Modeling the Emergence of Riots

Overview, Design Concepts, Details, and Human Decision Making (ODD+D)

This document provides an overview of model structure and is based on the ODD (Overview, Design Concepts, and Details) protocol initially developed by Grimm *et al.* (2006) and recently extended by Müller *et al.* (2013) to include human decision-making.

1. OVERVIEW

Immediately after the results of the 2007 presidential election were announced, Kenya broke-out in protest (De Smedt, 2009). Kibera, an informal settlement located within the city of Nairobi, became the "epicenter" of the violence that hit Nairobi (International Crisis Group, 2008). As soon as a presidential candidate was declared the winner, violence broke out within Kibera. Deep-rooted grievances and Kenya's long history of political and economic ethnic exclusion led many to believe that election results were rigged. These long standing issues combined with election results quickly escalated the riots to violence, including murder, looting, rape, and arson. This violence would continue for nearly two months, resulting in 1,100 deaths and up to 350,000 internally displaced people (De Smedt, 2009). According to Allport & Postman (1947), a rumor is necessary to "incite, accompany, and intensify" rioting. This was no different in Kibera, where rumors, serving as the external trigger, played a significant role in the riots. Between cell phones, text messages and radio, rumors spread quickly (De Smedt, 2009). Dividing hate speech heard across the media often served to intensify the violence (Chege, 2008). Approximately two months after the riots began, a power-sharing agreement was reached and the violence ceased almost immediately (De Smedt, 2009). An agent-based model (ABM) was developed in MASON (Luke et al., 2005) utilizing the GeoMason (Sullivan et al., 2010) spatial extension to explore the onset of riots in Kibera. Geographical information was utilized to create the modeling landscape, while socioeconomic data of Kibera provided initial agent attributes. Figure 1 displays the graphical user interface (GUI) of the model. For readers wanting to download the source code or executable of the model please see https://www.openabm.org/model/4865/.

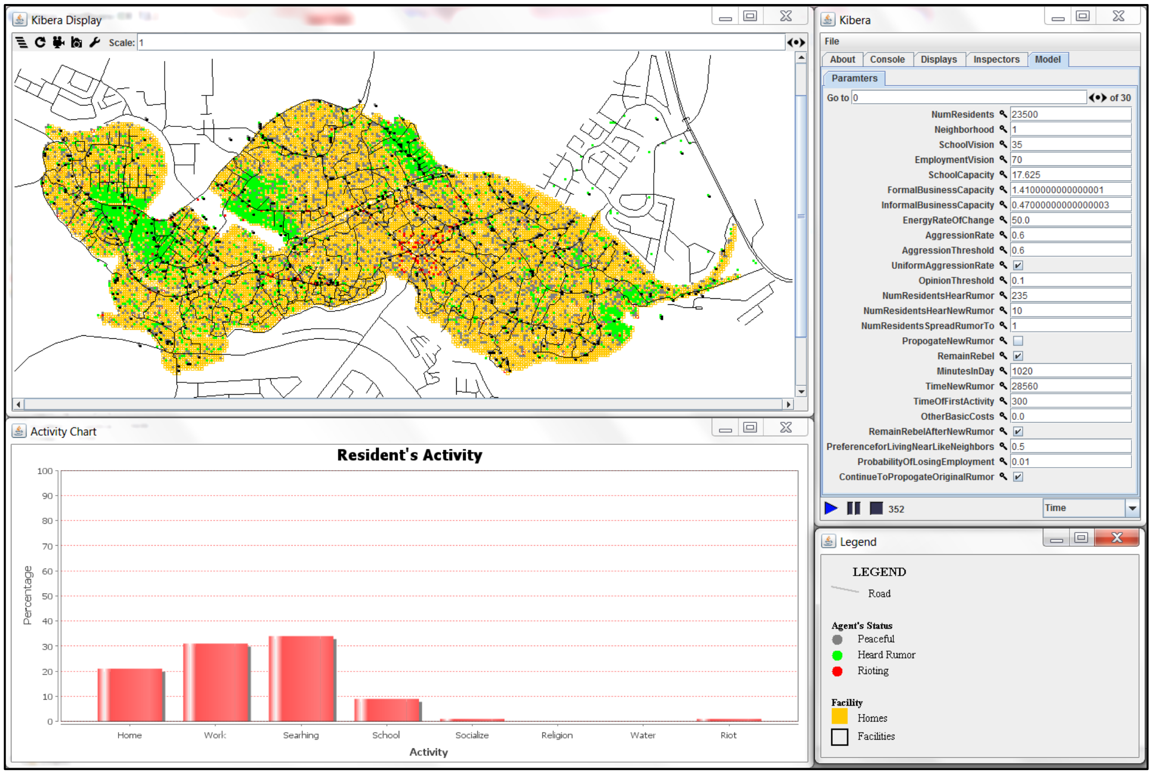

Figure 1: The model's GUI. Clockwise from top left; spatial environment and agents, input parameters, legend, and current *Residents'* Activities.

1.1: Purpose

The purpose of the model is to explore how the unique socioeconomic variables underlying Kibera, local interactions, and the spread of a rumor, may trigger a riot. An ABM is integrated with social network analysis (SNA) and geographic information systems (GIS) for this purpose. This integration facilitates the modeling of dynamic social networks created through the agents' daily interactions. GIS is used to develop a realistic environment for agents to move and interact that includes a road network and points of interest which impact their daily lives. This is an exploratory model and was thus developed for researchers and students interested in agent-based modeling, specifically the role of social networks pertaining to civil unrest.

1.2: Entities, State Variables and Scales

The model contains the following entities, from highest to lowest hierarchical scale: (1) Environment, (2) *Population*, (3) *Parcel*, (4) *Structure* and *Water Point*, (5) *Home*, *Business*, and *Facility*, (6) *Household*, and (7) *Resident* (individual), which will be discussed the following sections. Figure 2 illustrates a high-level Unified Modeling Language (UML) diagram of the model. There are two types of agents modeled, the *Resident* and the *Household*. The main agent is the individual *Resident*, while a group (or unit) of residents makes up a *Household*. *Households* must select a *Home* for which to live based on predefined preferences and affordability (e.g., Benenson, Omer, & Hatna, 2002). *Homes* are assigned a monthly rent and a set of amenities, including electricity, water, and indoor sanitation (Marras, 2008). A *Facility* can be one of many, including schools, health facilities, religious institutions, and businesses. A *Parcel* represents a piece of land within the modeling area and is characterized by a unique grid location. Structures, water points, and the transportation network are located on *Parcels*.

The model proceeds in one minute time steps (discussed further in Section 1.3) and is run for three simulation weeks.

1.2.1. The Environment, Population, and Parcels

The modeling world measures 3.9 by 1.5 kilometers (the approximate size of Kibera) with a cell (*Parcel*) size of 12.5 m x 12.5 m, which is based on the average size of a building (i.e., structure) in Kibera plus the average surrounding empty space (Marras, 2008). It is created by importing a set of GIS files, including the geographic area of interest (modeling boundaries), the transportation network (roads, walking paths, and railway), and the grid location of facilities (e.g., hospitals, schools, religious institutions). Thus, space is modeled explicitly and is based on the actual landscape of Kibera. More information about the inputs into the model can be found in Section 3.2. Upon model initialization, a *Structure* and/or *Water Point* is added to each *Parcel*. Each *Structure* can contain *Homes*, *Businesses*, and/or *Facilities* (or can remain empty). *Facilities* with exact GIS coordinates were added to the structure located on the same grid location.

The total population of Kibera is estimated to be between 235,000 and 270,000 (Marras, 2008), with a gender distribution of approximately 61% male and 39% female and an age distribution that is approximately 54% adult and 46% children (under the age of 18) (Marras, 2008). The population is made up of individual *Residents*, who are each part of a *Household*.

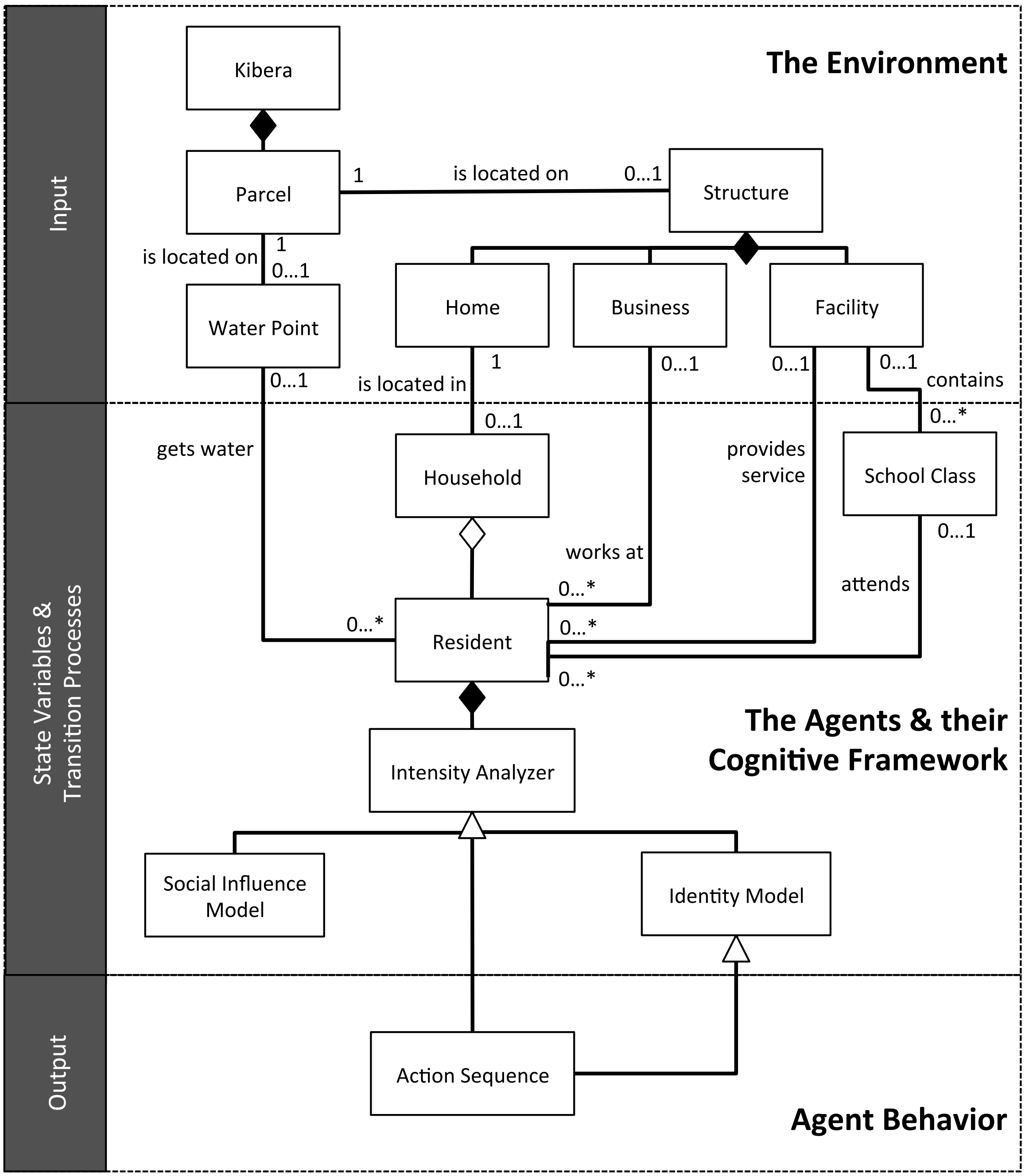

Figure 2: The high-level UML diagram of the model.

Using data from the Map Kibera Project (Marras, 2008) it was determined that *Household* size is approximately lognormally distributed. One *Resident* in each *Household* is designated head of household. This is done to ensure each *Household* has at least one adult *Resident*. In addition, *Households* are assigned an ethnicity and a religion based on the ethnic and religious distribution of Kenya (CIA World Factbook, 2013; De Smedt, 2009; Marras, 2008; Pew Forum on Religion & Public Life, 2010). With every ethnicity represented, Kibera characterizes Kenya's ethnic diversity (De Smedt, 2009). Given this similarity, the ethnic distribution of Kenya is used as a proxy when endowing the *Residents* with an ethnicity. In addition, a specified number of *Residents* are randomly selected to hear the exogenous rumor at initialization. Of those that heard the rumor, a proportion is selected to be influenced enough by the rumor to riot. Those initial rioters will attempt to influence other *Residents* as the simulation runs. Table 1 summarizes the population and environment input parameters used in the model. These input parameters are used to create the environment and the population.

Table 1: Population and environment parameters used in the simulation.

Parameter	Description	Reference
Initial number of *Residents*	Kibera is estimated to have between 235,000 and 270,000 residents.	Marras (2008)
Preference for living near "like" neighbors	The preference for living near (within the Moore neighborhood) a household of the same ethnicity.	Adapted from De Smedt (2009); Schelling (1978)
Number of *Residents* that heard the rumor	This is the number of *Residents* that heard the rumor at initialization.	User settable
Proportion of initial *Residents* that riot	Of those that heard the rumor, this is the proportion of *Residents* that riot at initialization.	User settable
Age distribution	If a *Resident* is head of household, an age between 18 and 59 is randomly selected. For all other *Residents*, there is a 25% chance that the *Resident* is an adult (age 18 to 62), and a 75% chance that the *Resident* is a child (under 18).	Marras (2008)
Gender distribution	*Residents* have a 61.3% probability of being male, and 39.7% probability of being female	Marras (2008)
Ethnic distribution	*Residents* are assigned one of twelve ethnicities: Kikuyu, Luyha, Luo, Kalinjin, Kamba, Kisii, Meru, Mijikenda, Maasai, Turkana, Embu, Other	CIA World Factbook (2013); De Smedt (2009)
Religious distribution	*Residents* can be Christian, Muslim, or Other	CIA World Factbook (2013);

		Marras (2008); Pew Forum on Religion & Public Life (2010)
Employment distribution	*Residents* are assigned one of the following employment status: employed, searching for employment, inactive, and unknown.	Kenya National Bureau of Statistics, (2009); UN-HABITAT (2003)
Income distribution	The income distribution is based on average, minimum, and maximum income data for Kibera. The Lorenz (1905) curve is then used to create an income distribution.	Gulyani and Talukdar (2008); Desgroppes and Taupin (2011); Lorenz (1905)
Informality index	The proportion of the employed population that works in the informal and formal sectors.	UN-HABITAT (2003)
Aggression	This is the *Resident's* current level of aggression (valued from 0 to 1).	Adapted from Green (2001)
Aggression threshold	The threshold a *Resident's* aggression must be over in order for the *Resident* to aggress or riot.	Adapted from Green (2001)
Aggression rate	The rate of the logistic curve (between 0 and 1). The higher the rate, the slower a *Resident* is to aggress.	Adapted from Green (2001)
Energy rate	The rate of change a *Resident's* Energy Reservoir will increase or decrease.	Adapted from Burke and Stets (2009)
Opinion threshold	This is how similar two *Residents'* opinions must be on the rumor to influence one another (between 0 and 1).	Adapted from Friedkin (2001)
Employment vision	The number of *Parcels* out from a *Resident's Home* location that it can search for employment.	User settable
School vision	The number of *Parcels* out from a *Resident's Home* location that it can search for a school.	User settable
Number of *Household* members	The number of *Residents* living together as part of a *Household*.	Marras (2008)
Household capacity	The capacity of *Households* that can live in one *Home*.	Marras (2008)
School capacity	The maximum number of students that can be enrolled in a school.	Ministry of Education (2007)
School Class capacity	The number of students in the same *School Class*.	OpenStreetMap (2013)
Formal employer capacity	The maximum number of employees a formal employer can hire.	Ministry of Education (2007);

		OpenStreetMap (2013)
Informal employer capacity	The maximum number of employees an informal employer can hire.	UN-HABITAT (2003)
Structure capacity	The capacity of *Homes* and/or *Businesses* in a *Structure*.	Marras (2008)
Home amenities	The amenities that come with a *Home*, such as electricity, sanitation, and running water.	Marras (2008)
Rent distribution	The distribution of rent prices across *Homes*.	Marras (2008)
Homes with water	The proportion of *Homes* that have running water.	Marras (2008)
Homes with electricity	The proportion of *Homes* that have electricity.	Marras (2008)
Homes with sanitation	The proportion of *Homes* that have sanitation.	Marras (2008)
Household expenditures	The average cost of *Household* expenditures, such as food, water, electricity, sanitation, and transportation.	Gulyani and Talukdar (2008)

1.2.2: Homes, Facilities, Businesses and Structures

At initialization, *Households* must select a *Home* for which to live based on preferences and affordability (see Section 3.2.1 for details). Each *Home* can contain up to one *Household*. *Homes* are assigned a monthly rent cost. In addition, some *Homes* may contain certain amenities such as electricity, water, and indoor sanitation as shown in Table 2.

Table 2: *Home* variables and descriptions.

Variable	**Description**
Rent	The monthly rental cost of the *Home* is drawn from a distribution as discussed in Table 1.
Has water	Identifies whether the *Home* has running water. The probability of a *Home* having running water is dependent on the proportion of *Homes* that have running water (see Table 1).
Has electricity	Identifies whether the *Home* has electricity. The probability of a *Home* having electricity is dependent on the proportion of *Homes* that have electricity (see Table 1).
Has sanitation	Identifies whether a *Home* has sanitation. The probability of a *Home* having sanitation is dependent on the proportion of *Homes* that have sanitation (see Table 1).
Expected electricity cost	The expected cost of electricity, if the *Home* has electricity (Gulyani and Talukdar, 2008)
Expected water cost	The expected cost of running water, if the *Home* has running water. (This is user settable.)

Facilities include schools, health facilities, and religious facilities. All facilities have an associated grid location (data provided by OpenStreetMap, 2013). The location of *Businesses*, on the other hand, was estimated from empirical survey data (Marras, 2008). The survey provided information on the number of businesses in each structure within a neighborhood in Kibera. Table 3 lists the full set of variables for *Facilities* and *Businesses* extrapolated numerous data sources.

Table 3: *Facility* and *Business* state variables and descriptions.

Variable	**Description**
Facility or *Business* type	This identifies whether the *Facility* or *Business* is a formal or informal employer (adapted from (UN-HABITAT, 2003).
School capacity	If the *Facility* is a school, this is the maximum capacity of students at the school. It is used to determine if the school has reached its maximum enrollment (Ministry of Education, 2007; OpenStreetMap, 2013).
School Class capacity	The number of students in the same *School Class* (OpenStreetMap, 2013).
Employee capacity	This is the capacity of *Residents* that can be employed at a *Facility* or *Business* at anyone time (Ministry of Education, 2007).

A *Structure* is equivalent to a building. Each *Structure* can contain *Homes*, *Facilities*, and/or *Businesses*. The number of *Homes* or *Businesses* within a *Structure*, which represents the capacity of the *Structure*, was determined from survey data (Marras, 2008). Since the exact grid location is known for the *Facilities* (e.g., schools, health facilities, and religious facilities), the *Structure* located on the same grid location will contain the associated *Facility*. Table 4 provides the set of state variables characterizing *Structures*.

Table 4: Structure state variables and descriptions.

State variable	**Description**
Structure Capacity	The capacity (number) of *Homes* and *Businesses* that can reside in the *Structure* (Marras, 2008).

1.2.3: Residents and Households

As discussed in Section 1.2, there are two types of agents modeled, the *Resident* and the *Household*. The main agent is the individual *Resident*, which are heterogeneous and are characterized by unique attributes such as age, gender, and ethnicity as shown in Table 5. In addition, a group (or unit) of residents makes up a *Household*. These agents were chosen due to our focus on the emergence of riots, and also in order to keep the model simple. While there is a wealth of literature pertaining to the role of government (e.g., ref) and the role of the police in responding to riots (e.g., ref), we chose to only to model government through the exogenous rumor (e.g., the disputed election results) and the police were not modeled as our focus on the emergence of riots, not on their control. For example, in a survey conducted by Gutttierrez-Romero (2011), the majority of respondents believed that election had been rigged and this is what triggered the riots, not the police. Subsequent waves of violence might have been linked to police activity (i.e., heavy handedness) but this is not the focus of our model, that being said, the model could be extended to include the role of police and this is one reason we provide the detailed ODD+D, source code, and data.

Table 5: *Resident* state variables and descriptions.

Variable	Description
Age	The *Residents'* age obtained from the age distribution as discussed in Table 1.
Gender	The *Residents'* gender obtained from the gender distribution as discussed in Table 1.
Ethnicity	The *Residents'* ethnicity, which is drawn from the ethnicity assigned to the *Residents' Household*.
Religion	The *Residents'* religion obtained from the religion distribution as discussed in Table 1.
Employment status	The *Residents'* employment status, which can be formal, informal, searching, or inactive. At initialization, this is drawn from the employment distribution as discussed in Table 1.
Income	If the *Resident* is not employed, income is set to zero. Otherwise, it is set based on the income distribution discussed in Table 1.
Aggression	This is the *Resident's* current level of aggression (valued from 0 to 1).
Aggression rate	The rate of the logistic curve (between 0 and 1). The higher the rate, the slower someone is to aggress (adapted from Green, 2001).
Aggression threshold	The threshold a *Resident's* aggression must be under in order for the resident to aggress or riot (adapted from UN-HABITAT, 2003).
Opinion threshold	This is how similar two *Residents'* opinions must be on the rumor to influence one another (between 0 and 1) (adapted from Friedkin, 2001)
Energy	This is the *Resident's* current level of energy in its reservoir (valued from 0 to 100).
Energy rate of change	The rate of change a *Resident's* Energy Reservoir will increase or decrease (adapted rom Burke and Stets, 2009).
Employment vision	The number of *Parcels* out from a *Resident's Home* location that it can search for employment.
School vision	The number of Parcels out from a *Resident's Home* location that it can search

	for a school.
Probability of losing employment	The probability that an employed *Resident* will lose their job in the formal or informal sector.
Identity	This is the *Resident's* identity (Domestic, Student, Employee, Rioter)

Households consist of a group of *Residents*. The size of the *Household* is determined as described in Table 1. *Households* are characterized by their ethnicity (it is assumed all *Residents* in the same *Household* share the same ethnicity), total income, and total *Household* expenditures (such as rent, food, water, and sanitation) as shown in Table 6.

Table 6: *Household* state variables and descriptions.

Variable	Description
Ethnicity	Each *Resident* in a *Household* shares the same ethnicity. The assigned ethnicity is obtained from the ethnic distribution of the country as discussed in Table 1.
Income	This is total monthly income of the *Household*. It is calculated by summing the individual income of all *Residents* living in the same *Household*.
Expenditures	The *Households'* daily expenditures, including food, water, electricity, and sanitation.
Discrepancy	The daily discrepancy between a *Households'* income and expenditures.

1.3: Process Overview and Scheduling

The model proceeds in minute time steps. A minute was selected because the spread of the rumor, the decision to riot (or not), and the mobilization of residents occurred quickly after elections were announced (Chege, 2008; International Crisis Group, 2008). While human decision-making can occur over seconds, minutes, hours, days, or even years, a minute allows us to capture the individual interactions and activity patterns that are important to the development of social networks (Torrens, 2014). Figure 3 sketches out the key model processes (discussed further in Section 3). The Intensity Analyzer is broken out into the three sub-models—the Daily Activity Scheduler (Section 3.4.1), the Identity Model (Section 3.4.2), and the Social Influence Model (Section 3.4.3)—shown within the dotted lines in the diagram. At the beginning of the simulation, *Resident's* run the Daily Activity Scheduler, which determines the activity they will perform. They will then execute the action sequence associated with performing the activity, including using the transportation network to move the location of the activity (e.g., walking from *Home* to school). While the action sequence for some activities simply require that the Resident remain at a given location for a specified amount of time (e.g., for the activity “go to school”, the *Resident* will remain at the school for a specified amount of time), other activities require additional steps. For example, the activity “search for employment” requires that the Resident search within its employment vision for any employer’s who have not reached their employee capacity. While at an activity, the Resident will establish new and/or strengthen any existing relationships with other Residents; propagate the rumor if applicable; and run the Identity Model. If the *Resident* has heard the rumor, the *Resident* will run the Social Influence Model, which will determine if the *Resident* will riot or remain peaceful. At completion of the activity, the Resident will return Home and re-evaluate its next action by re-running the Daily Activity Scheduler.

Resident variables such employment status and income are evaludated at the beginning of the simulation and is updated when there is a change in the employment status of the *Resident*. For instance, if a *Resident* that was performing the activity “searching for employment”, finds employment, the employment status will be updated accordingly and the *Resident’s* and *Household’s* income will be increased. *Resident* variables aggression and energy are updated at the end of each activity. The *Resident’s* identity is evaluated each time the Identity Model is run. Given the duration of the simulation (i.e., weeks), other Resident attributes such as age are not updated. *Household* variable expenditures and the discrepancy between *Household* income and expenditures are evaluated at the beginning of the simulation and when there is a change in the employment status of a *Household* member (e.g., transportation costs would increase after a *Resident* finds employment).

The three submodels that make-up the Intensity Analyzer are discussed in more detail in Section 3. However, before discussing the submodels further, we first will discuss the design concepts of our model.

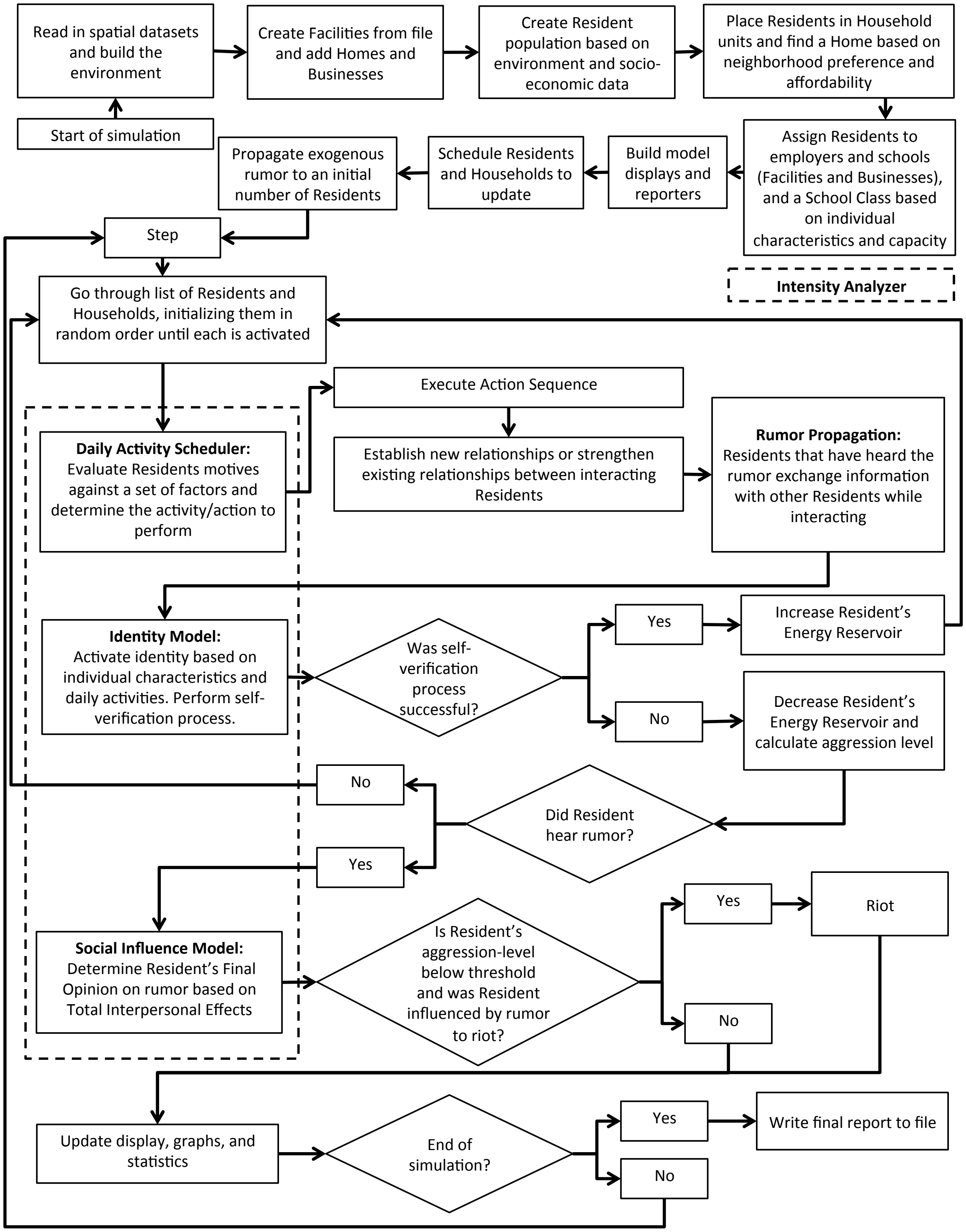

Figure 3: Flow diagram of the key processes in the model.

2: DESIGN CONCEPTS

2.1: Theoretical and Empirical Background

2.1.1: A Unified Theory of Identity

Modeling human behavior is not a simple task (Kennedy, 2012); humans neither behave randomly nor act perfectly rational (Simon, 1996). To this end, theorists have moved away from rational choice theory (e.g., Lichbach, 1995; Olson, 1971) and relative deprivation (e.g., Gurr, 1970; Morrison, 1971), and have stressed group identity as the driver of internal conflict and the emergence of riots (e.g., Brubaker & Laitin, 1998; Huntington, 1996).

Identity theory focuses on the concept of identities as *roles* (McCall & Simmons, 1978). It is the way a person is or wishes to be known by others (Stein, 2001) and how that translates to "being and acting" in that role (McCall & Simmons, 1978). Social identity theory, on the other hand, involves the concept of social *groups*, where a group is a "collection of individuals" who identify with the same social category (Tajfel & Turner, 1979) and is derived from an individual's membership in such a group (Hogg & Abrams, 1988). Such identification with a social group can lead to the differentiation between "we" and "they" when faced with an opposing group (Stein, 2001), and to intragroup cohesiveness and cooperation when intergroup conflict exists (Tajfel & Turner, 1979), which can allow for group mobilization for purposes of social movements. Individuals have an array of identities (Oyserman, Elmore, & Smith, 2012) and by combining *role*-based and *group*-based identities into one theory, Stets & Burke (2000) integrate collective identity with the individual, heterogeneous identities of group members, allowing for the dynamic modeling of individual and group identities under one theory of identity.

Identity salience is the probability that an identity will be activated in a given situation (Stets & Burke, 2000). Salience is a function of several factors, including: (1) commitment, or the embeddedness of an individual in a social structure (Stets & Burke, 2000; Stryker & Burke, 2000); (2) the fit of the identity with the situation (i.e., the probability that the identity will be activated in a given situation) (Oyserman, et al., 2012; Stets & Burke, 2000); and (3) the characteristics of the identity, such as its accessibility (Stets & Burke, 2000). Social networks play a critical role in identity theory in general, and identity salience in particular. An important aspect of commitment, for instance, is the number of other individuals someone is connected to that holds the same identity and the strength of the relationship with those individuals. The strength of these relationships can be attributed to various factors, including the physical distance, the number of interactions, or the frequency and length of communication between two individuals (Wasserman & Faust, 2009). Once an identity is activated, an individual will compare the output behavior associated with the identity to the identity standard, which contains the set of meanings and norms associated with the social category. This comparison process is known as the self-verification process. The complete process is shown in Figure 4.

It has been argued that an identity has four main components: an *Input*, an *Identity Standard*, a *Comparator*, and an *Output*. Furthermore, the identity model as shown in Figure 4 requires aspects of both the inner and outer environments. The inner environment is the person itself (shown as the blue shaded areas) and the outer environment is the person's surrounding (shown as the green shaded area). This can be compared to Simon's (1996) view of inner and outer environments, where the inner environment is the artifact itself (in this case, the person) and the outer environment is the surroundings for which the artifact operates. The person seeks a particular goal in the outer environment, in this case, to meet the identity standard, and this in turn dictates the processes of the inner environment. The outer environment thus goes beyond geographical space to include our complete surroundings, such as meaningful feedback from others (i.e., reflected appraisals) and others perception of our actions. The outer environment determines the conditions for goal attainment (the goal is to match environmental inputs to the identity standard). Perceptions, which make-up what we see of the outer environment, comprise the *Input*.[1] Our perceptions are driven by our surroundings (i.e., outer environment), which are effected by our routine activities. Moreover, these routine activities can be said to be driven by humanistic needs theory (e.g., Burton, 1979; Maslow, 1954; Sites, 1973). One of the earliest theorists on the subject, Maslow (1954), developed a hierarchy of needs. These include physiological, safety, love and belonging, and self-esteem, which is defined by how we evaluate ourselves (McCall & Simmons, 1978; Tajfel & Turner, 1979). The *Comparator's* role is to compare the perceptions associated with the identity to the *Identity Standard*. The *Comparator* will then produce an error signal – the difference between the perceptions and the *Identity Standard*. A large error signal can be a sign of an interruption, such as a rumor. The *Output*

[1] It should be noted that the use of *input* here is not the same as input parameters (Section 3.2) or input data (Section 3.3). Accordingly, throughout the rest of the paper the term *input* will be followed by parameter or data. Otherwise, input refers to the agents' behavior as outlined by identity theory. Similarly, the term *output* here refers to the agents' action (activity) and is not the same as the model output.

forms the behavior of the person, which occurs in the outer environment and is based on the error signal. Furthermore, the Output behavior alters the symbolic character of the outer environment, thus changing our perceptions (Burke & Stets, 2009). Thus, the relationship between perceptions and the *Identity Standard* predicts behavior (Stryker & Burke, 2000).

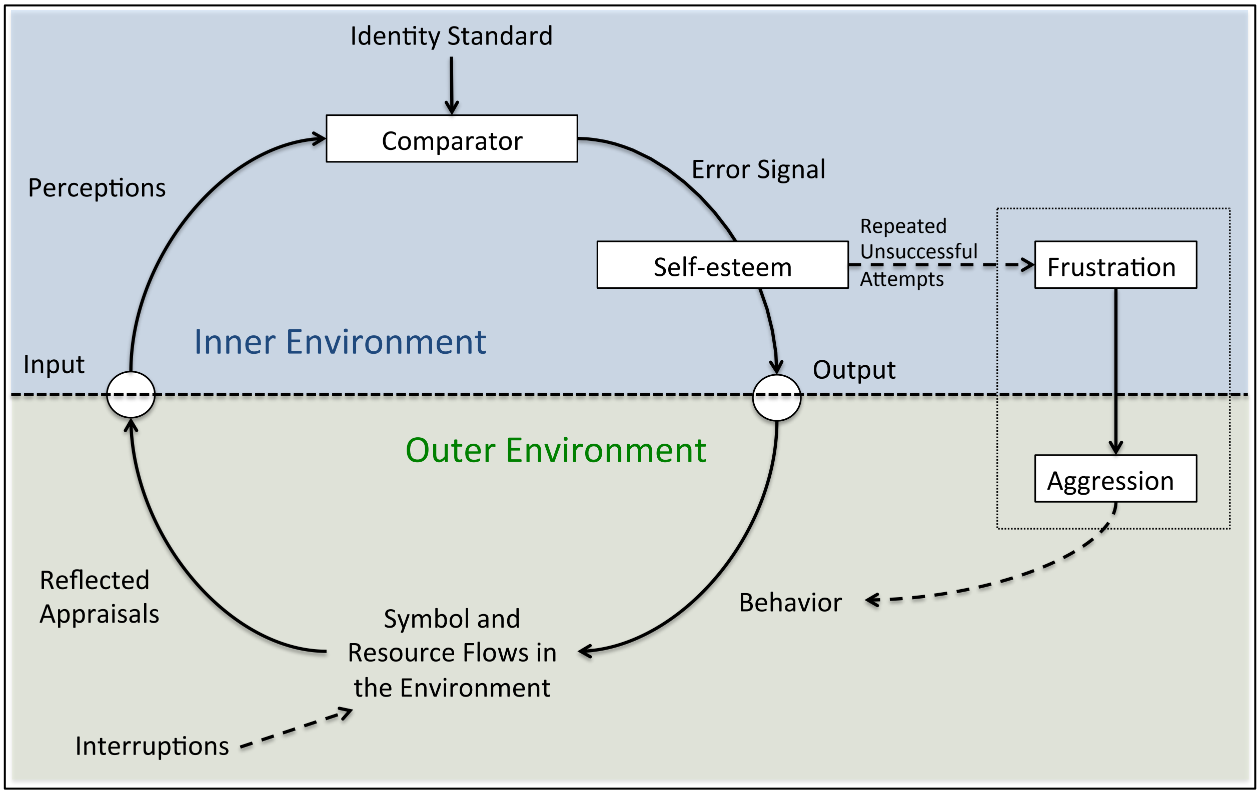

Figure 4: The identity model and the frustration-aggression hypothesis (adapted from Burke & Stets, 2009; Green, 2001). The inner environment (i.e., the self or person) is the blue shaded area, the outer environment (i.e., the person's surroundings) is the green shaded area, and the dotted line represents the boundary between the inner (person) and outer environments.

This process forms a continuous feedback loop. Perceptions are continuously fed into the system and behavior adjusted as the individual seeks to represent the *Identity Standard*. If successful, the result includes increased commitment to others with the same identity, shared membership in a group, and increased self-esteem, which produces a reservoir of "energy" (Burke & Stets, 2009). If unsuccessful, however, the reservoir of energy diminishes and self-esteem lowers (Cast & Burke, 2002). Similarly to other accumulator models (e.g., Purcell, Schall, Logan, & Palmeri, 2012; Schurger, Sitt, & Dehaene, 2012), which provide a quantitative means for modeling the time-lapse in human decision-making processes between receiving information and executing a response (Smith & Ratcliff, 2004), the reservoir of energy allows one to continue working towards the self-verification process even after unsuccessful attempts (Burke & Stets, 2009; McCall & Simmons, 1978). Depletion of the reservoir of energy, however, can potentially result in increased distress or frustration (Green, 2001). According to the frustration-aggression hypothesis, frustration produces the inner environment for which one can aggress, and aggression cannot occur prior to frustration. However, aggression does not always result from prolonged frustration (Green, 2001). Available resources, such as self-esteem, can help individuals cope with certain levels of frustration. On the other hand, a lack of personal resources such as education, income, and support from family and friends, can hinder the self-verification process for certain *Identity Standards* (Stryker & Burke, 2000). As the self-verification process succeeds or fails at the micro-level, macro-level social networks and group dynamics can be observed. The unified theory allows one to consider behaviors from the "more mundane expectations for a person occupying a role," such as going to work or school (Stryker & Burke, 2000), to meso- and macro-level formation of cohesive groups, which can lead to intergroup conflict, such as riots. We will come back to this in Section 3.4.

2.1.2: Rumor Propagation, Social Influence, and Social Networks

Extensive studies have looked at why a peaceful group may break out in riot (e.g., Bhavnani, Findley, & Kuklinski, 2009; Gurr, 1994), one thing that has been shown to influence riots is the notion of rumors (Allport & Postman, 1947). While identity theory provides the behavior aspect, a rumor provides the trigger. This was no different in Kibera, where rumors, serving as the external trigger, played a significant role in the riots (De Smedt, 2009). The question here is therefore, how do rumors propagate or diffuse? Diffusion can be defined simply as "the spread of something within a social system" (Strang & Soule, 1998). In the case here, we assume "something" to be a rumor. In addition, social networks play a key role in this diffusion process, both in terms of spreading the rumor and in terms of being influenced by the rumor (Granovetter, 1973). Thus, rumors are important in shaping attitudes and in norm formation (Centola & Macy, 2007). Many people will hear the rumor but whether they act on the rumor is largely based on the diffusion of influence through their social networks (Granovetter, 1973), such as in social influence network theory (Friedkin, 2001). Based on the theory, an individual's final opinion, $y^{(\infty)}$, on an issue is a function of their initial opinion on the issue, their relative interpersonal influence, and their susceptibility to influence. A person's final opinion can thus be determined by as follows (Friedkin and Johnsen, 1999):

$$y^{(\infty)} = Vy^{(1)}, \tag{1}$$

where $y^{(1)}$ is an $N \times 1$ vector of actors' initial opinions on an issue and V is an $N \times N$ vector of total interpersonal influence. V is calculated as shown below (Friedkin and Johnsen, 1999):[2]

$$V = (I - AW)^{-1}(I - A), \tag{2}$$

where $W = [w_{ij}]$ is an N x N matrix of interpersonal influences $\left(0 \leq w_{ij} \leq 1, \sum_j^N w_{ij} = 1\right)$ and $A = diag(a_{11}, a_{22}, \dots, a_{NN})$ is an $N \times N$ diagonal matrix of actors' susceptibility to interpersonal influence on the issue $(0 \leq a_{ij} \leq 1, a_{ij} = 0 \; when \; i \neq j)$.

Building on this, Friedkin (2001) develops a structural approach for determining opinion formation, an approach that is particularly useful in situations where the only information available is the communication network. This approach applies methods from SNA, including structural equivalence (which looks at how identical the ties, or relationships, to and from an actor to all other actors are in a network) and centrality (a measure of the importance of actors in a social network) (Wasserman and Faust, 2009). According to Friedkin (2001), the structural equivalence of the actors in the network is a measure of their initial opinion (the more similar actors are in terms of structural equivalence, the more likely they are to share a similar opinion on the issue). In addition, an actor's susceptibility to influence can be measured by the centrality of the resident in the network. According to Granovetter (1973), the analysis of interpersonal

[2] $V = (I - AW)^{-1}(I - A)$ assumes $I - AW$ is nonsingular. Otherwise, V can be estimated from the following: $V^{(t-1)} = (AW)^{(t-1)} + [\sum_{t-2}^{k=0}(AW)^k(I - A)]$, where I is the identity matrix.

influence networks provides “the most fruitful micro-macro bridge.” It is these networks that allow localized interactions to transform into global, large-scale patterns (Granovetter, 1973), such as riots. Through SNA, such opinion formation can be studied (e.g., Friedkin, 2006). This will be further discussed in Section 3.4.3.

2.2: Individual Decision-making

The decision-making process is modeled at two levels: the *Resident* and the *Household*. *Residents* make decisions around what their daily activities will be for that day (e.g., going to work, going to school, getting water) and, based on their interactions and susceptibility to aggressive behavior, whether they will riot or remain peaceful. This is discussed in detail in Section 3.4. At the household-level, *Households* make decisions around their daily expenditures (e.g., food, rent, water). Depending on income, *Households* will dynamically adjust their expenditures to reflect a decrease or increase in income (Gulyani & Talukdar, 2008).

2.3: Learning

Learning is currently not a part of the model.

2.4: Individual Sensing

With respect to sensing, *Residents* know their household income and expenditures. How much a *Household* can spend on certain household expenditures is proportional to their total income (e.g., Alonso, 1964). Residents will seek to make sufficient income by finding employment, which can include pulling younger household members from school (Erulkar & Matheka, 2007; UN-HABITAT, 2003). In addition, when the *Households'* water supply is short, a *Resident* who is *Home* will be required to purchase more water for the *Household* (Gulyani & Talukdar, 2008). *Residents* are also aware of who in their social network is rioting; this knowledge is a function of the social ties created through their interactions (as will be discussed in Section 3.4.1). Residents are heterogeneous in terms of their demographic data, including age, gender, religion, income, and employment status (as discussed in Section 1.2.3).

2.5: Individual Prediction

Prediction is currently not implemented in the model as the purpose is to understand the dynamics behind the emergence of riots.

2.6: Interaction

Interactions between *Residents* are direct. As *Residents* go about their daily activities, they interact with other *Residents* (e.g., family members at home, co-workers at work, students at school). With each interaction a social tie is created or an existing tie is strengthened (see Section 3.4.1). The interaction includes communication if one of the *Residents* has heard the rumor. If so, the *Resident* may spread the rumor during the interaction. In addition, *Residents'* likelihood to share similar opinions, their susceptibility to influence, and their interpersonal influence is a function of the social ties they have created through their daily interactions, which can impact an *Resident's* decision to riot or remain peaceful (see Sections 3.4.2 and 3.4.3). One of the novelties of this model is that the social network is dynamic and evolves as *Residents* interact with one another.

2.7: Collectives

There are three collectives represented in the model. The first is the *Household*, which is a collective of individual *Residents*. *Households* are created during the initialization process and therefore are imposed on the *Residents* and remain static through the simulation run. The second is the *School Class*, which is a collective of students attending the same school. Finally, the third collective represents the collective action of individual *Residents* that choose to riot. This collective emerges during the simulation. The *Residents* that choose to join this collective and riot congregate at a popular and central area in the informal settlement. This is representative of real world riots where collectives have gathered in a city's main square. Recent examples include Independence Square in Kiev, Ukraine in 2014 (Arango, 2013); Tahrir Square in Cairo, Egypt in 2011 and 2013 (Kirkpatrick, 2013); and Taksim Square in Istanbul, Turkey in 2013 (Arango, 2013).

2.8: Heterogeneity

Residents are heterogeneous in terms of their demographic data, including age, gender, religion, income, and employment status (see Section 1.2.3).

2.9: Stochasticity

Stochasticity is seen in several processes. These include the *Residents* selection of certain goals (e.g., the decision to riot), the chance that the *Resident* will be selected to hear the rumor, the probability that an employed Resident will be laid off, or the selection of a friend to visit (see Section 3.4). The assignment of certain attributes of the *Residents* are assigned based on distributions drawn from empirical data such as age, gender, and ethnicity (see Table 1 in Section 1.2). In addition, income is obtained from the Lorenz curve, which represents the wealth distribution of Kibera. At the household-level, *Household* size is obtained from a lognormal distribution. The rent associated with each *Home* is obtained from a distribution based on empirical data (see Table 1). In addition, *Structures* can contain *Homes* and/or *Facilities*, including businesses. Whether a *Structure* will contain at least one *Home* or business is based on a probability drawn from empirical data (see Table 1). At initialization, *Households* must find an affordable *Home* that fits their preference living near "like" neighbors (where likeness is based on ethnicity) as discussed in Section 1.2 and 3.2.1. They do this by randomly selecting an existing *Household* of the same ethnicity, evaluating the Moore neighborhood to determine if it fits their preference, and then finding an available *Home* that meets their rent requirements.

3: DETAILS

3.1: Implementation Details

The model was developed in MASON (a multi-agent toolkit) (Luke *et al.*, 2005) utilizing the GeoMason (Sullivan *et al.*, 2010) spatial extension. The source code can be found at https://www.openabm.org/model/4865/.

3.2: Initialization

Upon model initialization, the environment is created. *Parcels* and the transportation network are added; *Structures* and *Water Points* are placed on *Parcels*; and *Homes*, *Businesses*, and *Facilities* are added to *Structures*. All *Facilities* have an associated grid location based on data from OpenStreetMap (2013). The number of *Homes* and *Businesses* within a *Structure* was estimated from survey data (Marras, 2008). Since the exact grid location is known for *Facilities* (e.g., schools, health facilities, and religious institutions), the *Structure* located on the same grid location contains the associated *Facility*. Next, individual *Residents* are created and assigned into *Households* based on demographic information, such as age and ethnicity. *Households* are then added to *Homes* (discussed in Section 3.2.1). Employed *Residents* and students are then assigned employers or schools, respectively (discussed in Section 3.2.2). Finally, a specified number of *Residents* are randomly selected to hear the exogenous rumor at initialization. Of those that hear the rumor, a proportion will be selected to be influenced enough by the rumor to riot (see Table 7). Those initial rioters will attempt to influence other *Residents* as the simulation runs.

Table 7: Input parameters and variables.

Parameter	Range	Default values	Reference
Residents			
Initial number of agents	235,000 – 270,000	235,000	Marras (2008)
Preference for living near "like" neighbors	0 – 1	0.5	Adapted from De Smedt (2009); Schelling (1978); Authors estimation
Proportion of initial agents that heard the rumor	0 – 1	0.001	Authors estimation
Proportion that riot (of those agents that heard the rumor)	0 – 1	0.025	Authors estimation
Aggression	0 – 1	0	Adapted from Green (2001); Authors estimation
Aggression threshold	0 – 1	0.6	Adapted from Green (2001); Authors estimation
Aggression rate	0 – 1	0.6	Adapted from Green (2001); Authors estimation
Energy	0 – 100	100	Adapted from Burke and Stets (2009); Authors estimation
Energy rate of change	0 – 100	50	Adapted from Burke and Stets (2009); Authors estimation
Opinion threshold	0 – 1	0.1	Adapted from Friedkin (2001); Authors estimation
Employment vision	0 – 312	70	Authors estimation
School vision	0 – 312	35	Authors estimation
Probability of losing employment	0 – 1	0.01	Authors estimation
Identity (Domestic, Student, Employee, Rioter)	1 – 4	1 – 4	Adapted from Burke and Stets (2009); Authors estimation
Households			
Number of household members	≥ 1	$\ln\mathcal{N}(3.55, 1.61)$	Marras (2008)
Maximum number of households in a home	≥ 0	Distribution	Marras (2008)
Monthly cost for rent (Ksh)	> 0	Distribution	Marras (2008)
Per barrel cost of water (Ksh)	> 0	2.5	Gulyani & Talukdar (2008)
Monthly cost of electricity	≥ 0	286	Gulyani & Talukdar (2008)

(Ksh)			
Per visit cost of using public sanitation (Ksh)	> 0	5	Gulyani & Talukdar (2008)
Daily transportation cost (Ksh)	≥ 0	9.68	Gulyani & Talukdar (2008)
Per meal cost of food (Ksh)	> 0	14	Gulyani & Talukdar (2008)
Facilities			
Probability that a home has electricity	0 – 1	0.6	Marras (2008)
Probability that home has sanitation	0 – 1	0.03	Marras (2008)
Maximum number of students at a school	> 1	18	Ministry of Education (2007)
Maximum number of students in a class	> 1	23	OpenStreetMap (2013)
Maximum number of employees at a formal employer	> 1	13	Ministry of Education (2007); OpenStreetMap (2013)
Maximum number of employees at a informal employer	>1	5	UN-HABITAT (2003)
Structures			
Probability that a structure has one or more homes	0 – 100	0.86	Marras (2008)
Probability that a structure has one or more businesses	0 – 100	0.13	Marras (2008)
Maximum number of homes in a structure	> 1	Uniform (1, 5)	Marras (2008)
Maximum number of businesses in a structure	> 1	Uniform (1, 3)	Marras (2008)

3.2.1: Assigning Households a Home

Within Kibera's neighborhoods, one will typically find a majority ethnicity (De Smedt, 2009). For example, Luos make-up the majority of those living in Gatwikira and Kikuyus dominate the Laina Saba neighborhood. Luos originally arrived to Kibera as early as 1948. Coming from the Nyanza province of Kenya, they typically chose to move near family already living in the informal settlement as this assisted residents paying school fees, finding a job, and taking care of them until they settled in (De Smedt, 2009). Given Kibera's ethnic make-up and resident's decision process in selecting a location to settle, the Schelling (1978) segregation model is used as inspiration at model initialization as *Households* select a *Home* for which to reside. Schelling (1978) studied the behavior of two groups of agents on a grid. Agents were given a preference for the number of similar agents they wanted as neighbors. They then moved about the lattice until their preference for similar neighbors had been reached. Similarly, *Households* in the model here are assigned a preference for living near "like" neighbors (neighbors are alike if they share the same ethnicity). If this is the first *Household*, the *Household* will randomly select an affordable *Home* within a *Structure* to reside. As new *Households* are added to the landscape, they survey the current landscape. If the *Household* prefers to live near "like" neighbors, it will randomly select an existing *Household* with the same ethnicity. Within the Moore neighborhood of the selected *Household*, the new *Household* will assess (1) its ability to afford the new place and (2) its preference for living near "like" neighbors. The new *Household* will determine if the area meets its preference requirement and will search for a *Home* it can afford. Affordability is determined by comparing the *Household's* total income to the costs associated with living in the *Home* (including the cost of rent and any amenities that may come with the *Home*). It is assumed that families are willing to spend a certain proportion of their total household income on these costs (Alonso, 1964). If its preference requirement is met and the *Household* finds that the *Home* is affordable, it will move in. Otherwise, the *Household* will randomly select another *Household* with the same ethnicity and repeat the process. Figure 5 illustrates a typical model run after it has been initialized with 235,000 Residents and with a 50 percent preference for living near like neighbors. The different colors represent the ethnic diversity of Kibera (note that large clusters of agents with similar ethnicity have formed).

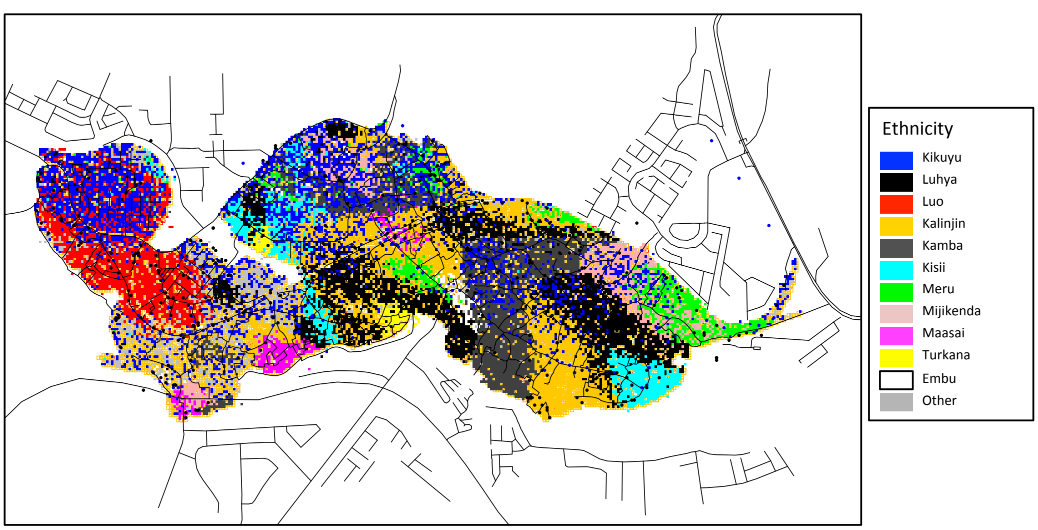

Figure 5: Model after it has initialized with 235,000 Residents. The different colors represent the ethnic diversity of Kibera.

3.2.2: Assigning Residents Employers and Schools

Once this environment is created and all *Residents* have been assigned a *Home*, they are given one of the following employment statuses: inactive (not working and not searching for work), formal (employed in the formal sector), informal (employed in the informal sector), or searching (not employed and searching for employment). At initialization, any *Resident* under the age of 18 is assigned the employment status of inactive. The employment status assignments for the remaining *Residents* (aged 18 and over) is based on empirical data for the area (Kenya National Bureau of Statistics, 2009b) and on the informality index (UN-HABITAT, 2003). Empirical data provides the percentage of *Residents* by gender that are employed, that are searching for employment, or that are inactive, while the informality index provides an estimate of the percentage of employed *Residents* that are working in the formal sector (40 percent) or the informal sector (60 percent). Employment status is dynamic and can change throughout the course of the simulation.

Next, all *Residents* employed search for an employer within their employment vision that has not reached capacity. Employers in Kibera that are considered formal are the *Facilities* (e.g., schools, religious facilities, and health centers). If the *Resident's* employment status is formal, it will search for a *Facility* in Kibera that has not reached its formal employer capacity, which was estimated using empirical data on the number of employees at the schools in Kibera. This value was used as a proxy for all *Facilities* given that this type of data was not available for the religious facilities and health centers. Informal employers in Kibera are the *Businesses*, which can include selling goods on the street, small restaurants, and markets. According to the UN-HABITAT (2003), a business can be defined as informal if it has a maximum of 5 to 10 employees. *Residents* with an employment status of informal will search for a *Business* within the employment vision that has not reached its informal employer capacity. At initialization, if a Resident cannot find an available employer, it is assumed that the *Resident* is employed outside of Kibera (i.e., in other parts of Nairobi). Because employment data is empirically sound and data on the number of Kibera residents working inside versus outside the informal settlement was not available, this ensures that the number of employed *Residents* more closely represents the data. Once the Resident has found an available employer, it is assigned that employer so that it goes to the same employment location each working day (e.g., Monday through Friday) moving forward.

Finally, all *Residents* under the age of 18 will search for an available school within their school vision to attend. Empirical data on the number of students at schools in Kibera was used to determine the student capacity at the schools (OpenStreetMap, 2013). If a *Resident* finds an available school, it is assigned that school so that it attends the same school each school day (e.g., Monday through Friday) moving forward. In addition, these *Residents* are assigned to a *School Class*. This ensures that students interact mostly with a smaller subset of students in a school. We had to make these simplifying assumptions because while we had good data on the environment (see Section 1.2.1), information pertaining to individuals and their activity patterns was lacking. This is common in many less developed countries, which often lack reliable quantitative data with respect to populations and workforce (Henderson, Storeygard, & Weil, 2012).

3.3: Input Data

As Kibera has received considerable attention from non-governmental organizations (NGOs) and other non-profits (Hagen, 2011), an extensive amount of data has been collected, including boundary shape files, transportation shape files, and the geocoded locations of many of its facilities. The two main data sources used to create the modeling environment are Map Kibera (Hagen, 2011) and the Map Kibera Project (Marras, 2008). Map Kibera is a project to geocode the Kibera, which as an informal settlement was previously a blank spot on the map. Using OpenStreetMap (2013), Map Kibera (Hagen, 2011) provided GIS files pertaining to the boundaries, the transportation network (including walking paths, road networks, and railway), the geocoded location of facilities (such as heath centers, schools, and religious facilities), and water points (Hagen, 2011). While this provides the GIS data, much of the socioeconomic and demographic data comes from another project of volunteers, similarly named the Map Kibera Project (Marras, 2008). This project performed an in-depth door-to-door survey of the Kianda neighborhood in Kibera. Survey data included information on the number of households within a structure, the number of household members, and the distribution of male and female as well as child and adult household members. In addition, the amount of rent paid by room and the characteristics of each room, such as whether it has electricity, running water, and sanitation, was included. The estimated locations and attributes of *Structures* comes from the Map Kibera Project (Marras, 2008). In order to create the *Residents*, we synthesized data from a variety of sources, including Marras (2008), CIA World Factbook (2013), De Smedt (2009), Pew Forum on

Religion & Public Life (2010), Kenya National Bureau of Statistics (2009), and UN-HABITAT (2003). Table 1 summarizes the population and environment input parameters used within the model.

3.4: Sub-models

Three sub-models were created in order to capture the full spectrum of behaviors that theory suggests leads to the emergence of riots (as discussed in Section 2.1), specifically the Daily Activity Scheduler (Section 3.4.1), the Identity Model (Section 3.4.2), and the Rumor Propagation and Social Influence Model (Section 3.4.3). The following sections will outline how these sub-models are linked to the PECS (Physical conditions, Emotional state, Cognitive capabilities, and Social status) framework using the common PECS vocabulary. A high-level representation of the *Residents'* behavior within the PECS framework is shown in Figure 6.

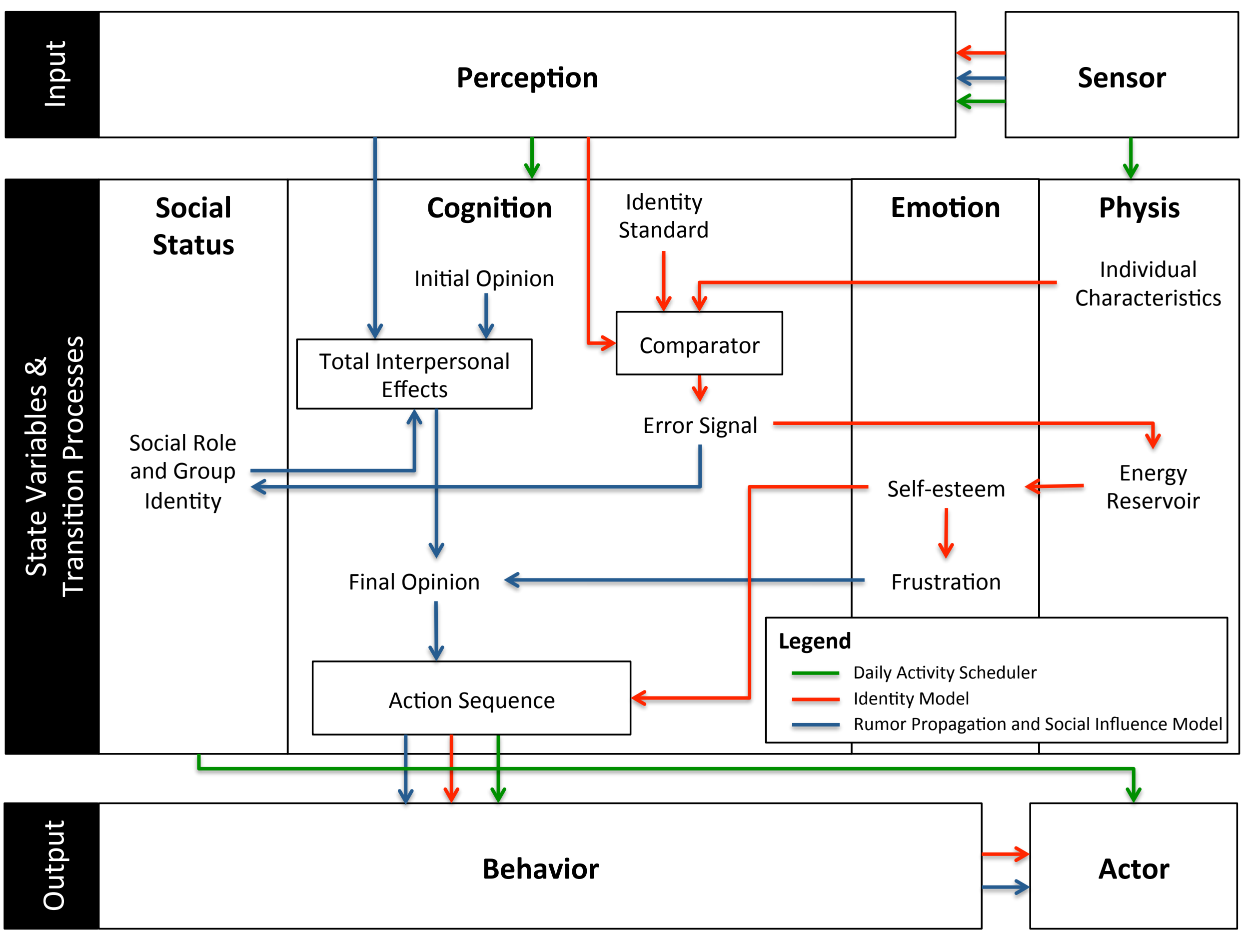

Figure 6: A high-level representation of the model's agent behavior incorporated into the PECS framework (adapted from Schmidt, 2000).

From Figure 6, *Perceptions* from *Sensor* (the environment) feed into both the self-verification (see Section 2.1.1) and social influence processes (see Section 2.1.2). In addition, these *Perceptions* help guide the routine activities of the *Resident*. Simple behavior (such as staying home to sleep or eat) may be determined directly in *Physis*. More intricate inputs are fed into *Cognition*, where the *Resident's* Identity Standard is compared to its *Perceptions*. The self-verification process occurs and once complete, the Comparator produces an Error Signal. This process is used to determine if the *Resident's* identity will be Domestic, Employee, Student, or Rioter. If there is no error (the *Resident* met its Identity Standard), the Energy Reservoir is increased and Self-esteem goes up. *Cognition* will then generate the *Action Sequence*, *Behavior* will determine the execution order, and *Actor* will execute the actions associated with the *Resident's* identity. If an Error Signal is produced, however, the Energy Reservoir in *Physis* is reduced and Self-esteem in Emotion goes down. Low Self-esteem can lead to frustration, which in turn, can cause aggressive behavior (Green, 2001; Stets and Burke, 2005). The *Resident's* susceptibility to influence from those in its social network is then evaluated in Total Interpersonal Effects. Its position in *Social Status*, both in terms of Social Role and Group Identity (outputs of the Identity Model) impact a *Resident's* susceptibility and Final Opinion on the rumor. If the *Resident* has heard the rumor, has reached a level of frustration that can lead to aggressive behavior, and has been influenced to riot by one or more *Residents* in its network, *Cognition* will generate the *Action Sequence*, *Behavior* will determine the execution order, and *Actor* will execute the action for one to riot. Otherwise, the *Resident* will remain peaceful. *Residents* will continuously run their Identity Standard through the Comparator and re-evaluate their Final Opinion on the rumor being spread. This process also allows for development of the *Resident's* Self Model (an important cognitive component to modeling human reflective behavior) as well as *Emotion* in the form of Self-esteem (Stryker and Burke, 2000). The *Perceptions* input into the Self Model are a factor of the individual's interactions with others and the environment. Internally, such interactions impact the Error Signal (difference between the input *Perceptions* and the Identity Standard) received by the Comparator, which directly predicts the *Resident's* behavior.

Figure 7 provides the complete set of motives and actions available to the *Residents*. The processes shown in Figure 6, between receiving information from *Perception* and generating the

Action Sequence, are implemented via the Intensity Analyzer, which is responsible for determining the action-guiding motive from the set of possible motives available to the *Resident*.

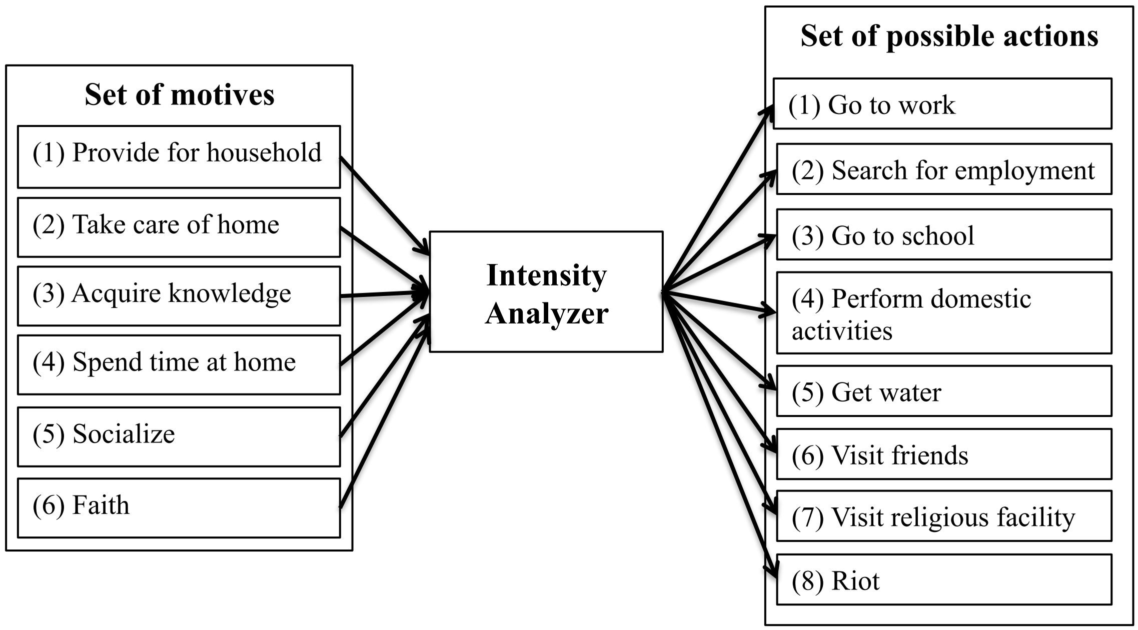

Figure 7: Motives and determining action-guiding motive via the Intensity Analyzer (adapted from Schmidt, 2002).

The three sub-models—the Daily Activity Scheduler, the Identity Model, and Rumor Propagation and the Social Influence Model—that make-up the Intensity Analyzer, and subsequently drive agent behavior, are described in detail next.

3.4.1: The Daily Activity Scheduler

The first step in determining agent behavior is to run the Daily Activity Scheduler, which drives the agents' daily activities. This sub-model draws from Maslow's (1954) hierarchy of needs as agents' strive to meet their physiological, safety, love and belonging, and esteem needs (see Section 2.1.1). Little is known about people's daily activities within the Kibera slum so the following simplified assumptions were made in accordance to Maslow (1954) and stylized facts based on the literature cited above (e.g., De Smedt, 2009; Marras, 2008; Stets and Burke, 2009; UN-HABITAT, 2003). In an informal settlement such as Kibera, physiological needs such as food, water, and sanitation must be purchased; this requires that one or more members of a household unit are employed and are providing sufficient income. If unmet, a *Household* would either increase its income (e.g., pulling a student out of school to work) or find a means to cut back on these basic necessities. Informal settlement residents may seek safety in terms of personal security through shelter (a home) and staying indoors past a certain hour, financial security through gainful employment or knowledge acquisition in school (as a means to insure future financial security). Love and belonging includes activities such as staying home to spend time with family, going to a friend's house to socialize, or attending church or mosque to feel like part of a community. Esteem is met by continuous successful attempts at self-verification. For example, the student identity is met by regularly attending school; the employee identity is met by having regular and stable employment; and the domestic identity is met by successfully attending to the home and family. If continuous attempts at self-verification are unsuccessful, however, self-esteem will be low and may lead to frustration. The final category, self-actualization, which is met when a person feels they are at their full potential in areas such as morality, problem solving, and creativity, is beyond the scope of this model.

The Daily Activity Scheduler begins with a set of available motives that are largely attributed to human needs theory. Intensity levels of the motives are evaluated against a set of influencing factors (both environmental and internal). The motive with the highest intensity becomes the action-guiding motive, which determines the goal the *Resident* will strive for. In this case, each goal is also the associated activity (e.g., if the goal is to 'Go to work', the activity would be the same). The set of motives, important influencing factors driving motive intensity, and their associated goals are listed in Table 8.

Table 8: The set of motives, important influencing factors, and the associated goals that drive agents' daily, routine activities.

Motive	Important Influencing Factors	Associated Action(s)
Provide for *Household*	Basic human needs (e.g., need for food and water), time-of-day and day-of-week, age, and employment status	Go to work, Search for employment
Take care of *Home*	Current levels water, time of day, age, and employment status	Perform domestic activities, Get water
Acquire knowledge	The need for future financial security, time-of-day and day-of-week, age, and availability of schools	Go to school
Spend time at *Home*	Basic human needs (e.g., need to eat and sleep), need for love and belonging, and time-of-day	Perform domestic activities

Socialize	Strength of the friendship, distance to friends house and whether friend is home	Visit friends
Faith	Importance of faith, distance to nearest religious facility	Visit religious facility

If we are to compare the set of motives in Table 8 to Maslow's (1954) hierarchy of needs, the first three listed (provide for *Household*, take care of *Home*, acquire knowledge, and spend time at *Home*) would be associated with fulfilling the first two most fundamental levels of needs: physiological and safety. The two remaining motives (socialize and faith) fall under the third level of Maslow's (1954) hierarchy of needs: love and belonging. In addition, from this table (under the important influencing factors) we see that the time-of-day and the day-of-week play important roles in the evaluation process. These factors are used by the Intensity Analyzer as part of the evaluation process. The times and days associated with each activity in addition to the amount of time a *Resident* will stay at the activity are shown in Table 9.

Upon determining the activity to perform, the *Resident* uses the transportation network (e.g., roads and walkways) created at model initialization to move to the *Parcel* where the activity is located. The *Resident* then stays at this *Parcel* for the activities staying period before returning *Home*. As an exploratory model, scheduling was kept simple. However, it can be extended to include more intricate scheduling if developed further.

At initialization *Residents* (nodes) are not connected to any other *Residents*. However, while at an activity, the *Resident* generally interacts with other *Residents* located on the same *Parcel* and performing the same activity. Table 10 shows the interactions that occur with each activity.

Table 9: Scheduling of activities by start time, day of week, and staying period at activity

Activity	Start Time	Day of Week	Staying Period	Activity Location
Go to work	8:00AM – 11:00AM	Monday – Friday	6 – 12 hours	Assigned work location (*Business* or *Facility*)
Search for employment	8:00AM – 11:00AM	Monday – Friday	6 – 12 hours	*Home*
Get water	7:00AM – 6:00PM	Everyday	10 minutes – 1 hour	Nearest *Water Point*
Go to school	7:00AM – 9:00AM	Monday – Friday	7 hours	Assigned school

Visit friends	7:00PM – 9:00PM (if a student or an employee and it is a school day or work day) Anytime (otherwise)	Any day	2 – 4 hours	A friend's *Home*
Go to religious *Facility*	(Church) 7:00AM, 9:00AM, 11:00AM, 7:00PM (Mosque) 5:00AM – 6:00AM, 12:00PM – 2:00PM, 3:00PM – 5:00PM	(Church) Sunday (Mosque) Everyday	(Church) 1 – 2 hours (Church) 20 minutes – 3 hours	Nearest religious *Facility* to *Home*

Table 10: The interactions that occur with each activity.

Activity	Interactions
Go to work	Coworkers working with the same employer at the same time.
Search for employment	*Household* members.
Get water	Assumed that no interactions occur.
Go to school	Students in the same *School Class*.
Visit friends	The friend visited and any other of the friend's connections currently at the same location (i.e., *Parcel*)
Go to religious institution	Randomly select another *Resident* to interact with that is also at the religious *Facility*.

These interactions create new *Resident*-to-*Resident* connections (ties) or strengthen existing connections. The weight of a tie between two *Residents* is a function of the amount of time the two *Residents* spend together. After a *Resident* has completed an activity, the weight of all the ties between any interactions is calculated. A weight of one at the end of one day would signify that two *Residents* spent the entire day together. The following equation shows how the weight of a tie at time t, w_t, is calculated.

$$w_{ij}(t) = w_{ij}(t - x) + x/m, \tag{3}$$

where $w_{ij}(t - x)$ is the previous weight of the tie between the two *Residents* i and j, x is the amount of time the *Residents* stayed at the activity where both *Residents* were present, and *m* is the number of minutes in one day. If a *Resident* were to stop interacting with another *Resident* (e.g., a *Resident* lost its job and therefore no longer interacts daily with its colleagues), the tie between the two is not removed as a simplifying assumption. However, as time passes, the tie will not strengthen and will eventually become proportional insignificant compared to relationships it has with other *Residents*.

Figure 8 provides an illustration of how the social networks of ten *Residents* at initialization can evolve across two full days. At initialization all *Residents* are *Home*, thus they will immediately connect with any other *Household* members. In this example the ten *Residents* make-up three different *Households*. As these *Residents* begin to interact with other *Residents* through their daily activities, their social network grows and tie strength, which is represented by the thickness of the lines, increases as *Residents* continue to interact and spend more time together.

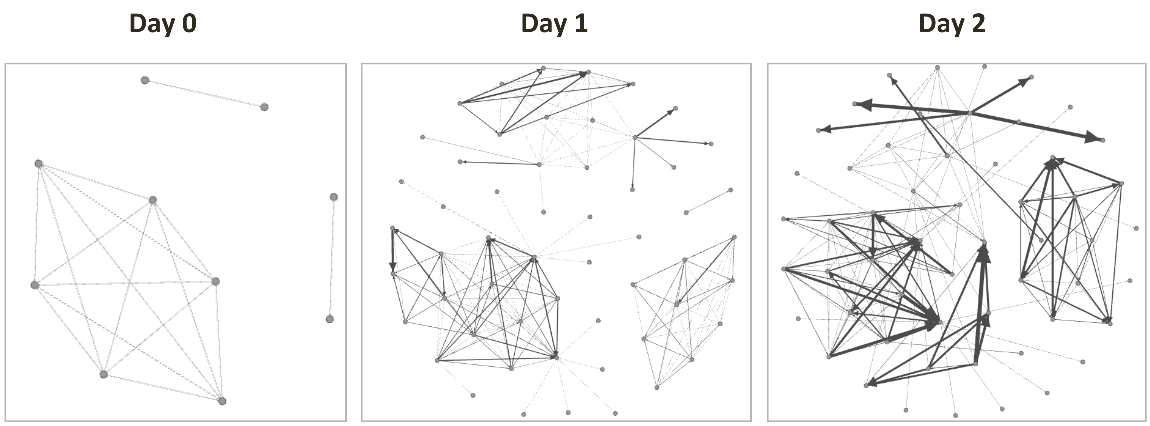

Figure 8: The social networks of ten Residents across the first two days of a simulation run.

Social networks play a key role in the model, both in terms of the salience, and subsequent activation, of an identity (as will be discussed in Section 3.4.2) and on a *Resident's* susceptibility to influence (as will be discussed in Section 3.4.3). Both of these factors are a major part of a *Resident's* decision to riot or to stay peaceful.

3.4.2: Identity Model

As the self-verification process succeeds or fails at the micro-level, macro-level social networks and group dynamics can be observed. The unified theory allows one to consider behaviors from the "more mundane expectations for a person occupying a role," such as going to work, searching for employment, or attending church (Stryker and Burke, 2000), to meso- and macro-level formation of friendships and cohesive groups, which could potentially lead to intergroup conflict and civil unrest (see Section 2.1). Kibera is a melting pot of ethnic diversity and for the most part, ethnic groups live peacefully. The Identity Model is a critical component of human behavior and it may help us shed some light into why former friends and neighbors turned on each other during the ethnic riots.

An identity is composed of four basic components: Input Perceptions, an Identity Standard, a Comparator, and a Output Behavior (as discussed in Section 2.1.1). The model assumes all *Residents* seek to meet the Identity Standard of one of three primary, non-deviant identities (Domestic, Student, and Employee), one secondary identity (Ethnicity), and one primary, deviant identity (Rioter). Primary identities are those that (at least for purposes of this model) cannot overlap. An agent will not strive to meet both the Employee and Student identities, for example. On the other hand, the Ethnicity identity can exist along with a primary identity (a resident can be a Student and a Kikuyu at the same time). However, this identity remains latent most of the time, and is only activated should issues arise in the identity verification process of one of the primary, non-deviant identities. The final identity is the Rioter identity. This is primary because it cannot co-exist (for modeling purposes) with another primary identity, but is deviant because, like Ethnicity, is only activated should the resident have trouble with the self-verification process of a primary, non-deviant identity. In addition, a Resident must be at least five years of age for the Rioter identity to be active. Five was selected because this is the age Kenya begins to collect employment statistics on its residents. If residents are eligible to work at the age of five, it is assumed that they might participate, at some level, in a riot. Table 11 summarizes the identities available to Residents in the model.

Table 11: The set of identities available to agents.

Identity	Type	Requirements for Residents Seeking This Identity
Domestic	Primary, non-deviant	*Resident* is not working or attending school and is performing domestic activities.
Employee	Primary, non-deviant	*Resident* is employed.
Student	Primary, non-deviant	*Resident* is under 18 and finds a school with availability.
Ethnicity	Secondary	A disruption in the identity verification process, sufficient failed attempts at self-verification of a primary, non-deviant identity, and influence from those in the *Resident's* social network.
Rioter	Primary, deviant	*Resident* is at least 5 years old and Ethnic identity is salient.

The relationship between the Daily Activity Scheduler, which executes the *Output* behavior and Identity Model, which produces the error signal that tells the Resident if it met its Identity Standard, is a feedback loop, each informing the other (as shown in Figure 4). The activity an agent performed as per the Daily Activity Scheduler helps inform the *Resident* of his/her ability to match its Identity Standard (this is equivalent to the self-verification process in the Identity Model). The *Residents* social networks are a critical component of commitment, which is defined as their embeddedness in a network, and can effect the activation of a given identity. For instance, network ties can impact the likelihood that a *Resident's* ethnic identity will be activated or remain latent. In addition, the fit of an identity in a given situation is also important. For instance, if a *Resident* is at work, their Employee identity is likely to be active. Meanwhile, the identity a *Resident* is striving to meet drives the activities it may look to perform. As an exploratory model, the rules for meeting an Identity Standard were kept simple. The inputs include information such as the *Resident's* employment status, age, availability of employers within a *Resident's* vision, and availability of schools within a *Resident's* vision. The Comparator compares the *Resident's* desired Identity Standard against a set of simple rules required for meeting the Identity Standard. Because domestic activities are not dependent on the availability of work or school and every *Resident* is assumed to have a *Home*, any *Resident* seeking this identity is able to achieve the Identity Standard. If a *Resident* is employed, the *Resident* has met the requirements to be happy in the Employee identity. However, if the *Resident* is searching for employment and has not found a job, the self-verification process for the Employee identity is said to have been unsuccessful. This is similar for the Student identity. If a *Resident* that is 18 or under is able to find an available school to attend, the identity verification process was successful. If, however, there are no available schools and the *Resident* must stay *Home*, the Student Identity Standard was not met. In addition, should a *Resident* seeking the Student identity not be able to attend school, he/she will then determine if its necessary to search for employment. If so, the employment status will change to reflect the fact that the *Resident* is now looking to enter the job market. If the *Resident* is able to find employment, his/her Employee Identity Standard is met.

The output of the identity verification process is an increase or decrease in the *Resident's* Energy Reservoir (this is consistent with the Identity Model described in Section 2.1.1). Each *Resident* begins the run with an energy level of 100. The amount by which the Energy Reservoir changes with each attempt at identity verification are based on the energy rate of change, a user inputted variable. The change in energy in a *Resident's* Energy Reservoir is calculated by using the following equation, where change in time is the amount of time a *Resident* has been performing the current goal divided by the number of minutes in a day.

$$\Delta\, energy = \; energy\, rate\; of\; change\; *\; \Delta time \tag{4}$$

If the self-verification process is successful, energy levels in the Energy Reservoir increase by the change in energy (but remain capped at 100). As *Residents* fail to meet their Identity Standard, their Energy Reservoir is depleted by the change in energy value. In addition, the model accounts for overall household "happiness." A *Resident* may continuously fail to meet the Employee identity. However, if its *Household* unit is sufficiently "happy" (i.e., household income is not an issue), the *Resident* may be less likely to become quickly frustrated. On the other hand, a lack of resources at *Home* may increase the rate at which a *Resident* becomes frustrated. *Household* happiness is a function of the discrepancy between a *Household's* total income and its total expenditures. Problems in self-verification reduce the *Resident's* ability to handle problems with identity verification. This causes increased stress, thus potentially leading to an aggressive response (Stets and Burke, 2005). In the model this takes the form of rioting.

The aggression threshold is the same for all *Residents* and is set at initialization of the model. A logistic curve is used to represent aggression in the model. As a *Resident's* Energy Reservoir gets depleted, aggression moves down the logistic curve. The initial rate of the logistic curve, called the aggression rate, is set at initialization and is specified by the user. In addition, *Household* happiness directly impacts the rate of the curve. If a *Household's* happiness level is high, the rate of the curve is increased so that it takes additional rounds of failed self-verification before the Resident becomes aggressive. On the other hand, low *Household* happiness decreases the rate of the curve, ensuring the opposite effect. Once a *Resident's* energy level dips below an aggression threshold, which is also a user inputted variable, the *Resident* may aggress.

Figure 9 illustrates the logistic curve at three different rates. Based on the figure, if the rate of the logistic curve is set at 0.6 (the red line) and the aggression threshold is set at 0.8, a *Resident* may aggress after its energy level has dipped below 61. When aggression goes below the aggression threshold, the *Resident* has the potential to aggress. Whether the *Resident* aggresses (and riots) depends on the results of the Rumor Propagation and the Social Influence Model, which is discussed next.

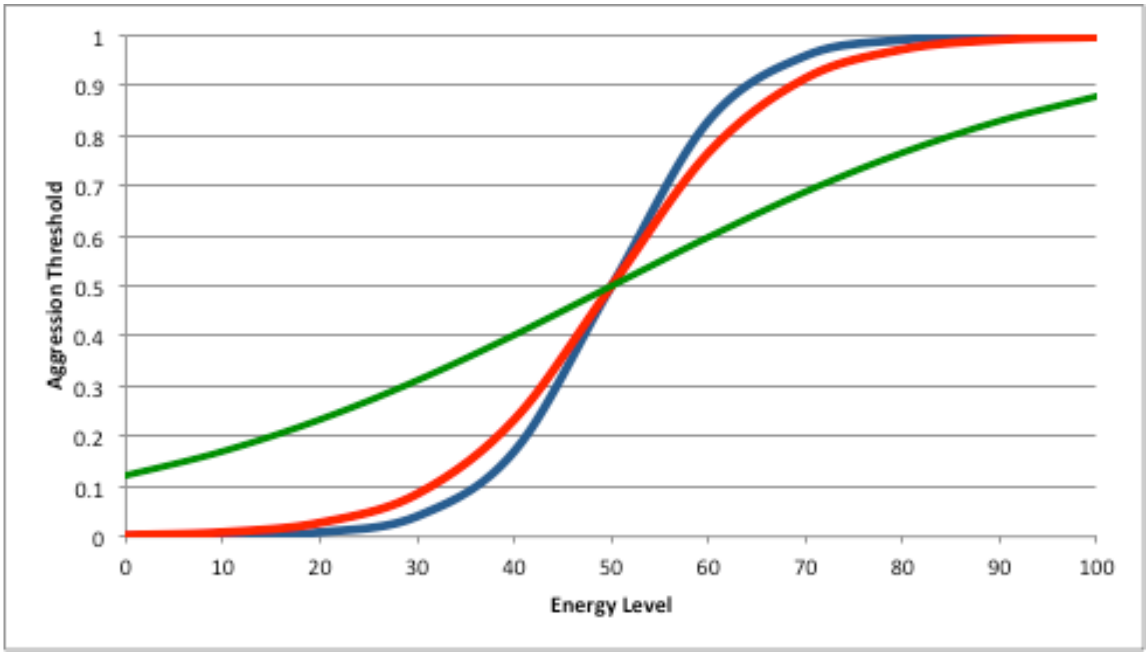

Figure 9: The logistic curve at three different rates (green line = 0.2, red line = 0.6, and blue line = 0.8).

3.4.3: Rumor Propagation and Social Influence Model

Rumors played a major role in the riots that hit Kibera, in terms of re-igniting it, escalating the intensity, and causing displacements. The question here is therefore, how do rumors propagate or diffuse? Diffusion can be defined simply as "the spread of something within a social system," where "something" can be a rumor, some piece of information, or even a disease (Strang and Soule, 1998). In the case here, we assume "something" refers to a rumor. Rumors can serve as a disruption in an individual's routine identity verification process, potentially heightening the salience of latent identities, such as one's ethnic identity. In addition, social networks play a key role in this diffusion process, both in terms of spreading the rumor and in terms of social influence and opinion formation induced by the rumor (Granovetter, 1973). Many people will hear the rumor (especially given the prevalence of mass media and social media) but whether they act on the rumor is largely based on the diffusion of influence through their social networks. Simply hearing the rumor through mass media is not enough; the spread of the information through personal ties is key in determining whether one will act on the rumor (Granovetter, 1973). In addition, Allport and Postman (1947) stress the importance of social networks and susceptible individuals in these networks in the spread of a rumor. Similarly, Friedkin and Johnsen's (1999) Social Influence Network Theory says that a recipient's decision to act on the rumor is a function of their initial opinion on the issue, their relative interpersonal influence, and their susceptibility to influence (see Section 2.1.2).

At initialization a predefined number of residents "heard" a rumor, and of those that heard the rumor, a proportion is initially influenced by the rumor. Although these agents are rebellious, they continue to go about their daily activities as a means to spread their "message" with others in their social network. Once a *Resident* has heard the rumor, it will randomly spread the rumor to another *Resident* in its social network. If a *Resident* has not heard the rumor, it will continue to go about its daily activities. If the *Resident* is influenced by the rumor and is at an aggressive state, the identity verification process of a primary, non-deviant identity will be broken while the Ethnicity identity and Rioter identity will be activated. Studies have shown that people seldom act on a rumor unless heard through personal ties (Granovetter, 1973). For this reason, the model assumes that acting on the rumor cannot occur unless through direct interaction with others who have also heard the rumor and have been influenced to riot.

The recipient's decision to act on the rumor is based on Friedkin and Johnsen's (1999) Social Influence Network Theory. Building on this, Friedkin (2001) developed a structural approach for determining opinion formation, an approach that is particularly useful in situations where the only information available is the communication (or interaction) network. Using this approach, the structural equivalence of the actors in the network is a measure of their initial opinion (the more similar actors are in terms of structural equivalence, the more likely they are to share a similar opinion on the issue). However, given the computational intensity of evaluating structural equivalence in an evolving social network, we modify the definition of similarity slightly. The similarity (homophily) effect measures the phenomenon where agents form ties with other "similar" agents. The tendency towards homophily is a central characteristic of many social networks (McPherson, Smith-Lovin, & M., 2001). Two actors are said to be structurally equivalent if they "have identical ties to and from all other actors in the network" (Wasserman and Faust, 2009). Instead of evaluating whether two actors are connected to the exact same nodes (i.e., share identical ties), the model assesses whether two *Residents* are connected to the same types of nodes, where node type is based on the active identity (e.g., Employee, Student, Rioter) of the node and the ethnicity of the node. This is consistent with Wasserman and Faust (2009) discussion on potential ways to relax the strict definition of structural equivalence by using a node's "role" (here role is defined as identity), for instance, as a measure of structural "similarity." The Ethnicity identity does need to be active for calculating similarity (homophily) as we are measuring how embedded a *Resident* is in a network of *Residents* with similar ethnicity, an important characteristic of identity salience (Stets and Burke, 2000). The similarity between the *Resident* in question is compared to each *Resident* it is directly connected to (out to one degree). An actor's susceptibility to influence, a_i, is measured by the centrality of the *Resident* in the network, particularly indegree centrality, and is determined by the following equation (Friedkin, 2001).

$$a_i = \left[1 - 1/\left(1 + e^{-(d_i - 2\bar{d})}\right)\right]^{1/2}, \tag{5}$$

where d_i is the degree centrality of the *Resident* and $\bar{d}$ is the mean degree centrality of the entire network. Interpersonal influence, w_{ij}, is measured as follows (Friedkin, 2001).

$$w_{ij} = a_i c_{ij} / \sum_k c_{ik}, \tag{6}$$

where $i \neq \{j, k\}$, c_{ij} is the probability that there is an interpersonal attachment between *Resident* i and *Resident* j, and c_{ik} is the probability that there is an interpersonal attachment between *Resident* i and *Resident* k, where k is all the other agents Resident i is connected to. To keep the network size small and computationally feasible, influence is only evaluated against those *Residents* already attached. Therefore, $c_{ij} = 1$ and $c_{ik} = 1$ in all instances. In Section 2.1.2, we defined V (see Equation 2) as the total interpersonal influence (both direct and indirect) of each actor. For simplification purposes, only the direct interpersonal influences, W, are evaluated here. Thus, in the model, a *Resident's* opinion on an issue at time t is calculated as follows (Friedkin, 2001).

$$y^{(t)} = W y^{(t-1)}, \tag{7}$$

where W is the matrix of interpersonal influence. The *Resident's* final opinion, $y^{(t)}$, is then compared to the opinion of its direct connections. If the *Resident's* opinion is similar (below a user inputted opinion threshold) to any of its connections, the *Resident* is influenced by that connection. Those most susceptible to being influenced are those already having trouble verifying their identity and those most similar (high ethnic salience) to rebellious connections. If the *Resident's* aggression has fallen below the aggression threshold and the influencing connection is a Rioter, the agent is now also influenced to riot.

4: Model Output

The main output of the model is the number of *Residents* that rioted, the number of *Residents* that remained peaceful, the individual demographics of these *Residents*, and the temporal dynamics on when the *Residents* rioted. The model exports a series of comparative statistics. These include the number of *Residents* by activated identity, activity, and employment status. Statistics are collected by time step so that changes in behavior or trends can be easily assessed. In addition, simple SNA statistics are gathered for the network as a whole, including mean degree centrality and total degree centrality. These statistics allow us to analyze the distribution of *Residents* by their identity (e.g., Rioter) and observe any interesting trends.

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