

INTEGRATING SOCIAL AND ENVIRONMENTAL IMPACTS OF GREEN
TRANSPORTATION INFRASTRUCTURE: A FRAMEWORK
FOR EFFECTIVE DECISION-MAKING

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ABSTRACT

Green Infrastructure (GI) gains recognition as a viable alternative to traditional infrastructure due to its economic, environmental, and social benefits. However, quantifying and monetizing GI's social and environmental impacts pose challenges, leading to their neglect in comparative evaluations. To heighten GI's appeal, this study introduces a novel framework that incorporates social and environmental impacts and public opinion using the Analytical Hierarchy Process and Monte Carlo simulation. The framework offers a comprehensive approach to evaluate GI's impact. Findings from a Philadelphia project demonstrate that projects with more GI elements are cost-effective when considering public opinion and long-term benefits. The research emphasizes the importance of incorporating GI's threefold benefits into evaluation frameworks, aiding decision-makers in making informed choices by accounting for social, environmental, and economic impacts.

DEDICATION

My family has been my rock, providing unwavering support through thick and thin. This work is dedicated to them.

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I would like to begin by expressing my heartfelt gratitude to the Almighty Allah, whose blessings and guidance have been instrumental in shaping my journey so far. Without His munificence, I would not have achieved what I have today.

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LIST OF ABBREVIATIONS

GI, Green Infrastructure

TI, Traditional Infrastructure

AHP, Analytical Hierarchy Process

LID, Low Impact Developments

SDOT, State Department of Transportation

TDOT, Tennessee Department of Transportation

CHAPTER I

INTRODUCTION

1.1 Background of Study

Green Infrastructure (GI) is a holistic approach that uses natural systems to provide multiple benefits in urban areas. It includes Low Impact Development (LID) techniques, which imitate natural processes to capture and treat stormwater close to its source [1]. GI not only helps to reduce the urban heat island effect and provides habitats for wildlife but also promotes sustainable transportation options that encourage non-motorized travel and compact communities.

Numerous state and federal authorities across the United States are presently incorporating sustainable practices into their infrastructure management plans and land use development strategies. The objective behind this is to stimulate economic growth while simultaneously creating a healthy environment that enhances the overall quality of life. These sustainable infrastructure practices, collectively known as GI, include an array of techniques such as green roofs, green sidewalks, permeable pavement, downspout disconnection, rainwater harvesting, bioretention, bioswales, urban tree canopy, and many more. In addition to the obvious economic benefits, the incorporation of GI practices also provides a range of social and environmental benefits. Due to these multifaceted advantages, the integration of GI practices into various infrastructure sectors such as transportation and communication, water resources, sewerage management systems, power production, etc., has been on the rise in recent years [2-5].

The conventional approaches to infrastructure planning, design, and implementation typically focus on the economic impacts of a project, while environmental impacts may also be considered but not consistently. Unfortunately, social impacts are often overlooked, as they can be challenging to quantify due to their subjective nature. Social impacts are highly variable in terms of space and time, which makes it difficult to generalize their effects in specific locations and periods. Consequently, by omitting social and environmental impacts the traditional approach to infrastructure planning may seem more cost-effective to policymakers than green infrastructure (GI) projects. However, by integrating the quantification of social and environmental benefits into the cost-benefit analysis of a project, GI projects could become a much more attractive option than traditional infrastructure [6-9].

After conducting a literature review, it was found that there have been some attempts to quantify and monetize the social and environmental benefits of green infrastructure (GI) in recent years. However, these studies do not consider the potential for randomness in public opinion and acceptance of GI within society, nor do they account for the hierarchy of importance among different social and environmental benefits. To address these limitations, this research employs the Analytical Hierarchy Process (AHP) and Monte Carlo simulation techniques to overcome the subjectivity, as well as spatial and temporal variations inherent in the social and environmental benefits of GI. The proposed framework is intended to be applicable to various regions across the United States [9, 10].

1.2 Problem Statement

The adoption of green infrastructure (GI) practices by many state departments of transportation (SDOT) in the United States aims to meet sustainability goals, promote economic

development, enhance traffic safety, and improve quality of life. GI refers to a living network that integrates landscape areas, natural areas, and waterways, including Low Impact Development (LID) techniques. However, traditional approaches to infrastructure planning tend to prioritize economic impacts while disregarding environmental and social impacts. While several SDOTs and the Federal Highway Administration have initiatives to quantify the benefits of GI [11-14], there is a need for a unified framework that considers economic, environmental, and social benefits along with public opinion and the comparison of importance of different benefits to aid decision making. Given the extensive research and documentation on the economic impacts of infrastructure, the scope of this study is specifically directed towards evaluating the environmental and social impacts. In this context, the proposed research aims to develop a systematic quantification framework that captures environmental and social impacts of infrastructure projects, including spatially-specific and temporally-dynamic metrics, objective weights, practical quantification methods, and calculations to value tangential benefits. The study will propose a framework that can be used by practitioners to promote sustainable infrastructure practices.

1.3 Objectives of the Study

The objectives of this study are as following:

1. To explore and examine the multifaceted benefits of green infrastructure (GI) and Low Impact Development (LID) techniques in promoting sustainable urban development and enhancing the quality of life in urban areas.
2. To identify and evaluate the existing approaches to quantify and monetize the social and environmental benefits of GI and LID in infrastructure planning and decision-making processes.

3. To apply the Analytical Hierarchy Process (AHP) and Monte Carlo simulation techniques to capture the randomness and hierarchy of social and environmental benefits in GI and LID projects and develop a practical calculation model.
4. To propose a systematic and comprehensive framework that integrates environmental, and social impacts of infrastructure projects, including spatially-specific and temporally-dynamic metrics, objective weights, and practical quantification methods.

1.4 Scope of the Study

As part of a larger research effort, this thesis is a significant contribution by the UTC research group toward creating a toolbox for practitioners. The goal of this undertaking, funded by the Tennessee Department of Transportation, is to assist decision-makers in selecting the most appropriate infrastructure alternatives. The thesis integrates social and environmental impacts of GI, public opinion of said impacts into the decision-making process, which is achieved by applying the Analytical Hierarchy Process and Monte-Carlo Simulation techniques.

1.5 Thesis Outline

The subsequent sections of this thesis are organized as follows: Chapter I provides an overview of the technologies utilized in this research, while Chapter II presents a review of the pertinent literature, which has been instrumental in informing the author's understanding of the state of the art and shaping the direction of the study. The first segment of Chapter III elucidates the methodology and approach adopted in employing the Analytical Hierarchy Process and Monte-Carlo Simulation, while the latter segment outlines the quantification framework developed for evaluating the various impacts of GI. Chapter IV presents the findings of the study, while Chapter V summarizes and concludes the study, accompanied by recommendations for future research.

CHAPTER II

LITERATURE REVIEW

Green infrastructure (GI) has the potential to serve as a cost-effective solution for fulfilling transportation infrastructure requirements while enabling DOTs to maximize the value of their investments in infrastructure by generating various environmental, economic, and social benefits. The implementation of GI in transportation projects has been successful in addressing stormwater management challenges, and an increasing number of projects are adopting a mix of both green and gray infrastructure to lower the overall costs of compliance with stormwater management regulations. GI projects can significantly enhance the aesthetics of communities, particularly when compared to traditional built environment expansion. Successful GI projects have the potential to enhance public safety, improve the attractiveness of communities, raise property values, and create new job opportunities in the green economy.

Recent studies have highlighted the importance of integrating social and environmental impacts into decision-making processes for transportation infrastructure projects. For example, a study by Strong et al. (2017) found that incorporating environmental and social considerations in transportation infrastructure planning and design can result in significant benefits such as reduced greenhouse gas emissions and improved public health outcomes [15]. Similarly, a study by Ameen et al. (2015) emphasized the need for a comprehensive framework that integrates both

environmental and social impacts of green transportation infrastructure, highlighting the role of community engagement and stakeholder involvement in the decision-making process [16].

In addition, recent research has focused on developing more robust and standardized frameworks for evaluating the social and environmental impacts of green transportation infrastructure. For instance, a study by Ramani et al. (2011) proposed a framework for quantifying the social and environmental benefits of green transportation infrastructure based on a set of performance indicators that account for factors such as accessibility, safety, and air quality [17]. Another study by Liang et al. (2020) developed a framework for evaluating the environmental and social impacts of transit-oriented development projects, which can help transportation agencies prioritize projects that maximize benefits for both the environment and communities [18].

Furthermore, recent studies have emphasized the need to address implementation challenges associated with integrating social and environmental impacts into decision-making processes. For example, a study by May (2022) identified institutional and regulatory barriers that can hinder the implementation of sustainable transportation policies, emphasizing the need for a coordinated and collaborative approach across different levels of government [19]. Another study by Romero-Bonsu et al. (2020) highlighted the importance of community involvement and stakeholder engagement in green transportation infrastructure projects, emphasizing the need to address power imbalances and ensure equitable outcomes for all stakeholders [20].

Overall, these recent studies highlight the importance of integrating social and environmental impacts into decision-making processes for transportation infrastructure projects. They also provide insights into the challenges and opportunities associated with developing more robust and standardized frameworks for evaluating these impacts and implementing sustainable transportation policies.

There is currently a lack of standardized and formalized frameworks for evaluating the environmental and social benefits of infrastructure systems. This makes it difficult for transportation departments to optimize their investment strategies. Existing quantification programs also vary significantly in terms of performance metrics, quantification methods, weighting schemes, and integration techniques. Furthermore, these frameworks often prioritize single economic aspects over environmental and social merits [21], resulting in biased decision-making. Additionally, individual programs often use subjective and ad-hoc methods for scoping performance metrics and determining their relative importance [22], without considering their effectiveness in benefit characterization or the implications to the corresponding community. While many individual benefit quantification/modeling studies exist, their results have not been efficiently used for quantitative framework development, leading to unstable analysis outcomes due to the strong dependency between explanatory variables. The frameworks often prioritize function [23] and fail to consider the natural variations in stakeholder perspectives and perceptions [24, 25], as well as temporal and spatial factors. Finally, integrating all the benefits into a single measurement tends to be subjective and uncertain, leading to a need for more objective and credible understanding of the mechanism of infrastructure impacts and causes.

The Environmental Protection Agency (EPA) and the Federal Highway Administration's Green Highways Partnership aims to engage public and private entities to enhance the functionality and sustainability of highways through GI practices such as bioretention, planting street trees, landscape improvement, and unnecessary pavement removal [26]. The partnership assigns a score to projects based on the extent to which they adopt such practices, among others. The FHWA Sustainable Highways Self-Evaluation Tool is a self-assessment tool that incorporates sustainable principles into system planning and processes, project development, and transportation systems

management, operations, and maintenance [27]. *Greenroads*, initiated by the University of Washington and developed jointly with CH2M HILL, is a rating system, similar to LEED, that certifies roads as "green" based on established standards [28]. The University of Wisconsin's BE2ST is a green highway construction rating system based on LCA/LCCA [29], while the Sustainable Infrastructure Project Rating System (SIPRS) assesses infrastructure based on economic, environmental, and social impacts using the "Triple Bottom Line" approach, which verifies the sustainability of civil engineering projects [30].

A significant gap in the literatures mentioned above is the limited consideration of stakeholder perspectives and perceptions [31]. Stakeholders, such as community members and local businesses, have unique perspectives and interests in transportation infrastructure projects. Their input is critical in understanding the local context and can provide valuable insights into the potential impacts of a project. However, the current frameworks often lack a systematic and inclusive approach to engage and incorporate the input from stakeholders. Furthermore, most existing frameworks do not consider temporal and spatial variations in impacts [32]. Impacts of green transportation infrastructure can change over time and differ based on the location of the project. Ignoring such variations can lead to inadequate understanding of the long-term impacts of the infrastructure and can result in poor decision-making. Finally, there is a need for more objective and credible understanding of the mechanisms of infrastructure impacts and causes. Many benefit quantification and modeling studies exist, but their results have not been efficiently used for quantitative framework development, leading to unstable analysis outcomes due to the strong dependency between explanatory variables. Therefore, the development of more robust models and tools to account for these complexities is necessary.

Addressing these gaps in the literature is crucial for developing effective decision-making frameworks that incorporate the social and environmental impacts of green transportation infrastructure. Future research could focus on developing standardized and objective metrics for quantifying the social and environmental benefits of green transportation infrastructure, incorporating stakeholder input systematically, accounting for temporal and spatial variations in impacts, and developing robust models that can account for the complexity of the infrastructure system.

Due to the literature-dependent nature of the frameworks developed in this study, the rest of the references have been cited within sections 3.5 and 3.6.

CHAPTER III

METHODOLOGY

The methodology employed in this study integrates several key components:

1. The Analytical Hierarchy Process
2. Monte-Carlo Simulation
3. Quantification and Monetization frameworks for various impacts of GI

The subsequent sections will delve into each of these subjects, providing a comprehensive overview of their roles and significance in this study.

3.1 The Analytical Hierarchy Process

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making (MCDM) method that was developed by Thomas Saaty in the late 1970s [33]. It is a mathematical model used for complex decision-making problems that require the consideration of multiple criteria and preferences. AHP has been widely applied in various fields, including engineering, economics, management, and environmental science [34]. The method involves a structured process that allows decision-makers to break down complex problems into smaller, more manageable parts, and to prioritize them based on their importance.

The AHP method is based on the principle that decisions can be made by comparing the relative importance of different criteria and alternatives. It involves a pairwise comparison of criteria and alternatives, where the decision-maker assigns values to each criterion or alternative

in relation to others using a scale from 1 to 9. These values are then used to derive a set of weights that reflect the relative importance of each criterion or alternative. The AHP method also includes a consistency test to ensure that the pairwise comparisons are logical and consistent.

Table 1 The Fundamental Scale for Pairwise Comparison

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong or essential importance
7	Very strong or demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values
Reciprocals	Reciprocals Values for inverse comparison

The AHP method has been widely adopted in various fields due to its ability to provide a structured, transparent, and flexible decision-making process. The method has also been extensively studied and validated by researchers, and its effectiveness has been demonstrated in numerous applications.

The AHP method is mathematically represented by a series of equations, which are used to calculate the weights of criteria and alternatives. The most widely used equation for AHP is the eigenvector method, which is based on the principle of maximizing the consistency of the pairwise comparisons. The AHP is deemed particularly appropriate for the current study given its focus on addressing the inherent subjectivity in evaluating the social and environmental impacts of green transportation infrastructure. The use of AHP can effectively transform subjective assessments into objective measures, making it a fitting approach for the current study. Furthermore, AHP was

chosen to address the complexities of the decision-making process that involves multiple levels and criteria, which requires a systematic and rigorous analysis to arrive at an optimal decision.

3.2 Monte-Carlo Simulation

Monte Carlo Simulation (MCS) is a powerful computational tool widely used in various fields such as engineering, finance, physics, and environmental sciences. It is a probabilistic method that uses random sampling to simulate different scenarios and estimate the probability distribution of outcomes [35]. MCS has been used in environmental sciences to assess the uncertainty and variability of different parameters and their impacts on the system [36]. It is particularly useful in assessing the uncertainty associated with the implementation of Green Infrastructure (GI) projects, which involves various uncertain factors.

The basic idea behind MCS is to generate a large number of random samples from a probability distribution function (PDF) of the input parameters and propagate them through a mathematical model to obtain the output distribution. The output distribution represents the probability of different outcomes for a given scenario, which can be used to estimate the expected value and variance of the output.

The Monte Carlo Simulation can be mathematically represented by the following equation:

$$I = \frac{1}{N} \sum_{i=1}^n f(x_i)$$

Where,

I = the estimated value of the output

N = the number of samples

x_i = a random sample from the PDF of the input parameters

$f(x_i)$ = the corresponding output of the model for the input sample x_i

The utilization of Monte Carlo simulation in this study was motivated by the need to account for the inherent randomness that may stem from public opinion. Given that the community survey was conducted solely within the state of Tennessee, the use of Monte Carlo simulation is expected to facilitate the extrapolation of the survey results to a broader scale encompassing the entire United States.

3.3 The Hierarchy Structure

The hierarchy structure for determining the best choice among GI, traditional infrastructure, and combined infrastructure is shown in Table 2:

Table 2 The Hierarchy Structure for Determining the Best Infrastructure Choice

Goal	Level 1	Level 2	Alternatives
Likelihood of Selection	Social	Recreational use	Green infrastructure (GI)
		Heat reduction	
		Job creation	
		Enhanced property value	
	Environmental	Reduced stormwater runoff	Combination of green and traditional infrastructure (CI)
		Reduced air pollutants	
		Reduced energy use	
	Economic	Initial cost	Traditional infrastructure (TI)
		Maintenance cost	

The research reported here however is concerned with only the social and environmental impacts of different infrastructures and determines the efficiency of infrastructure when we only consider its social and environmental impacts. The results of this research will later be used in an all-encompassing framework where all three kinds of impacts – social, environmental, and

economic – are considered in a similar methodology to help authorities decide between different choices.

However, the ‘Reduced Energy Use’ impact under environmental impact was discarded for two reasons:

1. In the case of transportation infrastructure, the area is typically open and not confined, rendering the shading effect ineffective in providing any cooling benefits.
2. The diminished urban heat island effect resulting from the majority of transportation infrastructures being situated in open areas may yield certain indirect financial advantages through the mitigation of extreme heat events. However, it should be noted that the benefit derived from this impact has already been considered within the 'Heat Reduction' impact discussed in the section on social impacts. Consequently, in order to prevent duplication of calculations, the 'Reduced Energy Use' impact was excluded.

As a result of considering only the social and environmental impacts, the hierarchy structure shown in Table 2 takes the form of Table 3:

Table 3 The Hierarchy Structure Considering only the Social and Environmental Impacts

Goal	Level 1	Level 2	Alternatives
Likelihood of Selection	Social	Recreational use	Green infrastructure (GI)
		Heat reduction	
		Job creation	
		Enhanced property value	Combination of green and traditional infrastructure (CI)
	Environmental	Reduced stormwater runoff	
		Reduced air pollutants	Traditional infrastructure (TI)

3.4 Framework Demonstration

Based on the hierarchy structure of Table 3, the framework to find the best alternative taking public opinion and monetary gain from co-benefits into concern is shown in Figure 1:

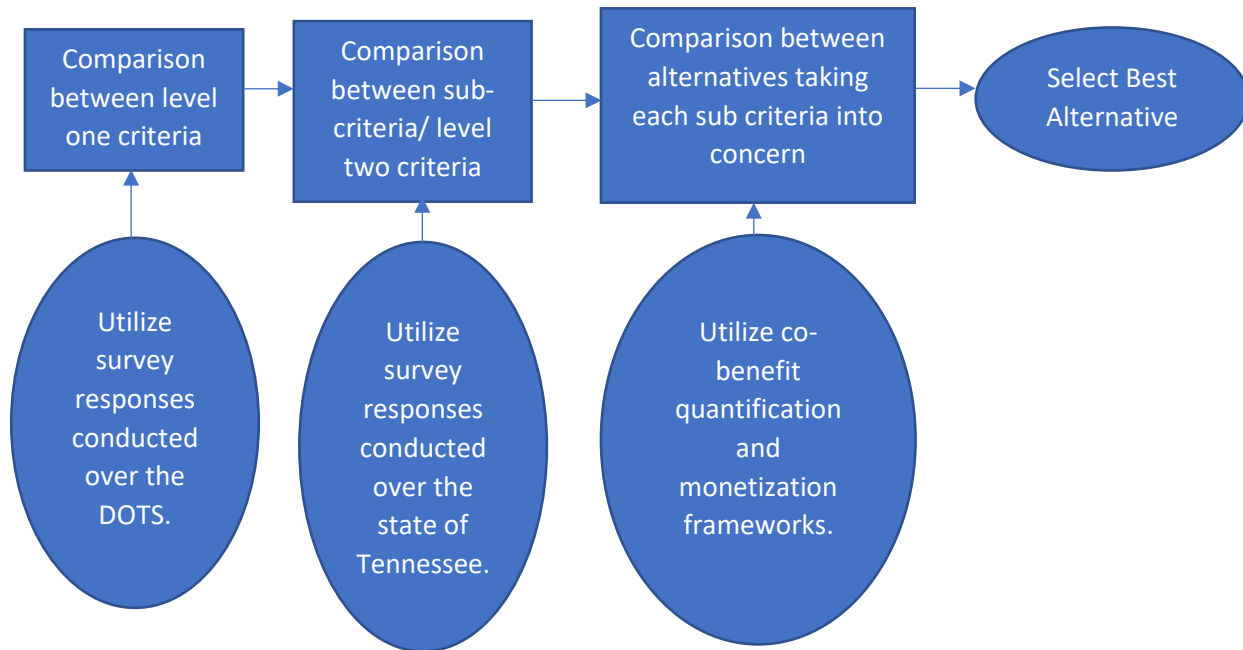


Figure 1 Framework to choose best alternative

To complete the framework, a total of nine pairwise matrices have to be constructed. One matrix for the level one criteria answering the relative importance of social and environmental criteria in the decision making process. Two matrices for the level two criteria or sub-criteria showing the relative importance between the sub-criteria and six matrices to compare each of the alternatives when each of the sub-criteria is in concern.

In order to construct the first pairwise matrix, aid was taken from a survey conducted across the United States over all the state Department of Transportation (DOT). In this survey, a representative from each DOT was asked to rank the order of importance they give to social,

environmental and economic impacts of infrastructures when choosing between alternatives. Figure 2 shows the responses. To complete the first pairwise matrix, first, the importance scale was inverted to conform to Table 1. Subsequently, a weighted average was taken to find the importance of each criterion.

$$\text{Importance of environmental criterion} = \frac{5 \times 3}{5} = 3$$

$$\text{Importance of social criterion} = \frac{3 \times 2 + 2 \times 3}{5} = 2.4$$

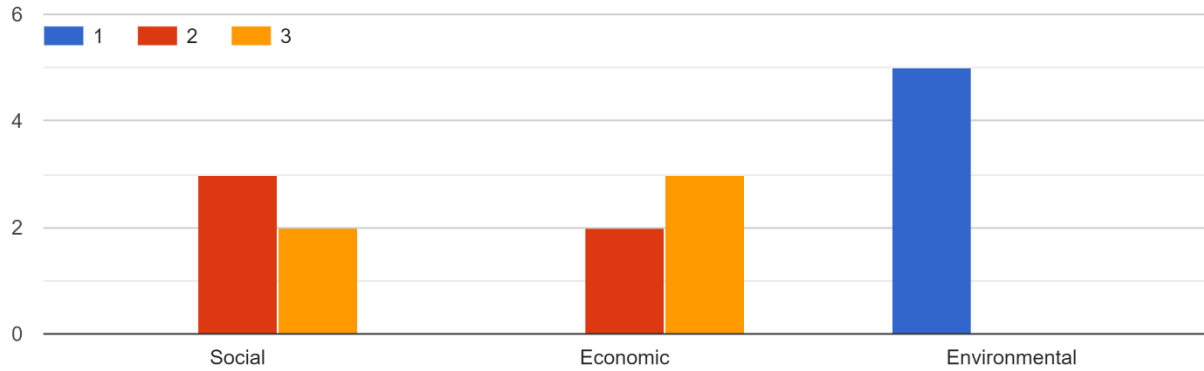


Figure 2 State DOT survey response

Therefore, the first pairwise matrix is as shown in Table 4.

Table 4 Pairwise matrix for level one criteria

	Environmental	Social
Environmental	1.00	2.08
Social	0.48	1.00

After having constructed the first pairwise matrix, aid was taken from a survey conducted over the state of Tennessee to construct the matrices for the sub-criteria level. The survey had 98 responses in total. Figure 3 shows the general demographics of the participants.

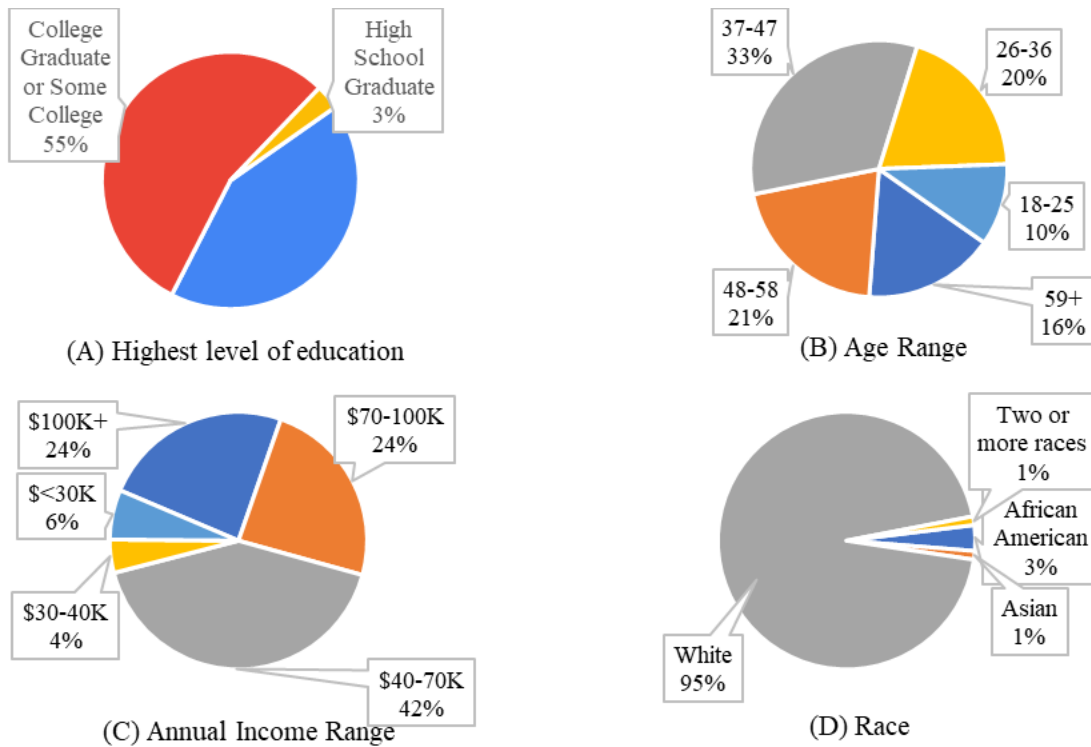


Figure 3 Descriptive statistics of the participants in the survey

In the survey, the participants were asked to rank the importance of GI in contributing to the social and environmental aspects shown in Table 3. The results are shown in Figure 4 and Figure 6.

The methodology will be described for the construction of the pairwise matrices for the social impacts. The choices were ranked with weights from ‘very important’ being 9 to ‘not

important' being 1 and the choices in between – 'important' and 'somewhat important' were given the weights 6.34 and 3.67 respectively to relate with Table 1 [37, 38] and to construct the pairwise matrix for Level 1. The 'not sure' responses were discarded as they do not contribute to the decision-making process, which yielded 93 participants.

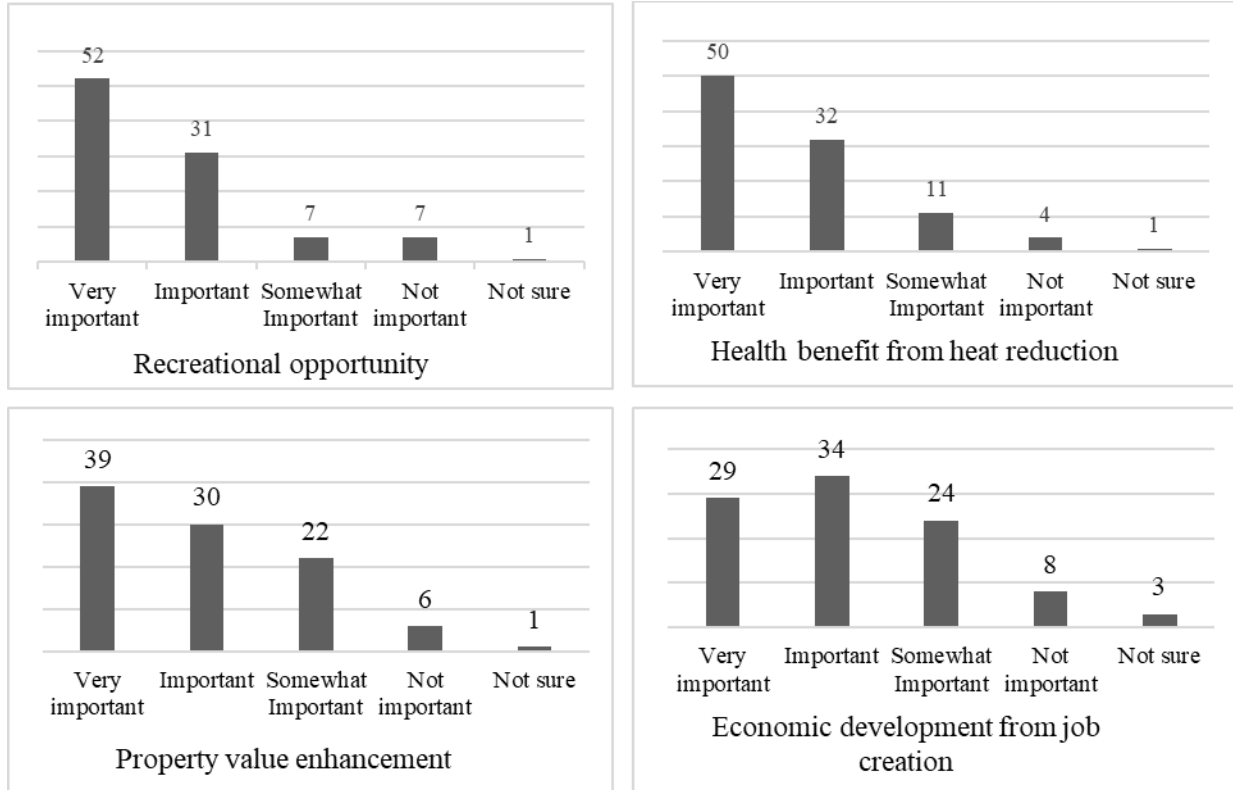


Figure 4 Survey results showing the participants' opinion about GI's social impacts

The weight for the i^{th} row was divided by the weight of the j^{th} column to determine the (i,j) entry of the matrix. 93 pairwise matrices were constructed in this process– one for each participant. One such matrix for the social impacts is shown in Table 5.

Here, the entry at (i,j) position refers to the relative efficiency of the i^{th} row when compared to the efficiency of the j^{th} column. Therefore, a value of 1.42 in the (1,3) position of the matrix infers that the participant believes GI will be 1.42 times more effective in increasing the recreational opportunity in the vicinity of the GI than contributing economically by creating jobs. The entry in the (3,1) position is the reciprocal of the value in position (1,3).

The diagonal values of such matrices will of course be one. Therefore, one would need only $\frac{n(n-1)}{2}$ values in order to build a pairwise matrix with n criteria which in this case is four. Six arrays- each containing 93 values were extracted to build six cumulative distributive functions (CDF) for each entry of the pairwise matrix.

Table 5 Pairwise Matrix for Level 1, Built from the Responses of Participant 1

	Recreational use (c_1)	Heat reduction (c_2)	Job creation (c_3)	Enhanced property value (c_4)
Recreational use (c_1)	1.00	1.00	1.42	2.45
Heat reduction (c_2)	1.00	1.00	1.42	2.45
Job creation (c_3)	0.70	0.70	1.00	1.72
Enhanced property value (c_4)	0.41	0.41	0.58	1.00

Since most of the participants had a positive outlook on the impact of GI, the CDFs are skewed towards the left as can be observed in Figure 5.

Having generated the CDFs for every entry, the next step in the Monte Carlo simulation is to generate a random number between zero to one and refer to the corresponding entry from the CDF curve. With the generated random entry, we can approach with the hierarchy process to

determine the best choice. The same process will be repeated 10,000 times to observe the range of weight each alternative assumes.

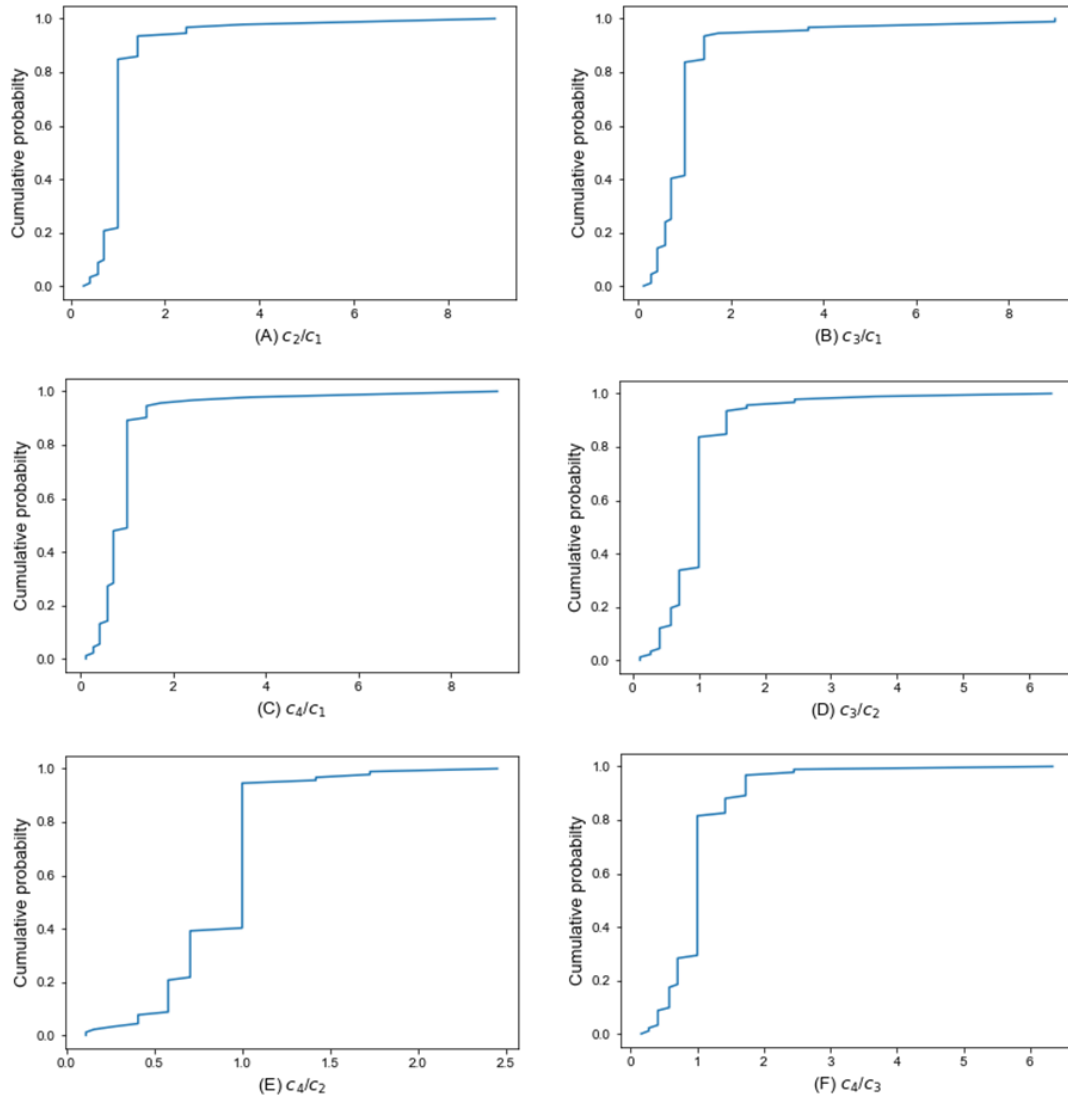


Figure 5 Cumulative distribution functions for entries in the pairwise matrix

Similar methodology was implemented to construct the pairwise matrices for the environmental impacts. Figure 6 shows the survey results that aided in the determination of hierarchy of importance between the environmental impacts.

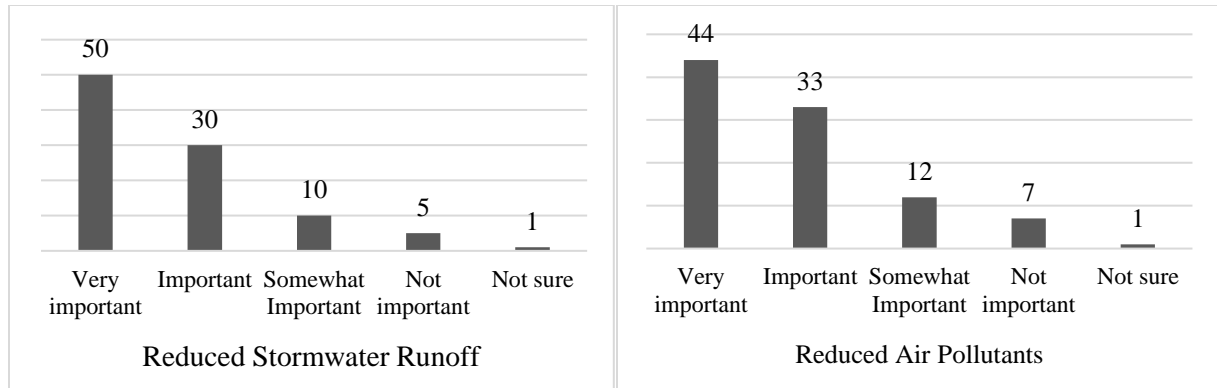


Figure 6 Survey results showing the participants' opinion about GI's environmental impacts

Therefore, the pairwise matrices for the environmental impacts have only 4 entries. One such pairwise matrix is shown for the first participant in Table 6.

Table 6 Example of a pairwise matrix for environmental sub-criteria

	Reduced Stormwater Runoff (c_1)	Reduced Air Pollutants (c_2)
Reduced Stormwater Runoff (c_1)	1.00	1.42
Reduced Air Pollutants (c_2)	0.70	1.00

The CDF of the entry for the environmental sub-criteria is shown in Figure 7.

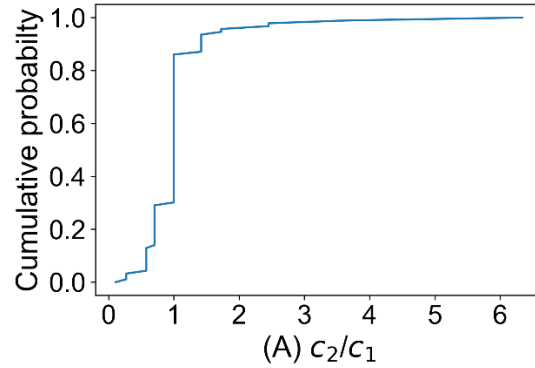


Figure 7 CDF for environmental sub-criteria entry

To demonstrate the comprehensive methodology by constructing the pairwise matrices required at the last step, the results from the report - *A triple bottom line assessment of traditional and green infrastructure options for controlling CSO (Combined Sewer Overflow) events in Philadelphia's watersheds* [39] were utilized. The authors in this report determined the monetary gain from GI over a 40-year period using the frameworks shown in the sections 3.6 and 3.7 for the social and environmental impacts of different GI options (100% GI, 75% GI, 50% GI, 25% GI) in four projects across the city of Philadelphia. However, in this research, only one project's (Lower Delaware river watershed) data will be used to demonstrate the comprehensive framework. The findings will be used to determine the entries of the pairwise matrices for the last step of the AHP where all the alternatives are compared to each other when each of the sub-criteria is concerned. The findings in the above-mentioned report for the Lower Delaware River watershed are tabulated below:

Table 7 Monetary gain from social benefits of proposed GI in the Lower Delaware river watershed

	Recreational use	Health benefit	Job creation benefit	Property value increase
25% GI	\$4,684,956	\$294,200,000	\$28,000,000	\$77,123,000
50% GI	\$34,016,111	\$420,900,000	\$60,000,000	\$154,246,000
75% GI	\$51,271,313	\$547,500,000	\$93,000,000	\$231,369,000
100% GI	\$62,912,556	\$674,200,000	\$121,000,000	\$308,492,000

Table 8 Monetary gain from environmental benefits of proposed GI in the Lower Delaware river watershed

	Reduced Stormwater Runoff	Reduced Air Pollutants
25% GI	\$6,713,580	\$9,820,003
50% GI	\$16,307,399	\$22,391,744
75% GI	\$22,785,416	\$31,204,186
100% GI	\$28,405,151	\$39,210,732

Since this report only determined the monetary gain for combined infrastructure and GI, the hierarchy structure of Table 3 is modified to take the shape of Table 9. This modification not only demonstrates the capability of the framework to function properly but also shows the flexibility it allows for the policymakers to shape the decision-making process in terms of the data they have at their disposal. The structure in Table 9 has four choices to relate to Table 3 and to help authorities decide between the alternatives. The importance of traditional infrastructure (TI) in contributing to the social benefits can be inferred from the trend of the results determined from the hierarchy process in Table 9.

Table 9 Hierarchy structure for the case study

Goal	Level 1	Level 2	Alternatives
Likelihood of Selection	Social	Recreational use	25% GI
		Heat reduction	
		Job creation	
		Enhanced property value	50% GI
	Environmental	Reduced stormwater runoff	75% GI
		Reduced air pollutants	100% GI

To populate the pairwise matrices for the next step of the AHP, Table 7 and

Table 8 were used. For each criterion, the highest monetary gain was assigned the value 5 and the lowest gain was assigned the value 1. The assignment resulted in the choice with the highest monetary gain being five times as important as the choice with the lowest monetary gain when compared as shown in Table 1. The rating for the values in between can be determined with Equation (1).

$$\text{Rating for the nth largest value} = 1 + \left\{ (\text{nth value} - \text{lowest value}) \times \frac{\text{highest rating} - \text{lowest rating}}{\text{largest value} - \text{smallest value}} \right\} \quad (1)$$

The user of the framework has the freedom to decide if the choice making the most monetary gain is more or less than five times as important as the choice with the lowest monetary gain. The resulting pairwise matrix for the first criteria – as an example- is shown in Table 10.

Table 10 Pairwise comparison matrix for recreational opportunity

Recreational opportunity				
	100% GI	75% GI	50% GI	25% GI
100% GI	1	1.19	1.658	5
75% GI	0.84	1	1.393	4.2
50% GI	0.603	0.718	1	3.015
25% GI	0.2	0.238	0.332	1

All six matrices were consistent. The weights from the pairwise comparison matrices are consequently integrated with the local weights obtained from the Monte Carlo simulation to determine the range of weights for the four alternatives.

3.5 Social Impact Quantification Frameworks

In the next step of the AHP, we need to determine entries for four pairwise matrices – one for each social criterion to compare the efficiency of the three alternatives in contributing to the social aspect in concern. One such matrix is shown in Table 11.

Table 11 Pairwise Matrices to Compare Between Alternatives

Recreational opportunity			
	GI	TI	CI
GI	1		
TI		1	
CI			1

In order to populate the matrices with appropriate entries, the social impact monetization framework, which has been developed through previous research, will be employed.

3.5.1 Recreational Use

The increase in vegetation due to the newly built GI would allow increased participation of the inhabitants of the areas encapsulated by the GI in activities like walking, biking, jogging on sidewalks, etc. These activities are similar to the ones performed in parks. Therefore, the benefits gained from recreational use resulting from the increase in vegetation can be compared to the benefits from the added area in a park.

As the first step to quantifying the benefit, the area which will serve for recreation is determined. The total amount of anticipated vegetation less the parking lot and green roof area will serve for recreation. After identifying the vegetated area, the GI's proximity to the available recreational area is determined. A Green Infrastructure (GI) in close proximity to a park may not function as effectively as a GI without such adjacency, in terms of its ability to serve as a park. Therefore, a GI's ability to serve recreational activities depends on its proximity to existing recreational opportunities. A 10-minute walking distance or 0.5 miles radius is selected as the proximity measure.

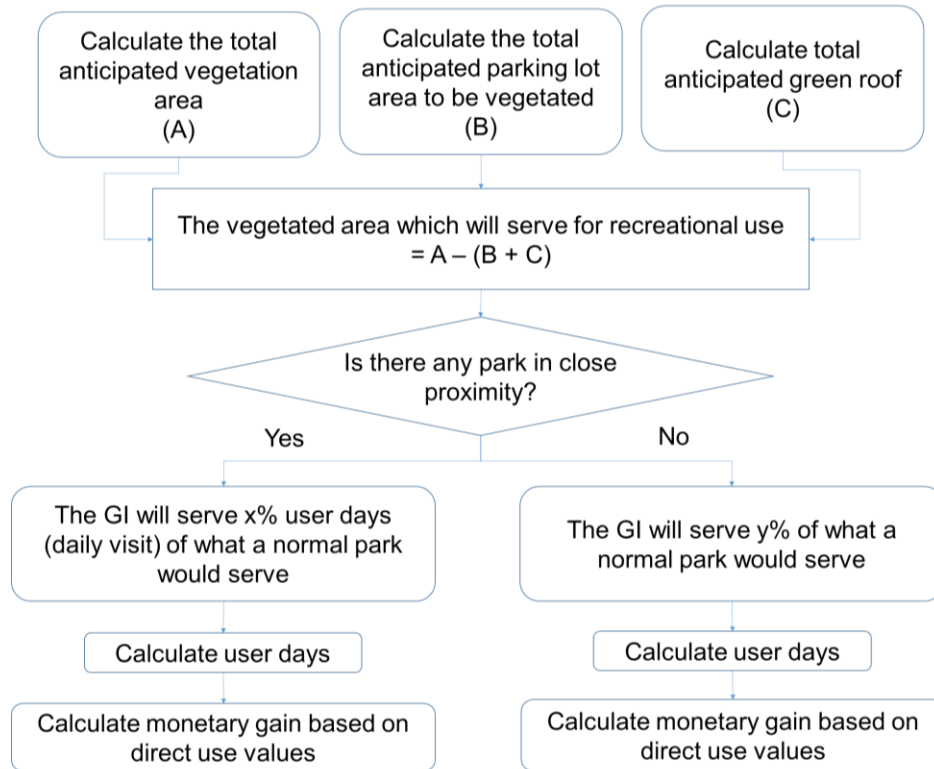


Figure 8 Framework for monetizing recreational use

The methodology relies on a report *How Much Value Does the City of Philadelphia Receive from its Park and Recreation System* [40] prepared by the Trust for Public Land to determine the increase in recreational activities per acre increase in vegetation. The report calculates the increase in the number of daily visits (user days) per acre of the increased area in the park. According to a survey conducted by the National Recreation and Parks Association, residents

frequent nearby parks at an average rate of 26.7 visits annually per 1000 acres of parkland [41]. The increase in the user days is then attributed to a monetary value by the ‘Unit Day Value’ method [42] as the last step of the methodology.

3.5.2 Heat Reduction

Extreme heat events (EHE) are one of the major reasons for loss of lives [43-45] and increased emergency room use due to morbidity impacts [46, 47] during the summer season. GI reduces the urban heat island effect as trees provide shading and replace dark paved surfaces with green vegetation that absorbs less heat [48-50]. Several heat-related hospitalizations and mortalities can be avoided due to the reduced heat resulting from the impact of GI.

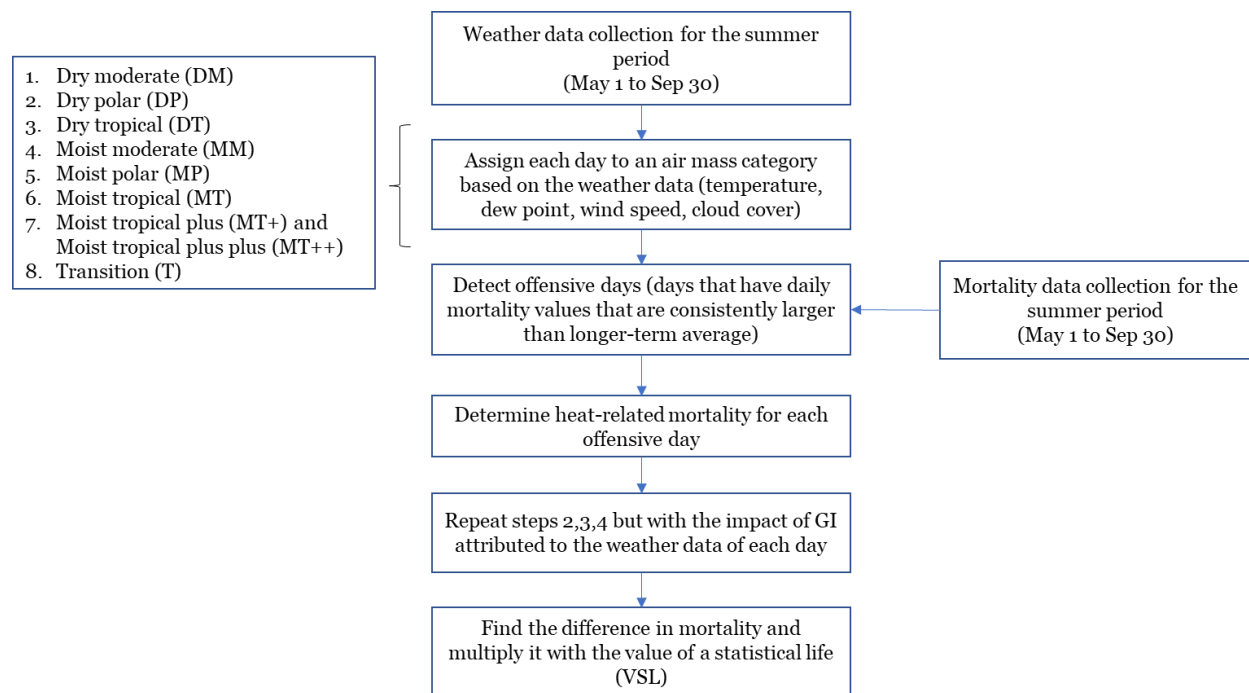


Figure 9 Framework for monetizing heat reduction benefit

The weather data for the summer season for the area where the GI is going to be built is collected as the first step of monetizing this benefit. Consequently, based on the weather data (temperature, dew point, wind speed, cloud cover, etc.), each day of summer is assigned to an air

mass category [51]. The mortality data for the area of interest is also necessary for this framework. Based on the air mass labels of each day and mortality data for respective days, the ‘offensive days’ are identified. An ‘offensive day’ is when daily mortality values are higher than the longer-term average. The next step is to determine the heat-related mortality on each of the offensive days.

The next step repeats steps 2,3, and 4 however with the impact of GI attributed to the weather data. The impact of GI is going to be determined by the existing meteorological models [49, 50]. Having the impact of GI attributed to the weather data, we can calculate the difference in the number of fatalities between the two scenarios. Based on the calculated number, we can anticipate the total number of lives saved throughout the project. The last step is to estimate the monetary gain based on the Environmental Protection Agency’s (EPA) recommended Value of Statistical Life (VSL) [52].

3.5.3 Enhanced Property Value

Due to increased aesthetics, vegetation, improved air and water quality, and better living standards in general, properties adjacent to a GI are expected to experience an increase in value. Previous studies have attempted to estimate the enhancement of value, and the value ranges from 1% to 7%. Table 6 shows a literature review of those studies:

Table 12 Literature on estimating property value enhancement

Study	% increase in value
The effect of low-impact-development on property values. [53]	3.5 – 5.0
How Water Resources Limit and/or Promote Residential Housing Developments in Douglas County. [54]	1.1 – 2.7
Piedmont community tree guide: benefits, costs, and strategic planting. [55]	3.0 – 7.0
What is a tree worth? Green-city Strategies and Housing Prices. [56]	2
Influence of trees on residential property values in Athens, Georgia (USA): A survey based on actual sales prices. [57]	3.5 – 4.5

As the first step of this methodology, the area where the GI is going to be built has to be identified. After the area is identified, the median value of the properties in that area will be calculated from the house sales data. The property sales data is a prerequisite in this framework. Having determined that, the enhancement in property value is estimated using the literature listed in the previous section. Consequently, the number of properties in the area of interest is calculated. As the last step of the framework, the total monetary gain is determined using the median value and the anticipated increase in value.

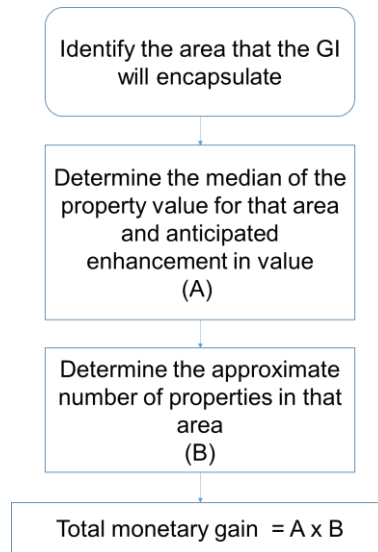


Figure 10 Enhanced property value quantification framework

3.5.4 Job Creation Benefit

Traditional infrastructures need skilled workers with esoteric knowledge whereas GI can create job opportunities that can be done by comparatively less-skilled workers. While the skilled workers can afford to manage jobs elsewhere, employing the unskilled people comes with additional social benefits.

The total work hours anticipated in the lifetime of the GI is a data prerequisite for this framework to quantify the benefit. Having collected the data, the framework utilizes existing literature [58-61] to estimate the number of jobs that will allow unskilled workers to be employed throughout the project.

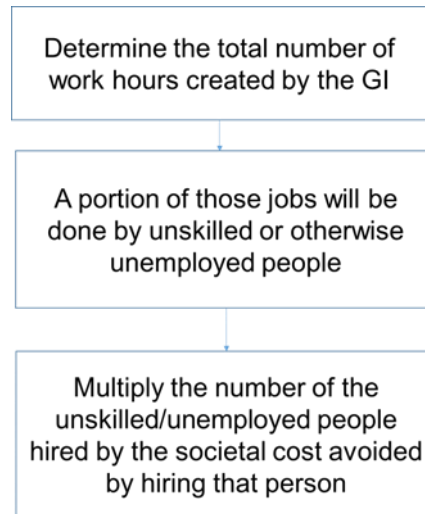


Figure 11 Framework for quantifying job creation benefit

The last step of the methodology is to determine the total monetary value of employing unskilled people by multiplying the number of jobs created by the social cost avoided by employing each person [62-64].

3.6 Environmental Impact Quantification Frameworks

Although this study will not incorporate the environmental benefits of GI in the case study conducted in the following section, the quantification and monetization frameworks of different environmental impacts of GI are still elucidated in order to facilitate the integration for the practitioners.

3.6.1 Reduced Stormwater Runoff

Green infrastructure is an approach that incorporates a combination of natural and engineered elements, including vegetation, pipes, soil, and stone, with the purpose of mitigating the speed of stormwater runoff, treating it, and enabling absorption and infiltration into the soil

where appropriate [13]. Various components of green infrastructure, such as trees, green sidewalks, green medians, permeable pavement, bioretention, and water harvesting, can collectively aid in the reduction of stormwater runoff [65-67]. The total amount of reduced runoff can be computed by consolidating the different components utilized in a green infrastructure project. The calculated figure can subsequently be translated into a monetary equivalent, taking into account the amount of water treatment costs saved as a result of runoff reduction [9].

Table 13 Data requirement for quantifying reduced stormwater runoff

GI Element	Data Requirements
Tree plantation	<ol style="list-style-type: none"> 1. Estimated number of trees to be planted 2. Annual precipitation
Bioretention and Infiltration	<ol style="list-style-type: none"> 1. Annual precipitation 2. Area covered by the element 3. Contributory drainage area to the element 4. Percentage of the rainfall captured
Permeable Pavement	<ol style="list-style-type: none"> 1. Annual Precipitation 2. Permeable pavement area 3. Percentage of precipitation retained
Water Harvesting	<ol style="list-style-type: none"> 1. Annual precipitation 2. Area covered by the element 3. Collection efficiency

While green roofs are a widely used feature in green infrastructure projects, they are not commonly utilized in green transportation infrastructure. As a result, the contribution of green roofs will not be factored into the benefit transfer framework being employed.

The equation for the total amount of runoff reduced can be expressed as below:

$$Q_T = Q_{TP} + Q_{BI} + Q_{PP} + Q_{WH} \quad (2)$$

Where,

Q_T = Total amount of reduced stormwater runoff

Q_{TP} = Runoff amount reduced by tree plantation

Q_{BI} = Runoff amount reduced by bioretention and infiltration

Q_{PP} = Runoff amount reduced by permeable pavement

Q_{WH} = Runoff amount reduced by water harvesting

The following sections will describe the procedure to calculate each runoff amount in Equation (2).

Stormwater Runoff Reduced by Tree Plantation

Accurate estimation of water interception at the individual tree level is imperative in determining the reduction in stormwater runoff for a given project. This necessitates the knowledge of the size, type, and number of trees being planted. It is worth noting that the extent of rainfall interception varies depending on the leaf surface area of the tree species, where larger leaf surface area results in increased interception. Moreover, the rate of rainfall interception by trees is influenced by the climate zone of the site, precipitation levels, and seasonal variability, which ultimately impact evapotranspiration rates.

Table 14 Average runoff interception amount by tree size and climate zones

	40 Year Avg Annual Interception i_t (gallon/year/tree)		
Climate Zones	Small Tree	Medium Tree	Large Tree
Coastal Southern California	1,583	1,396	2,120
Desert Southwest	570	1,818	930
Inland Empire	107	1,925	2,238
Interior West	281	573	1,245
Northern California Coast	420	369	673
Northern Mountain and Prairie	549	948	1,209
San Joaquin Valley	49	350	552
Temperate Interior West	161	893	1,111
Tropical	605	1,237	2,108
Central Florida	1,573	6,191	12,641
Coastal Plain	723	1,962	5,699
Lower Midwest	1,116	1,870	4,808
Midwest	292	1,129	2,162

Northeast	358	1,156	1,909
Piedmont	1,265	2,566	4,778
Western Washington and Oregon	182	346	549

The US Forest Services' Center for Urban Forest Research has developed a set of Tree Guides, which considers various factors to estimate the level of benefits offered by trees [68]. The following table illustrates the findings in the report and the intercept values to be used in the quantification procedure.

The following figure shows the climate zones used in the report.

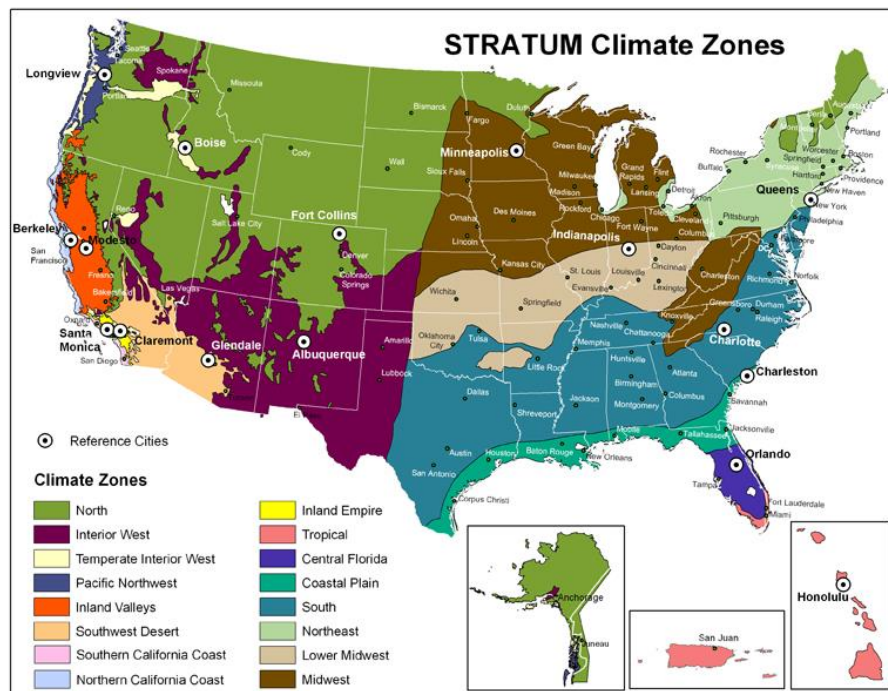


Figure 12 The climate zones used to estimate the rainfall interception of trees [68]

Based on the interception value i_t obtained from the Table 14 the equation for Q_{TP} is:

$$Q_{TP} \text{ (gallons)} = \text{Number of Trees} \times i_t$$

Based on the number of trees varied by sizes, the total runoff reduced can be determined by multiplying by the corresponding i_t value.

Stormwater Runoff Reduced by Bioretention and Infiltration

Bioretention and infiltration features that are well-designed are capable of capturing a significant portion, if not all, of the precipitation that falls within their coverage area, including the associated drainage area. However, the ability of these features to accommodate rainfall in urban settings is contingent upon the availability of square footage and the locally prescribed maximum ponding times. To determine a site-specific measure of performance, sophisticated hydrological modeling is required.

$$Q_{BI} \text{ (gal)} = [\text{Precipitation (in)} \times \{\text{Element Area (sq. ft.)} + \text{Drainage Area (sq. ft.)}\}] \times \text{\% Rainfall Capture} \times 144 \frac{\text{sq.in.}}{\text{sq.ft.}} \times 0.00433 \frac{\text{gal}}{\text{in}^3}$$

To enable a generalized quantification method across the United States, a straightforward equation will be employed, utilizing a default and conservative value of 80% for rainfall capture ability. Therefore, the equation converts to:

$$Q_{BI} \text{ (gal)} = [\text{Precipitation (in)} \times \{\text{Element Area (sq. ft.)} + \text{Drainage Area (sq. ft.)}\}] \times 0.80 \times 144 \frac{\text{sq.in.}}{\text{sq.ft.}} \times 0.00433 \frac{\text{gal}}{\text{in}^3}$$

Stormwater Runoff Reduced by Permeable Pavement

Research indicates that pervious pavement has the capacity to infiltrate between 80% to 100% of the rainwater that falls on a given site, depending on the precipitation intensity [65, 69,

70]. The following equation provides a means of quantifying the aggregate volume of runoff that a specific permeable pavement installation can mitigate on an annual basis, taking the capacity as 80% for conservative approach.

$$Q_{PP} \text{ (gal)} = \text{Annual Precipitation (in)} \times \text{Permeable Pavement Area (sq. ft.)} \times 0.80 \\ \times 144 \frac{\text{sq. in.}}{\text{sq. ft.}} \times 0.00433 \frac{\text{gal}}{\text{in}^3}$$

Stormwater Runoff Reduced by Water Harvesting

The advantages associated with water harvesting are contingent upon the quantity, measured in gallons, of stormwater runoff that is stored at the site. Under optimal conditions, a maximum of 0.62 gallons of runoff per inch of rain can be collected from each square foot of roof collection area. However, the following equation incorporates a conservative efficiency factor of 0.75 from the range of 0.75-0.9 to accommodate water loss resulting from a range of factors, including evaporation and suboptimal gutter systems [71].

$$Q_{WH} \text{ (gal)} = \text{Annual Precipitation (in)} \times \text{GI Element Surface Area (sq. ft.)} \times 0.75 \\ \times 144 \frac{\text{sq. in.}}{\text{sq. ft.}} \times 0.00433 \frac{\text{gal}}{\text{in}^3}$$

Benefit Monetization

In urban areas where combined sewer systems (CSS) are in place, stormwater runoff mixes with wastewater and proceeds to a treatment facility. To quantify the benefits of reducing stormwater runoff in these cities, an avoided cost method is a viable option. The value of reducing stormwater runoff is deemed equivalent to the expenditure that would be incurred by the local

stormwater utility to manage the same. Thus, the valuation formula is straightforward. The cost of treating stormwater has been reported varying from \$0.01 to \$0.03 per gallon of stormwater [72]. Considering the report is from 2009 and the corresponding time value of money, taking the conservative value of \$0.01/gallon to estimate avoided treatment cost, the total monetary gain from the avoided water stormwater treatment is given by the following equation.

$$\text{Monetary Gain from Avoided Stormwater Treatment} = Q_T (\text{gal}) \times 0.01 \times C$$

Where,

Q_T = Total amount of reduced stormwater runoff,

C = Conversion factor to calculate the time value of money from 2009 to current year.

3.6.2 Reduced Air Pollutants

The implementation of green infrastructure in communities can aid in the reduction of air pollutants [14]. The utilization of vegetated systems such as green sidewalks and tree barriers can effectively mitigate the adverse impact of urban heat island effects while also improving air quality [73]. This section aims to provide a quantitative analysis of the impact of green infrastructure on air quality, and outlines guidelines for assessing these impacts in monetary terms. Specifically, the pollutants of concern are carbon dioxide (CO₂), nitrogen dioxide (NO₂), ozone (O₃), sulfur dioxide (SO₂), and particulate matter with an aerodynamic diameter of ten micrometers or less (PM₁₀).

Trees, and bio-infiltration are examples of practices that offer a direct benefit in terms of uptake and deposition. While numerous studies have acknowledged that vegetative infrastructure, such as bioswales, rain gardens, and other bio-infiltration techniques, can offer substantial air quality benefits, there is a current absence of scientific research that measures and quantifies the direct uptake potential of these practices in relation to air pollution. The lack of studies that provide

specific uptake values for bio-infiltration practices impedes the ability to comprehensively calculate their direct uptake benefits. Therefore, the data requirement to quantify the total amount of pollutant reduction by the practices are only regarding the tree plantation practice and they are listed below:

Table 15 Data requirement for quantifying reduced air pollutants

GI Element	Data Requirements
Tree plantation	<ol style="list-style-type: none"> 1. Estimated number of trees to be planted by size 2. Average annual uptake of pollutant by each tree

Air Pollutants Reduced by Tree Plantation

The uptake potential of tree planting depends on various factors, such as climate zone, existing air quality and pollutant levels, and the size, age, and type of tree. The Forest Service's *Tree Guides* offer an estimation of air quality benefits from trees based on the climate zone [68]. The appendices in the guides are organized based on the size of the tree (including example tree types) and its location in relation to a surrounding building. By utilizing the "Uptake and Avoided" data available in the Tree Guides' appendices, one can calculate air quality benefits on a per-tree basis. The following table shows a summary of the value to be used in framework for the "Uptake and Avoided" value for trees based on its size and location.

Table 16 Average uptake and avoided amount of air pollutant by tree size and location [68]

		40 Year Avg Uptake + Avoided k_{ua} (lbs/year/tree)		
Climate Zones	Pollutant	Small Tree	Medium Tree	Large Tree
Coastal Southern California	O ₃	0.20	0.48	0.89
	CO ₂	14	34	140
	NO ₂	0.05	0.12	0.48
	SO ₂	0.13	0.21	0.42
	PM ₁₀	0.33	0.79	1.49
Desert Southwest	O ₃	0.21	0.47	0.21
	CO ₂	159	318	267
	NO ₂	0.31	0.74	0.42
	SO ₂	0.19	0.46	0.28
	PM ₁₀	0.25	0.64	0.46
Interior West	O ₃	0.26	0.48	0.92
	CO ₂	174	363	628
	NO ₂	0.46	0.84	1.51
	SO ₂	0.37	0.68	1.22
	PM ₁₀	0.20	0.43	0.67
Northern California Coast	O ₃	0.16	0.16	0.26
	CO ₂	82	134	158
	NO ₂	0.12	0.12	0.20
	SO ₂	0.03	0.03	0.04
	PM ₁₀	0.35	0.16	0.36
Northern Mountain and Prairie	O ₃	0.32	0.36	0.43
	CO ₂	37	85	161
	NO ₂	0.19	0.32	0.43
	SO ₂	0.20	0.34	0.46
	PM ₁₀	0.10	0.13	0.16
San Joaquin Valley	O ₃	0.16	1.46	2.71
	CO ₂	26.91	107.05	229.79
	NO ₂	0.16	0.80	1.56
	SO ₂	--	--	--

	PM ₁₀	0.14	1.15	2.17
Temperate Interior West	O ₃	0.20	0.31	0.70
	CO ₂	214	313	358
	NO ₂	0.33	0.52	0.69
	SO ₂	0.66	1.13	1.39
	PM ₁₀	0.17	0.27	0.59
Tropical	O ₃	0.16	0.31	0.6
	CO ₂	174	188	370
	NO ₂	0.45	1.03	1.18
	SO ₂	0.39	0.91	1.03
	PM ₁₀	0.25	0.51	0.73
Central Florida	O ₃	0.39	0.92	1.99
	CO ₂	99	187	584
	NO ₂	0.18	0.42	0.81
	SO ₂	0.12	0.29	0.55
	PM ₁₀	0.17	0.46	0.84
Coastal Plain	O ₃	0.17	0.29	0.88
	CO ₂	103	149	489
	NO ₂	0.22	0.33	0.93
	SO ₂	0.63	0.93	2.55
	PM ₁₀	0.14	0.31	0.63
Lower Midwest	O ₃	0.20	0.32	0.68
	CO ₂	91	150	374
	NO ₂	0.16	0.27	0.57
	SO ₂	0.53	0.89	1.86
	PM ₁₀	0.15	0.27	0.45
Midwest	O ₃	0.15	0.20	0.28
	CO ₂	336	444	734
	NO ₂	0.39	0.63	1.11
	SO ₂	0.23	0.42	0.69
	PM ₁₀	0.17	0.26	0.35
Northeast	O ₃	0.14	0.29	0.54
	CO ₂	144	250	485

	NO ₂	0.18	0.37	0.70
	SO ₂	0.15	0.40	0.85
	PM ₁₀	0.13	0.33	0.45
Piedmont	O ₃	0.14	0.35	0.21
	CO ₂	168	128	340
	NO ₂	0.22	0.33	0.41
	SO ₂	0.42	0.60	0.82
	PM ₁₀	0.17	0.56	0.31
Western Washington and Oregon	O ₃	0.14	0.27	0.43
	CO ₂	15	61	257
	NO ₂	0.08	0.17	0.28
	SO ₂	0.03	0.07	0.10
	PM ₁₀	0.15	0.29	0.45
Inland Empire	O ₃	0.25	0.78	1.36
	NO ₂	0.20	0.72	1.08
	CO ₂	24	157	275
	SO ₂	0.05	0.14	0.19
	PM ₁₀	0.16	0.61	0.90

Once the uptake value is determined, the total air pollutant reduction can be determined by the following equation:

$$\text{Total annual air pollutant reduction (lbs)} = \text{no. of trees} \times k_{ua}$$

Where,

$$k_{ua} = \text{average annual uptake and avoided pollutant emissions} \\ (\text{lbs/ tree}) \text{ obtained from Table 16}$$

This equation can be utilized to obtain the total reduction of each air pollutant (O₃, NO₂, SO₂, PM₁₀).

Benefit Monetization

The benefit transfer equation for the reduced air pollutant is as follows:

$$\text{Total value of pollutant reduction (\$)} = \text{Total annual criteria pollutant reduction benefit (lbs)} \times \text{price of criteria pollutant (USD/lb)}$$

Here,

The ‘price of criteria pollutant’ refers to the avoided cost of treating each pound of air pollutant. The value suggested by The Forest Service are as follows [9, 74-76]:

Table 17 Avoided Cost of Criteria Pollutants

Pollutant		Price of criteria pollutant (USD/lb)
O ₃		3.34
NO ₂		3.34
SO ₂		2.06
PM ₁₀		2.84
CO ₂	Low	0.023
	High	0.046

However, since these values correspond to the time value of money of 2006, additional conversion is required to convert them to current value.

CHAPTER IV

RESULTS AND DISCUSSION

The 100% GI option is the best choice among the alternatives as can be observed from Figure 13. The results are intuitive since the 100% GI was deemed to be accruing the highest monetary gain according to the frameworks.

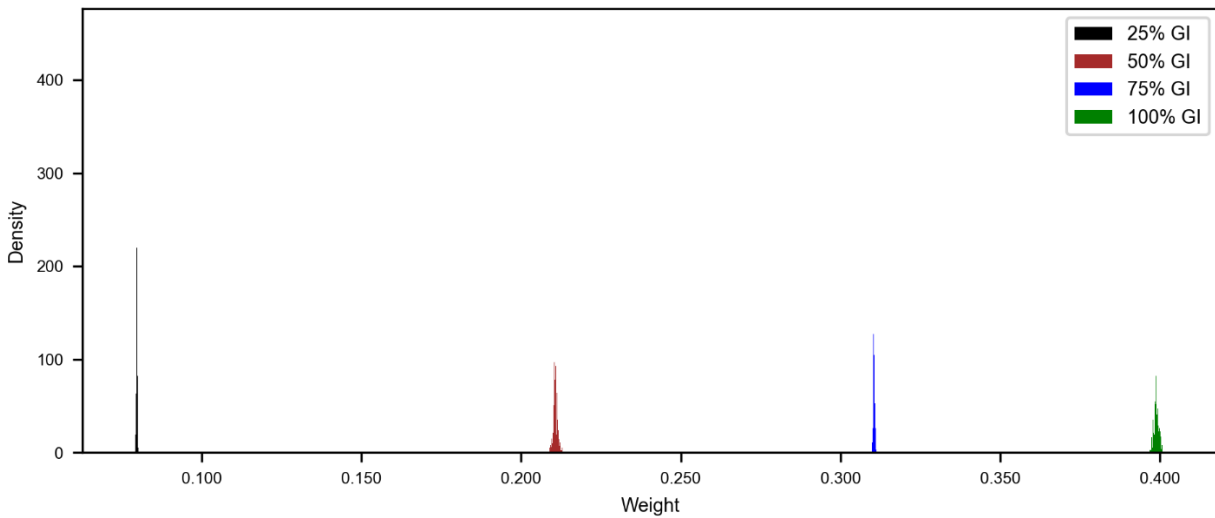


Figure 13 Range of weights for all infrastructure choices

The downward trend of the weights when more traditional infrastructure is integrated into the project indicates that a 100% traditional infrastructure would be the most inefficient choice in earning monetary value from the social and environmental aspects as well as having public

acceptance. After 10,000 simulations the range of weights for 25% GI, 50% GI, 75% GI and 100% GI are from 0.079 to 0.082, 0.198 to 0.214, 0.308 to 0.313 and 0.394 to 0.412 respectively.

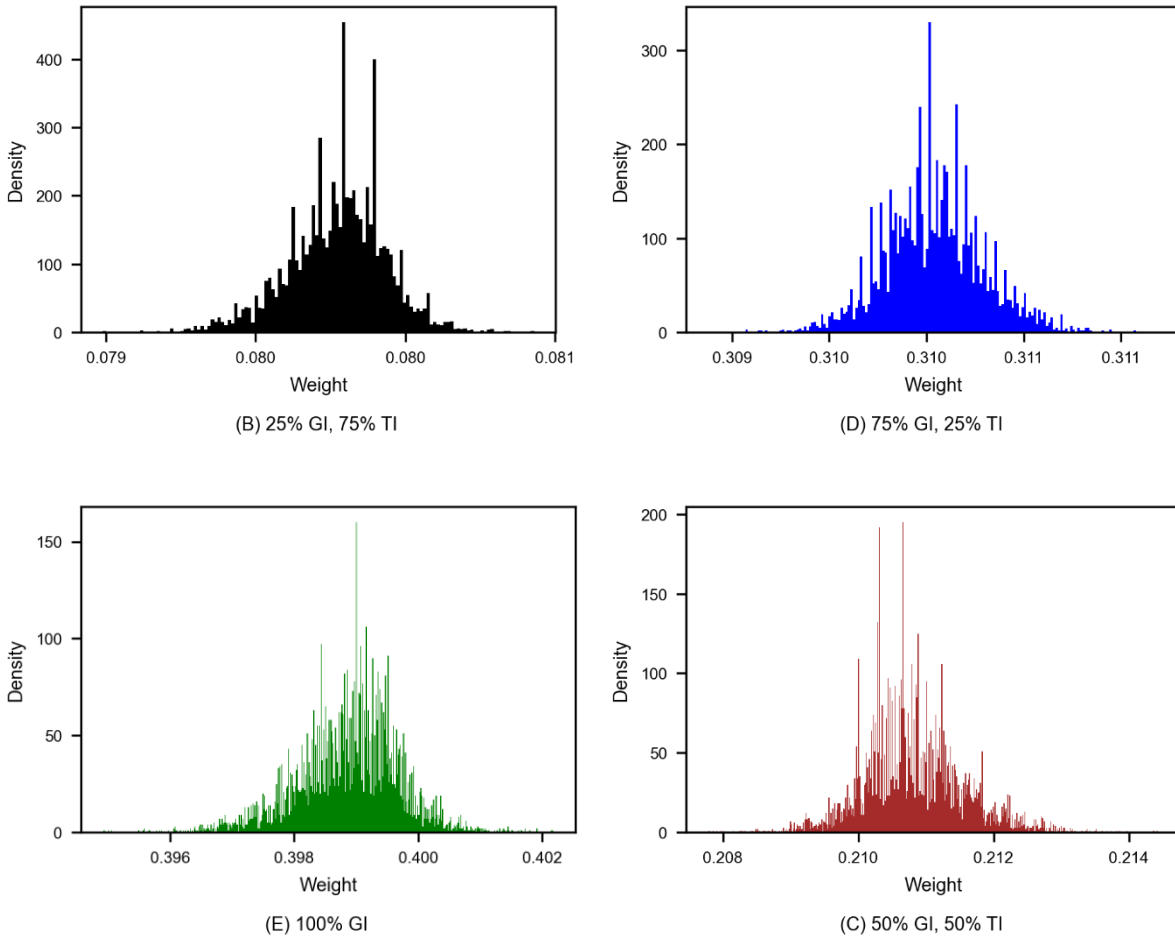


Figure 14 Range of weights for individual choices

CHAPTER V

CONCLUSION AND RECOMMENDATION

5.1 Limitations & Future Work

Although efficient, the framework comes with some inherent limitations:

1. The Likert scale was designed in a manner that did not permit participants to indicate the possibility of the GI being inefficient in comparison to TI. The scale solely featured positive response options, thereby limiting the participants' ability to express a comprehensive range of opinions on the subject matter. To enhance the scale's validity and comprehensiveness, it is imperative to incorporate response options that reflect negative perspectives and provide a more balanced assessment,

2. While determining the efficiency of GI in gathering more social and environmental benefits than TI may not require the use of Analytic Hierarchy Process (AHP), this research represents a component of a more extensive framework that seeks to incorporate social, environmental and economic factors in evaluating various infrastructure projects. In this regard, the AHP methodology will be essential in assessing the efficiency of the different alternatives proposed within the comprehensive framework. Therefore, while intuitive assessment may suffice for this particular research component, a more robust and comprehensive approach, such as AHP, will be required for the overall framework's successful execution.,

3. Presently, there is a lack of standard validation methods for social benefit quantification frameworks. Furthermore, the majority of these frameworks rely on survey-based approaches, which can introduce subjective biases into the assessment process. However, to establish a more objective benchmark, authorities can establish guidelines and standards at the local, state, or federal level for assessing all projects uniformly. This approach would promote consistency and transparency in the evaluation process, enhancing the reliability of the results obtained.

5.2 Closing Remarks

Despite its limitations, this study presents a novel framework that integrates public acceptance, benefit quantification frameworks, the Analytic Hierarchy Process (AHP), and Monte Carlo simulation to evaluate the effectiveness of various alternatives in generating monetary gain from social and environmental aspects. The challenge of selecting the optimal option when subjectivity is present is a complex one. The Monte Carlo simulation approach is utilized in this research to address the potential randomness that may occur in public acceptance across different regions. The AHP methodology is leveraged to convert subjective elements into quantifiable metrics. Social and environmental impact assessment frameworks are effective in identifying the monetary gain associated with different projects across varying spatial and temporal variables. This study also offers flexibility to users in shaping the decision-making process to determine the best choice. This methodology can be applied in a comprehensive framework that considers the social, environmental, and economic aspects of infrastructure projects.

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VITA

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Following a two-year period affected by the Covid-19 pandemic, Md Kamrul Hasan Sabbir briefly worked as a Technical Coordinating Engineer at Dhaka Water and Sewerage Authority. However, driven by his ambition to further his knowledge and expertise, he decided to embark on a master's degree in Civil Engineering, specializing in transportation engineering, in the United States. During his studies, he served as a Graduate Research Assistant in the Department of Civil Engineering at UTC, contributing to a project funded by TDOT (Tennessee Department of Transportation).

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