ij} Y_{ij}$ (1)	$Min \sum_a \sum_j v_a t_{aj} Y_{aj}$ (7)	$Max \sum_q f_q Y_q$ (13)
Subject to	Subject to	Subject to
$\sum_j Y_{ij} = 1 \; \forall i$ (2)	$\sum_j Y_{aj} = 1 \; \forall a$ (8)	$\sum_{j \in Z_a^q} X_j \geq Y_q \;\; \forall q, a \in A_q$ (14)
$Y_{ij} \leq X_j \; \forall i, j$ (3)	$Y_{aj} \leq X_j \;\; \forall a, j$ (9)	$\sum_j X_j = p$ (15)
$\sum_j X_j = p$ (4)	$\sum_j X_j = p$ (10)	$Y_q \in \{0,1\} \;\; \forall q$ (16)
$Y_{ij} \in \{0,1\} \;\; \forall i, j$ (5)	$Y_{aj} \in \{0,1\} \;\; \forall a, j$ (11)	$X_j \in \{0,1\} \;\; \forall j$ (17)
$X_j \in \{0,1\} \;\; \forall j$ (6)	$X_j \in \{0,1\} \;\; \forall j$ (12)	
where common terms for all models include: X_j = 1 if an HRS is opened at *j*, 0 otherwise (decision variable) *p* = number of HRS to open and		
Y_{ij} = 1 if demand node *i* is allocated to HRS *j*, 0 otherwise (dec. var.) a_i = population of node *i* (number of people) t_{ij} = travel time from demand node *i* to HRS *j* (hours)	Y_{aj} = 1 if arc centroid *a* is allocated to HRS *j*, 0 otherwise (dec. var.) v_a = traffic on arc *a* (vehicle-miles traveled) t_{aj} = travel time from arc centroid *a* to HRS *j* (hours)	Y_q = 1 if path *q* is refuelable, 0 otherwise (dec. var.) f_q = flow on O-D round trip *q* (number of weekday trips) A_q = set of directional arcs on round trip *q* Z_a^q = set of candidate sites that can cover directional arc *a* on round trip *q* given the driving range

The node-based p-median problem (PMP):

1. minimizes total weighted travel time from residential nodes to their nearest stations, weighted by node population;
2. requires that every demand node *i* is allocated to exactly one HRS *j*;
3. states that a demand node *i* can only be allocated to an HRS *j* if that station is open;
4. limits the number of stations opened to *p;*
5. limits the possible solution values of Y_{ij} to 0 or 1; and
6. does the same for location variables X_j.

The arc-based fuel-travel-back (FTB) model:

7. minimizes the total weighted travel time from vehicles driving on arcs to their closest stations, weighted by the arc's VMT, which is considered to represent the likelihood of vehicles needing a fill-up while traveling the arc, spurring the driver to seek the closest station to that arc at that time, and returning to that arc to continue their trip.

Constraints 8-12 are similar to constraints 2-6 except for substituting arc centroid a for node i.

For the path-based flow refueling location model (FRLM), we use the Arc Cover-Path Cover formulation by Capar et al. (2013):

13. maximizes the number of O-D round trips that can be completed while not detouring off their least-travel-time routes given a reasonable driving range of FCEVs;
14. ensures that a trip on path q can be completed (Y_q =1) only if *every* directional arc a on the round trip is covered by one of the HRSs (defined by the set Z_a^q) that can enable an FCEV to traverse the full arc without running out of fuel;

Constraints 15-17 are similar to constraints 4-6 for limiting the number of stations to p and defining the binary nature of the decision variables.

After the stakeholders reduced the recommended number of new stations from eight to six, we solved the same three optimization models for this lower number, and compared these new optimal solutions to the participants' recommendations. In addition, we felt it was necessary to also compare the geodesign recommendations to the Deviation Flow Refueling Location Model (DFRLM) [66], because the workshop participants clearly were assuming some willingness of early FCEV adopters to deviate from highway routes to refuel at the locations they were recommending. The DFRLM model runs assumed a maximum deviation of 12 minutes, with no penalty for deviations.

The AC-PC-FRLM was solved using FICO Xpress 7.9 on an Apple iMac running Parallels with Windows 7 with 3.4 GHz Intel Core i7 and 12 GB RAM allocation. The DFRLM was solved using the greedy-substitution algorithm in [66] on the same computer. The PMP and FTB were solved using ArcMap 10.6.1 Network Analyst's Location-Allocation function on a Dell laptop with 2.6 GHz Intel Core i7 with 16 GB RAM.

The data for all models were defined as consistently as possible for a fair comparison. All four models used the same network of 1,344 highway and major road arcs and 806 nodes. The nodes were both arc junction points and candidate HRS sites. All routing calculations used travel times based on posted speed limits with a 15% speed penalty for non-freeway travel. The PMP and FRLM used the same set of 514 travel analysis zones and zone centroids, aggregated from an original set of 1,829. The AADT volumes for the FTB were based on the 254,196 aggregated path flows from the FRLM for consistency. O-D flows were provided by the Capitol Region Council of Governments (CRCOG). A conservative FCEV driving range of 100 miles was assumed based on the HRS spacing required by the FAST ACT. See Zhao et al. [67] for details.

All four model implementations are capable of forcing selected stations into the solution to include existing and under-construction stations in the set of *p* stations. This feature, which sets X_j =1 for the given stations, was also used to calculate the objective function values for the set of stations chosen by the geodesign workshop's stakeholders.

2.5 Point Pattern Analysis Metrics

GIScience has developed a number of methods for summarizing and comparing sets of points. We use several common descriptive point pattern analysis measures to characterize and compare the spatial distributions of the arrangements of station locations produced by the models and the workshop participants [68]. For the four arrangements of station points, we compute each of the following metrics for comparing the workshop's arrangement of stations to the locations chosen by the optimization models:

- The mean center, or the point produced by the average x and y coordinate values of each arrangement of points.
- The mean distance between all pairs of stations generated in each optimization model or workshop output.
- The area and perimeter of the convex hull, i.e., the smallest convex polygon that bounds a set of points.
- The area and perimeter of the minimum bounding rectangle produced by using the maximum and minimum x and y coordinates observed in the set.

Comparing the mean centers and mean distances between all station pairs helps characterize and compare the distributions of points throughout the region and how close points are to each other in each arrangement. Comparing the area and perimeter of the bounding polygons and rectangles measures the spatial extent of the area participants chose for station deployment.

3. Results

3.1 Geodesign Workshop

During the moderated opening panel, stakeholders generated a list of factors critical to the task of locating HRSs in the Hartford metropolitan area (Table 5). While some of these factors can be incorporated into a single mathematical optimization model, the list illustrates the wide range of issues that different stakeholders considered to be relevant.

Table 5. Important factors to HRS siting determined by workshop participants prior to deliberation.

Highway access	Demography	Renewable sources of H_2	Funding
Long-distance connectors	Employment	Station capacity	Permitting & zoning vary by jurisdiction
Fleets	Destinations	Varying pressures required per vehicle type	Regulations

Bus / car interaction	Setbacks, footprints, parking	Redundancy (supply interruptions, equipment failure)	Tunnel restrictions
Routes		Zero-emission electricity credits	Fire hazards & safety perceptions

3.1.1 Stage 1

In Stage 1, we tasked the four stakeholder groups with locating eight new stations in addition to the one existing and one planned HRS in the study area, for a total of ten stations (Fig 4). A notetaker at each table observed each group's deliberations, summarized below.

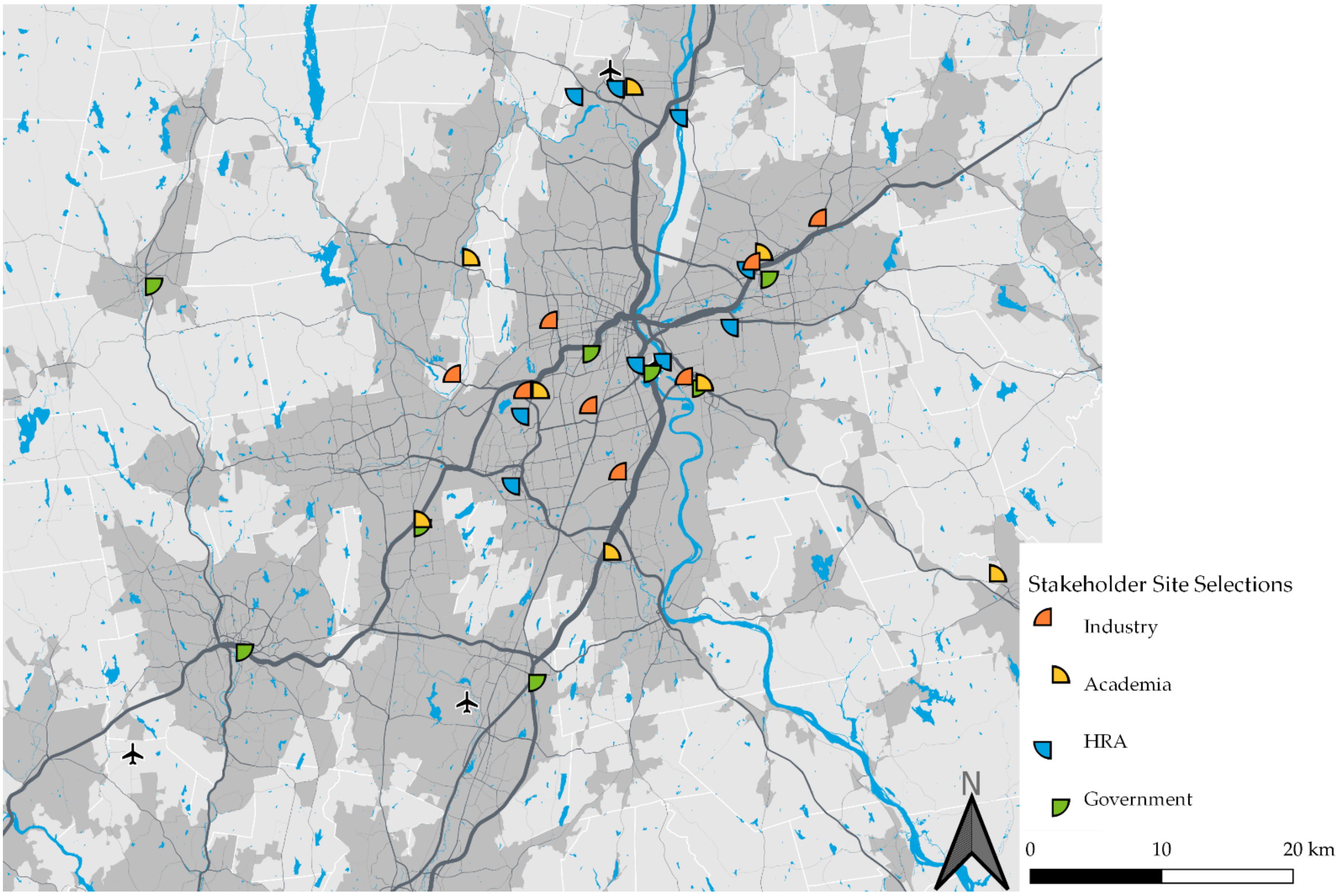


Figure 4. The final HRS network designs of each stakeholder group in Stage 1

3.1.1.1 Academia

The Academia group (7 stakeholders) considered two strategies for developing a nascent HRS network: serving populations of likely early adopters of private vehicles, or serving vehicle fleet operators. The group chose to prioritize early adopter populations by profiling primary travel corridors and co-locations with trip purposes that the group profiled as common to early adopters. They referred to the *p*-median model in their deliberation, and began their site selection by prioritizing clusters of homes and destinations. They identified locations near early adopter populations based on demographic profiles. The group then reasoned that co-locating with retailers that are frequented by higher-income customers—mainly the grocery stores Whole Foods and Trader Joe's—would also maximize the visibility of the HRSs as demonstration sites. The group used a mapping application external to the Collablocation platform to search for and locate these grocery stores. Upon achieving coverage of early adopter populations, the group next sited one station near Bradley International Airport and several stations to support long-distance travel. The group agreed a network of 10 stations would be more than necessary for an early HRS network, and that 5 or fewer stations would suffice for the region. This group generated only one design iteration.

3.1.1.2 Government

While the Government group (4 stakeholders) prioritized their first locations in areas that they profiled as high-income, they sought even geographical dispersion of HRSs across the Hartford metropolitan area. The Government group supposed that electric vehicle supply equipment (EVSE) installations would exist in locations convenient to early adopters. They therefore used a mapping application external to the Collablocation platform to search for and locate these EVSE installations. They sought locations near major traffic confluences, with driving times of five minutes or less from interstates. The group accounted for zoning by co-locating with CNG stations and accounted for setback requirements by using satellite imagery to determine if enough space existed on any potential site—though they noted that a topographic layer would be more useful in this regard. The group further considered how property taxes would factor into a station's operating costs. They independently came to the conclusion that a network of 10 stations would be too many for an early HRS network, and also generated only one design iteration.

3.1.1.3 Hydrogen Research & Advocacy

The HRA group first focused their attention on Bradley International Airport, noting the potential for servicing the fleets of airport vehicles, shuttles, and rental cars, as well as nearby employers. This group established clusters of stations to provide redundancy in the event of station unreliability. They surmised that clusters of stations near destinations common to early adopters and clusters along major travel routes would preclude the need to place stations in residential areas. This group used the Collablocation platform to assess the performance of their network, and consulted the FRLM (p=10) results when refining their final site selections. This group generated three design iterations and chose their second iteration as best.

3.1.1.4 Industry

The Industry group began by considering the setbacks, building footprints, available parking, and onsite H_2 storage code requirements needed to construct HRSs. This group noted that one station could service multiple bus routes and that passenger vehicles would require a network of stations; thus, co-locating HRS with bus depots would support multiple modes of transportation. This group emphasized servicing roads with high AADT, though they noted that stations with low performance metrics would suffice in an early network if they supported early adopters. This group generated fifteen design iterations. In the thirteenth iteration, the group removed the lowest performing stations in favor of stations with more highway coverage and network redundancy. The group then attempted to place a station near Bradley International Airport, but the resultant networks performed worse than their thirteenth iteration, which they preferred most.

3.1.2 Stage 2

3.1.2.1 Combining Stakeholder Groups

Following the presentations from each stakeholder group in Stage 1, the facilitator asked each stakeholder group to discuss among themselves and assess the compatibility of their plans with each other stakeholder group. Based on the resulting matrix, we paired Academia and Government together as one group with 11 participants and Industry and Hydrogen Research & Advocacy as a second group with six participants for Stage 2 deliberations

Table 6. Stakeholder group compatibility assessments

++ = *very likely compatible* + = *likely compatible* - = *likely incompatible* -- = *very likely incompatible*		**Stakeholder group being assessed:** Academia	Government	Industry	Hydrogen Research & Advocacy
Stakeholder group assessing compatibility	Academia		++	++	++
	Government	+		++	++
	Industry	-	++		+
	Hydrogen Research & Advocacy	-	+	++	

3.1.2.2 Academia & Government

This combined group began by consolidating their five agreed-upon points, then agreed to service the Bradley International Airport and its associated fleets with one station and a state highway with another. The groups narrowed their final selection by considering individual site characteristics, such as the space available on candidate gas station lots for locating HRS equipment that could support a high volume of sales. This group generated one design iteration (Figure 5).

3.1.2.3 HR&A & Industry

These groups began by combining their best iterations from Stage 1. The groups then eliminated redundant stations, determining which stations in any cluster contributed least to the overall network on a case-by-case basis. Where possible, the groups chose sites with common land owners—e.g., Shell or Whole Foods—to reduce the number of partners with whom leases would need to be negotiated. This group also generated one design iteration.

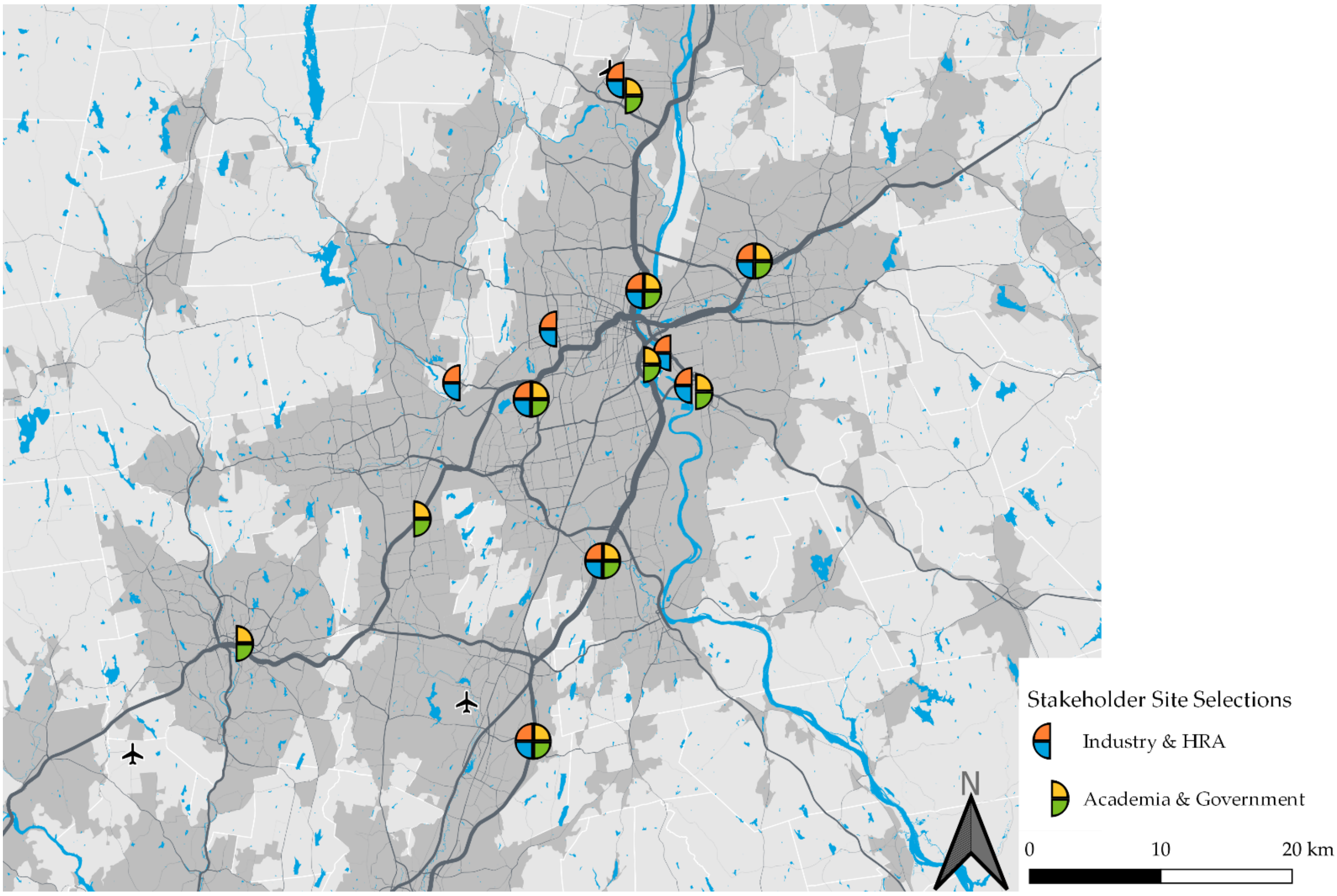


Figure 5. The HRS network designs generated by the combined stakeholder groups in Stage 2.

3.1.3 Stage 3

In the final stage, all stakeholders convened as one large group, with the Collablocation platform and the two Stage 2 designs projected on a large screen. In addition to the two existing/planned stations, three stations were selected by both groups and remained in the final group of recommended stations, and three pairs of stations were near enough to each other that the group selected one station from each of the three pairs. Participants deliberated on the final two stations based on the presence or absence of early adopter populations, the logistics of resupplying stations with H_2, and the experiences of participants in attempting to develop stations in certain areas.

After identifying these ten stations, the full group agreed that the Hartford metropolitan area needs only six new stations in addition to the two existing/planned stations in the area (Figure 6). They prioritized the three more central and consumer-oriented stations in an initial phase of construction, and the three more outlying stations, with larger capacities for trucks and other large vehicles in a second phase. Table 7 describes the perceived strengths and weaknesses of each recommended location

Table 7. Information about Existing, Under-Construction, and Recommended Stations

Approximate Location	Nearby Gasoline Stations	Strengths Cited	Weaknesses Cited
Phase 0 - Existing and Under Construction Stations Open to the Public			
Wallingford, CT Nel Research Parkway near I-91		Accessible from I-91 Short detour from Wilbur Cross Pkwy, I-691, US-5, CT-66, 68, and 15. Midway between Hartford and New Haven Near potential fleet adopters	
Hartford, CT I-91 & Liebert Rd.		Near Transit Facility Near auto mall Accessible from I-91 Short detour from I-84 and I-I-291. Near potential fleet adopters.	
Phase 1 – Highest Priority Locations (in alphabetical order)			
Glastonbury	7-11, Mobil, Cumberland Farms, Stop&Shop, Shell	Accessible from CT-2 & CT-3. Short detour from I-91 Near Pratt & Whitney First adopter demographics, Whole Foods, mall Connector to New London	Not a major fleet hot spot
Manchester Buckland Hills Mall Area	Mobil, Shell, BJ's	Accessible from I-84 Short detour from I-291, I-384 Major trip generator Commercial center and Trader Joe's Connector to Boston	Not a major fleet hot spot
New Britain CT-9 New Britain Ave./ Hartford Rd.	Sunoco, Costco	Accessible from I-84 Short detour from Near Blue Back Square mall in West Hartford Near UConn Health, CCSU First adopter demographics, Whole Foods and Trader Joe's	Not a major fleet hot spot Not realistic to site in Blue Back Square, so sited in less congested area in nearby New Britain
Phase 2 – Second-Priority Locations (in alphabetical order)			
Bradley International	Pride, Mobil, Valero, Sunoco	Accessible from CT-20 Airport fleet vehicles, including taxis, shuttles,	Good sites lacking directly off I-91 near airport, so sited

Airport/Ella Grasso Turnpike		rental cars, baggage carts, buses	near airport itself 3 miles from I-91
Cromwell I-91 & Berlin Rd.	Sunoco, Mobil	Accessible from I-91 and CT-9 Near Middletown and Berlin, Wesleyan College	
Cheshire CT 322	Mobil, Bouchard, Gulf	Accessible from I-84 and I-691 Near Southington, Waterbury, Meriden Connector to New York, Danbury, Waterbury	

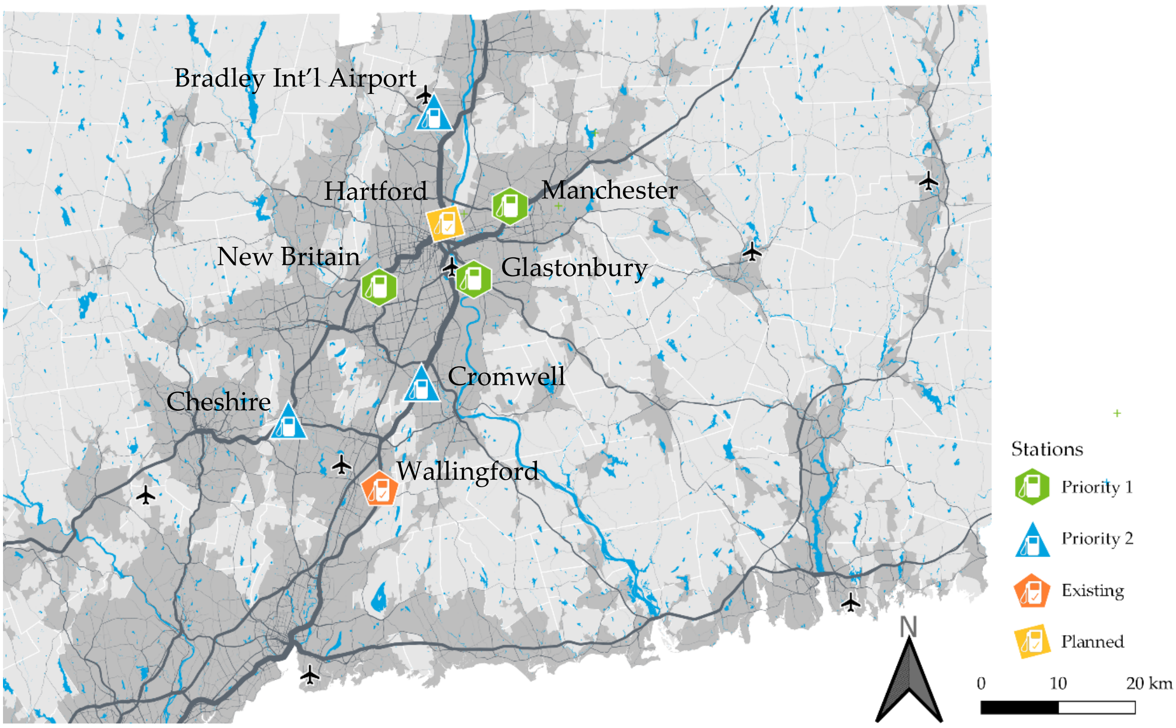


Figure 6. Map showing existing, under construction, and final set of recommended stations

3.1.4 Survey

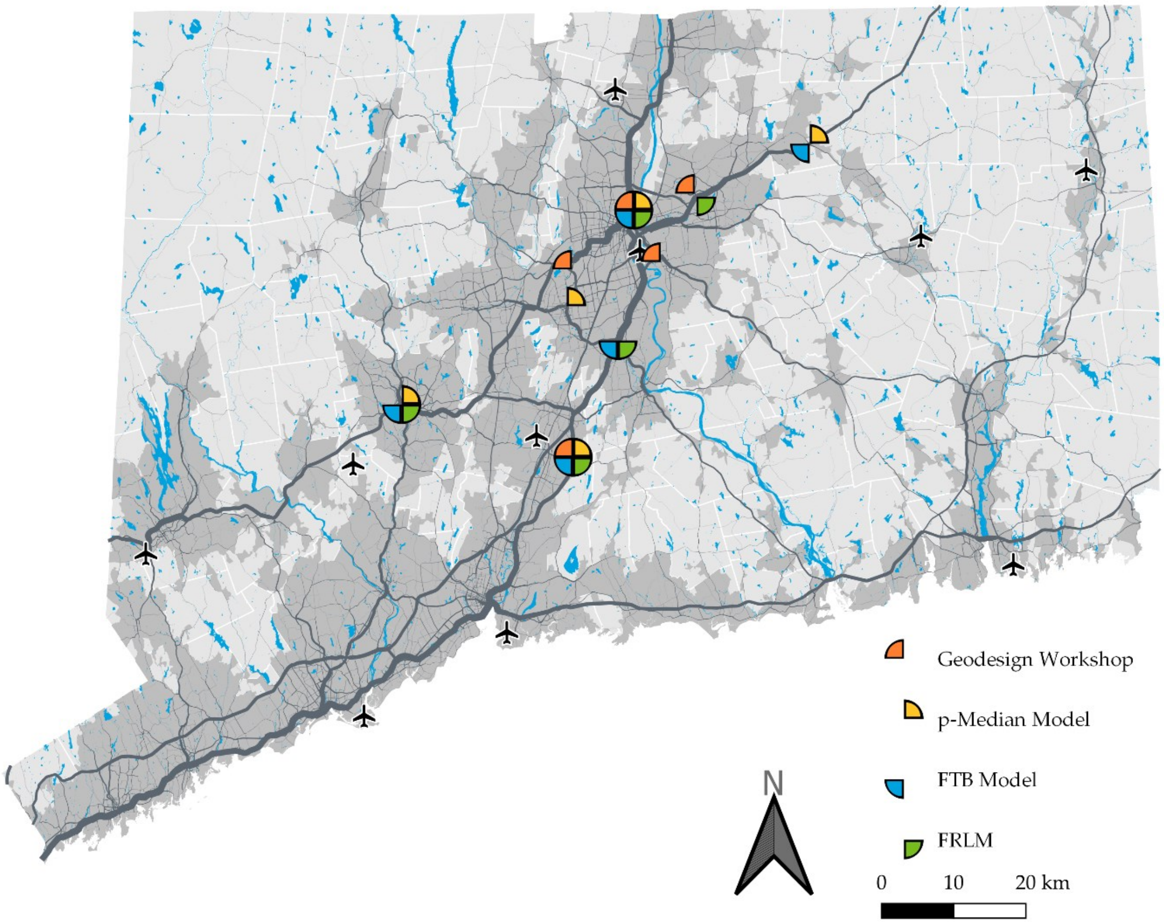
A nine-point Likert survey conducted at the end of the workshop demonstrated participant satisfaction with various facets of the workshop process (Table 8). Participants were most satisfied with the interdisciplinary knowledge exchange that took place during the workshop. Participants were least satisfied with the user experience and analytical capabilities of the Collablocation platform, though it still rated favorably on these criteria and overall, consistent with [64].

Table 8. Survey results demonstrating participant satisfaction with various facets of the workshop process (0 = dissatisfied , 9 = satisfied; n = 12)

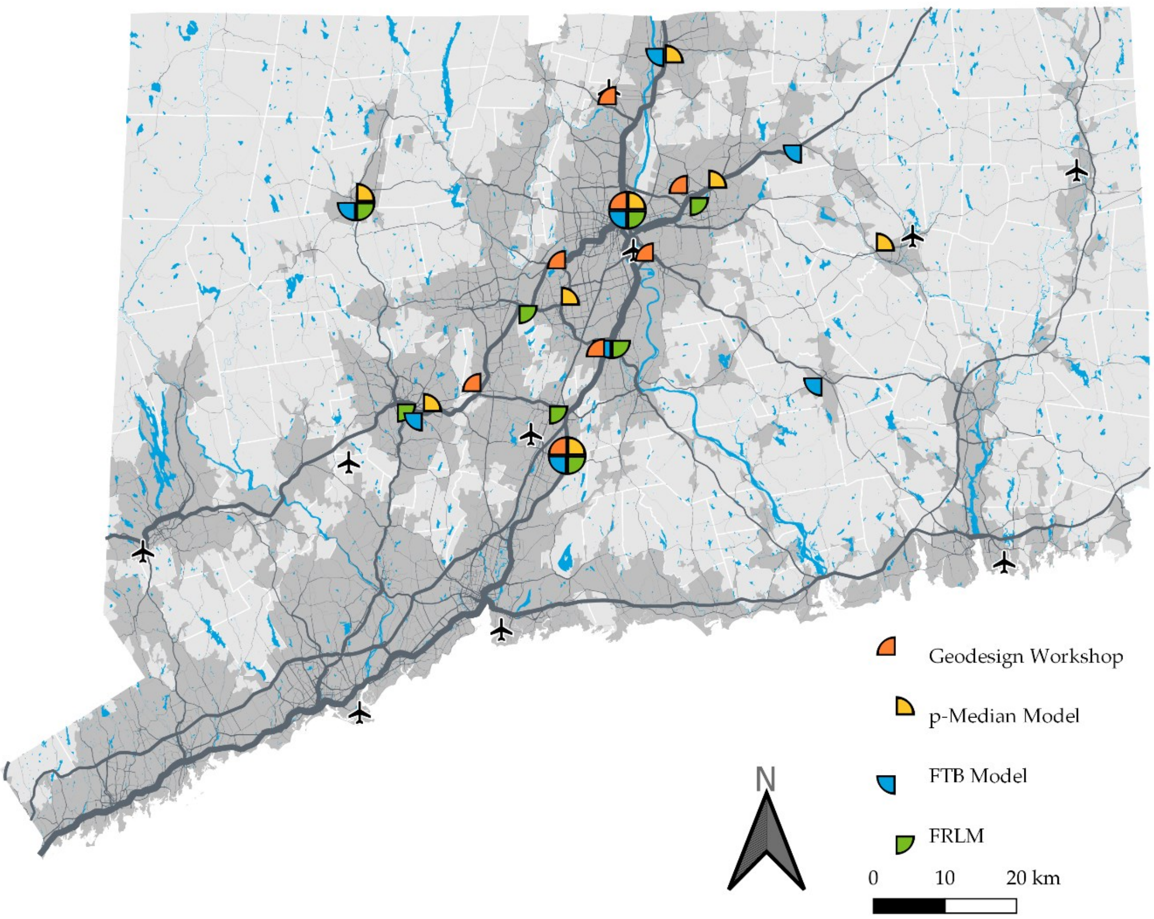
Question	Mean	Median
How satisfied are you overall with the workshop design?	8.1	8
How satisfied are you overall with the solution from Part III (the iterated constrained version)	7.7	8
How satisfied are you that the list of factors generated during the workshop is comprehensive (meaning, no significant factors are missing)?	7.7	8
How satisfied are you with the level of knowledge exchange the workshop promoted between YOU and OTHER PARTICIPANTS (not including the researchers and organizers)?	7.8	8.5
How satisfied are you with the EASE OF USE of the geodesign platform?	7.4	7
How satisfied are you with the TECHNICAL ANALYTIC capacity of the geodesign platform?	7.4	7

3.2 Qualitative Comparison between Geodesign and Optimization Results

Figure 7 compares the locations recommended by the workshop with the optimal stations generated by the p-median model, FRLM, and FTB model results for eight new stations and two existing/planned stations.



(a)



(b)

Figure 7. The HRS network designs generated by the geodesign workshop, the p-median model, the FTB model, and the FRLM for (a) 5 stations and (b) 8 stations.

Geographically, the workshop results are more tightly clustered around the Hartford urban core than any optimization model results. This is particularly true for p = 5, in which all three workshop-recommended stations are close to downtown Hartford and the planned station north of downtown. In contrast, the *p*-median and FRLM models located only one out of five stations centrally while the arc-based FTB model located no stations centrally. Instead, all three optimization models located a station in Waterbury, CT, which workshop participants considered too "industrial" to fit the typical early adopter profile. Two other highway-oriented locations were also selected by two of the three optimization models, which highlights the importance of travel times and volumes in all three optimization models. One area of agreement between the workshop recommendations and all three optimization models is to orient the 5 stations along the dense and heavily traveled New York-Boston axis.

In the p = 8 networks, all of the workshop-generated HRS locations continue this southwest-northeast orientation, while the optimization models add stations in the northwest and southeast quadrants. The optimization models provide better coverage to the far reaches of the study region than the workshop output did.

The workshop participants placed a station about 1 km from Bradley International Airport. The p-median and FTB models also locate stations about 10 km from the airport, closer to Springfield, Massachusetts than to Hartford, Connecticut.

3.3 Quantitative Comparison of Workshop and Optimization Model Results

3.3.1 Objective Function Performance Metrics

The *p*-median model minimized the overall travel time from population centers to their nearest HRSs. The FTB model minimized the overall travel time from the VMT on road arcs to their nearest HRSs. The FRLM and DFRLM maximized the number of round trips that can be conducted without running out of fuel. Table 9 compares the performance of the geodesign workshop's recommended locations on these same criteria to those of the single-objective solutions to each optimization model. Note that low travel time is better than high for the *p*-median and FTB models, while high trip coverage is better than low for the FRLM and DFRLM. The maximum travel time from any demand point to the nearest HRS location is also provided for the *p*-median and FTB models as an additional point of comparison.

Table 9. Comparison of model and workshop coverage results for 5 stations

Model	Network generator	Total travel time (weighted hours) PMP and FTB objective	Max. travel time(hours)	Covered Trips (%) FRLM/DFRLM objective
p-median	model	276,075 person-hours	0.69	n.a.
	workshop	334,599 person-hours	0.88	n.a.
FTB	model	3286023 VHT[1]	0.78	n.a.
	workshop	4,273,191 VHT	1.08	n.a.
FRLM	model	n.a.[2]	n.a.	15.34
	workshop	n.a.	n.a.	8.97
DFRLM	model	n.a.	n.a.	54.27
	workshop	n.a.	n.a.	38.76

[1]*VHT = Vehicle-Hours Traveled*

[2]*n.a. = not applicable*

Table 10. Comparison of model and workshop coverage results for 8 stations

Model	Network generator	Total travel time (weighted hours) PMP and FTB objective	Max. travel time(hours)	Covered Trips (%) FRLM/DFRLM objective
p-median	model	218,118 person-hours	0.64	n.a.
	workshop	264,734 person-hours	0.72	n.a.
FTB	model	2,469,915 VHT[1]	0.56	n.a.
	workshop	3,223,744 VHT	0.9	n.a.
FRLM	model	n.a.[2]	n.a.	23.4
	workshop	n.a.	n.a.	14.56
DFRLM	model	n.a.	n.a.	70.02
	workshop	n.a.	n.a.	53.71

[1]*VHT = Vehicle-Hours Traveled*

[2]*n.a. = not applicable*

For 5 stations, the workshop's recommendation did best in percentage terms on the *p*-median criteria (21% from optimal), followed by the DFRLM criteria (28.6% from optimal), and the FTB model criteria (30%); the workshop's recommendations performed worst on the FRLM criteria (41.6% from optimal). For 8 stations, the workshop's recommendation did best in percentage terms on the *p*-median criteria (21% from optimal), followed by the DFRLM criteria (23.3% from optimal), and the FTB model criteria (31%); the workshop again performed worst per the FRLM criteria (38% from optimal). As expected, the workshop's chosen stations did much better on the DFRLM's objective, which allows drivers to detour 12 minutes to refuel, than on the FRLM's more stringent objective allowing no route deviations whatsoever.

3.3.2 Point Pattern Analysis Metrics

Tables 11 and 12 compare the point-pattern metric for the three optimization solutions and the workshop recommendations for five and eight stations. The workshop results were objectively more compact than any of the models, as measured by convex hull area and perimeter; minimum rectangle area and perimeter; and the mean distance between stations. The FRLM results were nearest to the workshop results in compactness by all measures. However, the mean center of the FRLM was farthest (to the southwest and New York) from that of the workshop mean center for both $p = 5$ and $p = 8$, while the FTB model's mean center was closest to the workshop mean center for both $p = 5$ and $p = 8$.

Table 11. Point pattern analysis metrics for 5 stations (p = 5)

Network Generator	Convex Hull Area (km²)	Convex Hull Perimeter (km)	Minimum Rectangle Area (km²)	Minimum Rectangle Perimeter (km)	Mean Distance Between Stations (km)	Distance from Mean Center to Workshop Mean Center (km)
p-median	818.2	147.5	1391	175.0	3.544	5.477
FTB	818.2	147.5	1391	175.0	3.549	5.288
FRLM	580.2	115.8	1041	142.5	2.908	8.388
Workshop	247.4	86.95	445	102.6	2.030	-

Table 12. Point pattern analysis metrics for 8 stations (p = 8)

Network Generator	Convex Hull Area (km²)	Convex Hull Perimeter (km)	Minimum Rectangle Area (km²)	Minimum Rectangle Perimeter (km)	Mean Distance Between Stations (km)	Distance from Mean Center to Workshop Mean Center (km)
p-median	2304	190.3	2972	222.7	37.88	2.744
FTB	2585	193.5	3126	224.8	40.39	1.551
FRLM	1150	140.2	1673	165.0	27.99	9.775
Workshop	610.8	115.4	691.4	123.8	23.40	-

4. Discussion

4.1 Information and Goals Considered

Each of the optimization models entailed specific and invariable objective functions, with fixed data inputs. In contrast, the geodesign process began with a less-defined goal—to “recommend” an initial HRS network of 10 stations in the Hartford metropolitan area—and the participants defined relevant criteria and metrics for success rather than adhere to a single objective function. The criteria evolved throughout the workshop as participants negotiated with each other using Collablocation’s performance metrics and map layers in tandem with their own geographic expertise of the region. An example of criteria re-definition by workshop participants was their recommendation to prioritize station development into two temporal phases. None of the optimization models—nor the initial workshop agenda—called for separating the station rollout into different time periods. The geodesign framework, however, afforded workshop participants the flexibility to reconceptualize the design problem to include a phase-in strategy. A second example was the decision by workshop participants to consider population and travel dynamics outside the study area.

The criteria and parameters that stakeholders introduced to the geodesign process represented information that each stakeholder had acquired via their individual lived experiences associated with the study, development, and management of transportation and energy infrastructure in Hartford or elsewhere. Individuals develop unique understandings of their local geographies by virtue of their experiences in those places [69]; participants who live in the Hartford metropolitan area applied their unique understandings of the region's geographies to the geodesign process. Such information often entailed details of early adopter populations: typical neighborhoods, places of employment, non-work destinations, and commute patterns. Information also included zoning laws, building codes, and regulations that might impact HRS development. Participants further supplemented the information available to the design process using third-party applications—such as Google Maps—to locate facilities that would support HRS colocation.

Equipment and capacity are other examples of information that stakeholders introduced into designing the network that were absent from the Collablocation tool. The three Phase 1 stations were seen as having a smaller footprint because they are targeted mostly at consumer vehicles rather than trucks and buses. Participants noted that California had started building stations with a capacity of 400 kg/day or more because of fuel shortages at smaller stations. Building two or more modular 200 kg/day pumps and/or electrolyzers at a single station would improve throughput during busy times of day and also protect against equipment failures at one pump. While downsizing station capacity would save money up front, expanding capacity with rising demand would be difficult because it requires taking stations offline for 3-6 months. Participants discussed whether it would be better to add capacity by building an additional station nearby to provide redundancy and expand geographic coverage and visibility, even though it would be costlier.

Evidence from California suggests that some zero-emission vehicle shoppers investigate the carbon footprint of electricity and hydrogen fuels when choosing between battery EVs and FCEVs [70]. In our workshop, however, participants considered the source of hydrogen only during the moderated panel prior to Stage 1 and the workshop wrap-up discussion after Stage 3, and only minimally during the three design stages. In the moderated panel, participants noted that zero-carbon electricity generates valuable credits, that green hydrogen can be produced via centralized or decentralized electrolysis, and that road tunnels would constrain tanker transport of green hydrogen. In the wrap-up discussion, participants revisited the topic of green hydrogen supply and suggested offshore wind turbines as a potential source of renewable electricity for electrolysis. Availability of natural gas to produce hydrogen via steam reformation received little attention, perhaps because of the dense pipeline distribution network throughout the research area. If the workshop had included a stakeholder group representing consumer adopters, the source of hydrogen might have emerged as a higher priority in the geodesign workshop.

Geodesign's flexibility in conceptualizing design parameters further afforded participants the capacity to adjust the number of stations required in the region. The Academia and Government stakeholder groups identified the initial station number target as excessive during Phase 1 deliberations. While these two groups partnered in Stage 2 and did not adjust the number of stations during this phase, the sentiment resurfaced during Stage 3 deliberations.

The HRS sites located by workshop participants were closer together than in the networks generated by any of the optimization models used in this study. This reflects the participants' design decision to develop a robust and redundant network, as well as from their decision to focus on serving early adopter populations with their network. Participants may have conceptualized the study area differently from optimization models such that they focused their efforts on supporting travel primarily in Hartford and the municipalities nearest to it. In contrast, the optimization models afforded the same weight to any source of travel demand, regardless of demographic profile or conceptual inclusion in the "Hartford metropolitan area," and without special consideration for fleets. The optimization models also did not aim for any redundancy in HRS placement and only selected locations that maximized or minimized the coverage or costs of the network; as such, one station sufficed for serving any given set of nodes, arcs, or trips. Optimization models are capable of integrating more nuanced criteria—such as early adopter demographics and redundant station location—at the cost of increased complexity, data requirements, and computational run-time. In contrast, a set of human stakeholders participating in concert were able to rapidly integrate and adjust new and nuanced criteria and evaluate the results.

4.2 Advantages and limitations of the geodesign approach for point-facility location

4.2.1 Advantages

The post-workshop survey results indicate that participants most highly valued the knowledge exchange facilitated by the geodesign process. Participants could insert their ideas for the network design into the negotiation process at any point during the workshop; they simultaneously came to understand the perspectives and priorities of other participants. Participants could thus identify potential conflicts and synergies in network design, then implement their ideas and iterate and improve on them in a virtual space. Learning about these considerations may also help them in future station planning efforts elsewhere. The geodesign workshop framework and the Collablocation platform functioned together as a boundary object— a platform that supports interdisciplinary inter- and intra-organizational cooperation by collating and unifying perspectives, understandings, and contexts between parties with differing epistemologies, perspectives, and methods of problem-solving [71–73]. The knowledge exchange fostered by the geodesign process likely contributed to the consensus built around the final network design, as several participants concluded the meeting by expressing their enthusiasm and support for the design or acknowledging its feasibility. If any participant objected to the final network design, they did not voice their objection during the final deliberations, nor did they note their objection in the survey responses. Participants could also engage in communal data-vetting. In the absence of demographic census data, participants referred to local knowledge of the area. They also used the distribution of specific stores that they understood the targeted demographic groups prefer as a proxy for any spatial demographic data. Workshop participants acknowledged both datasets as valid and incorporated them into the final network design. Similarly, participants in the Government group readily discerned which candidate sites were invalid due to local ordinances. The geodesign process also carried the potential to integrate optimization models in the network designs. It is difficult to assess the extent to which the inclusion of optimization model results in the Collablocation platform influenced the final result, given that participants only checked those data layers during Phase 1.

4.2.2 Limitations

Stakeholder-centered geodesign workshops still suffer from the limitations of collaborative deliberation processes. Charismatic individuals can dominate the conversation, and less charismatic individuals face greater difficulty in suffusing their ideas into deliberations Technologically savvy individuals enjoyed more familiarity with the information technology underlying the Collablocation platform. In Stages 1 and 2, only one individual in each group could manipulate the platform's data layers, make candidate selections, and create performance results. We did not assess the extent to which these individuals influenced the final outcome of the design process.

This geodesign workshop took place in-person. Conducting this workshop thus entailed: facilitation of travel for participants (in the form of parking provision); a physical space in which to meet that had internet-connected computers, video monitors and projectors, tables, chairs, and whiteboards; provision of food; enough time for everyone in the meeting to attend for a full day, or enough flexibility to accommodate those who needed to arrive or leave early or late; and means of resolving any conflicts that might arise during the workshop. These requirements impart limitations on the geodesign process, and future studies might further need to include provisions to avoid propagating communicable diseases.

While the diversity of lived experiences and fields of expertise represented by each participant played an important role in the geodesign process, we did not capture those variables in this study. Variations in the backgrounds of participants of any given geodesign study could affect the outcome. This limits the extent to which researchers can accurately explain or predict the outcome or efficacy of any geodesign study.

4.3. Conclusions

The geodesign process shows promise in supporting HRS network design, and may further support the design of other AFV refueling or recharging infrastructure networks. The flexibility of geodesign in incorporating novel information sources and rapidly reconceptualizing design problems aided the development of a network design that enjoyed a consensus of approval from among workshop participants. Design decisions that emerged during the workshop included decisions to: service fleets and individual consumers; develop clusters of stations; prioritize sites with common land owners; account for candidate site topography and space available for HRS equipment construction; consider the impacts of HRS construction on congestion as well as the impacts of local traffic conditions on HRS usage; revise the number of stations to be built; and prioritize station development in temporal stages. Some of the design criteria considered by participants are also featured in GIS and optimization models, while others emerged that are not as commonly incorporated.

While no new stations have been constructed in the Hartford metropolitan area since the workshop—and the station planned at the time of the workshop is still not operational—workshop participants expressed optimism in the final design and several offered active support for manifesting such an HRS network. In post-workshop discussions with the Connecticut Hydrogen Fuel Cell Coalition, OEMs have referenced the workshop results when considering ideas for the next HRS locations in the region (personal communication). The general consensus was that the three additional stations in the first phase should be sufficient to move Hartford from an FCEV demonstration area and connector site between Boston and New York to a realistic market where automakers could begin selling and leasing FCEVs.

This paper makes several contributions to different literatures. For the geodesign literature, it provides the first case of planning a network of HRSs in a region using geodesign, and adds to the limited number of case studies where facilities are represented as points on a network instead of polygons on a landscape. We also uniquely incorporated optimal facility models in two ways: as inputs for the participants to consider in the geodesign process, and for comparison to the workshop recommendations. For the hydrogen and governance literatures, it is widely recognized that energy transitions are challenging and that diverse stakeholders must work together to overcome numerous barriers in a cost-effective and coordinated way. By developing a consensus vision for infrastructure deployment in a one-day workshop, we demonstrated the potential of geodesign for accelerating and enhancing efforts of similar coalitions. Future work should continue to improve geodesign tools and processes, and facilitate diverse groups of stakeholders to develop infrastructure plans in markets at different stages of H_2 integration and at different geographic scales.

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Data Availability Statement: The Collablocation platform and the spatial data generated during the workshop are available for viewing at collablocation.shinyapps.io/collablocation_ct_h2_2019. Workshop notes and other qualitative data analyzed in this study are available on request from the corresponding author. The data are not publicly available to maintain confidentiality and anonymity on behalf of this study’s participants.

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