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System dynamics-based evaluation of interventions to promote appropriate waste disposal behaviors in low-income urban areas: A Baltimore case study

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ABSTRACT

Inappropriate waste disposal is a serious issue in many urban neighborhoods, exacerbating environmental, rodent, and public health problems. Governments all over the world have been developing interventions to reduce inappropriate waste disposal. A system dynamics model is proposed to quantify the impacts of interventions on residential waste related behavior. In contrast to other models of municipal solid waste management, the structure of our model is based on sociological and economic studies on how incentives and social norms interactively affect waste disposal behavior, and its parameterization is informed by field work. A case study of low-income urban neighborhoods in Baltimore, MD, USA is presented. The simulation results show the effects of individual interventions, and also identify positive interactions among some potential interventions, especially information and incentive-based policies, as well as their limitations. The model can help policy analysts identify the most promising intervention packages, and then field test those few, rather than having to pilot test all combinations. Sensitivity analyses demonstrate large uncertainties about behavioral responses to some interventions, showing where information from survey research and social experiments would improve policy making.

1. Introduction

Many studies address the promotion of appropriate management of household solid waste and reduced littering (Barr, 2007; Cialdini et al., 1990; Steg and Vlek, 2009). Inappropriate waste disposal practices have been a serious problem in many cities, including Baltimore, Maryland, the focus of our research. Baltimore City is typical of a number of cities where inappropriate waste disposal, including abundant litter and dumping is visible and commonplace (Thompson, 2000). These waste disposal problems can contribute to many sociological and economic problems. For instance, they are believed to discourage business and homeowner investment in neighborhoods, consequently stunting local economic development (Baltimore City, 2009; Nwaka, 2005). Moreover, improper waste disposal is associated with, and is perhaps a contributing factor to increased crime (Cohen et al., 2003). Waste accumulation along with the associated rodent problems can also threaten the physical and mental health of residents (Childs et al., 1998; Latkin and Curry, 2003).

Several factors interact to cause inappropriate waste disposal behavior to reinforce itself and persist, including social norms, financial incentives, environmental cues, and physical infrastructure (Barr, 2007; Steg and Vlek, 2009; Thøgersen, 2005). However, the many systems models in the literature (Beigl et al., 2008; Cherian and Jacob, 2012; Eriksson et al., 2005) are rarely informed by sociological or economic research on how various incentives interact to affect waste disposal behavior, a neglect that we hope to address here.

Extensive sociological and psychological research has shown that social norms profoundly affect waste disposal choices (Biebeler, 2000; Cialdini et al., 1990; Coleman, 1991; Nolan et al., 2008; Vandenbergh, 2003). Social norms represent individuals' basic understanding of what others do and what others think that they should do (Cialdini, 2003). Social norms can be understood as dynamic systems (Maher, 2007). This suggests that System Dynamics (SD) (Forrester, 1958), a modeling approach that represents the evolution of complex systems over time, is potentially

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useful for modeling waste behavior. An advantage of SD is its ability to model key feedback loops within the studied system. We can therefore capture the dynamics of behavior change, in particular the positive and negative feedback loops that can reinforce or frustrate interventions. On one hand, modified behavior induced by interventions can positively influence social norms and the surrounding environment, which in turn will further encourage appropriate waste disposal (Tucker, 1999). On the other hand, a phenomenon called "policy resistance" can occur, in which a dynamic system with feedbacks may initially respond to a policy change in the desired manner, but return to its initial state due to negative feedback (Sterman, 2001). For instance, a rat-poisoning program will initially reduce rat populations, but after a certain period, rats may learn to avoid the poison so that populations return to the original level.

Our objective is to show how the SD approach can integrate physical models of solid waste flows with representations of dynamic behaviors and social norms in order to provide useful insights for designing intervention packages promoting appropriate waste disposal practices in low-income urban neighborhoods. In this paper, the causal relationships between waste-related behavior, factors that influence that behavior, and environmental impacts (such as visible trash and rat population) are first described and quantified. They are then integrated in a SD model that maps the various pathways in which residential solid waste is generated, disposed and collected. We develop and simulate five intervention packages in the model, which calculates performance indices that can be used to evaluate and compare candidate interventions. Our goal is to use the model as a tool that can assist in screening many potential packages, allowing subsequent pilot testing to focus on the most promising interventions.

The basic methods and concepts used in this research are described in Section 2, including SD along with relevant sociological and economic studies. In Section 3, we summarize the components of the SD model. The results of simulating municipal waste systems in a low-income neighborhood in Baltimore, Maryland are discussed in Section 4, while sensitivity analyses are presented in Section 5. Conclusions appear in Section 6.

2. Methods

2.1. System dynamics

System Dynamics, introduced by Jay Forrester in the 1950s, is a mathematical modeling framework that helps people understand the behavior of complex systems over time (Forrester, 1958). A SD model can be summarized by a stock and flow diagram (Fig. 1). Such a diagram includes stocks, flows, connectors, and converters. Stocks (symbolized by rectangles) are the state variables and represent, for instance, the major waste accumulations in the system or the status of social norms. A state variable, by definition, can accumulate or deplete over time. Flows (symbolized by valves with a block arrow symbol) are the rate of change in state variables and represent inflow and outflow (increases and decreases) of the

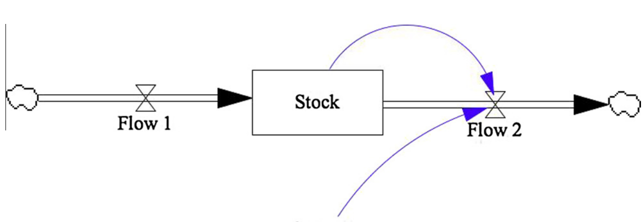

Fig. 1. Stock and flow diagram in system dynamics.

stocks. Converters (plain text not surrounded by any shape) are auxiliary variables used for miscellaneous calculations. Auxiliary variables can influence other variables, and can either be fixed or themselves influenced by other variables. Clouds are used to indicate that the source or sink of a flow lies outside the model boundaries. Finally, connectors (simple arrows) are information links that stand for causal relationships within the model structure (Zhao et al., 2011).

The function of the SD model is, in essence, to represent the dynamic evolution of a system's vector of state variables ("stocks") $\boldsymbol{x}$ over time. The evolution is governed by a set of ordinary differential equations $d\boldsymbol{x}/dt = f(\boldsymbol{x}, \boldsymbol{y})$, where t represents time. Each component of the vector-valued function $f(\boldsymbol{x}, \boldsymbol{y})$ consists of one or more flow variables ("flows") that are functions of the state variables as well as a vector of auxiliary variables $\boldsymbol{y}$ ("converters"). The differential equations of a SD model can be solved numerically via simulation software. Vensim® is the SD implementation used in this research.

System Dynamics modeling has been used to address many types of feedback systems, including business systems (Sterman, 2001; Strohhecker and Gröβler, 2012), environmental systems (Deaton, 2000; Feng et al., 2013; Grant and Marín, 1997; Guo et al., 2001; Zhou et al., 2011), social-economic systems (Forrester et al., 1976; Ke et al., 2013), agricultural systems (De Wit and Crookes, 2013; Kopainsky et al., 2015; Qu and Barney, 1999), and political decision-making systems (Dace et al., 2015; Naill et al., 1992). SD has also been applied to simulate complex waste management systems because it can explicitly represent the waste stream and monitor the effects of changes in subsystems (Chaerul et al., 2008; Cimren et al., 2010; Dyson and Chang, 2005; Hao et al., 2007; Kollikkathara et al., 2010; Sudhir et al., 1997; Zhao et al., 2011). Most of the relevant studies have primarily focused on physical waste streams and interactions among physical components. Only a limited number of studies have addressed the question of how to modify improper human waste disposal behavior at a local scale (Dace et al., 2014; Ulli-Beer et al., 2010). Dace et al. developed a system dynamics model to assess policies that promote packaging material efficiency. The model included various types of influential factors, such as economic incentives, behavioral aspects and ecological considerations. Ulli-Beer et al. addressed the phenomenon that antecedents of aggregate behavioral change influence when new behavior patterns emerge and a new social equilibrium state can be reached, by proposing a generic model structure for the simulation of acceptance-rejection behavior.

Meanwhile, governments and sociologists all over the world have been trying to develop interventions to reduce inappropriate waste disposal behavior. The ability of SD to characterize dynamic human behavior and feedback loops has the potential to offer insight on the effectiveness of such interventions. Limited efforts have been made to apply SD to gain insights on simulating waste-related behavior, primarily recycling behavior, and related social factors. For example, Karavezyris et al. (2002) developed a methodology to incorporate qualitative behavior variables such as voluntary recycling participation in a SD model. Meanwhile, Ulli-Beer (2004) created a SD model to analyze local policy initiatives to encourage recycling, incorporating feedbacks between human behavior and public policy.

Because many variables in the SD model are challenging to quantify, such as social norms and exposure to information, fuzzy logic has been used to quantify those variables, as in Karavezyris et al. (2002). Fuzzy logic deals with approximate reasoning, as opposed to fixed and exact reasoning (Perfilieva and Močkoř, 1999). Fuzzy logic is based on fuzzy set theory (Zadeh, 1988, 1965), an extension of classical set theory. Each element has a value called "membership", usually in the range [0,1], that