Towards sustainable urban basic services in low-income countries: A TIS analysis of sanitation value chains in Nairobi

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Abstract

The provision of basic services suffers from a multitude of sustainability challenges in many cities of low-income countries. Sanitation provision faces particular challenges in the form of environmental contamination, high costs, and large inequalities between urban residents. In recent years an increasing number of innovations in on-site systems have been developed, which have not yet developed into fully functional alternatives to the existing regimes. We study three prominent recent on-site sanitation initiatives in informal settlements in Nairobi, Kenya that aimed at developing entire "sanitation value chains", which we conceptualize as an emerging Technological Innovation System (TIS). The analysis leads us to propose alternative governance modes for the TIS to overcome system failures such as capability, coordination and institutional barriers. Conceptually, the paper extends conventional TIS analyses towards entire value chains, enabling a wide range of transition processes to be addressed beyond informal settlements and low-income countries.

Keywords

Innovation systems; TIS; Value chains; Governance modes; Sanitation; Informal settlements

1. Introduction

Fundamental changes in urban basic service provisioning in low-income countries are urgently needed to create more environmentally sustainable, socially just and affordable services, and thereby improve the livelihoods of residents in rapidly growing cities. Innovative basic service offerings have great potential to tackle sustainability challenges and transform sectors such as energy, transport, water and sanitation. However, the promise of many such service innovations have not been fulfilled. Some are not being adopted, or adopters face many challenges. Others fail to be maintained, or are not scaled-up/diffused (Jones et al., 2013; Kebede and Mitsufuji, 2014; Tigabu et al., 2017; Cherunya et al., 2018). One of the core reasons for failure stems from the fact that innovation processes have to appropriately relate to numerous aspects not directly tied to technology questions, such as regulations, finance, institutions, social issues, the environment, etc.

Socio-technical system perspectives used in the sustainability transitions and innovation system literature can help to gain insight into these multiple dimensions that affect innovation development and transition processes. The concept of innovation systems encompasses the interplay among a broad variety of actors, their networks and institutions (Weber and Truffer, 2017). One of the system frameworks that has been extensively applied to sustainable technologies is the Technological Innovation System (TIS). TIS are described as "socio-technical systems focused on the development, diffusion and use of a particular technology" (Bergek et al., 2008, p. 408). The TIS framework has mostly been applied to specific technologies or technological fields. This has been adequate for cases in which the innovation success depends primarily on the fate of a specific artifact (like PV cells or electric vehicles) and where it can be assumed that all other dimensions of a socio-technical system will follow suit once the core technology is established. This rather specific focus of many TIS studies led to the criticism that the framework is barely suited to addressing complex transition processes (Kern, 2015). In order to expand the applicability of the framework to address transition processes, we have to consider the broader embedding of technologies in various contexts (Bergek et al., 2015) and ultimately shift focus from single technologies to socio-technical systems that encompass production and consumption aspects. The shift generates questions about how to govern simultaneous and interconnected innovations as part of such socio-technical systems.

A first step in this direction is to extend the TIS framework by perceiving interconnected innovations as happening at and across different segments of a value chain that leads to the provision of the basic service. A value chain is conceptualized as "the full range of activities which are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use" (Kaplinsky and Morris, 2001, p. 4). The literature on value chains deals both with value chains within companies (Porter, 1985) as well as those spanning across industries and geographies (global value chains - see (Kaplinsky, 2000; Gereffi et al., 2005)). We take the latter meso- (industry-) level perspective

to extend the TIS framework. The literature on value chains has dealt extensively with understanding the interlinkages between segments of value chains, such as the inter-actor relationships or vertical (dis)integration processes leading to different governance modes by which value chains can be coordinated (Gereffi et al., 2001; Kaplinsky and Morris, 2001). As compared to the single-technology approach, the value chain perspective directs attention to various other dimensions of new products and technologies and hence provides a useful step along the way to understand the emergence and transformation of entire socio-technical systems.

In this paper, the boundary of a TIS is conceptualized as a socio-technical system encompassing different segments that span across the entire value chain of an innovative service offering. We first apply the well-established TIS functional analysis to each segment of the value chain separately. However, beyond this rather straightforward extension of the methodology, we take the critical complementarities of the different segments into account. This leads to the important question of how actors coordinate among themselves and how different power positions get established in a TIS. To tackle this question, we can draw on the existing value chain literature, which has developed a broad body of insights into different types of "governance modes". We propose to extend the notion of governance modes from value chain to system level. This entails identifying the relative power positions of a broad range of actors in the context of the entire innovation system.

We use this enlarged framework to answer the question why technology-focused service provisioning innovations often fail in urban informal settlements in low-income countries. Based on the above perspective, we claim that this is mostly due to neglecting two complexities: First, it can be due to development interventions focusing too narrowly on technical artefacts instead of the production and value distribution networks that are necessary to provide safe and affordable services. This represents a neglect of the value chain dimension of new service offerings (Springer-Heinze, 2018). The second reason for failure is because many initiatives are considered in isolation, without addressing potential synergies with other initiatives in a given region. We describe this as neglecting the innovation system dimension, which may give rise to all sorts of "system failures" (Klein Woolthuis et al., 2005).

The empirical case that we use to illustrate these claims is based on on-site sanitation innovations in informal settlements of Nairobi, Kenya. The study draws on qualitative data from interviews, reports, observations, and project visits. On-site sanitation technologies promise to improve the dire sanitation situation in many cities in low-income countries, especially in informal settlements. The toilets should be managed in the context of a coherent sanitation chain including emptying, collection, transportation, treatment, and safe disposal or use of waste (Koné, 2010; Wald, 2017; WSUP, 2017a). The development of such sanitation chains depends not only on technological, but also on organizational, social, and institutional innovations that are interconnected (exemplifying the value chain dimension). Several

initiatives have therefore been started by Non-Governmental Organizations (NGOs), donors, and social enterprises in Nairobi over the past few years that build up entire "sanitation value chains" with the aim to sell products made of fecal sludge. The current situation of Nairobi's manifold innovation projects can be analyzed as an emerging TIS.

The paper is organized as follows. In the next section we review literature on TIS and value chains in order to elaborate an extension of the TIS functions methodology. Section 3 introduces the case and methodology. Section 4 presents the results from the case of on-site sanitation in Nairobi. It outlines the evolution of three major on-site sanitation innovation projects in Nairobi and identifies the system weaknesses. In section 5 we discuss potential improvements in the innovation activities in informal settlements of Nairobi that result from our systemic analysis. The last section concludes and elaborates implications for broader research activities and management strategies.

2. Theoretical foundations and analytical framework

Innovative service offerings often fail to meet goals tackling sustainability challenges in low-income countries. One of the reasons for this failure is that the multiple dimensions that impact innovation development, such as regulations, finance, institutions, social issues, the environment etc., have not been given sufficient attention in the innovation processes. Romijn and Caniels (2011, p. 375) emphasize the "need for policy makers in the international development-cooperation community to adapt an integral dynamic innovation-systems perspective for stimulating innovation in developing countries" in order to realize technological change that fits the local context and meets local needs.

2.1 Broadening the perspective of TIS analysis

The innovation system literature provides insights into the role of a diversity of actors, their interaction in networks, and the role of institutional arrangements in the promotion or hindering of innovations (Weber and Truffer, 2017). One salient concept is the Technological Innovation System (TIS), which has been applied to many sustainable technology innovations internationally and which has increasingly been focused on cases in low-income countries recently (Blum et al., 2015; Kebede and Mitsufuji, 2017; Tigabu et al., 2017; Kriechbaum et al., 2018; Sixt et al., 2018). The TIS concept not only focuses on aspects exclusively dedicated to the technology of interest, but incorporates all components that have an influence on the innovation process for that technology (Bergek et al., 2008, p. 409).

The dynamics of TISs are commonly analyzed using their "functions" (Hekkert et al., 2007; Bergek et al., 2008). These are core processes that drive the development and maturation of a TIS, such as gaining technology legitimation, mobilizing resources, forming markets, guiding search activities, entrepreneurial experimentation and knowledge development (Hekkert et al., 2007). Analyzing these functions over time and comparing them across cases leads to the identification of system weaknesses in the form of coordination, capability, and institutional failures (Klein Woolthuis et al., 2005; Jacobsson and Bergek,

2011). These failures can be addressed by different actors who want to support the innovation, for example through developing specific forms of knowledge exchange, forming professional networks, or by changing the division of labor within the value chain (Stephan et al., 2017).

When applied to cases of low-income countries, the TIS framework has mostly been focused on single technologies or clearly delimited technological fields (see, for example, Agbemabiese et al. (2012); Blum et al. (2015); Tigabu et al. (2015)). This mirrors the broader TIS literature, even though the framework was originally cast in much broader terms, referring to entire industry sectors or technology fields (Markard et al., 2015). The narrow focus on single technologies is defendable in cases where innovation success depends on a key artifact, like photovoltaic modules, wind power plants or electric vehicles, where supply chains and institutional contexts can be supposed to follow suit with the rapidly increasing deployment of the core technology. However, in general, the success of technological innovations may be influenced by various "external" conditions, such as other TISs (Bergek et al., 2015), geographies (Binz et al., 2014; Binz and Truffer, 2017), or sectoral configurations (Stephan et al., 2017).

For example, the development of battery technology is related to mobile applications such as laptops, as well as to the integration of intermittent renewables in electricity grids (Stephan et al., 2017). The success of the solar photovoltaic energy industry does not only depend on the development of the photovoltaic cells and modules alone, but ultimately can be developed into entire socio-technical systems, for instance in the form of stand-alone systems that can operate rather independently from the grid (Dewald and Truffer, 2012). Different technologies may also become increasingly interdependent over time (Kieft et al., 2017).

In order to address these complexities, the functional analysis of TIS has to be extended to entire value chains. This is a stepping stone to the analysis of interlinked technological, organizational, and institutional innovation processes and by this the transformation of entire socio-technical systems.

2.2 Value Chain Governance in a TIS

In cases where technologies become interrelated, it is important to explicitly account for up- and downstream dynamics in value chains that the technologies are related to. A specific issue that has to be tackled is how the different actors relate to each other across different value chain segments and how these relationships are governed. The literature on global value chains (GVC) has been most explicit about this dimension. It offers a globalized perspective of how and where activities are organized across the value chains and how values are distributed across different geographies under the conditions of increasing globalization (Kaplinsky, 2000; Gereffi et al., 2001; Humphrey and Schmitz, 2001).

Complementarities between actors in value chains demand (more or less) explicit coordination in order to realize functioning research and development (R&D), production, and distribution networks. Gereffi et al. (2005, pp. 83-84) have categorized these relationships into five value chain governance modes: *market governance, modular value chains, relational value chains, captive relationships,* and *hierarchy*. Three key determinants help to characterize these modes: *complexity of transactions*[1] (i.e. how complex is the process of information and knowledge transfer in order to sustain a transaction); 2) *codifiability of information* (the extent to which this information and knowledge can be provided in written form and hence be transferred from one context/step to another one without transaction-specific investments); and 3) *capability of suppliers along the value chain* (the absorptive capacity of actual and potential suppliers in relation to the requirements of the transaction).

The five governance modes are characterized by different combinations of these three determinants (Table 1) and represent different forms of power asymmetries, which range from full integration of activities within a single vertically-integrated company on one end to pure market-based interactions on the other end. In between, we find different forms of networked relationships with a decreasing power position of the lead firm (Gereffi et al., 2005, p. 83). The framework laid out in Table 1 can also be used in a diagnostic form: e.g. a hierarchy mode is potentially very appropriate when "product specifications cannot be codified, products are complex, and highly competent suppliers cannot be found. This forces firms to develop and manufacture products in-house" (Gereffi et al., 2005, p. 87). On the other extreme, pure market coordination only works if transactions are rather simple, products can be easily standardized, and there are enough companies in the supply base that meet the required levels of capabilities.

Table 1 Key determinants of value chain governance (Gereffi et al., 2005)

Determinants / Modes	Complexity of transactions	Ability to codify transactions	Capabilities in the supply base	Degree of explicit coordination and power asymmetry
Market	Low	High	High	Low
Modular	High	High	High	
Relational	High	Low	High	
Captive	High	High	Low	
Hierarchy	High	Low	Low	High

Governance modes are not static. In many industries, increasing capabilities in the supply-base helped push the GVCs away from hierarchy and captive networks toward relational, modular and market types (Gereffi et al., 2005). Changes in governance modes can also be the result of new standards that enable

[1] As assets differ, (Gereffi, et al., 2005, p. 84) emphasizes "mundane" transaction costs – the costs involved in coordinating activities along the chain.

codification of product and process specifications (Gereffi et al., 2005). Governance modes are not only relevant for production and manufacturing. They also have implications for innovation processes (Gereffi et al., 2005; Pietrobelli and Rabellotti, 2011; Zhang and Gallagher, 2016). Learning in the GVCs can take place by adopting international standards "or be facilitated by direct involvement of the value chain leaders when the suppliers' competence is low and the risk of failure to comply is high" (Pietrobelli and Rabellotti, 2011, p. 1261). Chain leaders play an important role in knowledge transfer and technological learning to their suppliers (Morrison et al., 2008). Or, if the competencies of actors in value chains are complementary, learning can be mutual and take place through face-to-face interactions (Pietrobelli and Rabellotti, 2011).

These insights from value chain governance add an important new level to the analysis of a TIS. The governance modes introduced by the GVC literature facilitate discussion on the important question of who has a coordinating role in aligning the different segments of the value chain. While governance modes have been conventionally applied to value chains, we propose in this paper to extend this notion to entire innovation systems. The governance mode of a TIS can accordingly be differentiated by the degree to which a few core or a broad set of actors (be it companies, industry associations, government offices, or civil society organizations) coordinate the different activities in a technological field. If a single actor would be able to control most of the activities necessary to developing an innovation, this would result in a strongly coordinated mode in a TIS. An extreme form would be a single multinational company attempting to control most TIS functions within its own organizational boundaries. In that case, a hierarchical value chain governance mode would coincide with a strongly coordinated TIS governance mode. On the other extreme, a lowly coordinated TIS governance mode could be successful when system functions develop quite spontaneously and harmonically. In between, we may identify many different governance constellations where all sorts of coordinative structures are set up. In particular, we also have to consider that not all relationships among the actors have to be harmonious for a well-performing TIS. There is room for divergent strategies and even competition among sub-groups of actors in the TIS.

It is beyond the scope of this present paper to provide an exhaustive typology of different TIS governance modes. Such an endeavor would need to be based on a large sample of cases. We can, however, start to develop such a typology by distinguishing different degrees of coordination that are appropriate in order to improve the performance of a TIS given specific context conditions. Building on the insights of the GVC literature, it is useful to elaborate how the three determinants of value chain governance modes correspond to the three types of system failures that are key to the innovation system literature. We thereby extend the notion of governance modes of the value chain literature to entire innovation systems. First, the *complexity of transactions* is neatly related to the network and the institutional dimension of a TIS. The more internal institutions are developed in a TIS and the fewer coordination deficits prevail, the lower transaction costs will be. Second, *codifiability* depends on the types of knowledge that are predominant in the TIS, the quality of networks that exist among the diverse actors, and also on how congruent institutional contexts are between different segments of the value chain. Standards and regulations play a

particularly important role here. And finally, *capabilities of the supply base* relate rather naturally to capability deficits in a TIS. However, the TIS perspective would consider a broader range of actors than only suppliers and buyers. It also highlights the role of government offices, research institutions, civil society actors, and so forth, that may support an innovation development.

The three determinants proposed then reflect proximate conditions for the required strength of coordination in a TIS. A TIS with strong capability deficits, coordination failures, and institutional mismatches will require a rather centrally coordinated governance mode. On the other extreme, a TIS whose institutional conditions are mature, whose supportive contexts are in place and whose capabilities of suppliers are rather equally developed might work optimally under a more weakly coordinated mode.

Particular governance modes will therefore be more or less appropriate for enabling innovation system development, and these modes will most likely change in the course of system maturation. For example, when a TIS matures, economies of scale can enable the rise of industry standards and the development of specialist competencies among suppliers, which might then require a more weakly coordinated governance mode compared to earlier phases.

2.3 Assessing TIS performance using a value-chain perspective

So far, few TIS studies have explicitly addressed value chains in their research (for example (Hellsmark, 2010; Musiolik and Markard, 2011; Sandén and Hillman, 2011; Stephan et al., 2017; Andersson, Hellsmark, et al., 2018)). Some of these studies emphasize that the set-up of value chains is an important part of the system building process. Hellsmark (2010) reconstructs how value chains in biomass gasification are developed and Planko et al. (2016, p. 2330) take-up "coordination along the value chain" as one of the main aspects of their framework for strategic collective system building. Musiolik and Markard (2011) analyze the creation of an emerging fuel cell value chain. They conclude that the creation of value chains is a crucial task in an immature technological field, and emphasize that analytically, value chain development is not well covered by the existing TIS functions. Other authors use value chain arguments to delineate TIS boundaries (see for example Andersson, Hellsmark, et al. (2018)). Lastly, some of the studies used value chains to emphasize the connections of TIS to different sectors and technologies (Stephan et al., 2017). Sandén and Hillman (2011) use value chain arguments to define different modes of relationships between technologies in innovation development. However, none of these studies have elaborated how the assessment of TIS development has to be extended in order to account for the interdependencies among the different segments of a value chain.

In the following, we propose a specific approach for analyzing TIS performance across value chains. Before starting a TIS analysis, the system boundaries have to be defined (Bergek et al., 2008). In our case this implies that all the actors, networks, and institutions that contribute segments of a value chain must

be included, instead of being treated as part of the larger context or sector (see Andersson, Hellsmark, et al. (2018) and Stephan et al. (2017) for a similar view). We propose to start with a functional analysis of each segment of the value chain to identify the level of performance and the system weaknesses that characterizes them (see Table 2). Reading the table along a specific column results in a conventional TIS analysis of that particular segment of the value chain, e.g. of the panel manufacturing process in PV production, or strengths and weaknesses of innovation activities at the level of cell manufacturing. Reading each individual function from left to right provides a first indication of how well the innovation activities are balanced (integrated or not) across the different segments of the value chain, and whether bottlenecks can be identified (e.g. in terms of legitimacy problems or limits in the mobilization of resources). The virtual example that we have constructed in Table 2 describes a case in which innovation activities are well developed in segment 3 (e.g. the construction of the end product) but major legitimacy problems exist in terms of the extractions of core minerals and the disposal of the end products (such a configuration may be typical for high density batteries or smart phones).

Table 2 Functional profile of the TIS.
Functional analysis of each individual segment of the value chain (a darker shade indicates a further developed function). The lowest line represents the overall functional TIS assessment of each segment, the last column a first reading of the performance of each function across all segments. The lower right corner stands for the integration of all the partial analyses and adds the governance at the system level in order to achieve an integrated assessment of the TIS.

Functions	**Segment 1**	**Segment 2**	**Segment 3**	**Segment 4**	**Assessment of functions across segments**
Entrepreneurial activities					*Focused on 3*
Knowledge development					*Restricted to 3*
Guidance of search					*Restricted to 3*
Market formation					*Strong 1-3*
Resource mobilization					*Deficient in 4*
Legitimation creation					*Difficult 1&4*
TIS analysis for each segment	*Weakly developed*	*Emerging*	*Strongly scaling*	*Largely neglected*	**Integrated assessment of the TIS & analysis of the degree of coordination at system level (complexities, codifiability, capabilities)**

Reading Table 2 along horizontal lines, however, only provides a first glance at the overall innovation performance of the value chain. Deficiencies in a specific segment may be more or less important for the overall functionality, depending on how each segment relates to all the others. We therefore have to specify mutual interdependencies among the different segments in order to provide an overall assessment of the entire value chain. This is done through an analysis of the three governance determinants

(complexity of transactions, codifiability of information, capability of suppliers along the value chain) to explain the established governance modes in the TIS.

3. Case & Methodology

In this paper we use a case-study design (Yin, 2009). The case is innovative on-site sanitation[2] provisioning in cities in low-income countries. The lack of sanitation supply in these cities is one of the most persistent development challenges. Increasing urbanization and the failure of sewer systems in the majority of urban contexts in low-income countries enlarge this problem (Koné, 2010), demanding new types of solutions to solve the urban sanitation crisis. Innovative safely-managed on-site sanitation has received increasing attention in recent years because it has the potential to improve sanitation services in these cities in line with the Sustainable Development Goals that aim for safely-managed sanitation for all by 2030 (UN, 2017; Andersson, Otoo, et al., 2018).

This case can usefully be assessed with an extended TIS assessment because providing a specific technology (e.g. the toilet/latrine) will not solve any of the problems without appropriate emptying, collection, transportation, treatment, and safe disposal or use of waste. This has not always been obvious in development cooperation initiatives, especially during the times of the Millennium Development Goals, when governments, development agencies and NGOs responded to the lack of sanitation infrastructure by implementing programs to improve latrines without considering what to do with the waste (Koné, 2010; Wald, 2017). As a result, in these cities pit latrines overflow or households rely on cheap but inferior emptying services that dispose of the fecal sludge into the environment because they are not able to pay for adequate emptying services (if at all available) (see for example Boot and Scott (2009); Trémolet (2013); Tsinda et al. (2013)).

Improving the service level in informal settlements is difficult because on-site sanitation service providers face many challenges related to a lack of regulations, institutional constraints, socio-cultural resistance and a lack of government support, which all need to be leveraged to create a supportive "urban enabling environment" (Lüthi et al., 2011). Moreover, financial viability is challenging: on-site sanitation services are "either barely financially viable for entrepreneurs or not affordable for the urban poor" (Diener et al., 2014, p. 32). Parkinson and Quader (2008); Mbéguéré et al. (2010) provide examples of challenges in cost-recovery for emptying services. In order to improve the financial viability of (on-site) sanitation services, several authors have recently advocated exploring options of resource recovery from the waste (Diener et al., 2014).

Since 2008 the "sanitation chain" has become the standard terminology to describe the necessary components of sustainable urban sanitation: *user interface, storage, conveyance, treatment, use or safe*

[2] *On-site sanitation* is characterized by systems in which excreta and wastewater are collected and stored on the plot where they are generated. The treatment of excreta takes place on the plot or is conveyed for treatment elsewhere. On-site sanitation is different than *off-site sanitation* systems, in which excreta and wastewater are collected and conveyed away using a sewer technology (Tilley, et al., 2014, p. 173).

disposal of waste (Tilley et al., 2014). In this paper, we conceptualize these different segments as forming an ideal type sanitation value chain (Figure 1).

Innovating the sanitation chain requires a number of innovations at different segments of the value chain. Various innovations have been developed and implemented in each segment, such as pour flush and dry toilets, source separation of waste flows, different ways of emptying and transporting waste using mechanical and manual devices, and diverse treatment and reuse technologies (see for examples Muspratt et al. (2013); Larsen et al. (2014); Seck et al. (2014); Mkhize et al. (2017)). Because of the increased attention to handling the waste from on-site sanitation, so-called "fecal sludge management" has even become a field of expertise on its own in research and practice in recent years (see Strande et al. (2014)).

The extended TIS perspective is appropriate to analyze the role of governance models both at the level of the value chain and at the system level. The sanitation chain does not represent a traditional value chain in the sense that actors have shifted the focus from selling toilets towards dealing with the "unwanted side product" of this market, namely fecal sludge. However, we may interpret the recent shift in the sanitation chain as an attempt to make sellable products out of the fecal sludge, mostly biogas, animal feed, and fertilizer (see below). Even though the different initiatives have not yet achieved a convincing business case for these products, the associated innovation activities can be understood as innovating the whole value chain, considering upstream and downstream activities associated with human defecation. Moreover, although the on-site sanitation system in cities of low-income countries is rather a localized than a globalized value chain, applying the notion of governance modes helps inform us about the organization and coordination of the different innovation activities within a well-demarcated system.

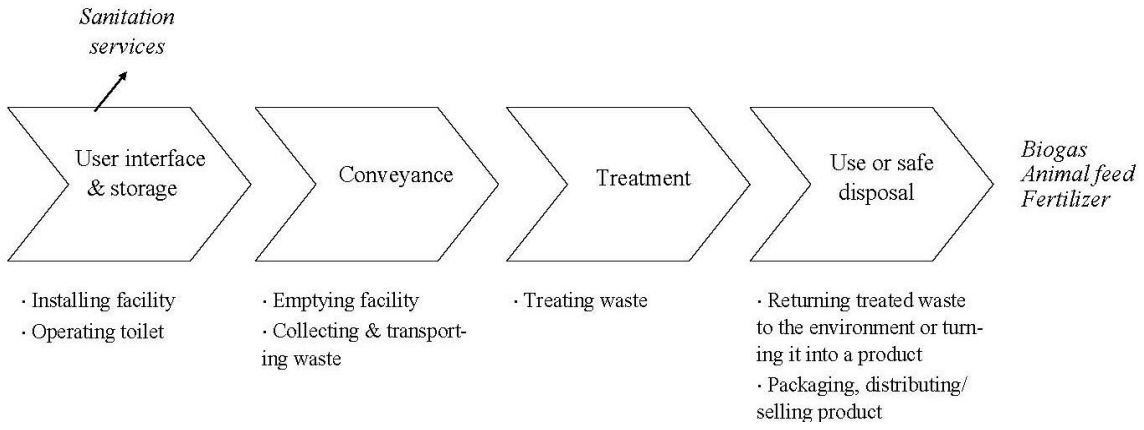

Figure 1. Segments, core activities and outputs of the sanitation chain

We specifically focus on the empirical case of on-site sanitation innovations in informal settlements of Nairobi, Kenya. Nairobi's sanitation sector is characterized by large inequalities between different areas in the city (Gulyani et al., 2006; Darkey and Kariuki, 2013; van Welie et al., 2018). Sanitation access varies from households using flushing toilets in high-income areas to residents in peri-urban or informal

settlement who combine public sanitation services with coping strategies on a daily basis (Cherunya et al., 2018; van Welie et al., 2018). These inequalities are a legacy of the colonial period, when social and spatial segregation between the city's inhabitants were created (Nyanchaga and Ombongi, 2007; Nilsson, 2011). Adequate provision of sanitation services in the city is thus a fundamental challenge, especially in the informal settlements, where 36% of Nairobi's population lives (Mansour et al., 2017). As a result, informal settlement residents' health is poorer than in other city areas of Nairobi, and even worse than in rural areas in Kenya (Kimani et al., 2007; Blessing et al., 2016). Despite a wide range of strategies to increase sanitation coverage, sanitation improvements have barely kept pace with the city's rapid population growth over the past few decades (Mansour et al., 2017).

The city has become a popular testbed for on-site sanitation innovations (Kalan, 2011; Bwire, 2016). Several social enterprises, NGOs, entrepreneurs and Community Based Organizations (CBOs) have attempted to introduce on-site sanitation innovations which are safer, more dignified, cleaner, and better-organized than the sanitation options currently in use in informal settlements – such as pit latrines, septic tanks, hanging and flying toilets, or even open defecation.

The analysis draws on semi-structured interviews with key informants in the sanitation sector in Nairobi. Interviews were conducted in two periods of data collection between February to March and October to December in 2016. The first period of data collection was used to gain an overview of the sanitation sector in the city (see van Welie et al. (2018)). The second period of data collection was specifically focused on gaining in-depth knowledge about on-site sanitation innovations for this paper.

The interviewees were selected from different stakeholder groups. Several interviewees were identified during the first period of data collection and snowball sampling was used to identify additional key informants. The sampling evolved during the fieldwork based on newly acquired insights. This paper builds on 36 interviews with actors that represent organizations implementing innovative solutions as well as Ministry and Nairobi County officials, Water Board officials, representatives of NGOs, CBOs, and international developmental agencies (see Appendix, we will refer to the interview codes in the remaining sections).

An interview guideline was developed beforehand. Questions were structured around the TIS functions and the different activities in the segments of the sanitation chain. For example, questions focused on the availability of resources for on-site sanitation innovators, the acceptance of on-site sanitation services, conveyance, and reuse activities, the undertaking of activities related to knowledge development and the expectations of the future growth potential of on-site sanitation services in Nairobi. Additionally, the interviewees were asked about their organizational role in the different segments of the on-site sanitation chain and their alignments to other organizations. The guidelines included small variations for the different stakeholder groups. Based on insights gained during the process, the interview guidelines were updated. In addition to the interviews, the first author also wrote notes based on observations during the fieldwork.

Lastly, various secondary data sources were used: reports, websites, journal articles, online newsletters and online articles. All the data sources were triangulated as much as possible.

All interviews were recorded, transcribed, and checked. The field notes and interviews were coded using MAXQDAsoftware. The TIS functions and value chain activities provided starting points for the coding scheme that evolved during the process in which new and more detailed codes were defined. This process can be described as "open coding": labelling the phenomena in terms of concepts or categories (Gray, 2004, p. 331). As a first analytical step, an overview of the various actors' histories, projects, and pilots along the sanitation chain was created. Secondly, both the TIS functions in each segment of the sanitation chain (vertical dimension Table 2) as well as across all segments (horizontal dimension Table 2) were analyzed. Finally, an analysis of the value chain governance determinants (complexities, capabilities, codifiability) lead to insight into the governance modes in the TIS.

4. Results: Assessing the performance of the on-site sanitation TIS in Nairobi

In this section, we outline the evolution of on-site sanitation innovations in Nairobi and analyze the three different sanitation chain initiatives that are currently implemented in the city. We then apply the TIS assessment framework to analyze the integrated functioning in each segment of the value chain and identify appropriate governance modes.

4.1 Evolution of on-site sanitation innovations in Nairobi

In the last few decades several innovative on-site sanitation activities in Nairobi's informal settlements have focused on individual segments of the sanitation chain. One example was several initiatives involving the introduction of portable in-home toilets. These innovations never exceeded the pilot phase because the initiators failed to set up a reliable collection system for the waste. Consequently, residents stopped using the in-home toilets and converted them for various other uses (Cherunya et al., 2018). A second example was an innovative project aimed at improving the conveyance of sanitation waste through the professionalization of manual pit emptiers. Several emptiers received management training and were being equipped with protective clothes and special mechanical pumps to empty the pit latrines (NGO4, iNGO4, CBO2, CBO3). A designated disposal point into the sewer was created in agreement with the utility (NGO4, iNGO4). This project failed because the designated waste collection point vanished quickly as slum dwellers built houses around/over it, and the utility never really took care of the disposal point (NGO4, iNGO4, CBO2, CBO3). In this project the focus was too much on the conveyance segment, and both the connection to the earlier and later segments in the chain were not well established. The pit emptiers went back to (illegal) business as usual, which included dumping the waste into nearby rivers (NGO4). Therefore, these two examples of innovative on-site sanitation activities were not successful as they did not address the interdependencies along the entire sanitation chain.

In order to overcome this oversight, several actors recently adopted more holistic approaches. They set-up and manage entire sanitation chains on their own. Currently, three individual sanitation chain initiatives

are being developed by independent actors in Nairobi's informal settlements: bio-centers, biodegradable bags, and Container Based Sanitation (CBS).

Bio-centers are community centers that have several functions, one of which includes public sanitation facilities. A biogas reactor in the bio-center treats fecal sludge to produce biogas. The biogas is used by local communities for cooking and to heat the showers in the centers (Wamuchiru, 2015). The digestion residues are collected and transported by exhauster truck services. The concept was developed by a Kenyan NGO that introduced it in Nairobi in 2007. Up to 2014, 42 bio-centers have been installed in Nairobi's informal settlements (UmandeTrust, 2014).

The second value chain configuration is built around *biodegradable bags*, which are personal single-use biodegradable bags used in people's homes or at schools. The inside of the bag is coated with urea to disinfect the feces directly (Tilley et al., 2014, p. 166). The bags are regularly collected and transported to a storage location for composting, after which they are reused as a fertilizer by coffee farmers (Patel, 2011; Wirseen, 2013). This approach was introduced in Nairobi in 2009 by an international social enterprise (Wirseen et al., 2009; Graf et al., 2014; Peepoople, n.d.). Currently, about 100 schools in informal areas are provided with biodegradable bags for free, which is supported by donors (SE9).

The last configuration forms around *container-based sanitation* (CBS). CBS services consist of stand-alone waterless toilets that capture waste in (portable) containers (Tilmans and Russel, 2015; WSUP, 2017b). The container toilets in Nairobi are so-called "Urine Diverting Dry Toilets" that separate urine and fecal matter. The containers are installed as public toilets, shared toilets, at schools and in homes. The containers are regularly collected and transported, and the waste is treated and disposed of or reused. The waste is composted and treated in a location outside of the city. Animal feed and fertilizer are produced and sold to farmers (Auerbach, 2016). CBS was introduced in Nairobi in 2011 by an international social enterprise (Esper et al., 2013; Auerbach, 2016). By the end of 2017, 1134 CBS toilets had been installed in the city (Sanergy, 2018).

In order to identify system weaknesses and potential synergies among these initiatives, we conceptualize the three initiatives as part of a local TIS of on-site sanitation.[3] Figure 2 provides an overview of the major actors and networks that make up the TIS.

[3] In this paper we only focus on on-site sanitation initiatives that take place in informal settlements, are highly innovative, take care of the complete sanitation chain, and aim to scale-up. Unhygienic on-site sanitation practices of pit latrines and septic tanks that are not emptied, or in which the waste is dumped into rivers, are not considered to be part of the TIS. We also exclude small initiatives such as a CBO that runs public sanitation facilities using composting toilets (see (KDI, 2014)) as there is no aim to scale-up. Lastly, we exclude on-site sanitation services such as mobile toilets for events as these are not being developed for informal settlements.

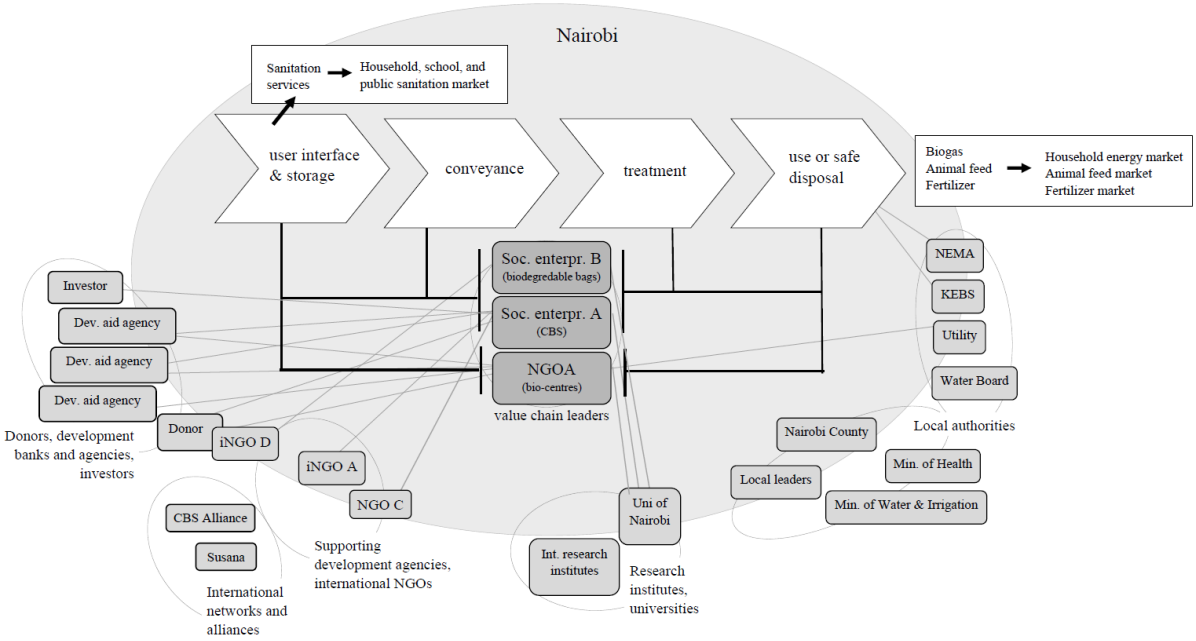

Figure 2. Main actors of Nairobi's on-site sanitation TIS in 2016 (compiled by the authors)

4.2 Functional TIS analysis of the individual segments of the value chain

The on-site sanitation TIS in Nairobi is only emerging. The three individual sanitation chain initiatives drive the operations and manage different value chains in a vertically integrated way. In the following, we present the most salient points of the functional analysis of each individual segment of the value chain across the three initiatives (vertical dimension in Table 3).

User interface and storage

Many different experiments and entrepreneurial activities take place in the first segment of the chain in the TIS. We see that this segment has progressed farthest in terms of TIS development. The experimentation and development in the TIS have resulted in approximately 76,000 daily users[4] of the different types of innovative on-site sanitation services in Nairobi's informal settlements. Innovation activity in this segment comes in various forms. For example, innovative designs of container toilets as Urine Diverting Dry Toilets are being developed to separate urine and fecal matter (Tilley et al., 2014, p. 46). New types of "in-home" CBS toilets are being developed (SE1, SE4) and a local production plant to produce biodegradable bags is being set up (iNGO6). Research is being done into various aspects, such as improving toilet designs and catering for different user preferences. Other research focuses on the production of different types of biodegradable bags (SE8) or improved construction methods of the CBS toilet (lighter, smaller) (SE6). These research projects are often carried out in collaboration with (international) research institutes and universities (SE2, SE8, iNGO6), with resources mobilized from

[4] 1134 container-based toilets, 53,436 daily users (Sanergy, 2018); 42 bio-centers, 5,000 daily users (derived from (UmandeTrust, 2014)); biodegradable bags provided to 100 schools, 18,000 children per day (Peepoople, n.d).

international donors (SE4, SE10, iNGO1). International investments and grant capital were most strongly mobilized for the CBS approach (Auerbach, 2016).

Most on-site toilet innovations have generally been accepted among users. However, for completely new toilet interfaces, such as biodegradable bags or Urine Diverting Dry Toilets, socio-cultural issues have had to be overcome (SE5). The founder of a social enterprise explains what sort of sensitivities innovators have to adapt their toilet to:

> *"… (some) communities will not accept to have children sit on the same toilet as the adult, or a man and a woman, you know, cultural taboos that are kind of sometimes difficult to understand… so the sensitivity around our design model in terms of service was very hard to be well-structured around different communities … trying to be as general as possible so it serves as many people as possible…"*

The sanitation chain leaders therefore organize different education and sensitization activities for residents in informal settlements to support market formation (and promote sanitation in general) (SE5, SE8, SE9, iNGO6). The bio-center approach has already gained widespread legitimation through the active involvement of local community groups (NGO1, NGO3) (Binale, 2011; Otsuki, 2016; Wamuchiru, 2017).

The legitimation of innovative on-site sanitation services among policymakers has progressed in recent years. This resulted in the recognition of well-managed on-site sanitation as a legitimate toilet option in cities (in addition to sewered toilets) in the Kenya Health and Sanitation (KESH) policy of the Ministry of Health (Kenya, 2016). The bio-center model has become a particularly accepted on-site sanitation option both by the Nairobi County government (NGO1, NGO3, GOV5) and the public utility (Wamuchiru, 2015). In contrast, the biodegradable bags are sometimes perceived as a sub-standard sanitation option among policymakers (IDO2) and only accepted as a temporary solution. The international social enterprise plans to lobby the government to take it up as a viable solution for schools (iNGO6).

The innovative on-site sanitation services hold a small share of the market for public and shared toilets (GOV1). A market for public toilets has existed for many years in Nairobi.[5] Many informal settlement residents use pay-per-use public sanitation services on a regular (daily) basis (Cherunya et al., 2018). In the bio-centers, innovations to improve the payments for public toilets, using cashless systems, have been tested (NGO1, NGO2, NGO3). Not all on-site sanitation services in the TIS are paid for; biodegradable bags are given for free to schools (SE8, SE9) (Wirseen, 2013; Graf et al., 2014). The CBS approach also fueled new types of market development: in the first segment of the chain the enterprise operates a franchise system in which entrepreneurs are provided with a toilet and run it as a business (Auerbach, 2016).

[5] The market for public sanitation increasingly gained attention as a result of the success of the "Ikotoilets", a public sanitation concept in Nairobi run by Ecotact, which, as one of the first actors, introduced a clean and good public sanitation service in 2006 (NGO6, SE11).

Conveyance

In the conveyance segment of the sanitation chain only a few innovations have taken place, focused on improving the collection efficiency in order to lower the costs of collection in the individual initiatives (SE6). This is perhaps the most poorly developed segment in terms of TIS performance. There is relatively little experimentation and research done to develop new technologies. Mostly conventional wheelbarrows, handcarts and trucks are used to manually transport the waste to collection points from which trucks transport the waste to treatment plants (SE6, SE8, SE9, NGO1). The bio-centers only need conveyance services for the residues from the anaerobic digestion, which is taken care of by conventional exhauster trucks. Few experiments with different manual and mechanical collection models for biodegradable bags and containers have been undertaken (SE6, SE8) (Wirseen et al., 2009). More research in this segment seems to be necessary because collecting waste in the narrow streets of informal settlements is sometimes difficult with the means that are currently being used, and without proper collection, on-site sanitation systems are bound to produce many negative side effects.

Waste is collected and transported on a relatively small scale by the individual sanitation chain leaders in the TIS. Increased legitimacy for the manual collection of containers and biodegradable bags is necessary. Local communities need to be sensitized to overcome the stigma surrounding human waste collection. For example, a CBO's founder points at a cultural problem that CBS innovations on conveyance of waste need to overcome:

> *"…a lot of people do not want to have their shit carried around in containers (…) the cultural issues around these are so many. And also there is something people attach to dignity, you know."*

A social enterprise's founder explains how the taboo around human waste complicates the work for TIS actors in informal settlements as follows:

> *"…in Kenya … we have very many cultures and when we talk about slums we have to be considerate of the different sections of the slums … certain cultures in Kenya are sensitive on who or how their waste is handled … there are all these taboos that go around how the waste is managed…"*

Trust needs to be created by the TIS actors so that the collection services are felt to be safe, clean and reliable. In container-based sanitation systems QR codes can, for example, be used to track whether the collected waste reaches the treatment site (Saul and Gebauer, 2018). Chain leaders also have to convince potential employees that it is a proper job to do (SE6, SE9).

The sanitation chain leaders successfully lobbied to get licenses for their conveyance services from the National Environment Management Authority (NEMA) to transport human waste in containers and bags on trucks (SE3, SE9). A market of human waste transportation services already exists in the city, provided by manual pit latrine emptiers and exhauster truck operators (CBO2, CBO3, PA1). This market is not

well-regulated and controlled. However, a lot of waste is dumped (iNGO2). The collection and transport services run by the on-site TIS initiatives are well-managed and hygienic compared to these services.

Treatment

Many different innovative treatment technologies have been implemented by the TIS actors, such as anaerobic digestion, (co-)composting and black soldier flies (NGO1, SE2, SE3, SE7, SE8). Moreover, some research on recovering nutrients from urine has been conducted (Sanergy, 2016). These treatment technologies are all used on a relatively small-scale. The corresponding TIS analysis of this segment therefore shows an emerging field of innovation experiencing increasing activities. Much research and testing is being done to develop these treatment technologies further in collaboration with local universities and international research institutes and universities (NGO1, SE2, SE7, SE8, iNGO6). Other options are also explored, for example the potential to install a separate treatment plant for the residues from anaerobic digestion in the bio-centers. Financial support for this research comes mainly from international donors.

The other system's functions in this segment are relatively underdeveloped. There seem no clear goals for the (large-scale or central) treatment of waste from on-site sanitation systems in Nairobi. Even though handling human waste is legal, the TIS's small-scale treatment activities of fecal sludge from on-site sanitation systems have not gained the same legitimacy as the publicly run large-scale waste water treatment plants. This can be explained from the fact that it is difficult to obtain land and permission to build a treatment plant for fecal sludge (NGO1, SE3). The possibilities of treating fecal sludge other than using anaerobic digestion are also somewhat unknown (NGO3). The legitimation for this segment of the value chain might be additionally hindered by the previously mentioned taboos concerning handling human waste in Kenya.

Use or safe disposal

Several reused products have been developed in the TIS, such as fertilizers, animal feed and biogas. This segment of the value chain is only emerging in terms of TIS performance, but has a high potential to enter other markets. A lot of research and experiments are conducted by the sanitation chain leaders in cooperation with (international) research institutes and local universities to optimize the reused products (NGO1, SE2, SE8, iNGO6). For example, experiments have been conducted in bio-centers with transporting biogas from the centers to households (NGO1, NGO3) (Umande, 2016). Waste from CBS was used to experiment with the production of liquid fertilizer and bio char (Auerbach, 2016). The "waste as a business" paradigm at policy level contributes to the legitimacy of reusing human waste. The 2009 Implementation Plan for Sanitation of the Ministry of Water and Irrigation states that facilities receiving high volumes of effluent, such as on-site sanitation facilities in public places and institutions, should be "designed for reuse of effluents to produce biogas, fertilizers, and water for irrigation to protect the environment and generate the advantages of sanitation for production" (Kenya, 2009). The KESH 2016

policy also encourages technologies that enable safe recycling and reuse of waste streams (p.52). Reused products such as insect-based animal feed also feature in the Kenyan press (see for example Mwendwa (2016)). Furthermore, attention to reusing human waste in the international press often focuses on the innovations in Nairobi (see for example Whitehead (2014); Scherer (2015); Njoroge (2016); Ruiz-Grossman (2016); Arbogast (2017)).

The reused products in the TIS are beginning to access various existing markets. Some of the products are licensed and sold as new (types of) products in markets of fertilizers, energy, and animal feed (SE3). For example, the organic fertilizer made from CBS sanitation waste is a new product in the organic fertilizer market (Auerbach, 2015). The insect-based animal feed from CBS complements the animal feed market. This market is underserved in Kenya and relies currently on fishmeal, according to the founder of the CBS enterprise (Auerbach, 2015). The fertilizer made from the biodegradable bags is currently given away to farmers as it still lacks the necessary licenses to be sold (iNGO6). The biogas produced in the bio-centers has so far mostly been used as an energy source to heat showers and cooking, services for which users pay a low price at the bio-centers (NGO1, NGO2, NGO3) (Wamuchiru and Moulaert, 2017). The bio-center NGO looks into other possible usages of biogas because it aims to commercialize its fertilizer and biogas production (NGO1) (Umande, 2016).

Despite policy support towards reuse, the adoption and sales of the reused products are to a certain extent hindered by the taboo of using human waste (NGO1, NGO3, SE12). Users with insufficient information about the product's safety can be hesitant towards using fertilizer or biogas made from human waste (NGO6). An iNGO's environmental health project officer explains this problem:

> *"… there is a knowledge gap to close, from the policy makers to the community, who have never seen waste as a source of income. We have always treated it as a waste and should not interact with it, we have always seen it as something that should be discarded away from the human environment…"*

Different strategies are used in the TIS to overcome these issues: marketing of fertilizer without mentioning the raw material that is used, demonstrations of the products to show their effectiveness, and education about the use and safety of the products (NGO1, NGO3, SE8, SE9, iNGO6) (Farmstar, 2016).

4.3 Overall functional profile of the TIS

In this section we present the assessment of the functions across all segments (the horizontal dimension in Table 3) in order to suggest different governance modes for coordinating the overall TIS in the next section.

Despite various activities in each segment of the value chain, the different TIS functions are overall still rather poorly developed across all segments. The *development of knowledge* takes place in all segments, to different degrees. The *diffusion of knowledge* in most segments of the TIS is, however, very limited. For example, many different treatment technologies have been developed and tested by different actors in

the city, which led to some replications (NGO1, SE7, SE8). A potential platform to exchange more information on on-site sanitation chains is the "Technical Working Group Urban Sanitation" consisting of NGOs, CBOs, and social enterprises under the Ministry of Health, aiming at accelerating sanitation provision in cities (NGO6, iNGO2). Conferences, meet-ups and networks at the international level seem stronger in coordinating knowledge exchange, for instance the "Sustainable Sanitation Alliance" and the "CBS Alliance" (CBSAlliance, 2017; SuSanA, n.d.). Most of the chain leaders in the TIS have strong connections to these international networks in which they coordinate with likeminded actors around the world. These coordination efforts do not show much effect at the local level, however.

Guidance of search for all segments of the TIS is hindered by an unclear and fragmented institutional mandate for sanitation in Kenya: the Ministry of Health is responsible for sanitation and the Ministry of Water and Irrigation for sewerage[6] (GOV4, IDO1). Additionally, the preference for sewerage systems as "modern, high-tech infrastructures" in cities among most policymakers, planners, and the utility hinders the TIS (GOV1, GOV2, NGO6, iNGO2, iNGO3). The Technical Working Group Urban Sanitation of the Ministry of Health has advocated for the creation of County guidelines for urban sanitation to guide on-site sanitation innovation developments (NGO6, iNGO2).

Market development is only just starting to take place and is correspondingly still rather weak; most notable developments happen in the first and last segment of the value chain. The variety of sanitation services that are offered in the first segment create some competition in the offerings of sanitation services in informal settlements. Market developments in the last segment are very recent. Reused sanitation products have started to be sold in energy, animal feed and agriculture sectors. The links to these sectors and the demand for the reused products have, however, high potential.

Resource mobilization for the TIS from the County and National Government is low (GOV1, NGO5, NGO6, iNGO2, IDO2). If these governmental actors invest in sanitation at all, their support will mainly focus on sewerage infrastructure. Private investments in the TIS are also low because sanitation businesses are not very lucrative (iNGO3). In contrast to the lack of resource mobilization for the TIS in Kenya, grants and investments from the international development cooperation community are increasing, especially for treatment and reuse activities (NGO6, SEI1). An NGO's environmental health project officer explains:

> *"…of late donors don't want to fund "flush and forget", they want it renewable: either reuse or recycle … they are more environmental friendly."*

As described for the individual segments in Section 4.2, *legitimation* for on-site sanitation has progressed overall in recent years, especially at a policy level, where it is now recognized as an appropriate option. However, the taboo of handling human waste continues to hinder the creation of legitimacy in individual

[6] This splintered responsibility for sanitation is supposed to be solved in new policies that are currently being developed in line with the new constitution of 2010.

segments of the sanitation chain, especially for the conveyance segment, which is further undermined by the widespread idea that sewerage systems are the most superior form of sanitation systems.

Table 3 shows the overall functional profile of the TIS.

Table 3 Functional profile of the TIS.
Functional analysis of each individual segment of the sanitation chain in Nairobi (a darker shade indicates a further developed function). The bottom line represents a summary the functional TIS analysis of each individual segment of the sanitation chain (section 4.2). The last column summarizes the assessment of each function across all segments (section 4.3).

Functions	**Segment 1** User interface & storage	**Segment 2** Conveyance	**Segment 3** Treatment	**Segment 4** Use and/or safe disposal	**Assessment of functions across segments**
Entrepreneurial activities					*Well developed, mainly focused on 1, increasingly 3&4*
Knowledge development					*Well developed, mainly focused on 1, increasingly 3&4; Diffusion of knowledge is poor*
Guidance of search					*Lacking along all segments*
Market formation					*Various developments in 1, high potential in 4*
Resource mobilization					*Lacking behind, mostly deficient in 2*
Legitimation creation					*Difficult, especially in 2, but also to a lesser extent 3&4*
TIS analysis each segment	*Relatively well-progressed*	*Poorly developed*	*Emerging, increasing activities*	*Emerging and high potential to enter other markets*	**TIS functions developed differently in each segment. Overall functional development is relatively poor due to lack of coordination between different initiatives**

4.4 Explaining established governance modes in the TIS

We now finally assess the currently dominant governance modes that can be observed in the presented on-site sanitation chain TIS.

As a first step, we have to identify the interdependencies among the different value chain segments. The activities in the individual segments of the value chain interrelate in many ways. Use and disposal depend on the reliable collection, conveyance, and treatment of the fecal sludge. Treatment depends in particular on a reliable conveyance system. Toilets can only be operated safely if conveyance works in a reliable mode. This requires coordination of the location, size and type of toilet facility and the frequency of the conveyance services. Conveyance needs to have access to the treatment facilities in order to be successful. Through analyzing these strong interdependencies, we see for instance that the most weakly developed segment (conveyance) is also the one which all the other segments depend on. We can therefore already identify a major weakness in the whole TIS, which substantially hampers innovation development.

We will now proceed to analyze the governance mode based on three determinants, as introduced in Section 2.2 (complexity of transactions, codifiability of information, capability of suppliers along the value chain).

Complexity of transactions

The complexity of information and transactions in the sanitation chains is high. A variety of on-site toilet types are developed and used in the TIS to meet the demands of the diverse informal settlement residents. These toilets are used at various locations, depending on the availability of space in the dense informal settlements. Facilities are operated in public spaces, used in homes, shared on plots and installed in schools. Emptying of the facilities and collection of waste is a precise job in the narrow streets and bad road conditions. These services are organized differently by the three initiatives. The vertically-integrated operators try to control the waste that is captured. For example, in the CBS initiative urine and feces are separated and the toilet operators have to therefore check which waste is captured in the containers in order not to hamper the treatment process. Similarly in the bags, waste that is captured has to be very well checked: toilet paper is allowed, but no menstrual hygiene products or pampers. It is difficult to determine how bags are used; for example, some schools only use the bags for urine collection and not for feces (SE8). Many different innovative treatment technologies are used by the TIS actors, such as anaerobic digestion, (co-) composting, and black soldier flies (NGO1, SE3, SE7, SE8). These are enabled by the incoming waste streams, but in some cases the treatment is also restricted by the quantities and qualities of the incoming waste (SE3).

All said, the information that needs to be exchanged between the activities in the segments of the sanitation chain is diverse and concerns various aspects (e.g. technical specificities, quality and quantity of waste, physical conditions, social habits, etc.). The complexity of transactions in the innovative on-site sanitation chain in Nairobi is therefore considered high.

Ability to codify transactions

The information needed in the transactions in the sanitation chain (e.g. toilet types, type of waste that is captured, quantity of treatment, characteristics of fertilizer from human waste, etc.) is currently barely codified. The new KESH policy ideally enables the development of guidelines and standards for sanitation and hygiene in the city. However, the policy is still being operationalized at the County level (GOV1, GOV4, NGO6, iNGO2). So far, County guidelines and standards are either vague or do not exist. There are some transnational guidelines set by the WHO, and the Sustainable Development Goals (NGO6, IDO2), but these are very general and do not help codification at a local level. For example, no standards exist for fertilizer from human waste, and at the bio-centers standards from the World Food Program are being used which state that fertilizer from human waste can only be used on indirect crops (NGO1). All-in-all, the TIS lacks workable guidelines and specific standards, and the codifiability of the transactions is low.

Capabilities of the supply base

The analysis shows that the complexity of innovating in on-site sanitation in Nairobi has increased since the value chain initiatives have started operating. The number of actors involved in operating sanitation chains is low. In Nairobi only three organizations act as sanitation chain leaders, almost without

outsourcing any of the activities since the capabilities of potential suppliers is low. There are many potential suppliers specialized in the conveyance of waste in the city, but these have barely been included by the initiatives (these exhauster truck businesses and manual pit emptiers work in rather unhygienic and unprofessional ways). The sanitation chain leaders in the TIS therefore do not source these services because the capabilities of these suppliers are low.

In sum, we posit that the complexity of transactions is high, the codifiability of transactions is low, and the capability of suppliers in the current TIS can be described as low. To accommodate these characteristics, individual sanitation chain leaders in Nairobi opted for a hierarchical value chain governance mode. This way, the leaders are in control of the core processes, and coordination among the segments can be dealt with inside of the respective organizations. However, at the TIS level, coordination between the initiatives is minimal. We are therefore confronted with a highly coordinated governance mode at the level of each value chain, but rather weakly coordinated activities at the TIS level. This implies that a high number of system weaknesses will not be tackled by the individual initiatives and, in the end, will hamper innovation success of the overall field.

5. Discussion: Improving the governance mode of the on-site sanitation TIS

We presented an approach to scrutinize how both the value chain dimension and the innovation system dimension could be leveraged to improve the overall innovation success in the on-site sanitation sector in Nairobi. In general, we can say that the corresponding TIS is still in a "formative phase" (Bento and Wilson, 2016) as several innovation system functions are absent or underdeveloped. The functional analysis of the value chain segments revealed a heterogeneous set of innovation activities in the different segments and also exposed considerable system weaknesses. Furthermore, we identified the governance modes of the local TIS that encompasses the three value chains. We saw that the individual sanitation chain initiatives adopted hierarchical governance modes: the chains are internally highly coordinated and the sanitation chain leaders have vertically integrated all the segments. While at the system level, we identified that there is little coordination among the core actors, and so the governance mode of the TIS provides rather weak coordination.

The governance modes at the system and the value chain level might hamper the overall innovation performance of the TIS. The hierarchical governance mode of the individual initiatives is appropriate to compensate for current system weaknesses. However, due to the lack of coordination at the system level it also leads to a high overall complexity of the individual innovation processes and a lack of sufficient critical mass to run certain segments of the value chain effectively. This is most obvious in the treatment part. As soon as treatment capacities are built up to an effective scale, the corresponding sanitation chain leaders will be confronted with bottlenecks in terms of collection and transport. Indeed, some sanitation chain leaders lack sufficient waste stream to utilize their treatment plants at full capacity (SE3).

The vertical integration of the initiatives may also create problems for new actors entering the TIS who could potentially provide higher levels of capabilities and resources. The hierarchical mode of governing the individual initiatives might ultimately hinder coordination and the scaling up of on-site services in the city. We will now discuss how this analysis can inform the future improvement of on-site sanitation innovation by strengthening of system functions through the establishment of alternative governance modes.

At the system level, governance mode should likely change from a very distributed form to a more coordinated mode. Firstly, this requires conditions for a better *codification of transactions* which can enable/stimulate knowledge diffusion among the different TIS actors, especially among the chain leaders. They have complementary skills, but currently do not interact much. This represents a missed opportunity because they conjointly have access to a broader set of knowledge sources, e.g. by translating knowledge from global networks to the city level through their research collaboration. Increased codifiability would ease the exchange of complex knowledge and create mutual learning opportunities between TIS actors. Codification could, for example, include explicit strategies in the realm of guidance of search activities regarding innovative products (e.g. for urine diverting toilets) or process specifications (e.g. guidelines for innovative treatment of waste) (see also, Yap and Truffer (2019). Additionally, increased codification might help to mobilize new actors (e.g. entrepreneurs, implementing NGOs) who can provide complementary capabilities and resources to enter the TIS. One way of codifying transactions in the sanitation chain is through innovative digital technologies (e.g. using QR codes on containers to ensure that all the collected waste ends at the treatment site (Saul and Gebauer, 2018)). Lastly, increased codification in the form of standards for reused products or standards for toilets (hygiene, location, opening hours, etc.) by the Kenyan Bureau of Standards (KEBS) is essential for market formation of the TIS in the first and last segment.

Secondly, reducing the *complexity of transactions* would also contribute to reconfiguring the TIS' governance mode. Complexities can be tackled when building on synergies at the system level. This could also help to overcome challenges of individual sanitation chain leaders. The different TIS actors could meet to exchange complementary knowledge and to potentially reduce the complexity of transactions in their current sanitation chain, for instance regarding the management of different waste streams or the coordination of the conveyance processes. This would help scale and legitimize one or a few of the innovative conveyance and treatment systems. Thus, the TIS could benefit from a more coordinated type of governance in the second and third segment of the sanitation chain by encouraging a dialogue between more or less equal partners (Gereffi et al., 2005). The recent efforts of Nairobi County's Health Department in setting-up a coordination mechanism between the different actors working on on-site sanitation in Nairobi might contribute to achieving such changes (GOV1).

Lastly, *increasing the potential supplier competencies* could seemingly help develop the TIS. In this paper, the chain actors barely rely on suppliers. This is mostly because the competencies of incumbent suppliers

in Nairobi - mostly exhauster truck operators and manual pit emptiers - is low. These incumbents do, however, deal with the majority of conventional (not hygienic, dignified) on-site sanitation services in the informal settlements. Increasing the capabilities of these actors might help scale-up the volumes of waste that are treated and reused. The capacities of the city's small-scale private service providers should be improved in order to comply with the requirements of sustainable services provision (e.g. use of protective gear, professional customer interaction, etc.). This could also prevent manual pit emptiers from becoming the losers of a transition to well-managed on-site sanitation services. For such small-scale sanitation service providers, participation in new sanitation chains can be a crucial means of obtaining information and learning about hygiene standards set by the local government or accessing new types of markets. However, working with manual pit emptiers has proven to be difficult, and increasing their capabilities might require substantial learning efforts and knowledge transfer.

All told, we provided new insights into how to improve the overall on-site sanitation TIS in Nairobi's informal settlements through illustrating how more coordinated governance modes would be appropriate at the system level. This also has some implications for how the individual value chain initiatives will be managed. The strong hierarchical mode will have to give way to more relational configurations to reap the synergies. We see, for instance, that the user interface and storage segment is amenable to competition and entrepreneurial experimentation. A competitive relationship is probably appropriate for defining the relationship between the different operators to stimulate the currently successful systemic innovational development of this segment. Conveyance, however, shows the highest coordination deficit and interdependency with other value chain segments and should therefore be more strongly coordinated by the different initiatives. Therefore, the individual initiatives would have to disintegrate this segment of their value chains and by this implement more relational value chain governance modes. This might help generate stronger guidance for innovation activities, improve legitimation and attract more resources.

Treatment, use, and disposal are important segments for the success of the integrative value chains and would need intermediary intensity of coordination in order to enable experimentation to test a variety of alternative approaches, to tap alternative markets, and to improve legitimacy. Furthermore, we may ask who could take over leadership in these new governance arrangements. As the current initiatives are run by rather independent organizations with clearly delimited business models, coordination would probably need support from actors that control resource flows such as local governments or international donors. We assume that these actors would have a strong interest in improving the overall effectiveness of their investments after so many years of rather limited successes. Finally, the analysis of potential system-level governance modes can be a starting-point to identify innovative financial arrangements between a broad range of public and private actors required to address challenges of financial viability of particular activities and services.

Figure 3 illustrates a summary of the development of on-site sanitation innovation in Nairobi. It started with splintered innovations focused on individual segments of the sanitation chain and has developed into

an emerging on-site sanitation TIS based on three sanitation chain initiatives observed today. As discussed in this section, potential future improvements in innovation development and diffusion could include a more coordinated governance mode at the system level.

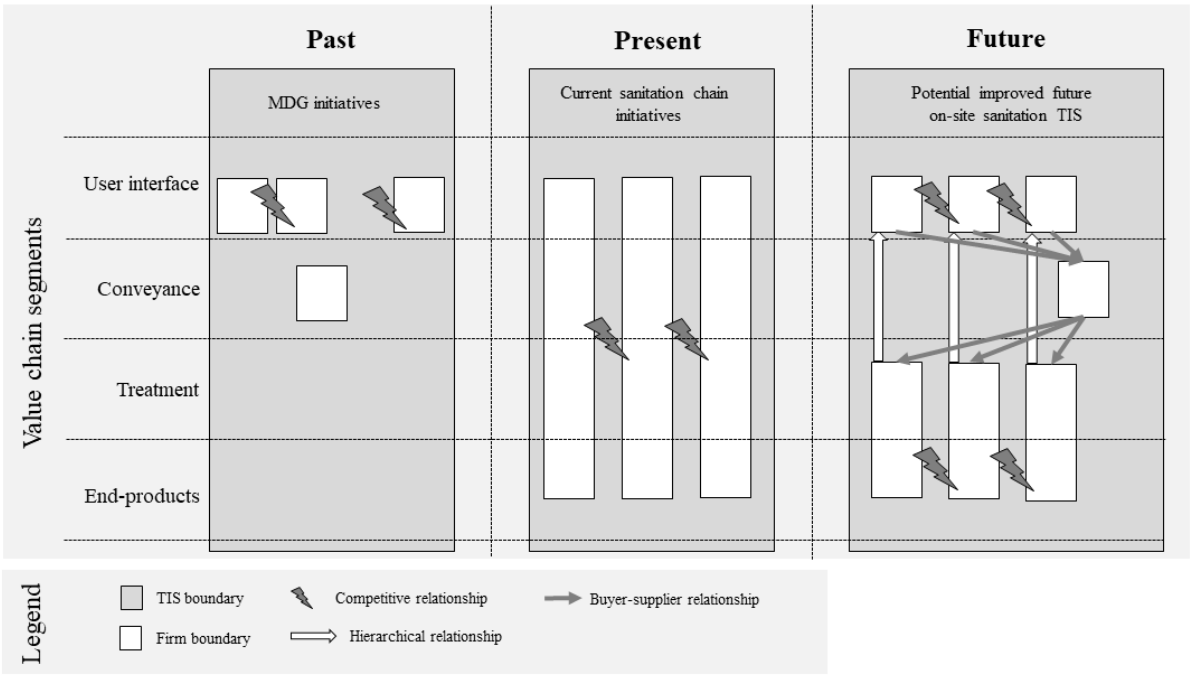

Figure 3. Three phases of on-site sanitation innovation in Nairobi: Innovations focused on individual segments of the sanitation chain in the past; three sanitation chain initiatives in the present; and possible changes in governance mode of the on-site sanitation TIS in the future.

6. Conclusion

The extension of the TIS analysis to entire value chains provides substantial insight into the challenges that innovational strategies in urban informal settlements in low-income countries need to address to transform basic service sectors. This paper showed how on-site sanitation innovations in Nairobi recently shifted focus from individual artifacts to the establishment of entire value chains. By extending the TIS approach towards value chains, we were able to identify a number of system weaknesses and mismatches in the governance modes, in and between segments, of individual value chains and at the TIS level. This explains (at least partly) the limited effectiveness of extant initiatives. Currently, social enterprises and NGOs have adopted rather hierarchical governance modes to coordinate the respective value chains. Through a systemic perspective that analyzes the different initiatives as one TIS, the paper identified the conditions of more relational or modular governance modes, which promises actors a fresh look at how to improve on innovation successes by transforming the sanitation sector towards a more sustainable state.

Systemic perspectives provide a deeper understanding of the interrelated success conditions related to regulation, finance, institutions, and social-cultural issues. Sanitation research has so far often focused too narrowly on the provision of specific products and infrastructures and, in doing so, promoted solutions with questionable sustainability impacts. More specifically, the enlarged TIS approach that we proposed

enables the identification of system weaknesses and suggests improvements both at the level of (segments of) value chains as well as at the system level.

The conceptual contribution of this paper has been twofold. As a first attempt to explicitly adopt the value chain perspective and its governance modes in TIS analysis, the paper opens up a broad variety of possible policy recommendations to improve innovation development by taking into account the interdependencies across different segments of the value chain. Our analysis identified how functional weaknesses could emerge out of inefficient coordination between upper and lower stream activities. A value chain perspective broadens the scope of TIS analyses and gives pointers for strategic "system building" in the form of potential coordination of actors and activities along the value chain (Musiolik et al., 2012; Planko et al., 2016).

Second, the paper translated the notion of governance modes to the level of innovation systems, which can encompass multiple (competing) value chains as well as broader system actors and processes. These provide new insights into the context conditions for desired governance modes at the TIS level and serve as points of interventions for lead actors and policy makers. In so doing, the paper also argues for a more proactive re/configuration of systemic governance modes by actors, especially under the conditions of a formative or newly emerging sector where key system managers play a crucial role. The Nairobi case shows how a conventional hierarchical model of single value chains might hamper new actors entering and interacting in the TIS, and how certain innovation activities could be more coordinated (e.g. conveyance and treatment of waste) by taking into account the multiple existing initiatives. Moreover, including new actors outside a TIS can contribute to overcoming individual capability failures and functional weaknesses, such as the lack of legitimation. The systemic perspective therefore helps generate integrative lessons about how individual sanitation chain leaders in Nairobi may improve the local situation, especially when aligning their respective initiatives through a more strongly coordinated governance mode in the overall TIS. Considering governance modes in order to improve TIS performance is therefore a novelty.

Although this paper has a limited focus on one particular sector in a city, the framework may be applied to other relevant cases in which the success of a TIS is also highly dependent on strategic coordination between upper and lower stream segments across the value chain of an entire socio-technical system. Extending the TIS framework in these directions will not only apply to cases in low-income countries, but to a whole new set of innovation and transition processes in other socio-economic contexts as well. Although the case presented only demonstrates the dynamics of governance modes within a value chain situated in Nairobi, the framework may be applied to the context of a globalized value chain provided that it refers to a sector/ socio-technical system i) that is emerging and is still in its early formative phase globally, ii) in which system building processes are still immature, or iii) that is undergoing transformation in which actors aim at changing the determinants/context conditions. These exemplify cases that require a coordinating role of lead firms or system managers in actively reconfiguring the governance modes of a

TIS. In the present paper, we were not able to develop a fully-fledged typology of TIS governance modes due to the limitations of a single case study. We hope, however, to have paved the way for such an endeavor by elaborating conditions for stronger and weaker coordination within a TIS as well as by revealing some possible modes of governance.

Appendix

Table 1. List of interviewees

Stakeholder Group	Interviewees	Code	Total
Government – ministries and other governmental bodies (GOV)	Nairobi County Health Department (3 interviews)	GOV1, GOV2, GOV3	5
	Ministry of Health	GOV4	
	Water Board	GOV5	
Local Non-Governmental Organizations (NGOs)	NGO A (4 interviews) *Implementing bio-centers*	NGO1, NGO2, NGO3, NGO4	7
	NGO B	NGO5	
	NGO C (2 interviews)	NGO6, NGO7	
International Non-Governmental Organizations (iNGOs)	iNGO A (Skype)	iNGO1	6
	iNGO B (3 interviews)	iNGO2, iNGO3, INGO4	
	iNBO C	iNGO5	
	iNGO D (owner of the biodegradable bag brand)	iNGO6	
International development (aid) agencies/organizations (IDO)	IDO A (2 interviews)	IDO1, IDO2	2
Firms/Social Enterprises (SEs)	Social enterprise A (7 interviews) *Implementing CBS*	SE1, SE2, SE3, SE4, SE5, SE6, SE7	12
	Social enterprise B (2 interviews) *Implementing biodegradable bags*	SE8, SE9	
	Social enterprise C	SE10	
	Firm D	SE11	
	Firm E	SE12	
Community Based Organization (CBO)	CBO A	CBO1	3
	CBO B (2 interviews)	CBO2, CBO3	
Professional (industry) Association (PA)	Private Exhauster Truck Association	PA1	1
Total			36

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