# The Fourth Pillar of Infrastructure Sustainability: Tailoring Civil Infrastructure to Social Context

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## Abstract

This research proposes technical performance over time as a fourth pillar of sustainability theory for infrastructure. It also describes a method that allows us to discover how changes in the technical pillar (operationalised as reduced breakage rates) may moderate the influence of the social pillar (operationalised as repair rates) on sanitation infrastructure outcomes. Oral histories were used to develop a history of sanitation for each of 152 poor households in four rural communities in Bangladesh that have gained access to sanitation in the past decade. Transcriptions and qualitative coding identified reported states of sanitation (for example, broken vs. functional) at three time steps. These were used to develop an initial vector and transition matrix for a Markov chain analysis. The breakage rate in this model was then adjusted to investigate the impact of improved technical durability on sanitation outcomes. For the case analyzed here, we found that increasing infrastructure durability by 50% (an estimated increase of two years) increased the rate of functional sanitation system use at model convergence from 54% to 88%. Increases in durability also caused households to use private rather than shared systems. Beyond this specific case, the generalisable theory and method presented here are analytic tools that permit targeted technical accommodation of social contexts specific to individual project sites.

## Introduction

Between 1990 and 2012, over 1.9 billion people gained access to improved sanitation infrastructure (World Health Organization and United Nations Children's Fund, 2013). By the definitions established for the Millennium Development Goals (United Nations, 2000), this number represents new construction. In parallel to this increase in infrastructure coverage, human health outcomes have dramatically improved. For example, between 1990 and 2002 the global average for infant mortality was 4.8 percent, which conservative estimates place as a 75% reduction over the past 120 years (Kenny, 2012, p. 77). While this improvement cannot be entirely attributed to infrastructure, sanitation has played a vital role. Indeed, it has been identified as one of the most important advancements for global public health (BMJ, 2007). To provide these benefits, sanitation infrastructure must be used and must be technically sound over time; initial construction is not sufficient. As such, in this research we study sustainable sanitation systems that can provide sanitation services indefinitely, or at least throughout some reasonable design life.

In this research we are interested in onsite household sanitation systems. The defining characteristic of these technologies is that they treat or at least store household effluent at the place of generation, without piping it to a combined treatment facility. These technologies are common worldwide. For example, in the United States septic tanks serve about 20% of the households (United States Environmental Protection Agency, 2008). In developing contexts, onsite sanitation technologies are more likely to be a type of pit latrine. Onsite sanitation technologies dominate in rural areas where low housing density means that long pipe runs are required for sewered systems, with associated high construction and energy costs for pumping. From a technical point of view, onsite systems are capable of providing waste treatment while avoiding those costs, and as such make up a large percentage of new systems constructed each year (United States Environmental Protection Agency, 2008).

Unfortunately, onsite sanitation systems have high failure rates worldwide. In the US, at least 10% of all septic systems have failed (United States Environmental Protection Agency, 2008). Internationally, Rodgers et al. (2007) found that in rural northern Ghana 40% of new (zero to two years old) latrines have failed. In an even more shocking example, a sample of 517 household sanitation projects in South Africa found that absolutely none complied with South African sanitation policy requirements, norms, and standards (Council for Scientific and Industrial Research, 2007). While there are various reasons for onsite sanitation system failures, one common reason is that constructed toilets have broken and not been repaired; this is the subset we study in this research. To do so, we frame pre-design life breakages (excluding cases of vandalism) as technical failures, and repairs as social interventions; next, we construct a model that allows us to investigate how technical changes could improve infrastructure outcomes in a empirically measured social context. In other words, this approach is a tool by which we can determine how the technical may better accommodate the social.

# Points of Departure

In this section, we discuss the triple bottom line of sustainability in the context of sanitation infrastructure construction. Next, we theorise technical performance over time as a fourth component of infrastructure sustainability theory. Finally, we identify the limited work treating interactions between technical and social factors that impact civil infrastructure as a gap in the literature with serious practical implications.

## *The Triple Bottom Line of Sustainability in Infrastructure*

The concept of sustainability was first popularised in 1987 by the Brundtland Commission as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). While this frequently excerpted line does summarise much of the Commission's findings, it is worth noting that the document explicitly emphasises the needs of the poor, both contemporary and future. However, this broad definition of sustainability does not help the engineer understand what changes must be made to design and construction tasks in order to rise to the stated challenge. As such, many more operational frameworks for enacting this definition have been proposed. For this project, we use the triple bottom line (Elkington, 1998) as the basis of our analytical framework. This portrayal describes three pillars of sustainability: Environment, Economics, & Society.

The environmental pillar of sustainability deals with protecting the environment, and at a national policy level is enacted by various government agencies. For construction engineers, environmental concerns might include the performance of green buildings (Issa et al., 2011), the environmental impacts of prefab construction (Jaillon and Poon, 2008), or liability concerns of environmental harm (Lavers and Shiers, 2000). Environmental sustainability has a clear connection with infrastructure, as infrastructure is often designed and constructed in order to either clean up pollution or to prevent it. For example, we might construct an improved wastewater treatment plant (Akunna and Bartie, 2014) or sewers to prevent groundwater pollution (Humphrey et al., 2014). Alternatively, we may design technology to serve a non-environmental purpose in a manner that lessens impact on the environment. For example, light bulbs are designed and used to provide light rather than for any environmental purpose. However (as noted in the recent Nobel Prize award (Nobel Media, 2014)) LED bulbs' particular manner of providing light reduces environmental impact, for example by reducing energy consumption in wastewater disinfection applications (Umar et al., 2015). Whether environmental protection is a primary (e.g. cleaning wastewater) or secondary (e.g.. providing light, but doing so more efficiently) purpose of a particular technology, performance over time is an important component of environmental sustainability.

Economic sustainability has also been a concern of construction and engineering professionals since the professions emerged. For example, in the United States, some of the first major infrastructure projects undertaken were canals, which flourished or starved based on a combination of rare technical expertise and economic capital (Larson, 2001). More recently, researchers have considered price impacts of green design (Feige et al., 2013), life cycle costing (Kirkham, 2005), or the long-term cost impacts of various contract structures (Cruz et al., 2014). Similar to environmental sustainability, economic sustainability must consider the element of time. Economic analyses typically include the element of time by resorting to life cycle costing methods, which at their full incarnation include costs from cradle to cradle, or from resource extraction to reuse (Braungart, 2002). For sanitation technologies, this might include life cycle analysis of energy recovery processes (Smith et al., 2014).

More recently, construction engineering has begun to directly address social sustainability (Buser and Koch, 2014; Kaminsky and Javernick-Will, 2015; Levitt, 2007). Indeed, both the poor in situ performance of our infrastructure described in the introduction to this paper and the increasingly global nature of our business (Javernick-Will and Levitt, 2009) means that the interactions between our infrastructure and people who use it is of increasing importance to the research community. As is true for the other pillars, time is a key component of this attention to social impacts. Unfortunately, there is very limited literature treating social sustainability of infrastructure with attention to the sanitation infrastructure that interests us here, and even less than does so with the intention of improving the theory and practice of infrastructure construction. In notable exceptions, Furber et al. (2012) examine health and safety implications of community construction projects, Kaminsky & Javernick-Will (2015) use legitimacy theory to explain household sanitation outcomes, and Sohail and Baldwin (2004) propose and test the use of performance indicators for micro-projects in developing countries.

## *The Fourth Pillar*

To achieve a sustainable design, all three of these pillars (environmental, economic, and social) must support and be supported by the others. Additionally, and building on construction literature that notes important relationships between technical design and the three pillars (Levitt, 2007), in this paper we frame technical performance as a fourth pillar of infrastructure sustainability theory. In the context of household sanitation, technical failure (for example, a poorly constructed sanitation system) functionally means that waste is not separated from people. A technically failed sanitation system costs money to build (an economic loss), permits groundwater pollution through escaped waste (an environmental loss), and does not help people achieve health benefits (a social loss). The point here is that a failure of any pillar may cause a failure of all; the pillars are an interdependent system. Alternatively, strengthening one pillar may reduce the load on another. For example, in this research we consider the impacts of strengthening technical performance such that it may better accommodate the existing social context.

The concept of the fourth pillar of sustainability analytically helps us to disentangle failures that occur due to social reasons (in this research, failures to repair) and those due to technical reasons (in this research, non-vandalised, pre-design life breakage). In the context of sanitation systems, an example of a social reason for sanitation system failure would be a household ceasing use of a sanitation technology in favor of none, which we call practicing open defecation. Alternatively, if a system does not perform technically, it is still a sanitation system failure even if a household continues to use it (a common situation, as discussed in Kaminsky and Javernick-Will (2015)). An example of this is a family using a septic tank system although it has overflowed and no longer provides separation of people and waste.

There are two ways we might try to address this latter situation. One would be behavior change communication to encourage the household to repair the system. However, past research has shown that infrastructure behavior change is an extremely complex and difficult undertaking (Shove et al., 2008). Alternatively (and as pursued in this paper), we might be able to change the technology such that the system can better accommodate existing human behavior patterns. In pursuit of this goal, the research objectives of this paper are (1) to describe a method that allows us to tailor civil infrastructure to individual social contexts, and (2) to discover how changes in infrastructure durability (reduced breakage rates) may moderate the influence of community behavior patterns (repair rates) on sanitation infrastructure outcomes, both using empirically derived case data.

# Method

To explore how the technical may be tailored to the social, we use a combination of qualitative methods and Markov chain analysis. Qualitative interview methods were used to develop a history of sanitation use at the household level. These oral histories were then used to create a transition matrix describing the likelihood of moving from one state of sanitation services to another (for example, the socially based transition between broken to functional (fixing), or the technically based transition between functional to broken (breaking)). Finally, the breakages rates in this matrix were modified in order to investigate the importance of technical sustainability on community sanitation outcomes within an empirically given social environment. The research context, these methods, the data collection process, and details on the analysis are given below.

## *Research Context*

Data for this project were collected in Bangladesh, the world's 7th most populous country (World Bank, 2011). Bangladesh is also one of the poorest nations in the world, with over 40% living on less than the international poverty line of $1.25USD/day (World Bank, 2011). At last count, nearly 40% of Bangladeshis were still living without access to improved sanitation. As high as this figure is, it represents real progress; as recently as the year 2000 nearly 60% were lacking sanitation services (United Nations Development Programme, 2011). However, these figures must be understood with the caveat of high breakage rates described in our introduction, meaning that the reality of achieved infrastructure services may be even worse than these already unacceptable numbers suggest.

## *Research Design*

The Markov chain method was selected as a way to analyse change over time, which as described above is an important component in sustainability analysis. While the method is discussed here, readers are referred to other sources for a more detailed discussion (for example, see Meyn et al., 1996; Norris, 1998; Seneta, 1996). In this genesis, it is a memoryless model where the probability of moving from one state to another depends only on the current state. We should note that this paper models the process as a discrete state process; in other words, a household's sanitation system is classified into one of several discrete states rather than being represented along a continuum of sanitation achievement. The states of sanitation were taken from the World Health Organisation sanitation ladder (World Health Organization and United Nations Children's Fund, 2008), adding a state to record broken systems that are still in use. The four states used were private and functional, shared and functional, broken but in use, and open defecation. For simplicity, in this paper we will refer to these states as private, shared, broken, or OD, respectively. A private system is used only by people living in a single house, even if they are not related. The shared systems in this study are shared between multiple houses but are not public toilets. Broken systems were either private or shared systems that were broken on the day of the visit in a way that causes them to not separate people from waste. For the ring slab latrine designs used in these communities (and described more fully below), examples of this are a broken slab or broken rings lining the waste receptacle pit. The most frequently reported breakage was the slab cracking or catastrophically failing from the load of people using the system. Our breakage definition did not include, for example, a broken superstructure intended to provide privacy. While broken, households were still using these toilets. Finally, open defecation means that the household is not using a toilet at all. The broken and open defecation states could reasonably be grouped together, as the broken systems are no longer providing sanitation services. However, we have left them separate to emphasise the difference between failed technology and absent social sustainability. If households have ceased using the technology, it is a socially based factor. If households are still using a toilet that has technically failed, it is instead a technical problem that may be addressed through better design and construction. This latter can be addressed by engineers, and it is this latter we are interested in here. Interestingly, in these communities, this is also by far the larger problem.

A Markov chain analysis requires two pieces of information, which are shown below in Equation 1. The first is a vector that describes a distribution of the initial states (1, 2, 3, and 4). For our analysis, this is a distribution of sanitation systems between the four states defined above. Based on the oral histories we collected for this project, we begin with every household practicing open defecation. This initial distribution heavily impacts the behavior of the model during initial time steps. However, in the absence of trapping states, the model will ultimately converge on a steady state solution that is independent of the initial state. This convergence is defined by a transition matrix, which is the second piece of information needed for a Markov chain analysis. A transition matrix displays the various probabilities of moving from one state to another. Convention places the state at time n on the left of the matrix, and the state at time n+1 along the top of the matrix. Abstractly, the number in each matrix cell should be understood as the probability (p) of moving from state j to state k ($p_{jk}$) over time step n ($p_{jk}(n)$). For example, the upper right cell in the matrix below should be read as the probability of moving from state 1 to state 4 over time step n, and the vector to the left of the matrix is the distribution of states 1-4 in the system as it enters time step

n. For our analysis, this could be the probability of moving from a private system (state 1) to a broken system (state 4) over one time step. More formally, this may be represented as

**EQUATION 1**

$$\Pi(\boldsymbol{n}) = \left\{\begin{array}{c}\mathbf{1}\\ \mathbf{2}\\ \mathbf{3}\\ \mathbf{4}\end{array}\right.\!\begin{bmatrix} \boldsymbol{p_{11}(n)} & \boldsymbol{p_{12}(n)} & \boldsymbol{p_{13}(n)} & \boldsymbol{p_{14}(n)} \\ \boldsymbol{p_{21}(n)} & \boldsymbol{p_{22}(n)} & \boldsymbol{p_{23}(n)} & \boldsymbol{p_{24}(n)} \\ \boldsymbol{p_{31}(n)} & \boldsymbol{p_{32}(n)} & \boldsymbol{p_{33}(n)} & \boldsymbol{p_{34}(n)} \\ \boldsymbol{p_{41}(n)} & \boldsymbol{p_{42}(n)} & \boldsymbol{p_{43}(n)} & \boldsymbol{p_{44}(n)} \end{bmatrix}$$

The transition matrix is applied to the initial distribution vector to generate a new vector that represents the distribution of states at n+1. Next, the transition matrix is reapplied to the new vector to generate yet another distribution at n+2. This process is iterated until a level of convergence appropriate to the analysis is achieved. In the absence of more detailed data, for this analysis we are assuming that the transition matrix is independent of the time step, or in other words, that the probabilities in the transition matrix do not change with each iteration. A steady state transition matrix may be read as the probability of finding a system in any given state at any given time. This enables us to use the observed states of systems as representative of those transition probabilities.

A self-evident and significant issue involved with performing any Markov chain analysis is the data needed to develop the transition matrix. While for more traditional engineering analysis these probabilities may be derived from physical tests of systems (such as bridge surface condition (Corotis et al., 2005)), these types of tests do not exist at the technology-society nexus. In particular, research in developing communities is commonly plagued by insufficient data, as there are rarely repositories of infrastructure (or other) data available. This research used qualitative methods to develop transition matrices in order to overcome this challenge. In the absence of any other source, interview methods and oral histories are one of the few ways in which data may be collected about these communities.

## *Data Collection*

Four rural communities in the Barisal District of Bangladesh were chosen for data collection with the aid of local NGO and sanitation officer knowledge as representative of a range of sanitation coverage, and as homogenous in terms of ethnicity, religion, and socioeconomic status. Here we define sanitation coverage as a system that was not broken on the day of the visit and that owners reported having fixed or emptied at least once. The selected communities averaged 42% coverage by this definition. Each of the four communities is located within 20 km of each other by road. Households reported that they ceased practicing open defecation in the last 10 years. Annual household income was self-reported and researcher estimated based on respondent-reported occupation as $300-$600 USD. Households have an average of five people living in them, ranging from one to 16 people. This makes the average per capita annual income about $80USD. This homogeneity allowed us to control for economic issues.

Interviews were conducted by a Bangladeshi research assistant in Bengali. Interviews were semi-structured but asked open-ended questions in an attempt to elicit detailed and locally relevant histories of sanitation. For example, participants were asked about when they first built a toilet, if it had ever broken, if they had ever needed to fix or replace the toilet, what problems they had had with it, and if they shared it with anyone else. We attempted a census of households in these four communities. Up to five visits on separate days were made to each community in an attempt to achieve a high level of participation. A total of eight (of 162) households chose not to participate or were not home during data collection. In one community, adults in 15 households were in hiding due to a recent murder. In this community adult children participated in the interviews in their place. A total of 154 household interviews were completed; two of these are not included in this analysis because the needed historical data was not captured due to audio recorder or interviewer error.

With the permission of the participant, interviews were audio recorded using a cell phone, as this device was considered less intrusive and more familiar to respondents than a dedicated audio recording device. Afterwards, interviews were concurrently transcribed and translated to English. Both the audio files and the translations were then transferred back to the United States for quality checks and analysis.

Most households use a variation of a ring-slab latrine design, which is standard in much of Bangladesh. This design uses a series of rings, typically made of concrete, that are stacked in a pit dug in the ground as a liner. Households may install any number of rings, depending on financial ability and (ideally) the water table depth. A slab with a hole, also typically made of concrete, is placed over these rings to support latrine users. In these communities, the slab is usually flush with the ground level in order to allow for squatting or for installation of a seat. Many but not all slabs are provided with a u bend that provides a water seal between the user and the waste receptacle (see Figure 6-8 in Harvey et al., 2002). This u bend was frequently broken in these communities. Informal discussions with participants indicated that many people break the u bend for easier maintenance, while others feel it is particularly important to reduce odor and flies. When the latrine pit is full, owners may choose to abandon the system in place and replace it, empty it themselves, or pay a company to empty it at a reported cost of less than $1USD. Household motivations for constructing and using sanitation infrastructure are discussed in Kaminsky and Javernick-Will (2015).

## Qualitative Data Analysis & Results

The transcribed interview data was imported into the software package NVivo 10 (QSR International Pty Ltd., 2012) for qualitative analysis. The statements made by the participants were used to trace the history of sanitation at each household. Each household was coded (Miles and Huberman, 1994; Saldaña, 2009) to show the state of sanitation at that home over time. Codes were developed from the World Health Organisation sanitation ladder (World Health Organization and United Nations Children's Fund, 2008) with an added category for broken but existent systems.

It was determined that three past time steps could be reliably developed from the data, with a time step being defined as an event representing change in sanitation (such as construction, repair, or abandonment of a system). In the few cases where the state in third step could not be determined, it was assumed that that state was open defecation. This was considered a valid assumption because the communities self-reported building sanitation systems over the past decade. For example, one interview fragment was coded as follows:

1. *Question: Do you have a functional toilet right now?*

   *Answer: Yes but broken…The slab is still broken.*

*We don't repair it.* (Time n: Code as broken)

2. *Question: How long have you had your toilet?*

   *Answer: After six or seven month from the day we came here.*

   *Question: That means 2.5 years?*

   *Answer: Yes.* (Time n-1: Code as private)

   *Question: What about these 6 months?*

   *Answer: We used our neighbor's toilet.* (Time n-2: Code as shared)

In other words, when this household first moved to the community, they shared a neighbor's toilet. After six months, they built their own. This toilet broke, and they have not fixed it.

Coding matrices were created to develop values for two tables. Table 1 shows a count of households distributed by the state of their sanitation system at time step n-2. This table was used as the initial distribution vector for the Markov chain analysis. Table 2 is the basis of the transition matrix. This matrix counts change in the state of sanitation for each household from time steps (n-1) to (n). As the interviews were not able to establish a common time frame for the states reported, the numbers below only represent instances of change. For example, in Table 2, two households were counted as moving from a shared system to the same type of system as in both of these cases there were different shared systems involved. The only exception to this was the status of open defecation. In this case, if a respondent was currently practicing open defecation, this state was entered for each of the time steps as there had been no change at all in sanitation practices.

**TABLE 1: STATES AT N-2**

| **System State** | | **Count** | |
|---|---|---|---|
| **Shared** | **Functional** | 12 | 85 |
| **Private** | | 73 | |
| **Open Defecation** | **Failed** | 54 | 65 |
| **Broken** | | 11 | |

**TABLE 2 TABLE 2: N-1 TO N**

| | | **State at time=n** | | | | |
|---|---|---|---|---|---|---|
| | **System State** | **Shared** | **Private** | **Open Defecation** | **Broken** | **Sum** |
| **State at time=n-1** | **Shared** | 2 | 7 | 0 | **4*** | 13 |
| | **Private** | 1 | 0 | 1 | **38*** | 40 |
| | **Open Defecation** | 2 | 9 | 4 | 0 | 15 |
| | **Broken** | 12 | 69 | 1 | 0 | 82 |

*BREAKAGE RATES

# Markov Chain Analysis and Results

In order to perform the Markov chain analysis, the numbers in Table 2 above were converted to percentages to form the needed transition matrix. This matrix was then applied to the initial distribution of sanitation states shown in Table 1, resulting in a new sanitation state vector. The transition matrix was again applied to the new vector. This procedure was iterated until the sanitation state vector had converged.

The bolded cells in Table 2 are the cells of particular interest for us. These two cells represent the ongoing breakage rate of the systems (private to broken or shared to broken). By performing a sensitivity analysis that investigates how changing these rates impacts the convergence state, we may investigate the impact of improved construction durability on system outcomes while maintaining the rest of the system, which is a function of human intervention rather than of degradation processes. Figures 1 and 2 below shows the system dynamics for both the raw empirical breakage rate and also if half of the breakages are transferred to the diagonals of the table. In other words, we are changing the breakage rate to be half of what it was empirically observed to be. Practically speaking, based on data from the oral histories this reduction in the breakage rate would require sanitation systems to last 2-4 years, rather than the existing 1-2 years.

FIGURE 1 : OBSERVED BREAKAGE RATE

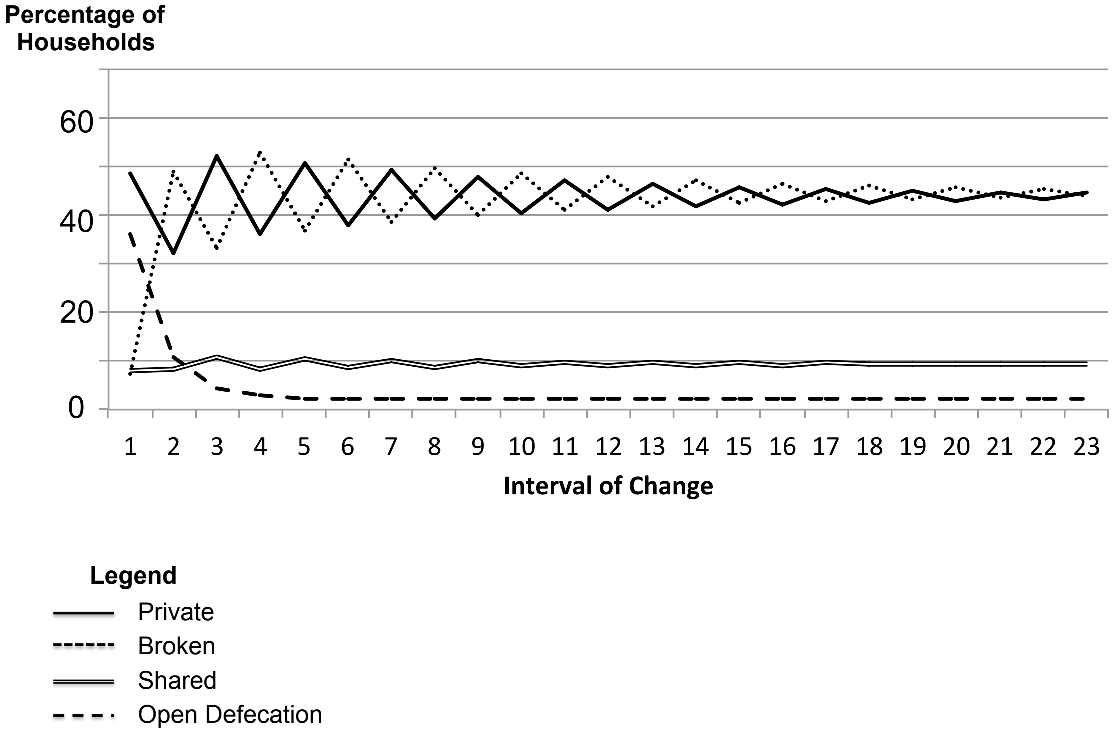
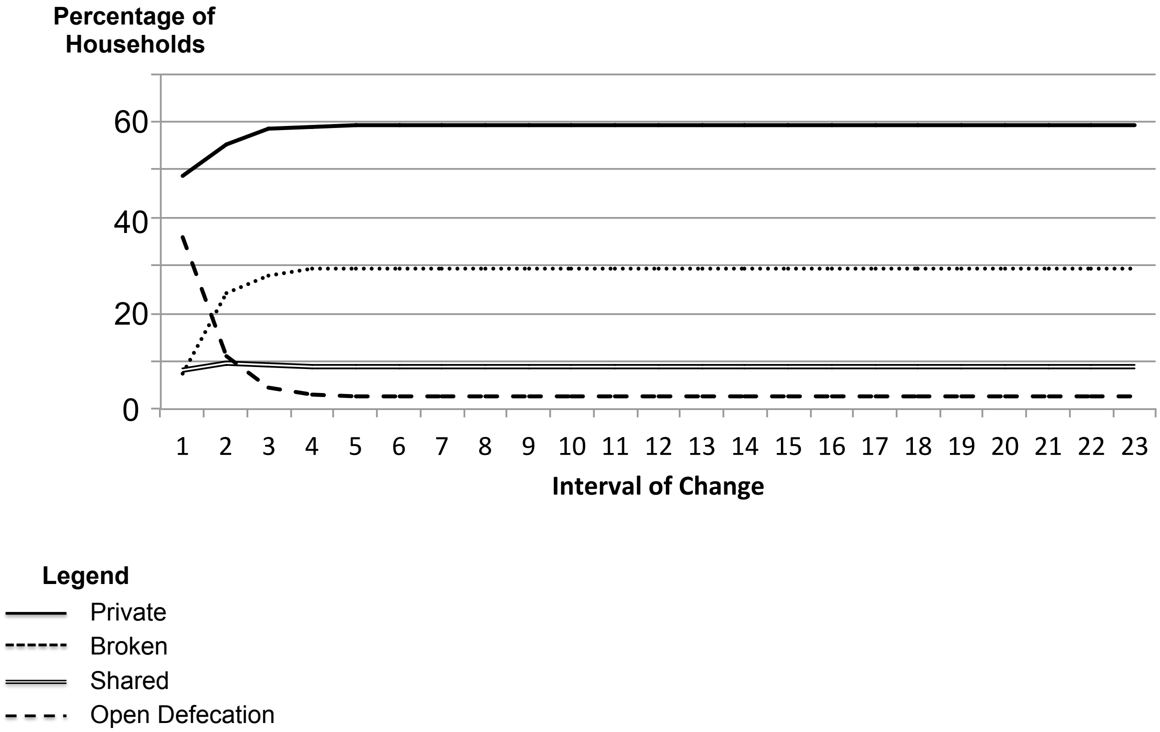


FIGURE 2 : 50% REDUCTION IN BREAKAGE RATE



There are immediately apparent differences between these system curves. When we reduce the breakage rate, system oscillations are dampened, and the rate of people using broken systems drops in favor of people using private or shared systems. The reduction of system oscillations should not be read as suggesting that each household is modeled as remaining in any given state for perpetuity. Instead, individual households are transitioning from state to state, but the total percentage of households in each state at any given time has reached a steady state. Practically speaking, if usage rates oscillate, it is harder to determine the status of sanitation use in a community through monitoring and evaluation, meaning that visits to measure sanitation coverage would need to be more frequent.

Table 3 shows the convergence solutions at selected breakage states. The rate of people using private or shared systems increases with a decreased breakage rate. By decreasing the breakage rate by half and making no changes at all in the likelihood of system repairs or other socially based transitions, the system solution increases from 54% to 88% of households using a functional sanitation system. As we further decrease the breakage rate, we see diminishing returns in the number of people using a functional sanitation system. Interestingly, however, the rate of people using shared systems first rises and then drops dramatically in favor of private systems, which the UN considers to be a higher form of sanitation achievement (World Health Organization and United Nations Children's Fund, 2008). This is initially due to the higher rates of unrepaired breakages observed in shared systems. Later this effect is overwhelmed as fewer breaks mean fewer people transitioning to a shared system after a private system breaks (in lieu of repairing it). Finally and unsurprisingly, rates of people practicing open defecation, which does not involve infrastructure use, are virtually unaffected by our modeled engineering intervention.

**TABLE 3: CONVERGENCE STATES AT VARIOUS BREAKAGE RATES**

| | | **Raw Rates** | | **50% Breakage** | | **20% Breakage** | | **10% Breakage** | |
|---|---|---|---|---|---|---|---|---|---|
| **Private** | **Functional** | 44% | 54% | 59% | 88% | 75% | 90% | 83% | 91% |
| **Shared** | | 9% | | 29% | | 15% | | 8% | |
| **Broken** | **Failed** | 44% | 46% | 9% | 12% | 7% | 10% | 6% | 9% |
| **Open Defecation** | | 2% | | 3% | | 3% | | 3% | |

## Discussion

The discussion is structured in three sections. First the theoretical implications of the proposed approach to infrastructure sustainability and construction research are considered. Next, the methodological contribution is described. Finally, the case used to demonstrate the theory and method is discussed with policy recommendations resulting from the case analysis.

### *The Theory*

In this paper we have argued that technical performance should be explicitly considered as a pillar of sustainability theory for infrastructure. The four pillars (environmental, technical, economic, and social) are proposed as the key analytic elements of sustainability theory for civil infrastructure. As each of these four elements operates through different mechanisms and thus impacts infrastructure systems and processes differently, it is analytically important to differentiate between them. However, as they most often work in combination they must be considered as a system to achieve an infrastructure outcome that we may understand as sustainable. Through this theoretical innovation, we were able to model interactions between social repairs and technical breakages in a way that better allows us to target and scale technical interventions to maximise their impact on infrastructure outcomes. The case presented here is specific to sanitation infrastructure; however, we claim that this conceptualisation is more broadly useful for all types of infrastructure. Similarly, we noted the well-established tie between economic and environmental sustainability and time, and extended that to the social and technical pillars. This suggests that research treating construction sustainability needs longitudinal data and methods whenever possible.

These two points—an expanded systems conception of sustainability and acknowledgement of its fundamentally temporal nature—represent important theoretical distinctions for construction researchers.

Together these distinctions shift attention towards the post-delivery phases of facility life, and direct attention to social performance as a project metric to be considered alongside of project cost, schedule, and quality.

## *The Method*

The first objective of this research was to describe a method that allows us to tailor civil infrastructure to individual social contexts. In other words, the objective is to examine how infrastructure can be adapted technically to accommodate aggregate infrastructure users' behavior, while achieving desired infrastructure outcomes. A contribution of this work is a way to incorporate social user behavior (for example, rates of repairs) into infrastructure design and construction that supports its longevity (for example, through the selection of a design life). For the particular case analysed in this paper (discussed further below), this would mean the construction of more durable infrastructure than would otherwise seem necessary when considering just technical, economic, and environmental criteria.

The method we present here enables researchers to use oral histories, collected through interviews, as longitudinal data in a powerful mixed methods approach. This method is expected to be particularly valuable in contexts with limited available historical data, such as the low resource communities under study here, and to construction research of any kind that incorporates social or temporal factors. While Markov chain analysis has previously been used in construction research to (for example) better understand residual service life in buildings (Kirkham and Boussabaine, 2005) or contractor default risk (Zhai and Russell, 1999), the application proposed here is novel. As in the case presented here, this type of model allows us to discover how technical interventions impact infrastructure outcomes for a particular social context; in theoretical terms, these are studies treating the institutionalisation of change (Scott, 2007) in construction projects. In addition, while the case presented in the current research was not intended to create a widely generalisable predictive model, with a larger and random sample this approach could be used to achieve just that[1]. In other words, this is a generalisable approach for research or practice that allows us to evaluate the impact of technical choices with attention to the social contexts of individual projects. For example, for the case presented here we now have an empirical basis for selecting the design longevity of latrine components that takes into account the particular social context they will be constructed in.

## *Case Analysis & Policy Recommendations*

The second research objective was to discover how changes in infrastructure durability (reduced breakage rates) moderate the influence of community behavior patterns (repairs) on infrastructure outcomes for the case of the four rural Bangladeshi communities studied here. By modeling the relationship between technical and social components of sustainability, we find that (for the case presented here) by improving construction durability we can dramatically increase the number of households living with improved sanitation without any owner behavior change. The percentages presented in Table 3 were not intended to be globally statistically generalizable; the same technical intervention would have a different effect in a different social context. However, we do claim that the relationships shown in Table 3 are analytically generalisable to communities with similarly high rates of latrine breakages. As discussed in the introduction, this would result in real increases in the global number of households benefiting from improved sanitation services. As improving construction material durability is significantly simpler—practically and ethically—than changing human behavior, this is an important finding. In communities where broken toilets are in use (like those in this study), construction improvements will affect significant and positive change. Development work currently focuses on social interventions such as public participation (Chambers, 1994; Cooke and Kothari, 2001) to improve the social sustainability of infrastructure. The targeted technical recommendation here, that accommodates the social rather than trying to change it, is a significant departure from current best practice.

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[1] We are indebted to an anonymous reviewer for this insight.

Respondents reported breakages every year or two. Thus, halving the breakage rate to reflect the modeled intervention means increasing the system lifespan to two to four years, and reducing it to a tenth only means increasing it to 10-20 years. Considering that the major components of ring-slab systems are sections of tubes to form a waste receptacle and a slab for squatting or sitting on, a 20-year life span is not technically unreasonable. However, this modification would significantly and positively change the sanitation coverage outcome in the case study communities. This suggests an important role for development agencies in ensuring the availability and affordability of high quality materials. In addition, if increased durability is to be achieved through the use of thicker cross sections for slabs and rings, some provision should be made for transport of these materials to rural villages, as respondents note this is already a considerable percentage of the cost to households. If reduced cost and transport can be provided to aid households in doing what they are already doing socially at a higher technical quality, we may be able to achieve important improvements in global sanitation and help drive up the appallingly low observed rates of sustained sanitation use.

## *Limitations*

Interview methods have several serious limitations, including the issue of free recall. This means that respondents may simply misremember or forget key information at the moment of questioning (Singleton and Straits, 2004). However, as gaining or losing the use of a sanitation system is a significant occurrence for households, recall is expected to be reasonably clear due to the availability bias of information (Clemen and Reilly, 2004, p. 313). Similarly, participants might choose to consciously misrepresent their sanitation history (social acceptability bias). However, in infrastructure research we are fortunate that systems have a physical presence that may be observed by researchers. While the past cannot be directly observed, the present may at least be verified. As the present state of sanitation is the most relevant to causing these types of misrepresentations (recency bias), it is expected that the oral histories collected here are at least as accurate as any other interview data. An additional limitation is that the transition matrix is applied iteratively to the same set of households. In other words, our model does not account for population change as new families arrive and established ones depart. This does not bias the case analysis presented here, as the communities we collected data from did not experience major population change; however, researchers seeking to apply this method in other contexts should be aware of this limitation. Finally, there are certainly other factors impacting sanitation infrastructure construction and maintenance that are not explicitly included in the method presented here, including but not limited to economics, geography, local regulations, and the reliability of public sanitation services.

## Conclusion

Achieving serious social goals—like basic sanitation for all people—is unarguably difficult. However, the analytic use of theory can help us understand places where we can intervene to bring about meaningful change. In this article, we conceptualise and model technical performance as a fourth and fundamental pillar of the sustainability of infrastructure. This granularity allows us to better understand how technical changes may be made to accommodate social contexts. As shown in the case study presented here, it also provides a way to discover and scale changes in infrastructure design and delivery that can moderate these social impacts. For the case analysed here, increasing construction durability by 50% (an estimated increase of two years) increased the rate of functional sanitation system use at model convergence from 54% to 88%. Increases in durability also caused households to use private rather than shared systems. These results show that in some frequently occurring contexts, improved technical durability can greatly increase the number of people using functional onsite sanitation systems without requiring any behavior change in infrastructure users (such as increased repair rates). This finding stands in contrast to dominant development theory that focuses on social interventions to support infrastructure sustainability. In addition, the achievable technical changes recommended here (improved material quality and selection, and potential support for transport of components to households) suggest a powerful place for government and development organisation intervention. Rather than attempting behavior change at individual households that promote more intensive maintenance and repairs, these organisations can instead focus on the far more centralised supply chain improvements and construction training.

Due to the strong practical implications of these findings, we recommend additional research that can explore this topic further with larger sample sizes in various geographies.  Similarly, future research could consider other types of infrastructure where user behavior has particularly strong implications for construction practice, such as building energy or transportation systems.

From the theoretical perspective, this research stands as a case discovering how technical design and construction can systematically accommodate local social contexts, with the goal of achieving more sustainable infrastructure outcomes.  We certainly do not mean to argue that there are technical solutions to all the world's problems; that approach has been tried, and arguably has failed (Ullrich, 2010).  However, this does not mean that engineers should stop searching for ways in which our technology may support positive social change.  For civil engineers in particular, technology and the use to which the public puts it are inseparable.

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