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# Municipal Benefits of Participatory Urban Sensing: A Simulation Approach and Case Validation

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**Abstract**

Involving citizens in public affairs through the use of participatory sensing applications is an emerging theme in Pervasive Computing and mobile E-Government (M-Government). Prior work, however, suggests that local governments place more emphasis on internal than on external M-Government projects. This paper takes an action design research perspective to provide insight into the often overlooked potential of citizen-centric, external M-Government services. We consider the scenario of a sensing application for reporting urban infrastructure issues to the municipality and present a System Dynamics model to estimate the diffusion, use, and municipal impacts of such service. The model is validated based on the case of a large German city, a dedicated survey, and further data sources. The simulation results indicate that, compared to internal information acquisition procedures, the use of urban sensing can improve a municipality's availability of environmental information at a comparable level of cost. Furthermore, we discuss a number of aspects and learnings related to an urban sensing implementation and provide an empirical estimation of the diffusion model. Our results provide an impetus for researchers and government practitioners to reconsider the benefits of urban sensing applications in E-Government endeavors.

**Keywords:** Urban sensing, Mobile government, Mobile reporting, Simulation model, System dynamics, Action design research, Cost benefit analysis

# 1 Introduction

Local governments increasingly understand citizen participation as an important building block of modern public administration. New public management poses that through participation, citizens and public agencies can co-create public value which also strengthens democratic authorization, legitimacy, and trust [41]. While participation has been primarily studied under the aspect of influence in public policy and decision making, citizens have ever since also participated in public service delivery and thus co-produced public value in the day to day routines of public administrations [1], [58].

Information and communication technology (ICT) plays an important role not only to enable participation, but also to dramatically reduce efforts and increase the speed of interaction compared to traditional ways of citizen involvement [30]. Today, the pervasiveness of mobile internet-connected devices, such as smartphones and tablet PCs, makes it possible to gather opinions and environmental data from citizens directly on the spot [15]. Currently, an expanding research community is developing participatory sensing systems for a broad range of applications, such as environmental impact assessment [43], air quality monitoring [4], traffic mitigation [24], and noise control [38]. However, most of these initiatives are designed in a grassroots fashion as individual projects, separate from the realm of integrated E-Government initiatives [12]. One reason behind this may be that public institutions are generally thought of as too slow to keep pace with the rapid developments in urban sensing and therefore place more emphasis on mobile applications for equipping internal staff [29]. Some *laggard* municipalities may even have the conception that mobile citizen participation is more a *nice-to-have* than an absolute necessity to sustain the efficiency of public service delivery [60]-[61].

This study argues in contra, that it is worth to bridge the gap between participatory sensing approaches and municipal E-Government strategies to embrace data from citizens in urban management. We show that not only soft, but also hard quantifiable benefits can be achieved for the municipality related to information quality and cost. As a scenario, we consider a mobile reporting service, i.e. a participatory sensing application where citizens can report urban infrastructure issues, such as potholes, waste and other defects to the local authority, ideally tagged with a photo and according location coordinates. Such services are becoming increasingly popular as part of the integrated mobile offerings of a number of cities (e.g., a prominent example is Site 1).

We take an action design research perspective and develop a simulation model as an organization-dominant artifact [53] that facilitates decision-making and fosters the acceptance of such services among municipal stakeholders. The simulation estimates the citizen adoption and benefits from a municipal perspective in terms of issue awareness and required street inspections. The model itself and its usefulness in decision-making contexts are demonstrated by the case of the State Capital of Saarbrücken, a large German municipality. As currently various possibilities of urban sensing emerge, the result of our work can aid local governments and service operators equally to engage in public-private partnerships and jointly foster more urban citizen participation.

In the remainder of this paper we will first review related work regarding urban sensing and the simulation method. Then, in Section 3 we describe the methodological approach of this research. Section 4 presents the proposed simulation model and its underlying assumptions. Section 5 describes the results of the case validation separated into the stages of process analysis, model instantiation, scenario simulation, qualitative analysis and parameter estimation. Finally, Section 6 concludes the paper by evaluating our methodology and outlining the contributions, limitations and future work.

# 2 Related Work

This section explains the underlying concepts of this research from a thematic and a methodological perspective. This work can be thematically attributed to the intersecting field of urban sensing and E-Government research. Methodologically we employ System Dynamics (SD) as a method to design our simulation model.

## 2.1 Participatory Urban Sensing

Urban sensing describes the leap in Pervasive Computing from embedded networked sensing in the laboratory to the real-world environment, e.g. in form of mobile phones [15]. As these *smart* mobile devices are increasingly capable of capturing, classifying and transmitting image, acoustic, location, acceleration and other data, they can be perceived as sensor nodes and location-aware data collection instruments [12]. Thus, urban sensing and its numerous applications that emerge can be seen as a first manifestation of the vision of ubiquitous computing [58].

Depending on the role of the user in urban sensing, two fundamental interaction patterns are differentiated. *Participatory* sensing refers to applications where conscious human interaction is required to decide which data is shared, while in *opportunistic* sensing the device acts autonomously and acquires data whenever its state matches defined context requirements [34]. The term participatory sensing itself has been coined by Burke et al. [12] and was primarily motivated by the idea to enable grassroots campaigns that gather data on issues of public interest.

Over the last few years, some municipalities have embarked on the concepts of participatory sensing. Regarding the given scenario, an example for a participatory application is the service NYC311 from New York City (Site 1) where users can report various local problems via their mobile device. In contrast, other applications (e.g., Street Bump piloted in Boston, Site 2) aim to report potholes and other street defects based on location and acceleration profiles of a driving vehicle, thus taking an opportunistic approach to sensing. In addition, there are a number of research projects that make tremendous technical advances for supporting these and further application scenarios.

An example provided by a team at University of California Los Angeles (Site 3) is PEIR [43], the personal environmental impact report, a system that uses GPS data from mobile phones and classification algorithms to determine the users' mode of transportation and travel routes. From this information the service deducts information on the environmental impact, e.g. the carbon footprint and pollution impact, and gives the user feedback [43]. The project Common Sense at Intel Labs Berkeley (Site 4) focuses on the development of mobile sensors for collecting pollution and air quality data (such as carbon monoxide, ozone, nitrous gases, temperature and humidity) as well as the visualization of data in sample applications. The device is designed such that it can be easily carried along by a person and transmits environmental data to via in-build GPRS or through the user's mobile phone [4].

Further examples are the CarTel projects at Massachusetts Institute of Technology (Site 5), which address road transportation issues including traffic mitigation and pothole detection [24]. The traffic mitigation application uses location data from mobile phones as input to algorithms for traffic analysis, prediction, and according traffic-routing suggestions. The pothole detection uses dedicated sensing devices mounted on vehicles, which measure 3-axis acceleration and location data [24]. A solution that addresses noise pollution has been presented by the Sony Labs Paris [38] and is now maintained at Vrije Universiteit Brussel (Site 6). The system NoiseTube uses mobile phones as acoustic sensors and records noise levels along with location data. These are combined in a noise map to raise the awareness for urban noise pollution. In addition, labels reflecting the noise sources can be assigned by the users or inferred by the system [38].

While many of these research projects have yet outgrown the realm of grassroots initiatives, only few have been incorporated in the official services of local governments and reached a broader user base. One of the reasons for this may lie in a low acceptance of urban sensing applications among administrative stakeholders and a lack of insights on the potential benefits. Nevertheless, when a governmental body acts as the recipient of sensing information, similar to the two examples mentioned above (Sites 1 and 2), we can instantly relate this stream of research to the emerging field of Mobile Government.

## 2.2 Mobile Government

Mobile Government (M-Government) can be defined as an extension of E-Government *involving the utilization of all kinds of wireless and mobile technology, services, applications and devices for improving benefits to the parties involved in E-Government* [32]. Depending on the target group, we may further differentiate between internal and external M-Government. The former is mostly concerned with equipping governmental staff (e.g., traffic wardens, food and veterinary inspectors, fire-fighters and police) with mobile devices to improve internal processes. External M-Government refers to applications that offer mobile services to the customers of government agencies (i.e., citizens and businesses) and expand the current service offering to this new channel of communication. Participatory urban sensing promises new applications particularly for external, citizen-centric M-Government [49]. Figure 1 illustrates the relationship between the mentioned fields and positions the service that his paper addresses.

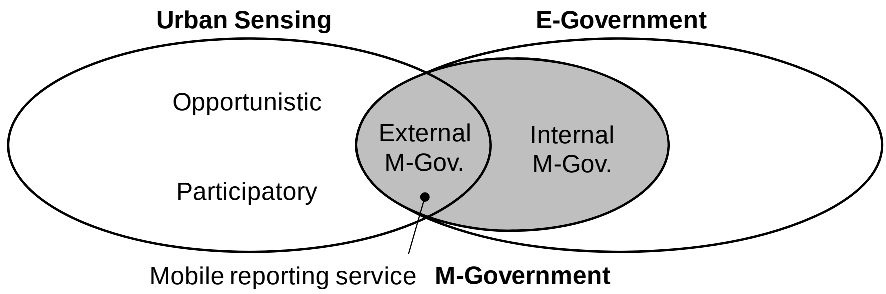



Figure 1: Field of research

Challenges and success factors of M-Government (i.e., internally and externally) are addressed by a number of authors (see [44] for a more structured overview). The most critical issues on user level are particularly seen in accessibility, user friendliness, quality, convenience, privacy as well as user education [2], [18], [31], [33], [50]. From a technological perspective, authors also emphasize the availability of communication networks, payment infrastructures, security requirements and compatibility between different online and mobile E-Government channels [32], [33], [61]. Economically, most works find that governments view investments in M-Government technologies as a means to achieve potential savings [50], [61], rather than simply a cost factor. Organizational challenges can be that sometimes centralized governance, political support and process re-engineering are necessary to leverage these cost advantages [11], [50], [61]. However, other authors find that M-Government initiatives primarily occur at the local level and rarely cause structural changes [11].

Prior work on M-Government also suggests that due to these drivers and inhibitors of adoption, agencies place more emphasis on internal than on external M-Government projects [61]. As many local governments are facing continual pressure to save costs, the benefits in internal processes appear more tangible and hence receive a higher priority. Moreover, government employees can be regarded of as a more controllable group of users, so that possible user-level acceptance issues can be better mitigated [61]. In contrast, citizen-centric mobile applications are often perceived as a dispensable feature reserved for those municipalities that can still afford to experiment with new innovations [60]. This reluctance and risk aversion is consistent with the broader literature, which generally views the public sector to lag behind the private economy in innovation adoption [29]. This is particularly lamentable from a citizen participation standpoint inasmuch as a recent study indicates that urban sensing tools actually do provide significant means for citizens to participate in urban management [62].

Altogether, given that one of the main barriers of external M-Government adoption particularly consists in the perceived uncertainty of process and cost improvements, researchers may take a closer look at evaluating the benefits of urban sensing as a means of citizen-centric Mobile Government.

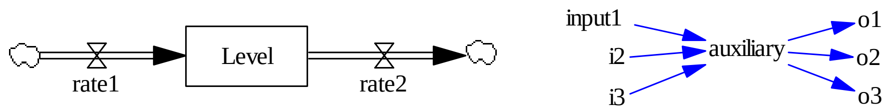
## 2.3 Benefits Case Appraisal and System Dynamics

The appraisal of information systems (IS) benefits, or more broadly, the question how information systems create value, has ever been a center of gravity in the IS literature [51]. The literature provides a number of measures and methods to evaluate IT investments prior to implementation [4], also specifically for an E-Government context [45]. Besides financial and operational indicators, these often include qualitative aspects such as benefits and risks [5], [19], [25], [45]. However, more recently authors also emphasize that the success of an evaluation (i.e., whether the expected benefits have been appropriately estimated) is not solely dependent on the appraisal method. These authors demand to view the investment decision as a staged process that primarily targets at aligning the interests of involved stakeholder groups [26], [57]. In this context, a *benefit case* refers to a high-level appraisal at the earliest stage of a project to justify the commencement before a detailed business case can be conducted [56].

During the appraisal process, stakeholders face different information requirements (e.g., for quantifying relevant benefits), knowledge requirements (e.g., in understanding the appraisal technique) and organizational problems (e.g., a lack of time and interest) [5]. For this reason we find rather simple methods among the most common methods for evaluating risks and uncertainty, such as brain storming and scenario planning, while simulation and other sophisticated techniques rank on the lower places [5]. However, these simple appraisal methods are often not able to sufficiently capture the complexity of a target domain, such as dynamic and mutually dependent behavior of variables [19]. Especially regarding the benefits of external M-Government services, where many variables of adoption lie outside the scope of the organization and only limited prior knowledge is available, there is high uncertainty in the investment evaluation. Therefore the use of an appropriate appraisal technique, that is both comprehensible to stakeholders and still able to capture the variable behavior of the target domain, appears to be of even greater importance.

System Dynamics (SD) is a method developed by Forrester and his colleagues [20], originally employed for explaining managerial and industrial problems. It essentially combines a notation for modeling complex systems with a mathematical representation to simulate a model behavior discretely over time. The main components of a model are level and rate variables, as well as inputs (i.e., constants, parameters or lookups) and auxiliaries. Mathematically, a model corresponds to a set of coupled first-order differential equations. The main feature of a dynamic system is presented by loops between variables, leading to reinforcing or balancing feedback behavior. In this sense, SD has the advantage to make complex systems comprehensible by disaggregating them into chains of cause-effect relationships and thus facilitates the solution of intricate decision problems. Prior authors have argued that this can be particularly helpful to improve communication in public decision making [54]. A summary of the basic SD syntax is presented in Figure 2.

**Notation**




**Formal** $Level = \int_{t_0}^{t} \left[ rate_1(t) - rate_2(t) \right] dt + Level(t_0)$ $auxiliary(t) = f(i_1(t),...,i_n(t))$

**Script** `Level = INTEG(rate1-rate2, L_t0)` `auxiliary = ...`

Figure 2: System Dynamics syntax and equations.

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Despite its origin in the field of management, SD has been used for a wide range of hard and soft modeling problems in physics, biology, psychology and other domains. SD has also been employed in strategic project management contexts to evaluate investment decisions and project benefits [35]. In the field of Information Systems, for example, SD has been used to evaluate investments into IT security and the effect on the number of attacks [9] as well as to model the benefit realization in the adoption of enterprise resource planning systems [22]. Therefore we contend that SD is also a useful method to evaluate the diffusion and municipal impacts of participatory urban sensing. In our work, we use a SD simulation in a real case from this problem domain and thereby obtain further insights on its practical applicability.

# 3 Research Method

Our approach for developing and validating the proposed simulation model took place in three main stages and has been oriented in an action design research methodology.

## 3.1 Methodological Perspective

Design research primarily seeks to address practical needs in a generalizable way through creating new and innovative artifacts [23]. Artifacts in this sense have been classified as constructs, models, methods and instantiations [39]. Our simulation model can be regarded as an artifact of the type *model* inasmuch as it aims to “aid problem and solution understanding” and the “exploration of the effects of design decisions and changes in the real world” in the domain of external M-Government services [23]. However, design research assumes that building and evaluating an artifact follows a clearly sequenced approach and thus implicitly separates the design process from its organizational application [53].

Our case organization has been studied and accompanied for a period of over 1.5 years, counting from the first impulses for implementing a mobile reporting service until its rollout and incremental use by the citizens. For this reason, the development process was inevitably characterized by several iterations as well as interventions of the researchers, which have potentially influenced both the design of the artifact as well as the design and implementation of the mobile reporting service itself [6]. Action design research (ADR) approaches have emerged as an alternative methodological lens that explicitly accounts for the iterativeness in the design process as well as the interventions by the researchers. More than that, ADR has been positioned as a design approach that can reflect the “theoretical precursors and intent of the researchers, but also the influence of users and ongoing use in context” [53].

Depending on the source of innovation in the designed artifact, ADR differentiates between organization-dominant and IT-dominant research approaches [53]. Since the primary focus of the presented simulation models is on facilitating organizational decision-making (and not on developing the reporting service itself), our research can be clearly classified as an *organization-dominant* approach. ADR posits that the methodological approach should comply with several principles in order to ensure that artifacts are both practically relevant and theoretically rigorous. These principles relate to: (1) inspiration through practice, (2) ingraining through theory, (3) reciprocal shaping, (4) mutually influential roles, (5) concurrent evaluation, (6) guided emergence, and (7) generalized outcomes [53]. Therefore at its core, ADR foresees an interwoven design process of building, intervention and evaluation (BIE) activities.

## 3.2 Research Stages

Although the process for designing and evaluating the proposed decision model was potentially not as highly interwoven as ADR would posit, it was clearly characterized by three distinguishable BIE cycles. These stages and evaluation cycles are depicted in Figure 4. We will use a chronological order to describe the major activities, outcomes and the interactions between researchers and practitioners (i.e., the *ADR team*, [53]) in each phase.

The contact to the City of Saarbrücken (south-western Germany) originated from prior research on M-Government adoption. The municipality (represented by the Head of IT Coordination) had expressed a major interest in evaluating the benefits of external E-Government services. In a fist interaction regarding this research in late 2010, the Head of IT Coordination stated that lack of cross-functional thinking and uncertainty regarding the potential benefits were some of the reasons why this topic had been given little attention in the past (problem formulation). The researchers developed a first version of the presented simulation model (*raw model*). In addition they prepared a catalog of questions to acquire more information (e.g., internal instructions and documentation) and to determine the first set of parameter values (e.g., for those related to street inspectors). The validation interviews with the Head of IT Coordination and the Chief of the Department for Street Maintenance took place in February 2011.

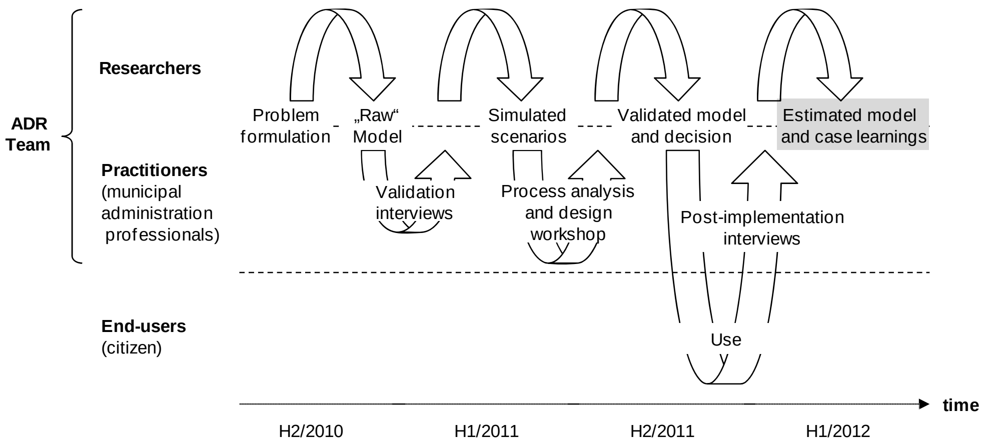


Figure 3: Build, evaluation, intervention cycles (adapted from [53])

The raw model was refined in a second iteration. The researchers conducted a survey and extensively drew on secondary data to make additional parameter estimations (especially for variables related to adoption and diffusion). Different scenarios were simulated based on the given assumptions. In May 2011, the ADR team organized a workshop that embraced a total of seven stakeholders from different departments and entities (IT Coordination, Street Maintenance, Public Relations, Office for Data Privacy, Internal IT department, Regional Association of Communal IT Providers) which allowed for a broad assessment of related benefits and concerns. The goals of the workshop were (a) to validate the model through a detailed process analysis and determine missing data (especially the costs for processing reports) and (b) to present results of the model scenarios and using them as quantitative basis for discussing solution design options.

(a) Process modeling can be regarded as a valuable validation method as it enables a common understanding of a domain of interest [3]. Compared to the SD model, where flows are aggregated to continuous variables, process models provide a more detailed representation of a process by assuming a discrete task and event logic [40]. The validation facilitated the researchers with a structured method to acquire the missing information from practitioners and their perceptions about the relevant activities. Furthermore, practitioners themselves, who pertain to diverse departments, got to a comprehensive understanding of the entire process which may likewise have improved their ability to understand the domain of interest, in our case the defect management procedures. (b) Two model scenarios (optimistic and pessimistic) were presented to the workshop participants and enabled a discussion on further qualitative aspects and design options for a mobile reporting service. For instance, the simulation supported the reasoning about appropriate means for handling the anticipated amount of citizen reports. Comprehensive workshop documentation was subsequently provided to the participants.

As a consequence of this joint workshop, the municipality (in responsibility of the Head of Public Relations) decided to include a mobile reporting service in a planned mobile offering, which was originally intended to incorporate merely non-transactional services (i.e., no urban sensing or similar functionality). Application development and server operation was organized through a public-private partnership between the municipality and a local information portal operator. In September 2011, the city launched the first version of the city's official mobile application for one popular mobile platform (see Site 7). The application includes an event calendar, city walks, information on the zoo, as well as a mobile reporting service called *Mängelreporter* (defect reporter). Application downloads as well as incoming reports from citizens grew steadily.

After about half a year of operation, the researchers conducted post-implementation interviews with the Heads of IT Coordination, Street Maintenance and Public Relations to evaluate the first learnings and obtain detailed usage statistics. Worth noting, in April 2012 the Saarbrücken mobile application has been awarded the prize as *best municipal app* in a national competition at a major IT trade show, which was according to the Head of Public Relations also due to the Mängelreporter. The Head of IT Coordination emphasizes that *the initiative from researchers in the area of urban sensing was crucial for the decision of whether or not to integrate a mobile reporting service into this offering*.

# 4 Simulation Model

The simulation model used in this research consists of four parts: (1) a diffusion model for the adoption of a mobile reporting service among a city's inhabitants, (2) a deterioration model that simulates the occurrence of new infrastructure issues, (3) a reporting model that estimates the number of reported issues, and (4) a cost model. We will describe each of these submodels separately by highlighting the required inputs, the underlying assumptions, and the characteristic functional relationships. The modeling and simulation was performed with Vensim PLE software. An overview of the entire model is provided in Figure 4.

## 4.1 Diffusion Model

The diffusion model estimates the number of adopters of a mobile reporting service in the municipality of interest. One of the most famous approaches for predicting adoption is the model introduced by Bass [7], who extended innovation diffusion theory by Rogers [48] by a mathematical representation. The Bass model is based on the behavioral assumption that the probability for a new product being adopted in period $t$ is a linear function to the number of previous adopters $A_{t-1}$.

$$P(a_t) = p + q\frac{A_{t-1}}{M} \tag{1}$$

This probability is composed of two influences. The first is the influence represented by the rate of innovators $p$ who adopt a product independent from the number of previous adopters. The second is given by the rate of imitators $q$ whose adoption is dependent on the share of past adopters by the total market size $M$ (i.e., the relative past adoption). This share has also been interpreted as a probability of *contagion* or *word-of-mouth* from adopters to non-adopters. The Bass model has been transferred to a SD representation by Sterman [55] p. 332. This model accordingly contains a balancing loop that determines the rate of innovation, and a reinforcing loop which adds the imitators to this to obtain the number of *new adopters* per period ($a_t$)

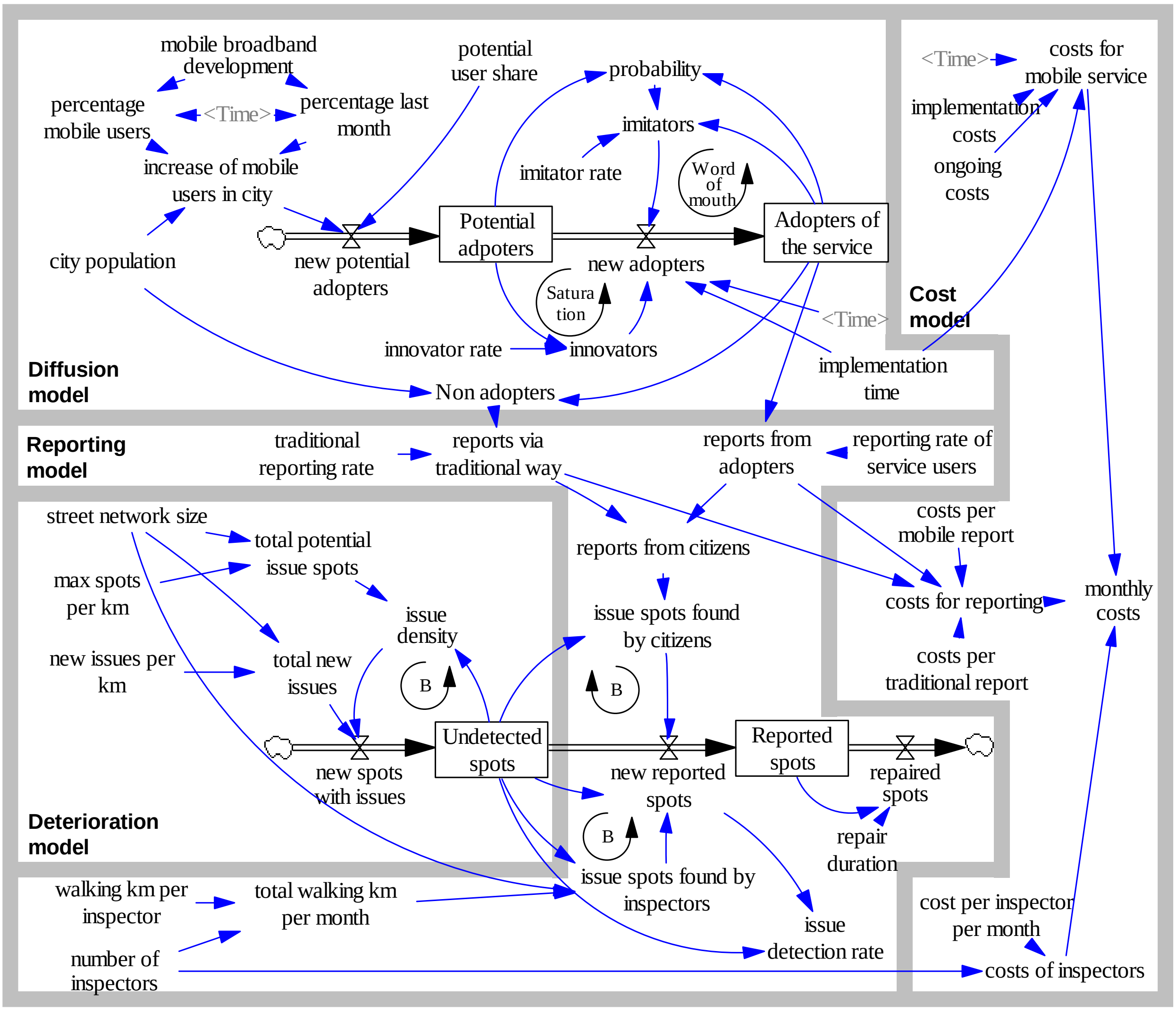


Figure 4: System Dynamics model

We embed the Bass model into our context of a mobile reporting service by defining the following input parameters:

- *City population*: the number of inhabitants of the city [citizen]
- *Mobile broadband development*: the share of users of 'smart' mobile devices on country-level [lookup]

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- *Potential user share*: the expected share of users who would install the mobile reporting application [dmnl]
- *Implementation time*: the time $t_i$ after $t_0$ when the mobile reporting service is released [months]
- *Innovators rate*: the share of potential adopters that would install the new application [1/month]
- *Imitators rate*: the pressure on potential adopters to imitate the adopters [1/month]

The level of *potential service adopters* at $t_0$ is initialized with the *percentage of mobile users* among the *city population,* multiplied with the *potential user share*. Obviously, only users of a smart device can potentially adopt the service and install a mobile reporting application on their device. The share of *new potential adopters* in a city is moderately increasing with the overall *mobile broadband development*. When the *implementation time* $t_i$ has been reached, the *innovators* among *potential adopters* incrementally become *new adopters*. Once the number of *adopters of the service* increases, the number of *imitators* increases and adds up to the *new adopters*. However, the *probability* for this word-of-mouth advertising decreases with the decreasing number of potential adopters. The equations of the diffusion model are listed in Appendix B.

## 4.2 Deterioration Model

The deterioration model simulates the occurrence of issues in the urban street infrastructure. The following inputs are required:

- *Street network size:* determines the total urban space where infrastructure issues occur [km]
- *Max spots per km:* limits and discretizes the potential spots where issues occur [spots/km]
- *New issues per km:* describes the constant occurrence of new issues on these spots; in other words the natural deterioration of urban infrastructure [issues/km/month]

This process assumes that a street kilometer is segmented into a number of spots (for example 1,000 spots with each 10 square meters of space, assuming that the average street width is 10 meters). Issues (e.g., potholes, waste, broken trees etc.) occur randomly within these spots. Since several *new issues* may fall on the same spot, the number of *new spots with issues* is less or equal than *total new issues*. (This also implies that spots can infinitely *get worse*.) Logically, the probability for such overlap increases the more spots already have problems, i.e. the higher the *issue density* is. Thus, overlapping issues still represent a single new spot with an issue, since it would still require a single report to the municipality. Before being reported, issue spots account up to the level of *undetected spots*. The equations of this submodel are given in Appendix B.

## 4.3 Reporting Model

The reporting model connects the deterioration model with the diffusion model. Municipalities typically employ dedicated workforce for inspecting urban infrastructure. The model calculates the number of reported issues based on the number of reports from these street inspectors, plus those from citizens that have adopted the mobile reporting service. The following inputs are required to parameterize this submodel:

- *Traditional reporting rate*: number of infrastructure issues reported via conventional means such as email and telephone [report/month]
- *Reporting rate of service users*: number of reports per adopter of the service [report/month]
- *Number of inspectors*: permanent workforce for inspecting streets [inspector]
- *Walking km per inspector*: the average length of the street network that an inspector controls per month [km/inspector/month]
- *Repair duration*: average duration for removing issues that have been detected [month]

The model assumes that *reports via traditional means* are issued by non-adopters whereas *reports from the adopters* replace traditional channels of communication. The total number of *reports from citizens,* as well as the level of *undetected spots,* are used to calculate the actual *issue spots found by citizens*. Similar to the issue generation model, reports from citizens are likely to overlap, e.g. if several citizens report the same spot with a pothole. In this case, the problem can be referred back to an occupancy problem, where citizens randomly distribute *x* balls (*x=number of reports*) on *N* urns (*N=number of undetected spots*). According to [21] p. 6, the expected value for the number of urns occupied with at least 1 ball ($U_x$*=issue spots found by citizens*) is given by

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$$E(U_x) = N \cdot \left[1 - \left(1 - \frac{1}{N}\right)^x\right] \tag{2}$$

At the same time, issues are detected by the city's street inspectors. Street inspectors accomplish a certain amount of *total walking km per month*. We assume that undetected issues are geographically equally distributed over the street network and that street inspectors find all the issues on their way, so that the share of *issue spots found by inspectors* on *undetected spots* is presented by the fraction of the total street network size covered. The effectively *new reported* spots ($s_{C\cup I}$) are given by the sum of spots reported by citizens ($s_C$) and by inspectors ($s_I$), subtracting the spots $s_{C\cap I}$ that overlap between the two sets. We assume that the citizens' reports are equally distributed over the street network. Therefore, the expected share of the overlapping spots $s_{C\cap I}$ by $s_I$ is equal to the share of $s_C$ by all undetected spots $s_U$. We can write

$$\frac{s_{C\cap I}}{s_I} = \frac{s_C}{s_U} \xrightarrow{in\ s_{C\cup I}} s_{C\cup I} = s_C + s_U - \frac{s_I \cdot s_C}{s_U} \tag{3}$$

This variable $s_{C\cup I}$ reduces the level of *undetected spots* and adds up to the level of *reported spots*. That is, citizens and street inspectors would not report these infrastructure issue anymore, as they have been logged and appear in the municipalities reporting system with an according status of processing. The *issue detection rate* can be regarded as a performance indicator for the overall effectiveness of this process. The further removal or repairing of an issue takes an average *repair duration* and takes place subsequent to issue reporting. The equations of the reporting model are given in Appendix B.

### 4.4 Cost Model

The cost model sums up the *monthly costs* related to infrastructure reporting, i.e. costs for the mobile reporting service, for the processing of reports and for street inspectors. For this purpose, a few input variables are required. The detailed equations employ simple arithmetic, see Appendix B.

- *Implementation costs*: the onetime costs for implementing the service in $t_i$, e.g. for application development or purchasing licenses [EUR]
- *Ongoing costs*: the running expenses of the mobile reporting service, e.g. for perpetual licenses or application maintenance [EUR/month]
- *Costs per traditional report*: average variable costs for reviewing, classifying and processing issues reported via phone or email [EUR/report]
- *Costs per mobile report*: average variable costs for reviewing, classifying and processing issues reported via the mobile service [EUR/report]
- *Costs per inspector per month*: total labor cost per street inspector [EUR/inspector/month]

## 5 Case Validation

We validated the correctness and usefulness of the simulation model (our artifact) in course of the different research stages and interventions at the case site of the City of Saarbrücken. This validation includes a detailed process analysis, a model instantiation with case data, the simulation of different scenarios, the assessment of further qualitative aspects and the estimation of model parameters. This section describes each of these steps.

### 5.1 Process Analysis

Process modeling was performed in a workshop with different municipal practitioners and stakeholders. The urban defect management process including defect identification, processing and removal was collaboratively discussed and incrementally drawn on a brown paper using process mapping methods [10]. For reasons of quick comprehension, we used a simple flow chart notation which was later documented by the commonly known business process modeling notation BPMN 2.0 (Site 8) and provided to the participants. This documentation consists of (a) an overview of the overall process and (b) detailed documentation of its sub-processes. For reasons of brevity, we will summarize the overall process and highlight two relevant subprocesses to explain, how implementing a mobile reporting service affects these processes.

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The overall complaint and defect management process in Saarbrücken is depicted in Figure 5. It starts either with a report from a street inspector or with a complaint from a citizen. Citizen complaints are directed to the Complaints Office via telephone, regular mail, email, a website form or—as a new medium—as a message from a mobile reporting service. The Complaints Office generally processes these issues and routes them to the department in charge (e.g., to public order, traffic authority, public utilities, or in the frequent case of infrastructure defects to the Head of Street Maintenance). The same applies to those defects regularly reported by the street inspectors, who are subordinate to the Office of Street Maintenance. Road workers responsible for repairing minor defects (e.g., potholes) are situated locally at the Saarbrücken districts. In some cases, district road workers are requested to perform an additional pre-inspection of an issue spot before (instantly or later) starting corrective maintenance (e.g., when size and condition of a pothole are unclear). In cases of larger defects, these are typically bundled and scheduled for a tender to external street construction firms (e.g., for asphalt coating of an entire street). Both repair works from the wards as well as those by external contractors are approved by the Head of Street Maintenance when completed. In case the repair was due to a complaint, usually a feedback to the citizen is provided.

Based on the process analysis, we find that the principal flow of the defect management activities is not affected by the existence (or non-existence) of a mobile reporting service. That is, the Complaints Office remains the main interface to the citizens so that the reporting service simply represents an additional communication channel. Nevertheless, the analysis reveals two main levers in the complaints and defect handling subprocesses where the choice of the medium may strongly affect throughput times, see Figure 5.

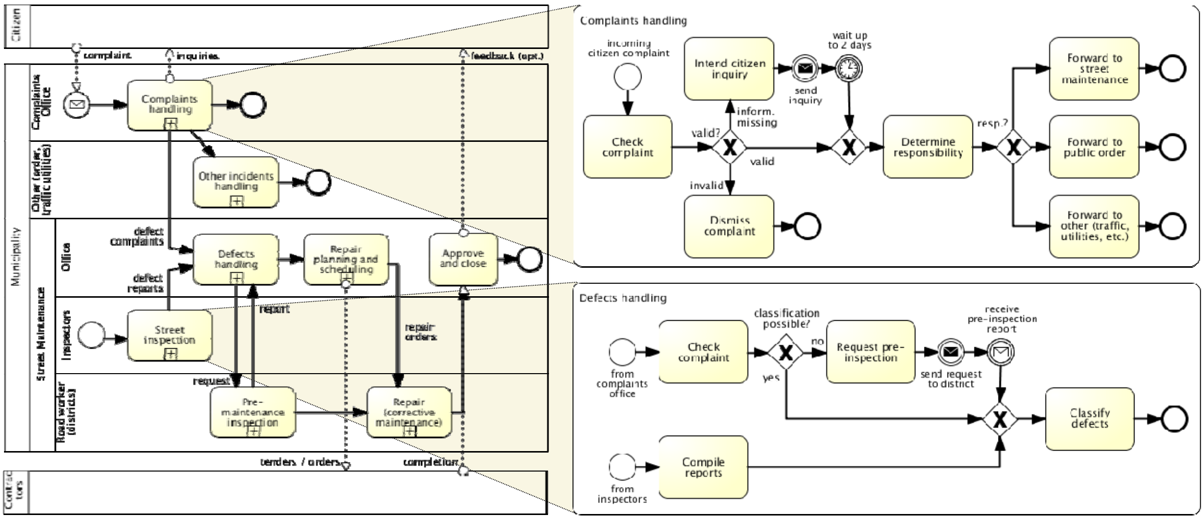


Figure 5: Complaint and defect management process and subprocesses

Regarding the complaints handling subprocess, the Head of Public Relations states that many incoming messages are invalid or do not provide sufficient level of information (e.g., regarding the recise location of a defect). Such messages cause additional time and effort for inquiring the missing details with the citizen (if possible) instead of being instantly forwarded to the department in charge. (This is considered later as *costs per mobile report* for the model instantiation in Section 5.3). Arguably, with the use of a mobile reporting service, which includes on-the-spot location coordinates and possible photos, the need for further inquiries and hence processing times can be reduced.

A similar effect is expected for defects handling. The Head of Street Maintenance states that defects reported by citizens are usually no support for their work at all, since they caused more effort for sending road workers and performing pre-inspections than they actually save in preventing damages. Even in some cases, the pre-inspectors are unable to locate the reported spot so that additional feedback loops with the Head Office and citizens are required. This would certainly change if the report featured precise location coordinates and a photo, as the interviewee affirms.

Altogether the process analysis indicate (a) that the assumptions made in the presented system dynamics model match the concrete process instance at the Saarbrücken municipality, and (b) that there are certain levers associated with the use of a mobile reporting service that would facilitate the process flow and reduce processing times.

## 5.2 Model Instantiation

Based on the case analysis, the simulation model has been instantiated with values of the Saarbrücken municipality, survey data and information from further data sources. We use the submodel logic to explain the parameters used and how they have been estimated. Regarding the diffusion model, we retrieved the percentages of the *mobile*

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*broadband development* in Germany from the annual report of the International Telecommunication Union [28]. These figures have been extrapolated by a time dependent lookup function from the years 2011 to 2016 in the system dynamics model, growing from 35% to 68% of the population. (Arguably, there would be a good argument to simulate this growth as a Bass model as well; however, we opted for a static function due to the good availability of past information on this variable).

The values for *innovator rate p* and *imitator rate q* determine the speed of adopting the mobile reporting service (i.e., the slope and skewness of the new adopters curve). Higher values generally signify that a product is more 'contagious' and $q$ is generally greater than $p$ (usually for a factor greater than ten, [37] p. 82). We reviewed several diffusion studies of technology products, for example, on mobile phones in Spain [14], and on an automatic telephone enrollment service at a New Zealand university [63]. Plausibly, the closed user group of an enrollment service exhibits a much faster adoption compared to the macroeconomic diffusion of mobile phones, which explains why the $p$, $q$-parameter estimates of both studies are similar despite being measured on different time scales (annual versus fortnightly). (Note that normally innovation diffusion parameters behave approximately proportional to the measurement scale, e.g. annual parameters are about twelve times the monthly parameter estimates [46]). We assume that a mobile reporting service on urban level ranks between those two cases and choose (monthly) parameters for our model which are slightly less than half of the fortnightly parameter estimates of the New Zealand example ($p$=0.02, $q$=0.2). While we acknowledge that these are rough estimations, we consider them as sufficient for the purpose of scenario simulation since they only influence the speed, but not the overall level of adoption and incoming reports. *Implementation time is* set to 5 months for illustrative purposes (which equals the time from the workshop to the implementation in the case example).

The most influential variables of the diffusion model, however, are the *potential share* and the estimated *reporting rate of service users* since they determine the total amount of reports that the municipality expects to receive from citizens. Ex-ante, these variables are hard to determine and therefore subject to uncertainty. Nevertheless, we draw on technology adoption theory [16] and assess the *intended* reporting rates as a proxy. For this purpose, we conducted a survey with potential service users across all age groups and professions. The survey was administered online and distributed via email across the personal networks of the authors. It contained an introduction to the topic and, amongst other items, a question on each of these parameters of diffusion. We effectively received n=213 usable responses, 48% from male and 52% from female respondents. Regarding occupation, 28% stated to be students, 37% working, 10% retired, and 11% others. The distribution of the considered survey variables are depicted in Figure 6.

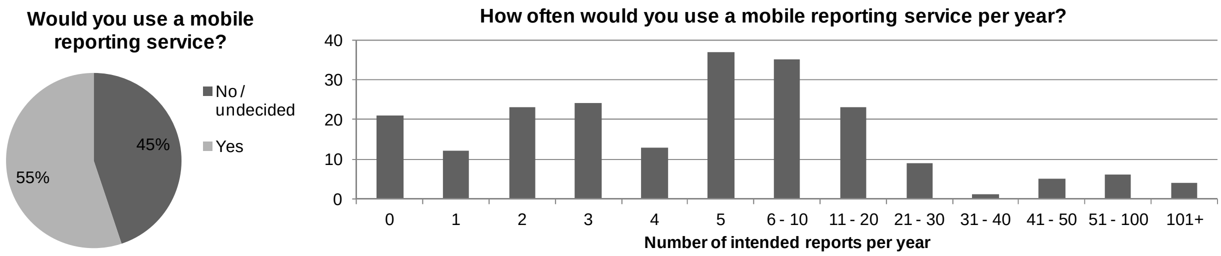


Figure 6: Survey results

According to the survey, 55% of mobile phone users would use a reporting service. The median (and also the mode) of intended reports per year is 5. We view these unexpectedly positive results with caution. While intended and actual technology adoption are clearly related (with typical correlation values in the range of 0.20 - 0.30, [16]), the literature provides numerous influences that moderate and distort this relationship. Such influences may result from (1) factors that affect the accurate expression of current intentions and (2) factors that affect the accurate prediction how these intentions will change over time [42]. Regarding the former, one bias in our setting may a particularly result from the survey setting and the respondents' tendency to give socially desirable answers [47]. For example, studies in the field of health behavior found that people translated their 'good' intention into action in about 50%, i.e. half of the cases [52]. However, while the literature demonstrates a significant correlation between intention and use, concrete 'rules of thumb' how to translate intended into expected usage frequencies are widely absent. To account for this uncertainty, we assume two scenarios: an *optimistic scenario* with a 22.5% (half of the stated 55%) potential user share and 2.5 (half of the mean 5) reports per user per year in line with the survey data and the references from behavioral studies, as well as a *pessimistic scenario* with a 5% potential user share and an average 1 report per user per year. For comparison, the average *traditional reporting rate* in the city Saarbrücken with 180,000 inhabitants is 15 reports per month.

Regarding the deterioration model, internal documentation informed that the *street network size* of Saarbrücken amounts to 665 km. We discretize a street km into 1,000 *max spots per km*. Streets are classified by priorities according to the intervals in which they need to be checked in order to comply with the city's due diligence. We learned that the city employs a *number of 6 inspectors* in the Department of Street Maintenance to do this job fulltime. We calculate that per month, each of the inspectors controls an average 40 km of the overall network. On his route,

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an inspector encounters in average 8 issues per km; that is, if streets were checked monthly, this occurrence would account for approximately 3 *new issues per km* per month.

Finally, we instantiate the cost model. In our case setting, a municipal inspector incurs about 50,000 Euro of total labor cost per year. Costs per report can then be calculated as differential process costs [17]. That is, we account only for the times for handling and processing citizen reports from receipt to repair (excluding material cost and overhead). Based on the process analysis, the workshop participants estimate that a defect report via traditional channels takes an average 20 min and a mobile report 10 min (due to less citizen inquiries) for classifying and routing within the municipal administration. Additionally, traditional reports are more likely to cause pre-inspections. The average (conservatively) estimated surplus for pre-inspections is 10 min (i.e., about 2 hours for one out of twelve defects). For demonstrative purposes, *implementation costs* are set to 10,000 EUR. The input variables and their values are summarized in Table 1.

Table 1: Model parameters

| **Submodel** | **Parameter** | **Value** | | **Unit**[1] | **Source**[2] |
|---|---|---|---|---|---|
| | | Optimistic | Pessimistic | | |
| Diffusion model | city population | 180,000 | | Citizen | Case |
| | mobile broadband dev. | 35% (2011) - 68% (2016) | | Dmnl | [28] |
| | implementation time | 5 | | Month | Assumption |
| | potential user share | 0.225 | 0.05 | Dmnl | Survey, [52] |
| | innovators rate (p) | 0.02 | | 1/month | [37], [46], [63] |
| | imitators rate (q) | 0.2 | | 1/month | [37], [46], [63] |
| Deterioration model | street network size | 665 | | Km | Case |
| | max spots per km | 1000 | | Spots/km | Assumption |
| | new issues per km | 3 | | Problem/km/month | Case |
| Reporting model | traditional reporting rate | 15/180,000 | | Reports/citizen/month | Case |
| | reporting rate of users | 2.5/12 | 1/12 | Reports/citizen/month | Survey, [52] |
| | number of inspectors | 6 | | Inspector | Case |
| | walking km per inspector | 40 | | Km/inspector/month | Case |
| | repair duration | 2 | | Month | Assumption |
| Cost model | implementation costs | 10,000 | | EUR | Assumption |
| | ongoing costs | 100 | | EUR/month | Assumption |
| | costs per mobile report | 1.68 | | EUR/report | Case |
| | costs per traditional report | 4.91 | | EUR/report | Case |
| | costs per inspector | 50,000/12 | | EUR/month | Case |

[1] Dmnl = dimensionless; [2] Simulation results are invariant to variables for which assumptions have been made

## 5.3 Scenario Simulation

We instantiate and simulate the model according to the two different scenarios (optimistic and pessimistic scenario) and compare these with a baseline scenario, i.e. the case if no mobile reporting service was implemented at *t*=5. For an additional comparison, we run a pessimistic scenario where one inspector less is employed by the municipality (i.e., *number of inspectors* = 5). Four selected variables from the model are depicted in Figure 7.

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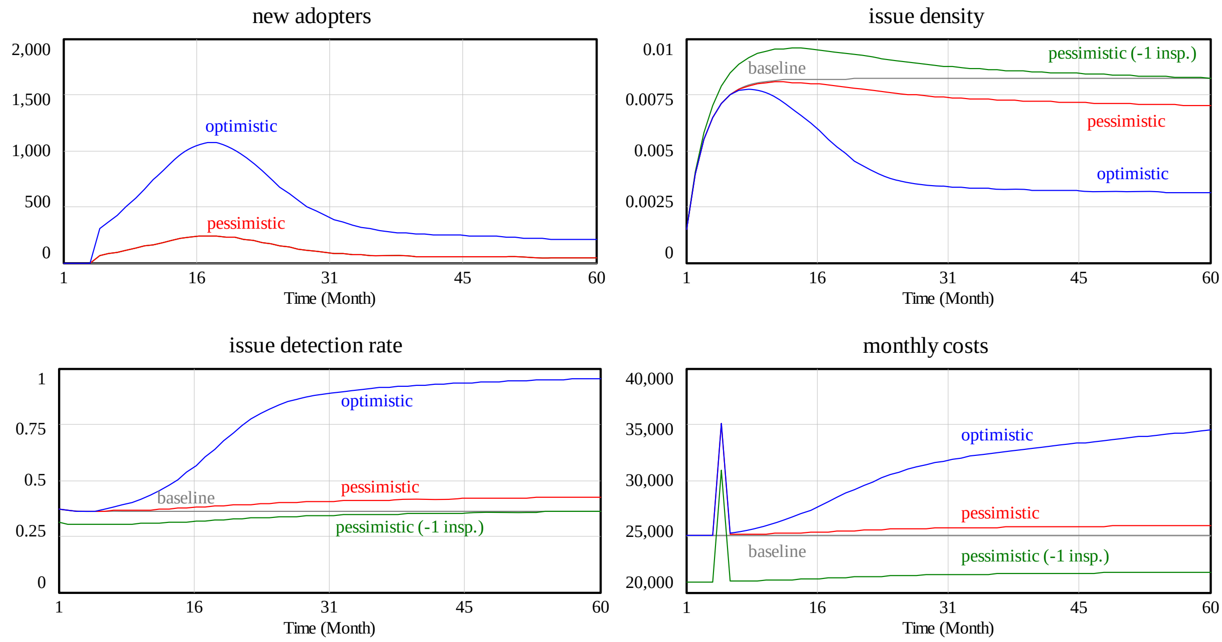


Figure 7: Simulation results (selected variables)

Regarding the diffusion model, the results show that the number of *new adopters* describes the typical bell-curved shape postulated by innovation diffusion theory [48]. In month 17, i.e. 12 months after the service is taken in use, the curve peaks at 1072 new adopters for the optimistic, and 238 for the pessimistic scenario. The curve is notably skewed whereas its long tail is superimposed by the overall *mobile broadband development* and an ongoing increase in new mobile phone users.

In terms of deterioration, it is obvious that the model first needs to get into equilibrium, since we start with a city free from defects (0 *undetected spots* in $t_0$). As we can see from the baseline scenario, this equilibrium is at an *issue density* of 0.82% within the urban space. However, in the optimistic scenario, this measure for the deterioration goes down after the adoption due on the large number of reports that the municipality receives and converges to 0.03%. This is also reflected in the percentage of issues that are detected. In the optimistic scenario, the *detection rate* increases to about 96% (in $t$=60). That means that practically every uprising issue would be immediately reported by the collective monitoring of the citizens. In the pessimistic scenario, the detection rate climbs up from 36.3% in the baseline scenario to about 42.3% in $t$=60, reducing the *issue density* to 0.7%.

With regard to process costs, we note that in the pessimistic scenario, after month 5 (and the initial investment peak for service implementation), *monthly costs* increase by +3.4% compared to baseline scenario (25,934 vs. 25,073 EUR/month until $t$=60) due to the increased efforts for processing reports from citizen. However, if we reduce fix cost by setting the *number of inspectors* to 5, then monthly costs are even below baseline by -12.9% (21,823 EUR/month). This is remarkable in view of the fact that the *issue detection rate* in this scenario almost equals the baseline level (36.2% in $t$=60). In other words, the results indicate that participatory sensing can provide a comparable level of information about the urban infrastructure at lower cost than single street inspectors, given there is a moderate participation by the citizens.

However, the chart on *monthly costs* also reveals one of the major risks of implementing such service: If the level of citizen participation exceeds the expectations, such as in the optimistic scenario, high costs and efforts accrue for processing the citizen reports without achieving any additional benefit in issue detection. Both scenarios have been presented and discussed with the stakeholders in the Saarbrücken case.

## 5.4 Qualitative Analysis

The presentation of the simulation results, besides providing indicative evidence of the potential benefits and risks, also fostered the discussion on further qualitative aspects connected to the implementation of a mobile reporting service. These aspects related to both expected benefits and potential concerns from which we can derive (functional and non-functional) design requirements that need to be addressed during a system implementation [36]. For example, the quantification of expected adopters and incoming messages helped to balance between privacy requirements and performance goals when deciding on the question of whether citizens would need to enter personal data with every report or not. Qualitative aspects can be broadly classified into four categories: user, process and organization, privacy and legal, as well as technical aspects. We will briefly summarize each of these points, see Table 2.

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Table 2: Qualitative aspects of introducing mobile reporting

| User aspects | Process and organization aspects | Privacy and legal aspects | Technical aspects |
|---|---|---|---|
| • Easy interaction<br>• Issue tracking<br>• Improved communication<br>• Exceeded expectations<br>• Increased satisfaction | • Increased report quality<br>• Reduced throughput times<br>• Accident prevention<br>• Analytics<br>• Routing across municipalities | • Needed citizen data<br>• Defined terms of use<br>• Deletion after closing<br>• Transparency issue<br>• Photo third party rights<br>• Liability in imminent danger | • Message filtering<br>• Broadband coverage<br>• Less media disruptions<br>• Integration with ticketing system |

Workshop participants stressed the importance that the client application of a mobile reporting service should possess high usability and enable easy interaction to outmatch traditional channels of communication. An additional feature refers to the tracking of reported issues, i.e. the mobile reporting service could communicate the status of issue processing and communicate this to the citizens. However, this may also raise the citizens' expectation that issues are taken care of at a faster pace (which can not necessarily be guaranteed). Therefore the issue status should only be presented to the sender. Altogether it was found that a mobile reporting service can improve the communication between the citizen and municipal administration (i.e., to make it more efficient and more effective), which is ultimately also expected to have a positive effect on citizen satisfaction.

Regarding process and organization, the process analysis revealed that due to the standardized form of a mobile report (including location coordinates and potential photos) the quality of citizens' reports is expected to increase. This can have positive effects on throughput times for complaint and defect handling, since additional loops for inquiries to the citizen and for visiting the issue spots are avoided. Furthermore, some workshop participants argued that a mobile reporting service could particularly help to detect hazardous spots faster and thus to prevent from traffic accidents in the urban area. In a more long-term view, the sensing data from citizens could also be used to perform analytics and thus gain additional knowledge on problem areas and general trends. A concern was raised regarding the need for routing reports to other municipalities in case citizens use the service out of other municipal districts.

Several privacy-related and legal aspects need to be considered when implementing a mobile reporting service. First, the data needed from citizens (e.g., for doing inquiries and giving feedback) was a subject to discussion. However, there was a consensus that data needs (especially for the location) should be stated clearly in the terms of use of the service and deleted after closing of a case. Publishing open issues (including photos) on the client application or a website and thus creating full transparency was viewed rather critically not only for raising false citizen expectations but also to avoid abuse and protect the rights of potential third parties (e.g., passers-by pictured on a photo). Finally, dealing with urgent issues and the liability in imminent danger (e.g., due to a missing street drain cover) was perceived as a concern inasmuch as in these cases the administration would still prefer to receive a phone call.

One important technical aspect refers to implementing appropriate mechanism for filtering redundant or invalid reports in order to prevent from information overflow (as shown in the simulation of the optimistic scenario). Further concerns relate to a lack of broadband coverage in rural areas as well as indoors (e.g., in subways). Regarding internal process flow and the support through IT systems, it was argued that a mobile reporting service would help to overcome media disruptions at the start process (e.g., compared to phone and email). This could be achieved through implementing an entire workflow management system which is integrated with the ticketing system used in the complaints office. Altogether the discussion unfolds a broad set of aspects that are correlated with the implementation of a mobile reporting service and thus need to be considered for the design of such service.

## 5.5 Empirical Estimation and Case Learnings

As a direct consequence of the design workshop, the Saarbrücken mobile application *Saarbrücken app* (including the mobile reporting service) has been implemented and released in mid September 2011. Seven months later, we conducted post-implementation interviews to inquire the major learnings from this project and to obtain first usage figures. The rate of new adopters can be expressed by the monthly number of users who download the Saarbrücken mobile application from the platform provider (i.e., from the 'app store') and install it on their mobile device. The number of incoming reports via this new medium is logged in the municipal Complaints Office, see Figure 8. We use these figures to estimate the actual parameters of diffusion and compare them to our previous model assumptions.

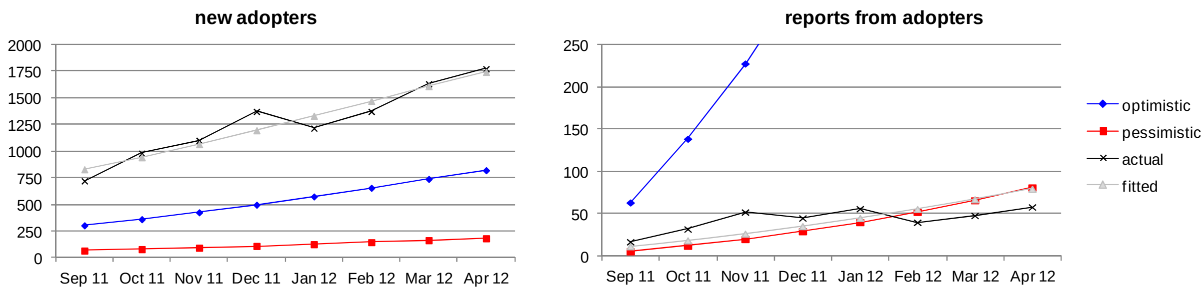


Figure 8: Estimated and actual adoption curves

The *innovator*, *imitator rates* as well as the number of *potential adopters* (i.e., parameters *p*, *q* and *M* of the Bass model) can be estimated by performing a quadratic regression of the number of *new adopters* on the number of cumulated adopters in $t_{n-1}$ [7] p. 219. As *fitted* model parameters we obtain *p*=0.019, *q*=0.156 and *M*=42,833 ($R^2$=99%). The number of *potential adopters* also allows us to derive an estimate for the *potential user share*, which would be around 63% according to the fitted model (calculating with 68,400 users of a smart phone in Saarbrücken at $t_i$ [28]).

The actual and fitted curves of new adopters are depicted in Figure 8. As we note, the actual adoption rates are clearly above the simulated scenarios, just as the calculated *potential user share*. We attribute this to the fact that the Saarbrücken app is as well downloaded for a number of other purposes than mobile reporting and potentially also by other people than local citizens, e.g. tourists. In our last interview, the Head of IT Coordination tells that the most popular part of the application is actually the information page on local movie show times. However, the actual adoption would potentially be even higher if the application had been made available for several mobile platforms. According to our interviewee, many citizens criticized that the application developed for a single operating system discriminates other potential users—a fact that he now considers a major weakness to be addressed in the near future.

In contrast to the application downloads, the incoming reports from citizens are at the lower end of the expected range. A linear regression of the cumulated adopters on the incoming reports shows that the empirical *reporting rate of service users* is 0.0066, i.e. much below the expected rate (presumably due to the high number of downloads not related to mobile reporting). Using this average reporting rate allows us to also define a fitted reporting curve, which approximately coincides with the number of reports in the pessimistic scenario, see Figure 8.

Although this short time series regression only allows for a first estimation [13], this indicates that the benefits outlined for the 'pessimistic' scenario actually appear quite *realistic*. In our follow-up interview, the Head of the Complaints office emphasizes that about 90% of incoming mobile reports are valid and usable. Concerns related to application abuse could be largely dispelled since the municipality decided to request senders to authenticate themselves with a name and phone number (analogously to traditional phone and email complaints). The Head of Street Maintenance affirms that the existence of a photo in citizens' reports facilitates their work, although their main source of information for urban street maintenance (i.e., the work of the street inspectors) remains unchanged.

# 6 Conclusion

In this work we provided insights on the benefits that urban sensing entails for local governments to simultaneously foster citizen participation *and* improve urban service delivery. We chose the example of a mobile reporting service and developed a simulation model that connects the adoption and diffusion of such sensing application with urban deterioration, municipality-internal defect processing and cost-related variables. The model has been validated based on a case study of a large German municipal administration over 1.5 years. The evaluation produced a detailed process analysis, a model instantiation, a simulation of different scenarios, a discussion of further implementation-related aspects, and post-implementation learnings as well as an estimation of the 'real' model parameters.

The results of this research are multifaceted. The detailed process analysis shows that the proposed quantitative simulation model generally fits to the activities and responsibilities in urban complaints and defects management. Thus the model captures the main characteristics of a real-world case well. Furthermore, it reveals that two potential levers of process improvement, namely reduced loops for citizen inquiries and fewer pre-inspections, can arise from the increased information capabilities (i.e., photo and location data) of mobile reports. In course of the model instantiation, we provide reasonable parameters for the proposed simulation model and demonstrate how it can be customized to the context of a specific case municipality. The subsequent simulation of different scenarios suggests that the use of mobile reporting can have substantial benefits in terms of available information (here: detected infrastructure issues) and does not necessarily lead to greater cost compared to internal defect reporting procedures.

Nevertheless, the main purpose of the proposed simulation model is not to provide an argument for introducing urban sensing services based on purely economic considerations—and neither it was the motivation in the given case. Conceptualized as an organization-dominant artifact [53], the major strength of this model is to facilitate a comprehensive understanding of the benefits and concerns at the intersecting domain of external M-Government services, which can help to improve communication and foster decision-making in various E-Government implementation contexts. We demonstrated this strength by summarizing the key qualitative aspects that emerged from the discussion with municipal stakeholders and ultimately led to an implementation of the mobile reporting service. These qualitative aspects related to user, processes and organization, privacy and legal, as well as technical categories. Finally, our post-implementation evaluation indicates that the scenario parameters are within the bounds of possibility. Based on the case learnings we provided insights on why these observed deviations occur.

## 6.1 Methodological Evaluation

This research was oriented in an action design research (ADR) paradigm. In the following we use the seven principles proposed by Sein et al. [53] to evaluate our approach methodologically: (1) Our research has been *inspired through practice* inasmuch as the idea to develop a simulation model was motivated by prior studies indicating that municipalities place less emphasis on *external* M-Government services [61] and by the municipality's interest in evaluating these opportunities. (2) The proposed artifact is especially *ingrained through theory* by drawing on innovation diffusion theory [48] and—in quantitative terms—on the Bass model for new product adoption [7].

(3) *Reciprocal shaping* took place in three major cycles (validation interviews, process analysis and design workshop, post-implementation interviews) which allowed us to flesh out the details of the model and determine its underlying parameters. Conversely, the quantitative simulation results allowed municipal stakeholders to reason about design requirements for example for handling the anticipated amount of citizen reports. This way, prior uncertainties and a lack of cross-functional thinking (see problem statement) have been addressed effectively. (4) During the design cycles, we observed several *influences* and effects of *mutual learning* among the project participants, not limited to the insights between researchers and practitioners. For example, after our workshop all participants confirmed that the conducted process analysis has provided them with greater understanding about the different ends of the overall complaints and defects management process. (5) Although we present the core artifact and its validation in separate sections, the development and evaluation took place in a largely *authentic and concurrent* manner. This may appear evident as with any new parameter assumption we could instantly test how this change would affect the overall model behavior.

Finally, (6) *guided emergence* denotes that the created artifact reflects not only the preliminary design created by the researchers (i.e., in our case the model itself) but also its shaping by the use in an organization [53]. We believe that this principle expresses the core finding of this research, in which the use of the model has first led to a broader discussion of implementation-related issues and then ultimately guided organizational decision-making. (7) We provide more *generalized outcomes* as a contribution of this research in the following section.

## 6.2 Contribution

In its nature as a design-oriented approach, the main contribution of this research is represented by the generated artifact, i.e. the simulation model for urban sensing adoption and benefits. Although we instantiated and evaluated this model in a specific case example (Saarbrücken), we argue that this model and our approach can be useful on different levels of problem classes. The narrowest of these classes is certainly the decision on implementing a similar mobile reporting service in a different municipal context. Besides numerous qualitative considerations, we presented a validated model and provided reasonable parameter estimations, so that government practitioners can simply adjust the specific case variables in order to obtain realistic and usable results for their respective city.

However, we put forward that our model and the demonstrated approach are also applicable in a much wider class of problems related to external E-Government services and organizational decision-making. That is, our model might as well be used to estimate the use and impact of other urban sensing applications, such as environmental impact assessment [43], air quality monitoring [4], traffic mitigation [24], and noise control [38]. As we motivated at the outset, many public agencies today struggle with introducing innovative M-Government services and opening this new channel of interaction to their customers (i.e., the citizens) partly due to their inability to moderate the internal decision process [61]. The principal logic of the model (stating that citizen information adds up to the level of organization-internal information and accounting for overlapping information) is likely to remain unchanged across different urban sensing scenarios. Therefore, this model can provide a valuable starting point to assess the potential impact of urban sensing in various emerging application scenarios.

Finally, our findings also contribute to the broader literature on investment appraisal and decision-making (e.g., [4], [19], [25], [26], [45], [54], [57]). Our case specifically illustrates how different types of models (more precisely, a conceptual SD model, a detailed process model, and a simulated SD model) can support organizational decision processes at different stages. Our case findings suggests that the *soft* modeling approaches (such as the SD notation and the process model) facilitate a mutual understanding of the problem domain among the stakeholders, while the 'hard' modeling approaches (such as the mathematical SD simulation) can be used to demonstrate different scenarios and thus (intentionally) enable a discussion on appropriate design requirements. In this sense, this research reconfirms the strengths of system dynamics as a valuable method to address both hard and soft modeling problems in organizational decision-making, especially in a public sector context [54].

### 6.3 Limitations and Future Research

Limitations of this study are primarily related to the content of the proposed model, the estimated parameters as well as the selection of a single case site. Since any modeling approach inherently represents a simplification of reality, one may find further potentially relevant variables that did not enter into our model. Also, the time period considered for the empirical estimation of the model parameters (especially for *p, q,* and *M*) limits the accuracy of the prognosis on the expected adoption and market sizes. However, as the focus of the proposed SD model was on demonstrating the interrelationships and dependencies of the presented variables, rather than delivering econometric parameter estimations, we consider the parameters as a sufficient approximation for the purpose of scenario simulation in our case of a decision-making context. As more empirical data accumulates, future researchers may have the opportunity to derive more precise estimations and extend the model by adding further potentially relevant variables [13].

The selection of the case site represents a limitation inasmuch as the case municipality had already signaled interest in evaluating external M-Government services at the time the contact was established. Thus, a positive bias may be present. Regardless, the selected municipality represents as a critical case for our research since it was one of the first municipalities in Germany to embrace urban sensing within its municipal M-Government offering. Therefore we are confident that our research, including quantitative and qualitative case findings, will represent a valuable source of information for other municipalities that aim to advance in this field. One promising approach to achieve this, as we learned from our case, is to work with external parties and engage in public-private partnerships to operate such novel M-Government services. Future research should expand the focus of investigation to multiple case sites and investigate how implementation decisions and operating models of such services vary across different municipal contexts.

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Site 1: NYC311, Government Information and Services, New York City, USA
http://www.nyc.gov/apps/311/about.htm

Site 2: Street Bump, New Urban Mechanics, Boston, USA
http://www.newurbanmechanics.org/bump/

Site 3: Center for Embedded Networked Systems (CENS), University of California Los Angeles, USA
http://research.cens.ucla.edu/

Site 4: Common Sense, Intel Labs Berkeley, California, USA
http://www.communitysensing.org/

Site 5: CarTel, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, USA
http://cartel.csail.mit.edu

Site 6: NoiseTube, BrusSense group, Vrije Universiteit Brussel, Belgium
http://noisetube.net/

Site 7: Saarbrücken App, State Capital of Saarbrücken, Germany
http://www.saarbruecken.de/de/rathaus/medien-_und_buergerkommunikation/saarbruecken-app

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# Appendix A: Glossary

| **English** | **German** |
|---|---|
| Complaints Office | Beschwerdestelle |
| Office of Public Order | Ordnungsamt |
| Office of Public Relations | Amt für Medien- und Bürgerkommunikation |
| Office of Street Maintenance | Amt für Straßenbau und Verkehrsinfrastruktur |
| Public utilities | Stadtwerke |
| Road workers | Bauhof |
| Street inspector | Straßenläufer |
| Traffic authority | Verkehrsbehörde |
| District | Stadtbezirk |

# Appendix B: Scripts

```
DIFFUSION MODEL

new potential adopters = increase of mobile users in city * potential user share

Potential adpoters = INTEG (new potential adopters - new adopters,
city population * percentage mobile users * potential user share)

new adopters = IF THEN ELSE(Time >= implementation time, innovators + imitators, 0)

Adopters of the service = INTEG (new adopters, 0)

innovators = Potential adpoters * innovator rate

imitators = imitator rate * Adopters of the service * probability

probability = Potential adpoters / (Potential adpoters + Adopters of the service)

Non adopters = city population - Adopters of the service

DETERIORATION MODEL

total new issues = new issues per km * street network size

total potential issue spots = max spots per km * street network size

issue density = Undetected spots / total potential issue spots

new spots with issues = total new issues * (1 - issue density)

Undetected spots = INTEG (new spots with issues-new reported spots, 0)

REPORTING MODEL

reports from citizen = reports from adopters + reports via traditional way

issue spots found by citizen = Undetected spots * (1-(1-(1/Undetected spots))^reports from
citizen)

total walking km per month = number of inspectors * walking km per inspector

issue spots found by inspectors = Undetected spots * (total walking km per month/street network
size)

new reported spots = issue spots found by citizen + issue spots found by inspectors –
issue spots found by citizen * issue spots found by inspectors / Undetected spots

Issue detection rate = new reported spots / Undetected spots

Reported spots = INTEG (new reported spots-repaired spots, 0)

repaired spots = Reported spots / repair duration

COST MODEL

costs for mobile service = IF THEN ELSE( Time> = implementation time, (IF THEN ELSE(Time =
implementation time, implementation costs, ongoing costs)),0)

costs for reporting = (costs per mobile report*reports from adopters)+(costs per traditional
report*reports via traditional way)

costs of inspectors = cost per inspector per month*number of inspectors

monthly costs = costs for mobile service+costs for reporting+costs of inspectors
```