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*Review*

# Choice Architecture as a Way to Encourage a Whole Systems Design Perspective for More Sustainable Infrastructure

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**Abstract:** Across fields, more sustainable and resilient outcomes are being realized through a whole systems design perspective, which guides decision-makers to consider the entire system affected including interdependent physical and social networks. Although infrastructure is extremely interdependent, consisting of diverse stakeholders and networks, the infrastructure design and construction process is often fragmented. This fragmentation can result in unnecessary tradeoffs, leading to poor outcomes for certain stakeholders and the surrounding environment. A whole systems design perspective would help connect this fragmented industry and lead to more sustainable outcomes. For example, a whole systems design approach to relieve traffic on a highway might see beyond the obvious, but often ineffective, response of adding a new vehicle lane to encourage a solution such as repurposing existing road lanes from automobiles to above-ground "subway" systems. This paper discusses influences to whole systems design and how intentional choice architecture, meaning the way decisions are posed, can nudge decision-makers to employ whole systems design and result in more sustainable infrastructure. By uncovering these influences and organizing them by the social, organizational, and individual levels of the infrastructure design process, this paper provides the needed foundation for interdisciplinary research to help harness these influences through choice architecture and whole systems design for the infrastructure industry.

**Keywords:** sustainable infrastructure; whole systems design; choice architecture; decision-making

## 1. Introduction

Infrastructure is inherently interdependent and these interdependencies are often bidirectional, meaning each infrastructure influences the state of another [1]. For example, the electric power grid uses natural gas for generators and rail transportation may supply the natural gas. Furthermore, not only is the electric power grid dependent on rail transportation for natural gas, rail transportation is dependent on electricity for network and communication operations. These infrastructure interdependencies influence the entire surrounding community and affect the public's mobility, health, and economic development [2,3].

Other industries with complex systems problems, such as health care, have intentionally implemented whole system design or systems thinking to promote improved solutions in comparison to conventional design techniques [4]. Whole system design is a design framework that encourages the consideration of interrelated components, people and systems. When applied to complex design issues, whole systems design aims to optimize the performance of an entire system rather than an individual part [5]. For example, systems thinking has been used in hospital operations modeling to define a hospital system in order to accurately portray the hospital state, which includes the events surrounding the hospital resources, patients, and staff [4].

A conventional approach to complex problems in science and engineering is the reductionist approach, in which we take things apart and then study the pieces in more detail. While reductionism narrowly defines perspectives and makes numerical measurement possible, to design interdependent infrastructures, reductionism must be complemented by systems thinking. Systems thinking is a way to catch what reductionism can miss: connections, relationships, patterns, processes, and context. Smartt and Ferreira [6] call for research to better determine the involvement of systems engineering in the bid process of contract work in order to better estimate the cost of a project to avoid losing money throughout the life cycle. In contrast, the goal of this paper is different in that we are not focused simply on cost, but in how to encourage systems thinking leading to a whole systems design approach throughout the infrastructure design process. The goal is to ensure that infrastructure design decisions are not made in isolation. A shift in perspective is needed in the infrastructure industry where the behavior of the overall systems is realized as more than the sum of the individual parts. The use of whole systems design promotes collaboration and leads to an outcome that better considers the social, economic, and environmental impacts when compared to conventional techniques [7].

The purpose of this paper is to better understand how to enable the consideration of whole system design for infrastructure. To do this, we investigate the influences throughout the decision process during infrastructure design. Decisions made early in the infrastructure design process determine the sustainability of an entire system for decades. Better understanding how these decisions are made can help enable a whole systems design approach.

We hypothesize that intentional choice architecture can help prompt whole systems design and result in more sustainable infrastructure. Choice architecture is the context in which people make decisions [8]. Put another way, choice architecture is the environment of a decision and determines how information is presented to a decision-maker. This is important because choice architecture has the potential to "nudge" decision-makers towards outcomes, whether intentional or not [9]. Section 2 will set the stage for the overarching goal of this paper: the definition of sustainable infrastructure and the need for more research in this area. Section 3 will define whole systems design and briefly explain how whole systems design promotes sustainable infrastructure. Section 4 describes the methods for completing the review of influences to whole systems design throughout the infrastructure process. Section 5 defines choice architecture and the existence of choice architecture within the infrastructure industry at the societal, organizational and individual levels. Section 6 discusses more specifically how choice architecture can help alleviate barriers and promote drivers to whole systems design through examples. This paper concludes with Section 7, a call for more research in the area of choice architecture with aims to expose potential intervention points in the decision-making process that can encourage whole systems design and result in the improved sustainability of infrastructure.

## 2. Sustainable Infrastructure Defined

This paper defines sustainable infrastructure using The Institute for Sustainable Infrastructure's (ISI) Envision rating system for sustainable infrastructure in order to have a common definition that was agreed upon by a group of relatively independent stakeholders and one that applies to all types of civil infrastructure projects.

ISI defines sustainable infrastructure as that which meets the overall community needs and enhances quality of life. This involves "integrating with existing systems and infrastructure in a meaningful way" [10]. Infrastructure must also improve the performance in key areas such as energy efficiency, water and material reduction when compared to a conventional infrastructure project. Envision emphasizes having key stakeholders involved in the early stages of the design process in order lower the risk of community issues down the road caused by poor infrastructure designs and instead create an outcome that is sustainable long term.

*Need for Research Leading to More Sustainable Infrastructure*

The National Academy of engineering points out the need to "restore and improve urban infrastructure" as a Grand Challenge for Engineering in the 21st Century [11]. These grand challenges were defined by an international community and aim to guide the next generations of the engineering community to issues that are in dire need of attention. There is a need for more collaboration in research between industry and academia that focuses on global systems and sustainability which involves better understanding the triple bottom line of economics, environment, and social issues through methods such as interdisciplinary research [12].

Leaders in construction engineering management are observing the need for more research on the entire lifecycle of infrastructure as opposed to just the construction phase, the involvement of key stakeholders, and use of more sustainable methods in the early phases of infrastructure design as opposed to the previous focus on cost minimization techniques [13].

Industry tools like Envision encourage principles of whole systems design, but the collaboration between industry and academic researchers can help us understand how to better enable whole systems design in practice. Programs such as the National Science Foundation's Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) promote this type of research [14].

In 2004, the National Academy of Engineering wrote *The Engineer of 2020: Visions of Engineering in the New Century* where they discussed the changes in thinking and focus that will be necessary to confront the challenges that engineers would be faced in the years to come. The discussion on physical infrastructure emphasized the need for the engineer of 2020 to put more focus on sustainability. In the past, infrastructure design neglected assessing the impact that infrastructure would have on the environment leading to poor aging of infrastructure and putting the United States in a vulnerable position in important areas such as water treatment, waste disposal, transportation and energy facilities [15]. These projected challenges are becoming exponentially more important as issues with aging infrastructure and limited resources are encroaching upon us, just a few years away from the projections of 2020. The National Academy of Engineering challenges the engineer of 2020 to help solve these infrastructure problems not only in industrialized countries like the United States, but also in developing countries.

Charles M. Vest, former National Academy of Engineering and Massachusetts Institute of Technology president, emphasized the importance of sustainably developing the earth. He pointed out that systems engineering is crucial to solve these complex problems and must be emphasized in engineering education [16] Research and application of whole systems design goes hand in hand with systems engineering that promotes sustainable development as it stimulates the collaboration of interdisciplinary engineering teams. Not only that, but whole systems design is general enough so that the outcomes of research in this area could be applicable to industrialized as well as developing countries. The next section will make the application and benefits of whole systems design more clear.

## 3. Whole Systems Design Defined

Systems thinking is a shift in perspectives: from the parts to the whole, from objects to relationships, and from structures to processes. The most essential properties, especially when it comes to sustainability, are often due to the relationships between parts.

Whole systems design is a way of incorporating systems thinking into design. Although a whole systems approach cannot guarantee a sustainable outcome, this approach can lead project stakeholders to consider the three major pillars of sustainability: social, economic, and the environment. For this paper, whole systems design is defined using the paper *A framework for sustainable whole systems design* by Blizzard and Klotz [17] in which the design process, design principles, and design methods are defined from a systematic literature review of whole systems design. Blizzard and Klotz pulled from topics including whole systems design, systems engineering and systems thinking and summarized the following steps, design principles, and design methods below.

Steps of the design process defined as:

(1) Establish common goals—then align incentives
(2) Practice mutual learning
(3) Share information with everyone

The major design principles are defined as:

(1) Focus on the fundamental desired outcome
(2) Learn from nature
(3) Apply systems thinking

The design methods are defined as:

(1) Define the scope to align with vision and desired outcomes
(2) Design on a clean sheet
(3) Start design analysis at the end-use and work upstream

Much of the literature that specifically focuses on sustainability principles in engineering or principles for green engineering, overlap with principles from whole systems design. For example, a major sustainability principle for engineers is to "solve problems holistically", which is very similar to the whole systems design principle of "apply systems thinking" [18]. The steps, principals, and methods outlined by Blizzard and Klotz (2012) [17] promote designs that involve affected stakeholders, and consider the interdependencies of the design. Whole systems design is broad enough to apply to any field and help improve the sustainability of design outcomes.

## 4. Methods

The goal of this paper is to describe situations within the infrastructure industry where choice architecture can influence design decisions and could be considered a driver or a barrier to whole systems design. All of the instances that we define could be either a driver or barrier to whole systems design depending on how the choice architecture is structured; therefore, we do not go into detail on which are considered barriers and which drivers. Our goal is not to provide exhaustive explanation of the influences of these drivers and barriers, as this is information that can be gleaned from the literature we cite. Rather, we hope to encourage exploration of how choice architecture influences these drivers and barriers in a logical way, by organizing them roughly by the level at which they operate: societal, organizational and individual level. This is not to say that influences cannot trickle down from a higher level or vice versa. Many of the drivers or barriers we describe have influence throughout the entire design process. Recognizing that all categorization is somewhat subjective, the following rules were used to determine how to organize the different schools of thought:

(1) References categorized under the societal level are those considering factors that influence the general population and are not necessarily determined by a specific industry or individual, but by larger outside entities.
(2) References categorized under the organizational level are those that identify specific tools or practices that can be applied to the construction or infrastructure industry.
(3) References categorized under the individual level are those that specify factors influencing a human's individual thought or decision process.

Influences in the infrastructure design process can be due to a plethora of triggers from fiscal, to social, to psychological. The influences of choice architecture can be better understood by using a behavioral sciences lens, so many of the identified influences originate from research in this area. The behavioral sciences aim to explain the causes behind behavior that can seem irrational at first glance and this paper aims to determine why whole systems design is not employed when the principles promote a more sustainable outcome.

## 5. Choice Architecture and the Influence on Whole systems Design in Infrastructure

As noted in the Introduction, choice architecture is the context in which people make decisions, defined as the way information is presented and can influence the decision-maker [8]. For example, the simple rearrangement of food in a buffet style cafeteria can increase or decrease the consumption of specific items by as much as 25% [8]. Although some may argue using designed choice architecture with aims to support a certain outcome could be considered paternalistic, choice architecture exists inherently within every display of information. Therefore, intentional or not, the choice architecture influences decisions about finance [19], medicine [20], law [21], and engineering [22].

For this paper, the goal of exploring choice architecture is to expose opportunities where choice architecture exists and that restructuring the decision environment could help alleviate barriers to whole systems design that might be unintentionally embedded within the influences to infrastructure processes. Table 1 is intended to summarize influences to the infrastructure design process and the potential choice architecture that could be used to encourage whole systems design at the societal, organizational, and individual level.

**Table 1.** Influences and Choice Architecture within the Infrastructure Design Process.

| Level | Influences to the Infrastructure Design Process | Potential Choice Architecture Modification to Encourage Whole Systems Design |
|---|---|---|
| 5.1 Societal | 5.1.1 Diffusion of Innovation<br>5.1.2 Legal Regulations | Governmental Incentives<br>Updated Codes |
| 5.2 Organizational | 5.2.1 Social Heuristics<br>5.2.2 Decision Support | Design Proposals<br>Integrated Project Delivery |
| 5.3 Individual | 5.3.1 Utility Maximization<br>5.3.2 Bounded Rationality | Project Definition<br>Request for Proposal |

### *5.1. Societal Level*

At the societal level, choice architecture can be embedded within direct and indirect social and legal instances where it could have an influence on the use of whole systems design. For example, in the difficulty of changing a structure of historical significance [23], or when building codes do not adopt a new infrastructure technology [24].

Well-established theories such as diffusion of innovations [25,26] and networks of power [27,28] can help explain how these societal level influences can inhibit the major design principle of whole systems design which is to define the scope to align with vision and desired outcomes [17].

#### 5.1.1. Diffusion of Innovation

An innovation is defined as "an idea, practice or object perceived as new by an individual or another unit of adoption" [25]. This section breaks diffusion of innovation into two phases: the original adoption of a new technology or method and the implementation of said technology or method. In order to better understand the slow diffusion of green technologies and methods in infrastructure, we pull from general research on innovation diffusion in the construction industry and attempt to understand how these barriers relate to whole systems design. For example, we want to understand why innovations such as green roofs have been slow to diffuse in the United States, despite the fact that they have been proven to reduce storm water runoff and reduce heat island effects, among other benefits [29].

Adoption of Innovation

Wilson and Dowlatabadi [30] adapt Rogers' model from *Diffusion of Innovations* [25] and develop a model for the innovation decision process in order to study diffusion of innovation in the context of residential energy use. According to their model, initialization of innovation diffusion, or adoption of a new innovation, involves the prior conditions of perceived need or problem, social norms, behavior, and previous existing practice [30]. After the prior conditions are met, the next steps are as follows: knowledge, persuasion, decision, implementation, and confirmation [30]. Barriers throughout all stages of this process can be anything from lack of resources, normative beliefs about the opinions of peers of certain actions and self-efficacy. These are barriers experienced by individuals, but are strongly influenced by outside factors such as social norms and market segmentation.

Implementation of Innovation

Sheffer and Levitt [31] explain that most research on diffusion of innovation focuses on the adoption phase, while neglecting to study the concept all the way through implementation, which is where diffusion can fail. Sheffer and Levitt find it important to focus on a firm's ability to adopt a new innovation as opposed to just their willingness to adopt. Their main focus is the implementation of integral innovations, which are those that make a change between the linkages of components, as opposed to an innovation within a component, and how this is affected by existing industry structure. Sheffer and Levitt argue that in fragmented industries, which are those that do not have consistent relations between the firms in the network, it is hard to accumulate architectural knowledge, which is knowledge about the way components work together in order for an innovation to function, and therefore, innovation implementation is difficult.

The industry designing and constructing infrastructure are often categorized as a fragmented due to the typical industry structure which involves contracts such as design-bid-build [32]. Operators may consistently work with a specific designer, but inconsistently work with contractors. When a new innovation requires integration throughout different phases of a project, from design to operations, it can be difficult for firms to communicate these needs when they have unstable or inconsistent relationships.

Product and material innovation can be a driver as well as a barrier to more sustainable design [33]. The industry that designs and constructs infrastructure can be known as one that has a tendency to maintain current practices, but with the emerging focus on the importance of energy efficiency (ranked as number 1 driver to sustainable design and construction), innovation is necessary to meet the needs of the trend towards more sustainable practices. Choice architecture can help guide decision-makers towards the use of new innovations and prompt the use of whole systems design to successfully implement them.

For example, a method of whole systems design is to "design on a clean sheet" [5,17,34,35]. Designing on a clean sheet while practicing other principles from whole systems design such as "learn from nature" [17,35,36] can encourage designers to look to new innovations that is meant to increase the sustainability of the design whether or not the innovation is institutionalized.

Governmental incentives are a form of choice architecture that can be used to encourage the industry designing and constructing infrastructure to incorporate new innovations. For example, the USDA Rural Development offers a financial incentive for the development, construction, and retrofitting of commercial-scale bio-refineries [37]. Incentives like this change design heuristic by encouraging designers to start anew, as opposed to continually designing infrastructure the same way.

Another method of whole systems design is to "start design analysis at the end-use and work upstream" [5,17,18,34,38]. This method is a tactic for ensuring that the architectural knowledge necessary to operate an integral innovation is defined at the beginning of a project, making a clear path for the implementation of said innovation. In this instance, choice architecture exists in the form of the project definition. For example, a highway project can be set up as solution based on assumptions that adding another road lane is needed to relieve highway congestion simply because this is the common solution on past highway projects. Choice architecture can help reframe the project as a problem. For example, asking for solutions to the traffic problem rather than stipulating a lane must be added, encourages the use of whole systems design which could lead to a more sustainable solution such as the development of a new form of public transportation.

#### 5.1.2. Legal Regulations

Legal regulations, such as at the local level, can delay and at times prohibit the use of certain sustainable practices [39], which in turn discourages the employment of whole systems design. Graywater systems use building wastewater that does not contain human pathogens for functions not requiring potable water. This saves water as well as reduces the need for energy-intensive processes to treat wastewater. However, codes in some states do not permit these systems [40]. Things like zoning regulations restrain site locations and can lead to the development of large parking lots [41] as opposed to the freedom of optimal building or structure location near things like public transportation. Often this is not the result of a rational deliberation, but oversight or infrequent updating of codes. Even where codes do allow such systems, and the technical engineering details work, perceived deviation from social norms may make them unpopular [42–44]. On the other hand, new codes for sustainable infrastructure may precede changing cultural values [45]. For example, the Energy Policy Act of 2005 encourages the development of innovative technologies that reduce greenhouse gas by-products by providing loan guarantees [46]. Innovation can inspire whole systems design and vice versa.

The choice architecture of legal regulations has a direct influence on the sustainability of an infrastructure project. A whole systems design approach encourages systems thinking which in turn leads designers to attempt to find ways to divert waste into reusable streams. Codes prohibiting practices such as graywater systems is a direct block to the lifecycle thinking that whole systems design encourages. Updated codes and regulations incentivizing sustainable practices are employing choice architecture to encourage innovation in design.

#### 5.1.3. Other Societal Level Influences

Some other societal level influences include cultural values and networks of power. Within cultures, there are different values for aspects such as the aesthetics of infrastructure. For example, in an interview with Clemson University Parking and Transportation Services, a barrier to the implementation of electric vehicle charging infrastructure was that the chargers did not exactly fit the look and feel of campus [47]. These aesthetic societal level influences are especially relevant in design projects that cross cultures [39]. Networks of power explain the power balance that results from the relationships between different stakeholders based on their official hierarchical position or their individual attributes within an industry [48]. This power balance can influence the outcome of a design. In the past, urban development approaches focused on human services and private-sector requirements [15]. Traditional approaches to infrastructure development did not emphasize environmental impact and this could be partially attributed to cultural values and legal regulations.

These are just a few of the societal level influences to whole systems, which are motivators for the organizational level influences explained in the next section.

### *5.2. Organizational Level*

A strong influence to whole systems design at the organizational is contract structures, which govern relationships in infrastructure projects. Relationships influence decision-making, which, in turn, affects the end design of an infrastructure project. A contractor working in a design-bid-build procurement arrangement, in which the eventual builder is not hired until the design is complete, will not provide the same input as one working in a design-build arrangement, in which the eventual builder is also contracted to support the design phase [49].

Whole systems design requires that all project information is shared with all affected stakeholders. This is not possible when the involvement of important stakeholders is fragmented like in the design-bid-build procurement arrangement.

One approach to infrastructure design that encourages whole systems design is Integrated Project Delivery. Integrated Project Delivery aligns stakeholder contract incentives with overall project goals [50] and makes the goals and values of various stakeholders more transparent, which is helpful as the psychological research shows these goals and values can otherwise be misperceived [51]. Still, Integrated Project Delivery is not widely practiced and, even when it is, creating the alignment between incentives and goals is a challenge [32]. This is because infrastructure development stakeholders operate in a unique culture that influences their decisions [52–54]. Influences to whole systems design fostered by this culture are explored in the following subsections.

#### 5.2.1. Social Heuristics

To define social heuristics, we draw from Beamish and Biggart's [55] research in the commercial building industry. Social heuristics are defined as "collectively held principles of evaluation that act as (quasi) models for choice and in so doing make agent search, assessment and selection processes both simpler as well as socially accountable" [56]. For example, rules of thumb are all under the umbrella of social heuristics.

Study of the industry that designs and constructs infrastructure from an economic sociology perspective found tacit social heuristics that aid coordination among particular groups but also lead to reluctance to depart from industry standards and unusually high reliance on reputation [55]. Decision processes at this level often depart from the assumption of rational deliberation and rational information use, and possibly in ways that deviate from the biases exhibited by consumer decisions [57]. Beamish and Biggart [55] reveal why new technologies are slow to be adopted. Unlike microeconomic theories, that suggest green technologies fail to be implemented due to a perceived higher cost, they instead found practitioners rely on social heuristics that do not necessarily consider cost at the forefront. This suggests that price is not in fact the critical criterion when making design decisions, but it is rather a combination of fear of departure from: established reputation, network governance relationships and conventional design. Therefore, design and construction practitioners for infrastructure rely on social heuristics such as consensus, reflexivity, and reputation.

Although choice architecture is not completely transposed to social heuristics, as these principles are often not explicitly written down, there are choice architecture methods that can influence commonly accepted ideas. For example, designers are able to develop a good reputation with clients due to repetition of successful designs. The implementation of a new technology could potentially delay a normally simple construction project and this is a risk that many designers are not willing to take. Reliance on the reputation heuristic is common in commercial construction [55]. A designer with a good reputation could use choice architecture in their design proposals to nudge infrastructure stakeholders to consider a change to a more sustainable design. Highlighting how whole systems design can lead to more sustainable aspects could encourage taking a risk on a new concept, such as a green roof, which encompasses the principles of whole systems design.

#### 5.2.2. Decision Support

Computational models remain the most readily available tool for visualizing, predicting, and managing complex civil infrastructure system dynamics. While these tools can be used as a decision support for design decisions, the outcome of these types of software rely on the implemented model to capture tradeoffs in designs and in reality may not be the best representation of the interdependencies between infrastructure and the community [58]. Past research has defined the complex relationship that involves interdependencies between infrastructures as a system of systems and attempted to model these systems, but this is with little regard to the dependence of humans on critical infrastructure [1]. Not only that, but modeling software requires data accessibility, model development, and model validation, and also, a certain level of expertise [58,59].

In a sense, the choice architecture of modeling software can influence the use of whole systems design. Since it is impossible to analyze all of the uncertainties of infrastructure, the outcome of modeling software can simplify the intricacies of infrastructure design, which can help designers make decisions, but the assumptions the model makes can take advantage of choice architecture to ensure that the output considers sustainability. A survey of U.S. and international research on critical infrastructure interdependency modeling grouped models as either using an integrated system model or the coupling of a series of individual simulations together asserting that integrated models "tend to model at a much higher level than coupled models" [59]. It is important that designers of infrastructure understand. The limitations and pitfalls of the models they are working with, such as those that simply couple individual simulations. Whole systems design encourages the use of systems thinking, but the use of modeling software cannot take the place of designers employing systems thinking and considering all affected stakeholders and the community. For example, the use of integrated project delivery could help frame the project in a way that the use of modeling software could help designers make tradeoffs without sacrificing something important to a major stakeholder.

#### 5.2.3. Other Organizational Level Influences

Other organizational influences to whole systems design include: governance, knowledge transfer, and work place norms. Although economics supports the use of relational governance in infrastructure projects, the different phases of infrastructure projects are often disconnected, which makes the relational governance of these projects difficult. The use of relational governance can be improved through fundamental changes in work places norms and regulations, but more integrated research is needed to show how to make these changes effective [60]. These organizational barriers can be triggers for the individual level barriers described in the next section. For example, knowledge transfer is crucial for the successful application of whole systems design and is often unsuccessful at the organizational level, but knowledge fundamentally resides with individuals [61]. An opportunity for changes in choice architecture arise in boundary objects like rating systems or building codes that are often read or used by individuals. Small changes in the structure of these materials can prompt changes in perceived ability [62].

### *5.3. Individual Level*

Infrastructure development stakeholders are influenced by goals, incentives, and available information as they make decisions [63]. Stakeholders may make decisions that do not optimally trade sustainability objectives against other outcomes, when they are unaware of the impact of infrastructure on sustainability [64]; when sustainability is not an objective, perhaps because of misaligned incentives or insufficient feedback on the consequences of decisions [64]; when they believe that the client is more interested in other goals, such as minimizing upfront costs [44]; or, when they have sustainability goals, but lack the time to allocate sufficient thought or attention to them [63].

#### 5.3.1. Utility Maximization

The concept of utility theory from economics claims that when an individual is presented with a decision in an environment with a limited budget, their goal will be to maximize utility, or value [65,66]. Utility theory assumes individuals make rational assessments of decision outcomes. This becomes difficult in infrastructure design due to varying definitions of utility depending on stakeholder groups. For example, the definition of utility for a commercial builder might be to maximize profit, and the definition of a facility manager might be reducing maintenance costs. Moreover, there is a difference between short term and long term utility. Designers often have difficulty seeing the long term utility of an infrastructure project and tend to make decisions based on present benefit which can lead to a tradeoff between money and the environment [67].

A whole systems design approach asks designers to align design goals with all stakeholders and consider the effects of design decisions on the entire system. In other words, all design decisions should aim to maximize the utility of the entire system (which includes the utility of individual stakeholders).

The choice architecture used in a project definition greatly affects an individual's concept of utility when making a design decision. For example, if the cost of a parking garage project is defined as just the design and construction phases, a designer would be less likely to include more sustainable technologies like LED lights because although they have been proven to have a return on investment, their initial cost is more expensive than conventional lighting options such as metal halide [68].

#### 5.3.2. Bounded Rationality

Bounded rationality means that decision-makers are constrained by their computational ability and the environment of the choice and information presented [69]. Bounded rationality attempts to augment traditional economic theory that assumes decision-makers are economical and completely rational [70]. Simon theorized that humans could subconsciously manipulate the environment of a choice to reduce their respective computational ability.

Related to infrastructure, this becomes relevant when a designer or decision-maker is attempting to make tradeoffs when it comes to infrastructure design outcomes. As stated in the Introduction, infrastructure is interdependent making it infeasible to consider the outcome of all design decisions.

Attribute substitution is an underlying process of bounded rationality that occurs when a decision-maker substitutes complexity for more simple, point specific traits or elements of options [71]. When designing infrastructure, engineers are often confronted with challenging design choices, such as, material options within environmental and cost parameters or, design options that meet flow capacity and physical space limitations. Under these circumstances, the decision-maker may simplify the situation by focusing on one attribute, like cost or durability, at a time in order to determine an appropriate outcome. The problem considering one attribute at a time is the tendency to consider some attributes over others or overly weighing attributes considered first, leading to attribute substitution [71].

Attribute substitution can be detrimental to design for sustainability because substitutions can occur without rational analysis. For instance, assessing the sustainability of a project material, like an asphalt roadway, an engineer may substitute full life cycle emissions calculations for recycled material when specifying a pavement mix, which may lead to a short life span of the product and an increase in emissions compared to other design options. Cardin, Neufville, Geltner [58] suggest that to analyze all designs and outcomes of infrastructure is time intensive. Simplification through attribute substitution maximizes utility for the individual decision-maker by decreasing the time to make a design choice.

Whole systems design encourages focus on the fundamental desired outcome, which means stakeholders work together to determine the necessary tradeoffs as opposed to tradeoffs that focus on one evaluation metric and might degrade sustainability of the resulting design. The use of choice architecture in the definition of a project's goals can help simplify a project scope without suggesting tradeoffs that diminish sustainability outcome of a project. Choice architecture can be used to shape the environment of the choice; for example, in request for proposal (RFP) design. A request from a city for design proposals for a waste overhaul strategy may yield more options than a proposal for a zero waste franchise. Although both RFPs aim to focus on the waste and recycling program, the request for a waste overhaul strategy might lead to more creative solutions like the inclusion of a waste to clean energy facility [72].

## 6. Choice Architecture in Infrastructure

Infrastructure decisions, at the societal, organizational and individual scale, often rely on social heuristics or rules of thumb to improve design decision outcomes. However, when these heuristics do not align with reality or between stakeholder groups these tactics can lead to less than sustainable outcomes in which buildings and infrastructure are designed in isolation. Buiten and Hartmann [73] point out that cognitive bias within public–private partnerships can lead to prematurely narrowing project scope and look to research in judgment and decision-making for a solution. Levitt et al. [74] observe the disconnect between a private–public partnership and its network and emphasize the importance of more research on stakeholder engagement within these partnerships. Research goals such as these can be expanded with aims to encourage whole systems design, meaning, employing systems thinking during the design and construction process to realize the interconnectedness between the systems the design will influence and make changes in order to increase the sustainability of the design or project. By better understanding the influences on decision-making from a choice architecture point of view, researchers can develop interventions to encourage a whole systems design perspective and in turn lead to more sustainable design outcomes. The focus of this section is the decision-making process of infrastructure design and points where manipulating choice architecture encouraged more sustainable outcomes.

### *6.1. Decision Aids Defined*

A decision aid is anything used during a decision process to facilitate a choice. In healthcare, decision aids such as those that provide information on treatment options and risk factors increase patient knowledge when making medical decisions under uncertainty [75]. Similarly, building codes, modeling software, even green rating systems act as decision aids for professionals designing and constructing infrastructure. These tools reduce uncertainty from outside factors like storm events (codes used to design to 100-year floods), energy costs (modeling energy consumption using building information modeling) and environmental impact (with Leadership in Energy and Environmental Design guide). Modifying these tools to focus on particular choices can encourage higher considerations for sustainability during design [76].

### *6.2. Examples of Choice Architecture Interventions*

Empirical research involving interventions within decision aids for infrastructure are known to influence the decision-making process of infrastructure design. Examples include studies testing the effect of role models, framing effect, anchoring bias, and the coupling of multiple choice architecture interventions.

An empirical study tested the effect that a role model project would have on the consideration of sustainability by professional engineers. The role model project illustrated the feasibility of high levels of sustainable achievement. By manipulating Envision, a rating system for sustainable infrastructure [77], providing a positive role model, illustrating high levels of achievement, led engineering professionals to believe their projects could also meet a higher sustainability performance while a negative role model led to decreased performance when compared to a control group with no role model [22].

Using a role model as an intervention within a decision aid such as Envision is a form of choice architecture. The study manipulated the presentation of design options and influenced what professional engineers believed was possible, in turn, helping them set realistic but higher sustainability goals.

A more nuanced approach using choice architecture is framing decision outcomes as a loss in value (rather than a gain), which can increase a decision-makers' acceptance of risk and lead to high goals for achievement. Researchers can make accurate predictions about decision-making based on framing effects [78] and loss aversion [79] due to the last 30 years of research [65]. An example of framing effects and loss aversion applied to infrastructure decisions is another empirical study using the rating system for sustainable infrastructure, called Envision. The study concluded that by endowing points to professional engineers in the sustainable rating system significantly influenced their decision-making. Professional engineers endowed points (with the option to lose points rather than gain them) set high achievement levels goals for sustainability [62].

Of course, infrastructure decisions are subject to varying constraints, goals, and resources with different stakeholder mandates and budget cycles. Decisions about infrastructure are made in groups. Coupling the role model and framing effect in a group setting using Envision led to similar effects as individual decision-making. This study also showed that disclosing the interventions to participants did not curtail the effect of choice architecture on decision-makers considerations for sustainability [80].

Just as role model projects illustrate high levels of sustainability and framing effects take advantage of loss aversion, which can improve decision-making, anchoring bias can hinder decision-making for sustainability. Anchoring bias is the tendency of decision-makers to base their decisions off of a predefined standard whether or not it is representative of reality, which could fall under the previously discussed category of bounded rationality [81]. Anchoring bias in regards to energy performance goals for U.S. buildings was tested in an empirical study with owner representatives from the United States Green Building Council finding that building rating systems can unintentionally result in lower energy performance goals depending on the anchor used to set these energy use reduction goals [82]. This is relevant because when it comes to the choice architecture of decision aids in infrastructure engineers may adjust their goals based on the initial anchor that they are presented. For example, the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) establishes a 30% minimum energy reduction as a target for future building codes [82]. This 30% can act as an anchor for building energy goals based. Setting a higher energy reduction target may increase the average energy goal set by building owners.

Not only are decisions about energy and sustainability influenced by choice architecture but also decisions about contract pricing. A study involving civil engineering students tested the coupling of multiple choice architecture methods: reordering criteria, the insertion of emoticons, and explicit examples of risk and uncertainty, within a preliminary design trade-off matrix with aims to increase the attractiveness of particular design options that were defined to be less risky than an alternative [83]. Although the results of the study were inconclusive, a similar experiment with a larger sample size may hold significant results.

This merging of theories from behavioral science with infrastructure design and construction holds promise to aid in making complex decisions. Choice architecture clearly exists throughout the infrastructure design and construction process and intentional or not, decision-makers are influenced by the way information is presented to them. While our goal is to encourage the use of whole systems design during building and infrastructure design, this approach can be leveraged towards other outcomes as well. The next section details the need for more research in this area, in effort, to take full advantage of the potential of intentional choice architecture.

## 7. Conclusions

Understanding how to promote whole systems design in the infrastructure industry using choice architecture has the potential to lead to low cost implementation that would have a dramatic increase on the sustainability of infrastructure, for example, a request for proposal that does not prescribe the exact solution, but is instead vague and asks for innovative solutions to a particular problem. The previous section gives only a few examples of where choice architecture has been tested in the framework of infrastructure decisions. For researchers, the contribution of this paper is helping realize the ample opportunities there are to research in this area; to help better understand which choice architecture interventions are the most effective at promoting whole systems design and where already existing choice architecture is having the opposite effect. For industry, the contribution is making the benefits of whole systems design evident and how choice architecture can influence design outcomes. Not only that, but helping industry recognize that small changes in things like common decision aids and social norms can promote more sustainable infrastructure.

Those responsible for infrastructure design and construction realize the need for more research with a focus on the triple bottom line, meaning the economic, social, and environmental impact of a design or project [13]. Approaches through choice architecture to encourage a whole system design process can help. At the societal level, research is needed to better understand how things like governmental incentives effect the diffusion of new green technologies within the infrastructure design and construction industry. At the organizational level, a closer look at infrastructure project delivery could reveal opportunities for choice architecture to nudge designer and constructors towards a whole systems design approach. At the individual level, multiple empirical studies have resulted in an increased level of sustainability based on a choice architecture change [22,76,80,83–85], which is further evidence that changes in choice architecture have the potential for a significant impact on the infrastructure design and construction industry.

In conclusion, the research of choice architecture with aims to promote whole systems design can help answer the emerging question on how to promote the design of more sustainable infrastructure with small, but intentional changes, to already existing decision aids and structures.

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