Models and Simulations as Boundary Objects in Infrastructure Construction and Maintenance

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Research Problem:

How do models and simulations act in the role of a boundary object between government officials and engineers working in public infrastructure construction and maintenance?

Introduction

In recent decades, predictive modeling has become a cornerstone of modern engineering practice. The widespread adoption of compact digital computers and data science techniques allows engineers to rapidly test their designs before final implementation. Perhaps more importantly for critical applications, predictive modeling allows one to predict how and when a structure, component, or assembly will fail by various modes, such as mechanical fatigue or corrosion. In doing so, designers are able to make rapid, intelligent decisions that reduce the tendency for over-design while also optimizing designs for the most desired parameters.

Besides the obvious technical advantages, predictive modeling has a nontechnical benefit in the ability to enhance communication and learning between engineers and other professionals. In the context of public infrastructure, predictive modeling may act as a means to convince management or government planners that technical implementations proposed by engineers are worth financial and time investments. This paper will establish and further examine the actor network between engineers, non-engineers, and predictive models. Identification of the mechanisms by which predictive models mediate two groups with very different skills holds significance for institutions and businesses; sociotechnical artifacts acting in similar roles may be recognized and applied to improve organizational efficiency.

Background

Predictive models are numerical representations of the physical world built from experimentally observed patterns, allowing one to infer the properties of a system given a set of input parameters. When building these models, valid empirical data, which may come from in situ sensors or laboratory tests, must be available for the models to be trained to predict the future. The supply of computing power and data has rapidly grown in recent decades to satisfy the technical demands of predictive modeling (Bukhsh & Stipanovic, 2020), and new statistical/numerical methods are constantly developed to gain an edge in predictive power. As part of modern engineering practice, these models allow engineers to make informed design decisions when considering infrastructure lifespan criteria and prevention of over-design. While the outputs of such models are typically numerical, they can be summarized through graphical representations in order to convey information to a broader audience. With graphical representations, engineers are better able to communicate their design ideas in a way that a non-technical audience can appreciate by keeping technical details latent while still conveying the necessity of the design implements.

When large public infrastructure projects are being planned, government officials and workers often consider the price tag of the project as top priority. Meanwhile, engineers that are responsible for designing these structures and systems are trained to regard the safety and quality of their designs as the most critical consideration. This conflict of priority has the potential to create a tug-of-war between these two professional groups. Government planners may lack technical knowledge to appreciate safety features in design and judge if they are worth the increased cost. On the contrary, engineers may be prone to over-design for safety and ballooning the project budget. Thus, there is cause for disagreement in what constitutes necessary design or maintenance decisions, which may cause the time spent in the preliminary engineering phase of infrastructure planning to inflate. In light of this friction, predictive modeling not only acts as a necessary design tool, but also as a potential way to mediate the two groups of stakeholders.

Literature Review

Models can serve a variety of roles, both in the design process and in communication. Dodgson et al. (2007) examined how the engineering profession and its practices have changed due to the popularization of digital modeling of physical systems. Three particular uses of digital modeling, which they call “innovation technology” (IvT), are defined: I) judgment and validation, II) new combinations of technology and components, and III) design conversations. Most importantly for the research here, the “design conversations” section states that modeling allows engineers of different disciplines to collaborate more closely and to communicate design decisions with policy-makers and management, particularly by using visual models that graphically show the design feature and the project outcomes that flow from it.

The idea that models can connect different social actor groups is a not new one. Bayer et al. (2014) present simulation models as interfaces that can serve several different social roles in which these models facilitate group learning among stakeholders that vary by expertise and backgrounds. Of the four roles presented in the paper, we will most examine the roles of models as boundary and technical objects, which “helps to transmit information between group members by demonstrating already existing knowledge and by giving group members lacking this knowledge the opportunity to engage with the system.” (p. 128, Table 7.1)

Identification of tangible benefits of predictive modeling is complicated by several confounding factors in infrastructure planning and construction, with the intricacies of social behavior within structured organizations being one of them. Flyvbjerg et al. (2002) conducted a large statistical study on cost inaccuracies in public transportation projects. Notably, the cost of the vast majority of infrastructure projects is significantly underestimated. It was also found that the degree of cost underestimation had not improved in the 70 years prior to the study, and no new methods that would alleviate this problem appeared to help. The authors investigated several possible causes of cost underestimation, such as technical, economic, psychological, and political explanations. The authors concluded that the observed cost-estimate discrepancies were best explained by systemic deception, often made by engineers and price forecasters to satisfy their superiors and to increase the chances of the projects being started. Thus, difficulty in quantifying the usefulness of predictive modeling in terms of material benefit is expected, and other confounding variables will have to be identified and controlled for this research. Despite the difficulty in quantifying material benefits from predictive models acting as boundary objects, Flyvbjerg et al. (2004) in a later study concluded that much of the cost of construction projects lies in the preliminary and implementation engineering phases. Predictive models may be capable of shortening these phases by allowing design decisions to be made more rapidly and confidently. From this information, it can be inferred that modeling may be able to lower some construction costs by expediting both the time needed to create an engineering design and to convince management or government workers to approve said design.

Theoretical Framework

The system as described will be evaluated through the lens of actor-network theory (ANT) in order to illustrate the ability of models to persuade and inform non-technical professionals to the ideas of engineers. In simplified terms, actor network theory is a framework for studying sociotechnical systems in which actants define their problems and attempt to enlist the aid of other actants through a process of "translation". The translation process involves initial problematization, interessement, enrollment into the actor network, and, finally, mobilization (Muniesa, 2015). In our case, the main actants of interest are government planners, models, infrastructure, and engineers. The engineers enlist the help of models to further enlist the help of government planners and officials in approving designs and allocating necessary funds. Traditional actor-network theory can be modified with the introduction of the concept of boundary objects, which are actants that help translate and simplify information between human parties of different expertise (Star & Griesemer, 1989). Clearly, this is the role of predictive models in our scenario, and it will be evaluated through this modified framework.

Methodology

In order to establish predictive models as acting as boundary objects in public infrastructure planning and maintenance, a scaffolding approach was used. First, a case study was performed on a historical example of predictive models and simulations acting on behalf of engineers and transportation experts when working with government entities in a large public infrastructure project. Specifically, the example of the London Congestion Charge was thoroughly examined to identify both the technical and social roles played by simulations in this case. Next, ANT as described above was applied to create a theoretical lens through which this real-world case was examined. After application of the ANT framework, a more generalized model of how simulations act as boundary objects will be able to be formulated.

Results: The London Congestion Charge

Historical Context

In the later half of the 20th century as motor vehicles became increasingly popular, central London suffered from severe traffic congestion. The magnitude of the congestion was such that a trip by car in the 1990s took the same or more time than the same trip undertaken by other means in the time period before the invention of the car (Newbery, 1990). Not only did this serve as an annoyance to motorists, but it also represented an economic sink in which hundreds of millions of potential work-hours were wasted sitting in traffic (Dodgson et al., 2007). In response to this problem, a charge for use of roads in central London had been proposed as early as the 1960s. Though road congestion was ranked as one of the top issues of London residents, it was historically perceived by politicians that charging a fare for use of roads in the city was overwhelmingly unpopular (Leape, 2006). Enforcement of the charge was also thought to be prohibitively expensive and impractical in urban areas, especially with charges that vary by road location, usage, and time of day. Additionally, simply determining the optimal geographic area and price of the charge was found to be quite difficult for the complex network of roads that compose central London.

The Role of Models and Simulations

Despite this unpopularity and impracticality, whether real or perceived, the Independent Transport Commision (ITC), a public policy think tank, called for a study on the effect of a national congestion charge in England (Dodgson et al., 2007). In this study, Stephen Glaister and Daniel Graham from the Centre for Transport Studies at the Imperial College London created a model to show the change in road traffic speeds and generated revenue resulting from such a charge, all under the assumption that charges would change based on traffic levels and would reflect the costs associated with that traffic. Several traffic simulations and visual representations were also created based on this model, such as bus interactions with other traffic. Figure 1 shows an example of the model in action in which road speeds are predicted after the introduction of a congestion charge. Notably, the London metro area was predicted to have an especially large increase in road speeds. Through this set of visually-based simulations, the researchers gained insight into the inner-workings of this complex traffic system and predicted a significant reduction in road congestion with the implementation of a charge. Other independent studies involving simulation exercises were performed around the same period, and reached similar conclusions. For example, Newbery and Santos (2001) created a simulation model that predicted a significant decrease in traffic congestion, pollutant emission, and increase in social surplus with the introduction of a toll.

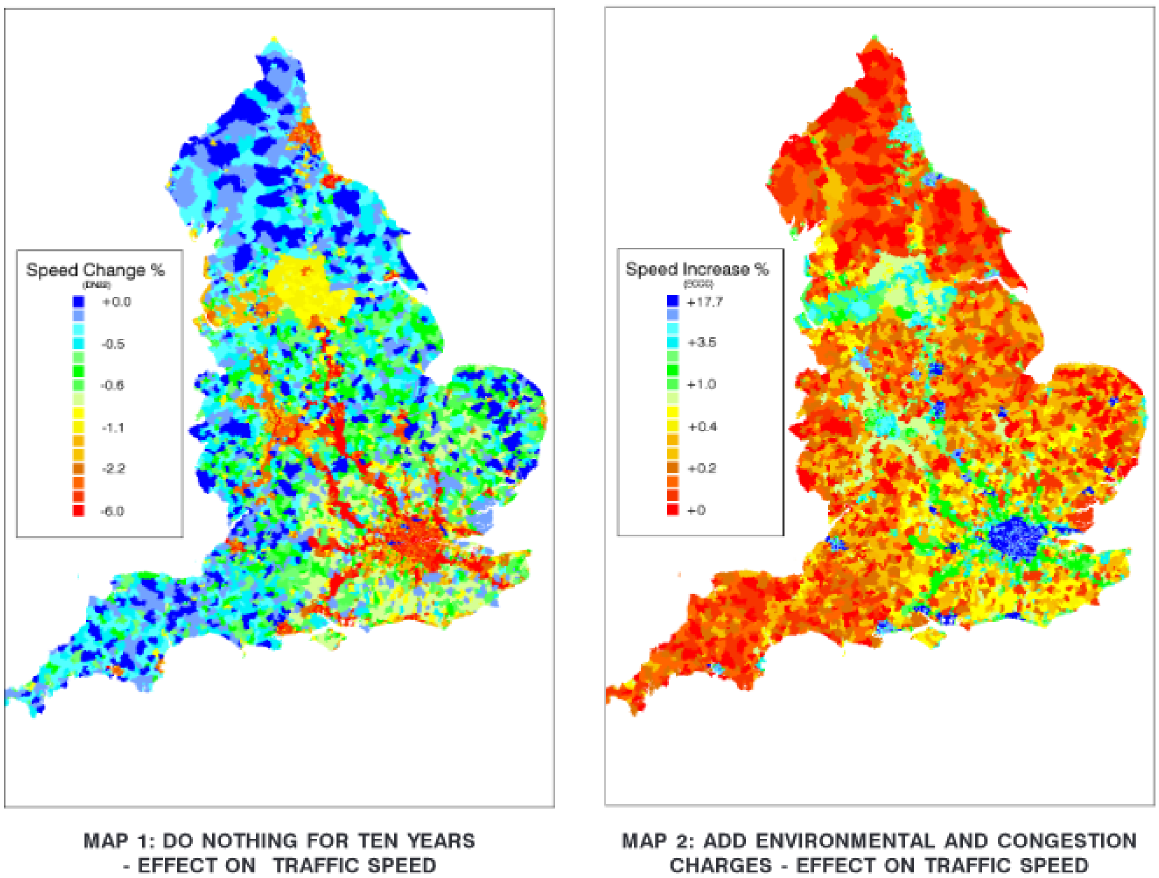

Figure 1. Results of simulation of road congestion in England following implementation of congestion charge (Independent Transport Commission, 2003).

Resolution

Ken Livingstone campaigned for the office of first mayor of London, and had made the charge a key part of his platform. After winning the election in 2000, he ordered an 18-month public consultation regarding the charge. From this consultation, and being informed by both the previously described ITC study and the 2000 report called *Road Charging Options for London* the city government finally made the decision to create the London Congestion Charge. The 2000 report recommended the implementation of an “area license” that allows motorists to travel into and within the charging zone of central London, and this schema was implemented in February, 2003 with a daily charge of £5.00 (today, the charge is £15.00 (Transport for London, 2023)). The program is widely recognized as a success, with the inflow of motor vehicles into central London being decreased initially (and sustainably) by 27% between 2002 and 2003 (Leape, 2003).

Discussion: Applying Actor Network Theory

In order to construct the actor network involved in the creation of the London Congestion Charge, the actors involved must first be specifically identified. As stated broadly in the methods, the primary actors of interest are engineers, models, the infrastructure of interest, and representatives in government. Specific to this case, the engineers are represented by civil engineering professors from the Centre of Transport Studies which were commissioned by the ITC. The two main nonhuman actors are the predictive model that the engineers made and the congestion charge along with its associated infrastructure. Finally, the local government workers and the Mayor of London are the actors that are being targeted for mobilization. However, examination of this case quickly shows a need to broaden the scope of our initial concept of the actor network.

First, the engineers were subjected to translation by the ITC to carry out the work of creating a model that would support the think tank’s goals of having a congestion charge implemented. This is necessarily true for the commissioning of research by a third party. The translation process at this region of the network starts with problematization. Here, the ITC describes the problem to the engineers, being high traffic congestion in central London, and the potential remedy, being the implementation of the charge. The ITC and engineers then negotiate the engineers' role in promoting this remedy, being the creation of a predictive model with the scope of simulating various aspects of traffic congestion and the effect of a congestion charge. Interessement then takes place by binding the engineers to their assigned role. The engineers can be convinced to take on this role by a combination of methods, the most obvious being funding provided by the ITC. Additionally, the high status of the ITC having close ties with the government and important patrons, as well as its reputation as a politically neutral and respected voice on transport (Clement et al., 2003), may convince the engineers that their assigned role is worth taking. Enrollment proceeds with the engineers accepting their role within the defined scope of the project and beginning their work. Finally, mobilization occurs with the engineers creating their model and delivering a report to the ITC to solidify the role of the engineers in the ITC's constructed network.

As the engineers work, it could be said that they perform the same general translation process to the concept of this particular model, which represents a distinct nonhuman actor. By using simplifying assumptions, prior knowledge of the nature of traffic congestion, and applying statistical and/or mathematical methods to computer code, the engineers use their expertise and ideas to enroll the model into a finalized product. The model is then mobilized through careful analysis of different test conditions and their respective outputs. Here, the model was prescribed a role as the basis for simulations that produces predictive data for traffic patterns. This data was then converted into visual representations that may be easily understandable for non-technical professionals and government workers.

At this region of the actor network, the role of the model (in this case, a visual one) as a boundary object begins to reveal itself. Figure 1 showed one example of such a visual model produced by the engineers which is easily understandable by those not well-versed in the complexities of the underlying numerical model. Consistent with its assigned role, the visual model allows for rapid transmission of information across the boundaries defined by areas of expertise by reducing important effects of policy decisions in an infinitely complex system to few strictly technical elements when communicating inherently technical ideas. Bayer et al. (2014) noted this property of visual simulation models observed in several case studies. Here, the models were described to act as interfaces for individuals of differing disciplines to engage with "real-world" relationships visually, allowing for increased accessibility to the outputs of the model. In this context, the boundary is between those of technically inclined policy advocates and engineers and nontechnical human actors such as politicians, government workers, and their constituencies. Thus, if the underlying numerical model is critically evaluated to be valid, the nontechnical human actors can be easily enrolled into the actor network constructed by the ITC.

The region of the actor network containing non-technical actors includes three main human actors groups: politicians and representatives, government workers that carry out directives of the representatives, and the voter base. In the case of the London Congestion Charge, mayor Livingstone made it clear from his campaign platforms that he was receptive to enrollment into an actor network that concerned itself with solving the traffic problem. When presented with quantitative evidence from various predictive models in support of the charge, individual government workers that were directly presented with the prestigious ITC's commissioned findings were enrolled into the actor network to carry out implementation of charge. Eventually, through various actors involved in the intricacies of government bureaucracy, the mayor and members of the London assembly were enrolled into the ITC's actor network and were fully mobilized when they voted in favor of the charge in 2003.

However, the role that the ITC and other transportation agencies played in enrolling government actors into their actor network to address the congestion problem is only part of the picture. Ultimately, government representatives in democratic societies answer to their voter base. Considering the previously stated urgency for a solution to the traffic jam in central London expressed by English voters, it can be said that the average citizen played a large role in the final enlistment of local government in implementing the charge, though they may not necessarily have communicated that particular solution. With the goal of appeasing voters, the boundary object in the form of visual models provided by the ITC, in addition from direct voter feedback from public consultation, may have given the London city government the confidence to pursue the charge as a solution, even if it was expected to be unpopular. Thus, with the enlistment of human actors that possess the power to resolve the London congestion problem, the actor network was finally satisfied by the administration of a solution that was overwhelmingly effective in the form of the congestion charge.

Conclusion

By analysis of a historical example through the lens of Actor Network Theory, it has been established here how models and simulations, particularly visual ones, can be used by technical experts to convince non-technical government workers to implement certain solutions in infrastructure system and design challenges. In the case of the London Congestion Charge, the efforts of transportation experts and engineers led to the creation of visual models representing the effects of a congestion charge on central London traffic. These visual models served as boundary objects to inform government bureaucracy of a solution to a problem that was perceived as important by London citizens. Finally, this prompted the complete enlistment of elected representatives into the actor network created by the ITC, transportation agencies, and voters. With the methods used in this paper, future work may examine other historical cases in public infrastructure, such as the Peruvian Interoceanic Highway (Harvey & Knox, 2015), to identify more examples of the phenomenon described here. In doing so, this framework and idea of models as boundary objects may be granted further robustness and utility.

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