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Technological innovation system analysis of a value chain: Identifying synergies among urban on-site sanitation innovations

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Abstract

Innovative technologies have great potential to tackle sustainability challenges in sectors such as energy, agriculture, water, and sanitation in low-income countries. However, the potential of many of these innovative technologies has often not been met, because they are not being adopted, maintained, scaled-up, or diffused. Innovation system approaches can help to gain insight in the multiple dimensions that affect innovation development. In this paper we use the *technological innovation system* (TIS) framework. The TIS framework has mostly been applied to one technology or a technological field to analyze a single technology`s innovation process. This is sufficient for cases in which the innovation`s progress can be optimized in isolation of other external conditions, such as context structures and other TISs (Bergek et al., 2015), geographies (Binz, 2014), and sectoral configurations (Stephan et al., 2017). An often used broader view on technology is a *value chain perspective*. Such a perspective steers the attention of a TIS analysis to the necessary systemic change across an entire value chain in which the technological innovation process takes place: from production to consumption. In this paper we extend the TIS framework in order to analyze entire value chains, by drawing on insights from the value chain literature. This extension requires that a functional analysis of each individual step as well as on the level of the value chain. We apply the framework to the case of on-site sanitation in the informal settlements of Nairobi, Kenya. Several innovators attempt to set-up and govern a complete sanitation value chain in the city. This holistic innovation approach results from the lessons from the failure of past innovations that only focused on one step of the sanitation value chain (i.e. implementing toilets without a feasible waste collection system). The TIS perspective provides a systemic and integrated view across all these initiatives. The analysis is based on qualitative data from in-depth interviews with key informants and various secondary data sources. The analysis shows system weaknesses and the identification of potential useful future synergies between the individual innovative sanitation chains, which can lead to more systemic change in the sanitation sector. Optimization of the innovation system could accelerate the development and institutionalization of well-managed on-site sanitation chains in the city. The results can inform development agencies, NGOs, social enterprises, and policy makers.

Keywords

Innovation system, TIS, value chains, on-site sanitation, Global South

1. Introduction

Innovative technologies have great potential to tackle sustainability challenges and stimulate economic growth in sectors such as energy, agriculture, water, and sanitation in low-income countries[1]. However, the potential of many of these innovative technologies has often not been met. Some technologies are not being adopted (Owen et al., 2012) or adopters face many challenges (Kapurubandara and Lawson, 2007). Other technologies fail to be maintained (Hosman and Armey, 2017) or are not scaled-up/diffused (Painuly, 2001). One of the core reasons for the failure of innovative technologies in low-income countries comes from the fact that innovation processes relate to manifold aspects such as regulations, finance, institutions, social issues, the environment etc. These dimensions are not always all sufficiently considered in innovation processes. The innovation system literature can help to gain insight in the multiple dimensions that affect innovation development. Innovation systems are based on the idea that innovations do not develop in isolation, but are influenced by a "system" of actors, their networks and institutions (Hekkert et al., 2007). Such a systemic perspective on innovations helps to gain a better understanding how actors, their interactions in networks, and the role of institutional arrangements, promote or hinder innovations (Truffer, 2015).

One of the innovation system concepts is the technological innovation system (TIS), which are socio-technical systems consisting of networks of actors and institutions that interact and contribute to the development, diffusion and use of a new technology (Bergek et al., 2008; Markard and Truffer, 2008). The TIS framework has mostly been applied to one technology or a technological field to analyze a technology`s innovation process. This is sufficient for cases in which the innovation`s progress can be optimized in isolation of other TISs or contextual processes. However, many technological innovations are increasingly influenced by various "external" aspects, such as context structures and other TISs (Bergek et al., 2015), geographies (Binz, 2014; Binz and Truffer, 2017), and sectoral configurations (Stephan et al., 2017).

Thus, applying the TIS approach to a single technology or technological field has its limitations. When this problem arises, one potential way forward is to broaden the analytical perspective when applying the TIS framework. An often used broader view on technology is a value chain perspective. A value chain is a conceptualization of "the process by which technology is combined with material and labor inputs, and then processed inputs are assembled, marketed, and distributed…"(Kogut, 1985, p. 15). Such a perspective steers the attention of a TIS analysis to the necessary systemic change across an entire value chain in which the technological innovation process takes place: from production to consumption.

[1] We use the term "low-income countries" and "countries in the Global South" or the "Global South" interchangeably in this paper. The terms Global South and Global North in this paper are not a direct reference to the Northern or Southern Hemispheres, but applied to differentiate nations in terms of socio-economic capabilities and related characteristics. Global North are higher-income nations (with a GNI per capita > $3,956), while Global South are lower-income nations (GNI per capita < $3.955) (http://data.worldbank.org/about/country-and-lending-groups; accessed 29 January 2018). For more discussions on these contested terms, see (Pagel et al., 2014).

This includes technical, social and organizational innovations in provision, transportation and use. The literature on value chains has extensively dealt with analyzing the interlinked processes and governance of value chains (Gereffi et al., 2001; Kaplinsky and Morris, 2001). In this paper we systemically apply a TIS analysis to a value chain. We therefore draw on insights from the value chain literature to take the necessary analytical steps: both a functional analysis of each individual step of the value chain as well as on the level of the entire value chain. This conceptual expansion of the TIS framework contributes towards analyzing increasingly complex technological innovation development processes.

We apply the framework to the case of on-site sanitation in the informal settlements of Nairobi, Kenya. The set-up of on-site sanitation value chains might contribute to adequate provision of sanitation services to the city`s inhabitants, which is a fundamental challenge, especially in the informal settlements. The city has become a popular testbed for on-site sanitation innovations, and has even been called "the Silicon Valley of shit" (Kalan, 2011; Bwire, 2016). The analysis is based on qualitative data from interviews, reports, observations, and project visits. Using the conceptual framework we analyze the evolution of innovations from focusing on one step of the value chain to the set-up of entire value chains. We discuss the system weaknesses that lead to suggestions for systemic improvements of potential synergies between the individual innovation activities. Optimization of the innovation system could accelerate the development and institutionalization of well-managed on-site sanitation services in the city. The results can inform development agencies, Non-Governmental Organizations (NGOs), social enterprises, and policy makers.

The paper is organized as follows. In the next section we review literature on TIS and value chains. We build on insights from value chain literature to develop a conceptual framework of systemically applying a TIS analysis to a value chain. We then introduce the case of on-site sanitation innovations in Nairobi and explain the methodology. We use the framework to analyze the case, the results outline the evolution of on-site sanitation innovations in Nairobi and identify current system weaknesses. In the last sections we discuss potential systemic improvements, which leads to the conclusion and implications of using this approach for the broader research realm and practice.

2. Theoretical foundations and analytical framework

Many technological innovations have failed to meet the expectations of contributing to economic growth and tackling the sustainability challenges that are faced in many sectors 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., are not always all given sufficient attention in technological innovation processes. Romijn and Caniels (2011, p. 375) signal the need for policy makers in the international development-cooperation community to adapt a more systemic

perspective on technological innovations in low-income countries, towards realizing pathways of technological change that fit the local context and meet local needs.

2.1 Broadening the perspective of Technological Innovation System (TIS) analysis

Innovation system literature provides insights about the role of a diversity of actors, their interaction in networks and the role of institutional arrangements in the promotion or hindering of innovations (Truffer, 2015). One specific concept is the Technological Innovation System (TIS), which is generally defined as "a set of networks and actors and institutions that jointly interact in a specific technological field and contribute to the generation diffusion and utilization of variants of a new technology and/or a new product" (Markard and Truffer, 2008, p. 611). In addition to identifying the structural elements, TIS analyses focus on several key formative processes (knowledge development and diffusion, entrepreneurial experimentation, market formation, guidance of the search, creation of legitimacy and resource mobilization (see Hekkert et al. (2007); Bergek et al. (2008)). A functional analysis identifying these processes, leads to the identification of system weaknesses such as coordination, capability and institutional failures that hinder innovation development (Klein Woolthuis et al., 2005; Jacobsson and Bergek, 2011). A systemic and integrative view on different individual innovation activities can help to overcome these failures, for example through identifying possibilities for knowledge exchange, coordination, network formation, or division of labor in the value chain (Stephan et al., 2017, p. 720).

The TIS framework has mostly been applied to a technology or a technological field to analyze a single technology`s innovation process (see for example Agbemabiese et al. (2012); Blum et al. (2015); Tigabu et al. (2015) for TIS analyses of a single technology in low-income countries). This is sufficient for cases in which the innovation`s progress can be optimized in isolation of other TISs or contextual processes. However, many technological innovations are increasingly influenced by various "external" aspects, such as context structures and other TISs (Bergek et al., 2015), geographies (Binz, 2014; Binz and Truffer, 2017), and sectoral configurations (Stephan et al., 2017). For example the development of battery technology, which is related to the development of mobile applications such as laptops, and to the integration of intermittent renewables in electricity grids (Stephan et al., 2017, p. 713). Or in sectors such as photovoltaic (PV), in which TISs transcend different scales and the globalized PV value chain influences the maturing of an innovation system (Dewald and Fromhold-Eisebith, 2015). PV`s success does not only depend on the development of PV cells and PV modules, but also on the integration of PV systems into the electricity grid and the end use of the energy produced by households and industries. Systemic innovation problems are also increasingly interrelated, but are often identified independent from each other (Kieft et al., 2017). For example in agri-food systems, where the strongly interconnected components of the system are mostly managed separately, which leads to innovation processes in one domain that deal with constraints of the other (Meynard et al., 2017, p. 330). Innovation processes should take into account the up- and downstream dynamics in the value chain.

Thus, a too strict delineation of a TIS analysis to a single technology or technological field can in some cases be insufficient to understand the evolution of a technology, especially in cases of TISs that have many "structural couplings" (shared elements between a TIS and specific context structures) (Bergek et al., 2015). And also in cases where technological, organizational and institutional change along an entire value chain are necessary for the success of the innovation. It is thus important to consciously delimit the object of analysis and define an insightful focal TIS, to be able to gain a thorough understanding of increasingly complex technological innovation processes. This will then lead to well-founded policy recommendations based on a TIS analysis.

2.2 Value Chain Governance in a TIS

One potential way forward is to broaden the analytical perspective when applying the TIS framework. An often used broader view on technology is a value chain perspective. In this section we use the concept of value chain governance to broaden the perspective of TIS, enabling analysis of increasingly complex technological innovation development.

A value chain is "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). In this paper we borrow from the literature on Global value Chains (GVCs), which is a branch of value chain studies that focusses on the effects of globalization on development in different parts of the world (Kaplinsky, 2000; Gereffi et al., 2001; Humphrey and Schmitz, 2001). GVC analyses focus on organizational interlinkages and the interrelationship between different activities and actors in the value chain. These activities in a value chain - within firms and between firms - can be governed in different ways, for example by the value chain leaders (Kaplinsky and Morris, 2001; Morrison et al., 2008). Gereffi et al. (2005, pp. 83-84) distinguish five different types of value chain governance: market governance, modular value chains, relational value chains, captive relationships and hierarchy. The modes of coordination in these different typologies range from explicit coordination (vertically integrated firms) at the one end, to market based relationships on the other end. Network relationships are an intermediate mode of value chain governance (Gereffi et al., 2005, p. 83).

Three key determinants help to identify these different value chain governance modes: *complexity of transactions* (i.e. the complexity of information and knowledge transfer required to sustain a particular transaction); 2) *codifiability of information* (the extent to which this information and knowledge can be codified); and 3) *capability of suppliers along the value chain* (the capabilities of actual and potential suppliers in relation to the requirements of the transaction). These determinants can have two values, either "high" or "low", which leads to the five typologies of value chain governance (Table 1). For example in a hierarchy value chain "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).

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

Governance type	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 typologies are not static. The case studies presented by Gereffi et al. (2005) show that in many industries, increasing capabilities in the supply-base helped to push GVCs away from hierarchy and captive networks toward relational, modular and market types (p. 96). Changes in governance typologies can also be the result of new standards that enable codification of product and process specifications. Standards are different across different sectors and are constantly evolving, they can for example become obsolete as technologies change (Gereffi et al., 2005, p. 97).

When studying innovation development in a value chain, learning is crucial. Learning mechanisms differ between the various forms of governance (Gereffi et al., 2005; Pietrobelli and Rabellotti, 2011; Zhang and Gallagher, 2016). Learning and acquisition of new capabilities by actors in the value chain is affected by the codifiability and complexity of the knowledge (Morrison et al., 2008).Learning in the value chain "can be the result of pressure to achieve international standards, or be facilitated by direct involvement of the value chain leaders when the supplies` competence is low and the risk of failure to comply is high" (Pietrobelli and Rabellotti, 2011, p. 1261). Value chain leaders play an important role for knowledge transfer and technological learning to their suppliers. 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 on value chain governance add an important new level to analyzing innovation development using TIS. Even though there is no single best way to organize a value chain (Gereffi et al., 2005, p. 97), the governance mode influences innovation development and should thus be part of the analysis. Particular governance modes might hinder or enable innovation development. For example, certain modes might hinder the entrance of new actors to the TIS, the development of supplier capabilities (learning), or the creation of markets, which all reduce systemic innovation development. We also presume a causal relationship in the other direction: the structural elements and functioning of a TIS influence the determinants of value chain governance (for a similar view on interaction between National Innovation Systems and GVCs see Pietrobelli and Rabellotti (2011)). For example, when a TIS

develops, economies of scale can enable the rise of industry standards and development of specialist competencies among suppliers, which might change the governing mode. An evolving TIS can lead to reduced complexity (of technologies, processes, activities, etc.) which may increase the ability to codify knowledge and transactions. Based on these insights, we argue that analyzing value chain governance` influences on innovation development and vice versa, can help to optimize innovation development in a TIS. In this paper we will apply the value chain governance insights at the meso-level, instead of the macro-level in GVC literature. The determinants of value chain governance (complexity of transactions, ability to codify transactions, capabilities in the supply base) seem a helpful addition to TIS analyses to come up with policy recommendations at the level of the value chain. Such recommendations have not been made explicit in TIS studies so far.

2.3 Previous TIS studies

So far few TIS studies have paid attention to value chains in which technological innovation development takes place (Hellsmark, 2010; Musiolik and Markard, 2011; Sandén and Hillman, 2011; Stephan et al., 2017; Andersson et al., 2018). Some previous TIS studies emphasize that the set-up of value chains is important part of the system building process (Hellsmark, 2010; Musiolik and Markard, 2011; Planko et al., 2016). Hellsmark (2010) reconstructs how value chains in biomass gasification are developed in his TIS analysis, and Planko et al. (2016, p. 2330) take-up "coordination along the value chain" as one of the main aspects of their strategy framework for strategic collective system building. Musiolik and Markard (2011) analyze the creation of an emerging fuel cell value chain in their TIS study. They conclude that the creation of a value chain is a crucial task in an immature technological field, and emphasize that analytically, value chain development is so far not well covered by the functions of innovation systems. Others only use the value chain to delineate the TIS boundaries. For example Andersson et al. (2018) define their TIS by the artifacts, actors and rules along the industry-level value chain of electricity from a tidal kite power plant. Lastly, some previous studies use value chains to be more attentive to how a TIS relates to other sectors and technologies (Sandén and Hillman, 2011; Stephan et al., 2017). Stephan et al. (2017) refer to the TIS`s value chain to elaborate how a TIS relates to other sectors and Sandén and Hillman (2011) use the value chain to define different modes of interaction among technologies in innovation development. All these studies lack an explicit systemic analysis of the TIS development within each step of the value chain and at the level of the entire value chain. We aim to develop a framework building on insights from the value chain literature that fills this gap.

2.4 Framework for analysis

Building on the TIS literature and insights from value chain governance we develop an analytical framework. The complete value chain is conceptualized as being part of the TIS and not as the larger context or sector (see Stephan et al. (2017) for a similar view). The TIS is delineated by the

sociotechnical system structures along a value chain[2], and thus consists of core activities, technologies, actors, networks and institutions along a value chain (Andersson et al. (2018)for a similar view). The framework consists of two steps. In the first step we analyze the innovation activities in the individual steps of the value chain. Therefore we conduct a functional analysis of each step of the chain, to identify the heterogeneity functional development along the value chain (Table 2).

Table 2
Systemic functional analysis of each individual step of the value chain

	Step 1	Step 2	Step 3	Step 4
F1: entrepreneurial activities				
F2: knowledge development				
F3: knowledge diffusion				
F4: guidance of search				
F5: market formation				
F6: resource mobilization				
F7: legitimation creation				

In the second step we analyze the innovation development at the level of the entire value chain and identify the governance mode of the value chain. Therefore we analyze the determinants of value chain governance: complexity of transactions, ability to codify transactions, capabilities in the supply-base (high or low), and the degree of coordination (low to high) (Table 3).

Table 3
Analysis of the value chain governance determinants

	Complexity of transactions	Ability to codify transactions	Capabilities in the supply-base	Degree of explicit coordination
Interlinkages between core activities	*high or low*	*high or low*	*high or low*	*low to high*

3. Methodology

Case and system delineation

In this paper we use a case-study design (Yin, 2009). The case is innovation development in on-site sanitation[3] in cities in the Global South. The lack of sanitation supply cities in the Global South is one of the most persistent development challenges. Increasing urbanization and the failure of sewer systems in the majority of urban contexts enlarge this problem (Koné, 2010) and ask for new types of solutions to

[2] The value chain can exist at industry or sector level, but can as well cross sectors.
[3] *On-site sanitation* is "a sanitation system in which excreta and wastewater are collected, stored and/or treated on the plot where they are generated", as opposed to *off-site sanitation*, which is "a sanitation system in which excreta and wastewater are collected and conveyed away from the plot where they are generated. An off-site sanitation system relies on a sewer technology for conveyance" (Tilley et al., 2014, p. 173).

solve the urban sanitation crisis. Innovative safely managed on-site sanitation has the potential to improve sanitation services in cities in the Global South (Andersson et al., 2016).

This is an interesting case for the novel analytical framework, because focus on one technology (the toilet/latrine) cannot be successful without emptying, collection, transportation, treatment, and safe disposal or use of waste. This has not always been obvious, especially during the time 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 consideration of what to do with the waste (Koné, 2010; Wald, 2017). This led to cities in which overflowing pit latrines and flying toilets[4] became a normality, especially in the informal settlements. Since 2008 the "sanitation chain" has conceptually be the standard terminology to describe the necessary components of sustainable urban sanitation: *user interface*, *storage*, *conveyance*, *treatment*, *use or safe disposal* of waste (Tilley et al., 2014). Conceptually, these steps form a value chain that can enable the success of on-site sanitation systems (Figure 1). We define the on-site sanitation TIS by the infrastructures, technologies, actors and institutions along the sanitation chain. We do not only include the core activities of installing and operating sanitation services, but also the downstream activities of waste management, treatment and reuse. These activities are essential for the success of the early parts of the value chain.

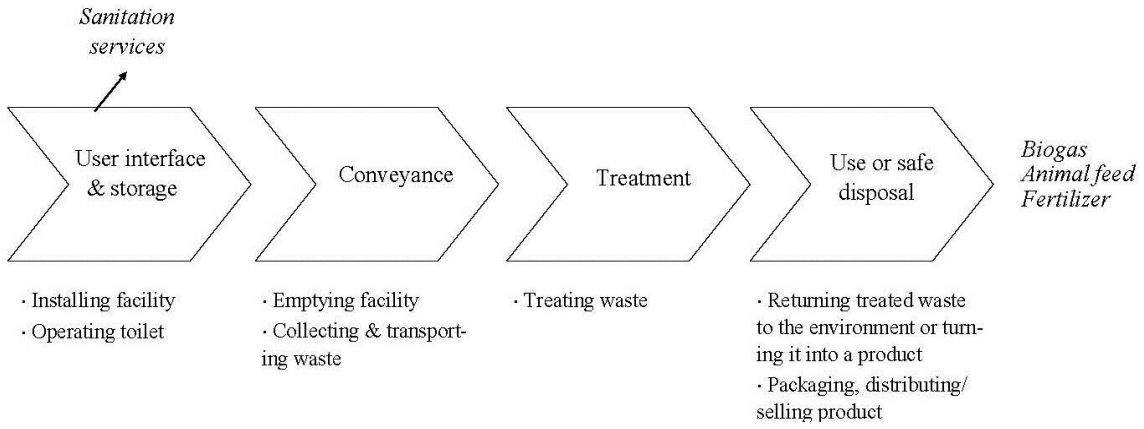

Figure 1. Steps, core activities and outputs of the sanitation chain

This paper focusses specifically on on-site sanitation innovation development in the informal settlements of Nairobi, Kenya. Adequate provision of sanitation services to the city`s inhabitants is a fundamental challenge, especially in the informal settlements where 36% of Nairobi`s population lives (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) try to introduce on-site sanitation innovations, which are more safe, dignified, clean, and well-organized than the sanitation options that are currently in use in informal settlements – such as pit latrines, septic tanks, hanging- and flying toilets.

[4] Flying toilet is when a plastic bag is used for defecation, then secretly thrown away in ditches and on rooftops

Methods and data

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

The interviewees were selected in different stakeholder groups. Several interviewees were identified during the first data collection period and snowball sampling was used during the data collection to identify additional key informants. This paper builds on 36 interviews with actors that represent organizations that implement innovations, as well as Ministry, Nairobi County and Water Board officials, representatives of NGOs, CBOs, and international developmental organizations. The Annex provides an overview of the interviewees, we will refer to the interview codes in the remaining sections. An interview guideline was developed on forehand. Questions were structured around the TIS functions, and focused on the different activities along the sanitation chain. The guidelines included small variations for the different stakeholder groups. Based on insights gained during the process the guidelines were updated. All interviews were recorded, transcribed and checked. In addition to the interviews, the first author wrote field notes based on observations. Lastly, various secondary data sources were used: reports, websites, journal articles, online newsletters, and online articles. As much as possible, all data sources were triangulated.

The interviews were coded using MAXQDA software. The TIS functions and value chain activities were starting points for the coding scheme that evolved during the process in which new and more detailed codes were defined. This processes can be described as "open coding"; labelling the phenomena in terms of concepts or categories (Gray, 2004, p. 331). Based on the data, an overview of the various actors` histories, projects, and pilots along the sanitation chain was created. Secondly, the TIS functions in each step of the sanitation chain were analyzed. Finally, an analysis of the value chain governance determinants at the level of the entire sanitation chain was conducted.

4. Results

4.1 Evolution of on-site sanitation innovations in Nairobi

Based on insights from interviews, observations and secondary data, we describe the evolution of on-site sanitation innovations in Nairobi. In the last decades several innovative on-site sanitation activities in Nairobi`s informal settlements focused on individual steps of the sanitation chain. For example the development of portable in-home toilets by different actors. However, these innovations never exceeded the pilot phase, because a feasible collection system for the waste was not set-up. Consequently, residents stopped using the in-home toilets and converted them into various other uses (Cherunya et al.,

submitted). Another innovative project aimed at improving the conveyance of sanitation waste through the professionalization of manual pit emptiers. Manual pit emptiers were equipped with protective clothes and special mechanical pumps to empty the pit latrines (NGO4, iNGO4, CBO2, CBO3). They also received management training. A designated disposal point into the sewer was created in agreement with the utility (NGO4, iNGO4). This innovative 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). Also, the legitimation of manual pit emptiers among customers remained low, so their service was not always accepted. In this project, both the connection to the earlier and later steps in the chain were not well established. The focus was too strongly on the conveyance step. The pit emptiers went back to (illegal) business as usual, which included dumping the waste (NGO4). Concluding, these innovative on-site sanitation activities were not successful, because they did not address the entire sanitation chain.

In order to overcome the problems of innovations that only focused on one step of the sanitation chain, several actors have recently come-up with a more holistic approach. They set-up and govern entire sanitation chains. Currently, three different sanitation chain approaches are demonstrated in Nairobi. These are: the bio-center, biodegradable bag, and Container Based Sanitation (CBS) approach. Taken together, we conceptualize these three innovative approaches as a TIS of on-site sanitation in Nairobi.[5] Figure 2 shows the TIS actors that are involved in or related to these three approaches. We now describe these three different sanitation chain approaches and analyze their performance.[6]

[5] In the TIS we focus on the approaches that are highly innovative and try to scale-up the entire chain. We exclude on-site sanitation initiatives that are not focused on the informal settlements, such as mobile toilets for events. We also exclude some other small initiatives. For example a CBO that runs public sanitation facilities using composting toilets (see (KDI, 2014)).
[6] In this specific empirical case we have to analyze three different value chain configurations that we together conceptualize as the TIS. This can differ from case to case, in other cases a TIS analysis can thus also comprise only one value chain configuration.

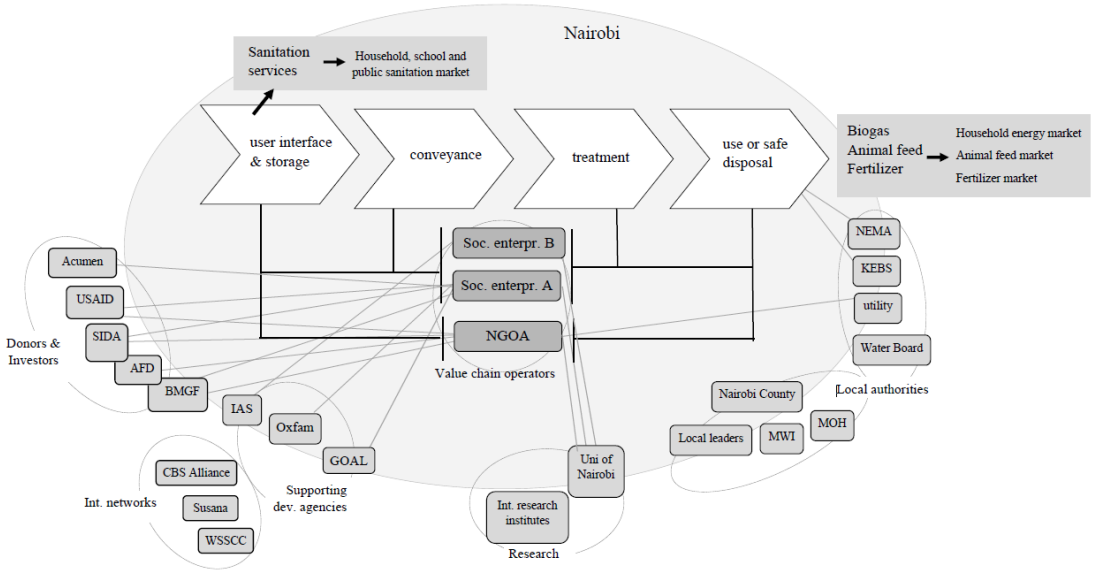

Figure 2. Main actors of Nairobi`s on-site sanitation TIS in 2016 (compiled by the author)

Bio-center approach

Bio-centers are community centers that have several functions, one of them are public sanitation facilities. A biogas reactor in the bio-center is used to treat the waste and produce biogas. The concept was developed by a Kenyan NGO that introduced it in Nairobi in 2007 and act as a value chain leader in this approach. 64 bio-centers have been installed in Nairobi`s informal settlements (Umande, 2016a). The biogas produced in the bio-centers is used by local communities for cooking and to heat the showers in the centers (Wamuchiru, 2015). It is difficult to sell the biogas that is produced in the bio-centers (NGO1). Conveyance of waste is not necessary in this approach, because it is treated on site. Various entrepreneurial- and knowledge generating activities take place to improve this approach. For example, research on the potential of installing a treatment plant for bio slurry and experiments transporting biogas to households (Umande, 2016b) (NGO1, NGO3). The NGO has a large partner network in Nairobi and internationally, in which ideas and knowledge are exchanged (NGO1). Funding for the bio-centers comes from the local water board, Nairobi County and international donors, who support the bio-center concept as a proper solution for sanitation in informal settlements (Binale, 2011). The bio-center`s sanitation services are offered on the public sanitation market in the informal settlements. Bio-centers are well accepted sanitation services among informal settlement`s residents, whereas the use of biogas is less accepted. Treating waste using anaerobic digestion is a well-known and accepted technology. The functional development of this approach is summarized in Table 4.

Table 4
Overview TIS analysis of the bio-center approach. A darker shade indicates a further developed function (see Annex for details).

Bio-centers approach	Sanitation chain			
	User interface & storage	Conveyance	Treatment	Use and/or safe disposal
F1: entrepreneurial activities				
F2: knowledge development				
F3: knowledge diffusion				
F4: guidance of search				
F5: market formation				
F6: resource mobilization				
F7: legitimation creation				

Bio-degradable bag approach

The biodegradable bag approach is based on a personal single-use biodegradable bag, used in people`s homes or at schools for the storage of waste. 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 the composting process, 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 that acts as a value chain leader in this approach (Wirseen et al., 2009; Graf et al., 2014; Peepoople, n.d.). The iNGO did a lot of experimentation and research on the use of the bags and the optimal treatment and reuse process (SE8). In the first years, the bags were sold to households and there was a good demand among informal settlements` residents (SE8, SE9). Currently, the bags are not sold, because of production problems (iNGO6). However, about 100 schools in informal areas are provided with biodegradable bags for free (SE9). Among policy makers and planners the biodegradable bags are sometimes perceived as a sub-standard sanitation option (IDO2), and only accepted as a temporary solution. The legitimation of this innovative on-site sanitation option is thus lacking behind. The functional development of this approach is summarized in Table 5.

Table 5
Overview TIS analysis of the biodegradable bags approach. A darker shade indicates a further developed function (see Annex for details).

Biodegradable bags approach	Sanitation chain			
	User interface & storage	Conveyance	Treatment	Use and/or safe disposal
F1: entrepreneurial activities				
F2: knowledge development				
F3: knowledge diffusion				
F4: guidance of search				
F5: market formation				
F6: resource mobilization				
F7: legitimation creation				

CBS approach

The container based sanitation (CBS) approach is based on stand-alone waterless toilets that capture waste in (portable) containers (Tilmans and Russel, 2015; WSUP, 2017). The containers are regularly

collected, transported and the waste is treated and disposed or reused. CBS was introduced in Nairobi in 2011 by an international social enterprise that acts as a value chain leader (Esper et al., 2013; Auerbach, 2016). The containers used are Urine Diverting Dry Toilets (UDDTs) that separate urine and fecal matter (Tilley et al., 2014, p. 46). The containers are installed as public toilets, shared toilets, at schools, and in homes. The collection is human powered using handcarts to bring the waste to collection point from where trucks transport the waste to the treatment plant (SE6). The waste is composted and treated and animal feed and fertilizer are produced and sold to farmers (Auerbach, 2016). The enterprise experiments a lot and develops knowledge in all steps of the chain. The initiative has attracted a lot of interest from international donors and investors. And in Kenya, CBS was recently mentioned in the new Kenya Health and Sanitation (KESH) policy of the Ministry of Health (Kenya, 2016). The approach fueled several market developments in the sanitation sector. In the first step of the chain the enterprise operates a franchise system in which entrepreneurs franchise a toilet and run it as a business (Auerbach, 2016). At the end of the chain reused products are sold on different markets. The organic fertilizer made 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 enterprise farmers are dissatisfied with currently available options (quality, inconsistent supply) (Auerbach, 2015). The functional development of this approach is summarized in Table 6.

Table 6
Overview TIS analysis of the CBS approach. A darker shade indicates a further developed function (see Annex for details).

CBS approach	Sanitation chain			
	User interface & storage	Conveyance	Treatment	Use and/or safe disposal
F1: entrepreneurial activities				
F2: knowledge development				
F3: knowledge diffusion				
F4: guidance of search				
F5: market formation				
F6: resource mobilization				
F7: legitimation creation				

4.2 Functional analysis of the TIS

We transcend the individual approaches and take an integrated systemic perspective on each step of the sanitation chain to analyze the key formation processes.

User interface and storage

The innovative activity in this step of the sanitation chain is mostly focused on improving toilet designs, based on the different preferences of users. Various TIS formative processes take place in this step of the sanitation chain. For example, many different experiments and entrepreneurial activities take place. This

has resulted in approximately 76.000 daily users[7] of the different types of innovative on-site sanitation services in Nairobi`s informal settlements. Various innovative pilot projects mobilized resources from international donors to develop improved toilet designs (SE4, SE10, iNGO1). Most on-site toilet innovations have generally been accepted among users. However, for completely new toilet interfaces such as biodegradable bags or UDDTs socio-cultural issues have had to be overcome. A social enterprise`s founder 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 and trying to be as general as possible so it serves as many people as possible…"*

The legitimation of innovative on-site sanitation services among policymakers has progressed in recent years. The 2016 KESH policy recognizes urban on-site sanitation as an option and gives various innovative toilets recognition. One can state that the innovative sanitation services in this first step of the chain have developed into a market niche and hold a small share of the total market of Nairobi`s public sanitation services. Such a market for public sanitation services has existed for many years in Nairobi.[8] Many informal settlement`s residents use pay-per-use public sanitation services on a regular (daily) basis (Cherunya et al., submitted).

Conveyance

The innovative activities in this step are focused on improving the collection efficiency to lower the costs of collection and transportation services. However, in this step of the sanitation chain only a few TIS formation processes take place. There is relatively little experimentation and research done to develop new technologies, and mostly conventional wheelbarrows, handcarts and trucks are used (SE6, SE8, SE9, NGO1). More research in this step seems useful, because collecting waste in the narrow streets of the informal settlements is difficult and time-consuming. Waste in the TIS is collected and transported on a small scale coordinated by the individual sanitation chain leaders. Not only research into, but also legitimation creation 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. A CBO`s founder points at a cultural problem that for example CBS innovators need to overcome:

[7] 1134 container-based toilets, 53.436 daily users (Sanergy, 2018); 42 bio-centers, 5000 daily users (Umande, 2014); biodegradable bags provided to 100 schools, 18.000 children per day (Peepoople, n.d).

[8] The market for public sanitation increasingly gained attention as a result of the success of the "Ikotoilets", a public sanitation concept which was one of the first to introduce a clean and high quality public sanitation services in Nairobi in 2006 (NGO6, SE11).

"…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."

And a social enterprise`s founder explains how the taboos around human waste complicates the work for on-site sanitation innovators 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…"

Officially, the transportation of human waste in containers and bags on trucks was licensed by the National Environment Management Authority (NEMA) (SE3, SE9). However, in order to create full legitimacy for this step of the TIS, on-site sanitation innovators have to show that they can handle raw fecal sludge safely to informal settlements` residents as well, because it is a critical point for many Kenyans (IDO1). Lastly, the sanitation chain leaders also have to convince potential employees that it is a proper job to do (SE6, SE9).

A market of human waste transportation services already exists in the city. Services are operated by manual pit latrine emptiers and exhauster truck operators who empty septic tanks and pit latrines (CBO2, CBO3, PA1). This market is not well-regulated and controlled, so a lot of waste is dumped (iNGO2). The collection and transport services in the TIS are well-managed and hygienic compared to these services. The TIS`s conveyance services do not access the existing market, because they are operated at a small scale as part of a bigger system and only serve the toilets of their "own" sanitation chain. However, if the TIS scale sup, the TIS`s conveyance services might become competition for the existing services in future. Consequently, manual pit emptiers could be among the major losers of a transition to well-managed on-site sanitation. This should be on the agenda to avoid perverse livelihood outcomes (similar to the local artisans that do not benefit from a transition to clean cook stoves (Atteridge and Weitz, 2017)).

Treatment

The innovative activities in this step focus on new treatment technologies. Various TIS formative processes take place in this step of the sanitation chain. Several new technologies have been implemented by the sanitation chain leaders, such as anaerobic digestion, (co-)composting, and black soldier flies (NGO1, SE3, SE7, SE8). These treatment technologies are all used on a relatively small-scale. Much research and testing is done to develop these treatment technologies further, in collaboration with (international) research institutes and universities (NGO1, SE7, SE8). Financial support for this research comes mainly from international donors. The other systems functions in this step are relatively underdeveloped. There are no policies or goals for the (large-scale or central) treatment of waste from

on-site sanitation systems in Nairobi. Also, the innovative small-scale treatment 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 derived from the fact that it is difficult to obtain land and permission to build a treatment plant for fecal sludge (NGO1, SE3). The legitimation for this step of the value chain might also be hindered by the earlier mentioned taboos of handling human waste in Kenya.

Use or safe disposal

Innovative activity in this step led to the development of several reused products, such as fertilizers, animal feed and biogas. Research is done by the sanitation chain leaders in cooperation with (international) research institutes and universities to optimize the reused products. The general "waste as a business" paradigm at policy level is strong and 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). Also the KESH 2016 policy 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)). And general attention for reusing human waste in the international press often features the innovations in Nairobi (see for example Whitehead (2014); Scherer (2015); Njoroge (2016); Ruiz-Grossman (2016); Arbogast (2017)).

Several of the products are licensed and sold as new (types of) products in existing markets of fertilizers, energy, and animal feed. Fertilizers and animal feed are sold on agricultural markets. Selling biogas has so far been difficult and biogas produced in the bio-centers is mostly given away or sold for a low price (Wamuchiru and Moulaert, 2017). Despite the policy support and market demand for reused products, the adoption of the products is to a certain extend hindered by the taboo of using human waste. Especially users with insufficient information about their safety can be hesitant towards using fertilizer or biogas made from human waste. An iNGO`s environmental health project officer explains hindrance in legitimation creation:

> *"…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 like human environment…"*

Another Officer of a local NGO explains (NGO6) explains the cultural taboo of handling fecal waste:

> *"I think the biggest barrier remains in the mind because there people who still don't believe that the faecal matter should be handled in a way that it's done under on-site sanitation. Some people believe you should flush it and forget about it. It should never be used for fertilizer,*

making fertilizer; it should never be used for any productive purpose because it's human faeces. So that's a hindrance"

Different strategies are used in the TIS to overcome these issues, for example: marketing of fertilizer without mentioning the raw material that is used, demonstrations of the products to show their effectiveness, and education about the safety of the products.

Overall functional development

Based on the analysis of the formative processes in the individual steps of the sanitation chain, Table 7 summarizes the differences between the individual steps. Certain functions are better developed in particular steps then in others. The functions of entrepreneurial activity and knowledge development are overall the best developed along all the steps of the entire chain, as a result of the individual efforts of the chain leaders. The systemic functions such as knowledge diffusion, guidance of search and resource mobilization are underdeveloped in most steps of the sanitation chain.

The *diffusion of knowledge* in Nairobi is very limited, because research and piloting is led by individual chain leaders who are strongly vertically integrated in their own value chain, but do not interact much. For example, many different treatment technologies have been developed and tested by different actors in the city (NGO1, SE7, SE8). A potential platform to exchange more information on on-site sanitation innovations is the "Technical Working Group (TWG) Urban Sanitation" under the Ministry of Health (MOH). This group consists of representatives of NGOs and social enterprises. However so far, the group`s focus has mainly been on advocacy and the creation of County guidelines for urban sanitation (NGO6, iNGO2). Thus a clear platform or network for coordination and knowledge exchange in Nairobi seems missing. In contrast, some of the chain operators have strong connections to international networks and platforms in which they exchange knowledge with likeminded NGOs, development agencies and social enterprises around the world.

Guidance of the search is hindered by the unclear and fragmented institutional mandate for sanitation in Kenya (iNGO3). The MOH is responsible for sanitation, which includes hygiene education, behavior change, sanitation marketing, etc. (GOV4). The MOH supports on-site sanitation systems as a permanent service option in urban areas (GOV4). In contrast, the Ministry of Water and Irrigation (MWI) is responsible for the construction of water-borne sewer systems and does not support on-site sanitation systems in urban areas (IDO1). This splintered responsibility for sanitation in Kenya is supposed to be solved in new policies that are being developed as part of the new constitution of 2010. This fragmented mandate results in the absence of visions and expectations for on-site sanitation.

Financial *resources* for on-site sanitation from the County- and National government are lacking (GOV1, NGO5, NGO6, iNGO2, IDO2), and aid to public actors (e.g. the utility) is used for the expansion of sewers, not for on-site sanitation. However, the international development community and some investors have increasing expectations about the potential of on-site sanitation innovations to

improve the situation of the urban poor in the Global South (NGO6, SEI1). This leads to funding for most of the activities of thee on-site sanitation innovators in Nairobi. One of the expected benefits of on-site sanitation chains is their environmental sustainability compared to sewer systems (NGO6). An iNGO`s environmental health project officer puts it:

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

Because the TIS relies heavily on donor funding, the agendas of international donors have a guiding influence on the entrepreneurial activity and research done (NGO7).

Table 7
Summary of the complete TIS analysis. A darker shade indicates a further developed function (see Appendix 2 for details).

Complete TIS	Sanitation chain			
	User interface & storage	Conveyance	Treatment	Use and/or safe disposal
F1: entrepreneurial activities				
F2: knowledge development				
F3: knowledge diffusion				
F4: guidance of search				
F5: market formation				
F6: resource mobilization				
F7: legitimation creation				

4.3 Identifying the value chain governance

The analysis of the evolution of on-site sanitation innovations in Nairobi illustrates that the current innovation approaches in on-site sanitation are more complex than in the past when the focus was on innovations in only one step of the sanitation chain. In the current holistic approaches of the innovators, individual steps of the sanitation chain cannot be optimized on their own. We therefore identify the interlinkages in the sanitation chain and analyze how the sanitation chains are governed, in order to understand how systemic innovation development of these holistic innovations can be improved.

The activities in the individual steps of the sanitation chain are linked in three ways. First, the location, size and type of toilet facility are influenced by the physical context and users` preference, and this affects the possibilities, reachability and frequency of innovations in emptying, collection and transportation activities. For example, the smaller a toilet, the more frequent it needs to be emptied or collected. Second, possibilities of treatment innovations are enabled or restricted by the quantity, quality and type of waste that is collected, emptied and transported. And lastly, innovation in the production of reused products and their possible applications are linked to the type of treatment and the intensity and technology used.

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 settlements`

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 in installed at schools. Emptying of the facilities and collection of waste is a precise job in the narrow streets and under bad road conditions. The individual chain operators try to control the waste that is captured. For example, the containers separate urine and feces and the sanitation chain leaders try to control which waste is captured in the containers, necessary for the treatment process. Similarly, waste that is captured in the biodegradable bags is ideally controlled: toilet paper is allowed, but no menstrual hygiene products or pampers should be mixed with the waste. However, it is difficult to control 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 implemented by the sanitation chain leaders, such as anaerobic digestion, (co-)composting, and black soldier flies (NGO1, SE3, SE7, SE8). These technologies 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 sanitation chain is diverse and concerns various aspects (e.g. technical specifies, quality and quantity of waste, physical conditions, social habits, etc.). The complexity of transactions in the innovative on-site sanitation chains are thus high.

Ability to codify transactions

The complex information in the transactions in the sanitation chains (e.g. toilet types, type of waste that is captured, quantity of treatment, characteristics of manure from human waste, etc.) is currently barely codified. The new KESH policy will ideally lead to the development of guidelines and standards for sanitation and hygiene in the city in the future. However, the policy still needs to be operationalized and implemented to the County level (GOV1, GOV4, NGO6, iNGO2). So far, County guidelines and standards are vague or not existing. There are some transnational guidelines set by the WHO, and the SDGs (NGO6, IDO2), but these are very general and do not help with the codification of the specific transactions in the sanitation chain. For example, no standards exist for manure from human (NGO1), and NGO1 thus uses standards from the World Food Program which say that manure from human waste can only be used on indirect crops (NGO1). All-in-all, the on-site sanitation innovators lacks workable guidelines and specific standards and consequently the codifiability of the transactions is low.

Capabilities in the supply-based

The analysis shows that the complexity of innovating in on-site sanitation in Nairobi has increased since the innovators apply more holistic approaches. The number of actors involved in operating sanitation chains in the TIS is low. In Nairobi only three actors lead and govern an entire sanitation chain, almost without outsourcing any of the activities, because the capabilities of potential suppliers is low. However, especially for the emptying, collection and transportation of waste, there are many potential suppliers in the city, who could contribute to the innovative on-site sanitation approaches with their experience and

knowledge about the local circumstances. These are enterprises operating exhauster truck businesses and manual pit latrine emptiers, which are experienced in transporting human waste in the city, but in an unhygienic and unprofessional ways. Therefore, they are not considered to take part in the innovative on-site sanitation chains. All-in-all, the sanitation chain leader do not use (potential) suppliers to outsource certain activities, because the capabilities these suppliers in the city are low.

Degree of explicit coordination

In sum, the complexity of transactions is high, the codifiability of transactions is low, and suppliers are barely included in the sanitation chains. The sanitation chain leaders in Nairobi are explicitly coordinating their entire sanitation chains and are highly vertically integrated. We conclude that the sanitation chains that form the TIS are characterized by *hierarchy* value chain governance (Gereffi et al., 2005). The sanitation chain leaders are in control and the coordination is flowing from managers to employees within the sanitation chain governing organizations (Table 8).

Table 8
Interlinkages core activities on-site sanitation chain and value chain governance determinants

Interlinkages activities in the on-site sanitation chain	**Complexity of transactions**	**Ability to codify transactions**	**Capabilities in the supply-base**
Emptying, collecting and transporting waste are linked to installing and operating toilets	- toilets are located in various different places, difficult to reach, difficult to collect waste	- no standards for opening hours toilets - no standard locations for public toilets - no standard operational mode of public toilets - no standards or guidelines for emptying, collecting and transporting human waste	- few actors (employees sanitation chain operators) are trained for the proper and hygienic collection of human waste - potential suppliers have low capabilities (i.e. unhygienic and unprofessional practices)
Treatment of waste is linked to emptying, collecting and transporting waste	- the quality of collected waste can differ a lot - variety of containers, carts, bags used for transport	- quality/type of waste is difficult to codify, there are no standards for faecal sludge - quantities of collected waste are not codified - no standards or guidelines for treatment processes	- only the sanitation chain operators have the capabilities and knowledge on treating faecal sludge
Producing reused product is linked to treatment of waste	- complex to deal with different types of waste in treatment process - different types and a variety of products are produced for different purposes and sectors (e.g. household energy, animal feed, fertilizer)	- there are no specific standards for reused products or guidelines for reusing processes	- only the sanitation chain operators have the capabilities and knowledge to produce reused products
Score	**High**	**Low**	**Low**
Degree of explicit	**High** - the three main chain operators all govern the entire on-site sanitation chain		

coordination	

5. Potential synergies among TIS in- and outsiders

The analysis of the on-site sanitation TIS in Nairobi showed that the overall field of activities in on-site sanitation innovations in Nairobi does thus not show a lot of systemic interaction. The on-site sanitation TIS is thus in a "formative phase" (Bento and Wilson, 2016), many of the innovations have been tested in isolation from each other – even though they target the same problems in the same city. The functional analysis of the individual steps of the value chain illustrated heterogeneous innovation development along the chain in the TIS. When comparing the steps, innovation development in the conveyance and treatment step lack mostly behind. In the entire TIS knowledge diffusion, guidance of search, and resource mobilization lack behind.

The sanitation chains in the TIS of this paper are governed in hierarchies: the chains are highly coordinated. This might contribute to the lack of systemic innovation development, because research and piloting is led by individual chain operators who focus on their own sanitation chain and do not interact much. The vertical integration of the value chain leaders might create difficulties for new actors to enter the TIS, who could provide complementary capabilities and resources.

All-in-all innovative on-site services have difficulties to scale-up. Scaling-up such services an contribute to improving public health situation in Nairobi. Innovative on-site sanitation services influence the dimensions of several configurations in the sanitation sector of the city, and could potentially contribute to aligning and improve city-wide sanitation services (e.g. coordinated collection of waste from various on-site services in different configurations) (van Welie et al., forthcoming).

As systemic functions cannot be developed by individual actors, we discuss how changes in chain governance determinants might improve synergies among TIS actors and TIS outsiders to develop the systemic functioning.

Knowledge diffusion among the different TIS actors is low, especially among the chain leaders. There is a lack of coordination between the actors. *Increased codifiability* of knowledge and information might help to exchange complex knowledge, create mutual learning processes and deliberate knowledge transfer between actors. Codification could for example include innovative product specifications (e.g. for UDDTs) or processes specifications (e.g. guidelines for innovative treatment of waste). Secondly, increased codification in the form of standards for reused products, standards for toilets (hygiene, location, opening hours etc.) is essential for market formation of the TIS in the first and last step. The available national policies international standards therefore need to be adapted to the County level. This requires strengthening of the capabilities of the County government, which has worked on adapting national policies since the decentralization in 2010. Lastly, increased codification might help to interest new actors (e.g. entrepreneurs, implementing NGOs) who can provide complementary capabilities and resources, to enter the TIS. For example, for new actors interested in contributing to the reuse activities in the TIS, codification of the quality and quantity of the collected waste is important. 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)). However, the entrance of new actors that take care of certain processes in the value chain would require a more modular governance mode. This would require coordination of different actors covering all the activities in the sanitation chain, and it might not be of interest to the current chain leaders to open-up their sanitation chains to other actors.

The current TIS is made up by three different approaches led by three different chain leaders, which do not complement each other much. For example, the collection and transportation services are taken care of by all three chain operators in different manners. And each actor has implemented one or more innovative treatment technologies. This large variation of experimenting and pilot projects sometimes leads to inefficiencies from a city-level perspective. For example, when particular actors lack sufficient waste stream from earlier steps in their sanitation chain to utilize the full capacity of their innovative treatment facilities. Different actors could increasingly complement each other`s capabilities and activities. A more relational governance mode in which the activities in the TIS are coordinated would potentially *reduce the complexity of transactions* (Pietrobelli and Rabellotti, 2011, p. 1265). The conveyance and treatment step can for example be coordinated among the different TIS` actors. This would reduce transaction complexities, and help to scale one or a few selected innovative conveyance and treatment systems. Additionally, scaled conveyance or treatment activities could contribute to creating legitimacy of on-site sanitation among (public) actors that are sewer focused. Thus, the TIS could benefit from a more relational type of governance in the second and third step, characterized by a dialogue between more or less equal partners (Gereffi et al., 2005), as opposed to several splintered actors controlling individual innovation activities. The recent efforts of Nairobi County`s Health department to set-up a coordination mechanism between the different actors working on on-site sanitation in Nairobi could contribute to achieving such changes (GOV1).

Lastly, *increasing the potential supplier competences* seems necessary to scale-up innovative on-site sanitation services in Nairobi. In this paper`s case, the innovative chain leaders do currently not use many suppliers, mostly because the competences of potential suppliers in Nairobi is low. Potential suppliers such as manual pit emptiers do however take care of the majority of conventional on-site sanitation services in the informal settlements at the moment. Integrating them in the innovative approaches might bring new competences to the TIS, especially because these men do really know the local conditions and customers well. Their capacities should therefore be improved towards complying with the (hygienic) standards of the conveyance activities of the innovative sanitation approaches (e.g. use of protective gear, professional customer interaction, etc.). Their involvement could for example lead to scaling the volumes of waste that are treated and reused (iNGO2). An additional benefit of including them in innovative approaches would be to 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 the innovative sanitation services can also be a crucial mean to obtain information and learn about hygiene standards set by the local government, or accessing new types of

markets. However, increasing their capabilities requires substantial learning efforts and knowledge transfer (Pietrobelli and Rabellotti, 2011). Actors that could take care of such learning processes are the chain leaders. Alternatively, supportive NGOs, the local government, or educational institutes can also train potential suppliers, because it is in the interest of public health in the city. Education and training of such actors can be enabled by better codification of the innovations developed. Working with manual pit emptiers in Nairobi can however be challenging, as has been learned in previous NGO-led projects, among many other things because of their use of alcohol and drugs and their bad reputation among residents (NGO4, iNGO4). Power asymmetries and conflicts might thus hinder knowledge transfer (Morrison et al., 2008).

These examples show how increasing codifiability of transactions, reducing particular complexities, and increasing capabilities of potential suppliers, can benefit the systemic functioning of the TIS. Different in traditional TIS analyses, these recommendations are not based on a sole functional analysis, but on the identification of different systemic weaknesses in individual steps of the value chain.

Empirically, this paper contributes to the sanitation field with insights on how different arrangements of sanitation chain governance can enable or hinder innovation development. This might add a new perspective to the current debate and trials on optimizing stakeholder arrangements in city-wide fecal sludge management and on-site sanitation management.

This paper had a limited focus on a particular value chain in one sector in a city. The framework`s applicability is broader, for example to cases of technological innovations which develop in value chains that span several sectors or different geographical levels. And future studies could elaborate how a value chain governance is impacting innovation developments in the growth phase of a TIS.

6. Conclusion

A value chain perspective to a TIS analysis can be useful to enable the analysis of increasingly complex technological innovation developments. This paper showed how innovative on-site sanitation activities in Nairobi moved beyond a focus on individual steps of the value chain to demonstrating complete sanitation chains. Currently, social enterprises and NGOs govern strongly vertically integrated chains. A systemic perspective on these individual innovation activities showed heterogeneous functional in each step of the chain. The TIS in Nairobi is currently in a formative phase, because it lacks certain systemic formative processes, such as knowledge exchange and guidance of search.

The value chain perspective opened up a broad variety of possible policy recommendations to improve the TIS, both at the level of individual steps as well as the entire value chain. The case shows how the hierarchical model might hamper new actors to enter the TIS, and how certain innovation activities could be more coordinated (e.g. conveyance and treatment of waste). Also, increasing division of labor in the chain, including TIS outsiders, can contribute to overcome individual capability failures and system weaknesses, such as lack of legitimation. The systemic perspective helped to generate integrative

lessons about the individual sanitation chain leader's efforts in Nairobi and potential improvements of aligning the individual innovative approaches towards a better functioning innovation system. A better functioning innovation system can improve city-wide alignments in the sanitation sector, which is benefits the public health situation in the city.

The approach taken-up in this paper of systematically applying a TIS functional analysis to a value chain contributes to the innovation system literature. Identifying opportunities to develop a TIS through changes in value chain governance is a novelty, especially compared to traditional TIS analysis that focus on innovations in an individual step of a value chain. Such approach enables the analysis of the increasingly complicated development of technological innovations which are influenced by external aspects such as linkages to other TISs and structural couplings. This increasing complexity is not just confined to low-income countries, but is also relevant in high-income countries where we see a similar increase in interlinkages of TISs, for example in the use of renewables for electricity generation. A value chain perspective can broaden the scope of TIS analyses and can give 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). The approach informs the sustainability transitions research field as sustainable innovations can challenge established industries and lead to systemic changes of entire value chains.

Annex

Table A1. List of interviewees, 2016

Stakeholder Group	Interviewees	Code	Sum
Government (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	
	iNGO C	iNGO5	
	iNGO D	iNGO6	
International development organization (IDO)	IDO A (2 interviews)	IDO1, IDO2	2
Social enterprises (SEs)	Social enterprise A (7 interviews) *Implementing container based sanitation*	SE1, SE2, SE3, SE4, SE5, SE6, SE7	12
	Social enterprise B (2 interviews) *Implementing biodegradable bags*	SE8, SE9	
	Social enterprise C	SE10	
	Social enterprise D	SE11	
	Social enterprise E	SE12	
Community Based Organization (CBO)	CBO A	CBO1	3
	CBO B (2 interviews)	CBO2, CBO3	
Professional Association (PA)	Private Exhauster Truck Association	PA1	1
Sum			36

Annex

Table 4 in detail

Bio-centers approach				
	User interface & storage	**Conveyance**	**Treatment**	**Use and/or safe disposal**
F1: entrepreneurial activities	- development bio-center model (Umande, 2014) - installation 64 bio-centers (Umande, 2016a) - pilots cashless payments systems (NGO1, NGO2, NGO3)		- on-site anaerobic digestion in bio-centers (Umande, 2014) - planning treatment plant bio-slurry (NGO1, NGO6) (Umande, 2016b)	- biogas tried for different purposes in bio-centers (NGO1, NGO2, NGO3) (Umande, 2014; Wamuchiru, 2015) - liquid fertilizer byproduct of digestion process used by CBOs (NGO1) - experimenting with transport biogas to households (NGO1)
F2: knowledge development	- research on bio-center concept (NGO1)		- research on anaerobic digestion and possible treatment bio-slurry (NGO1)	- research on possible new usage options biogas (NGO1)
F3: knowledge diffusion	- collaboration with local universities and international researchers (NGO1, NGO3) - community trainings, raising awareness (NGO1, NGO3) (Binale, 2011; Wamuchiru, 2015)		- collaboration with local universities and international researchers (NGO1)	- collaboration with local universities and international researchers (NGO1) - educating people about use biogas (NGO1)
F4: guidance of search				
F5: market formation	- created large demand for bio-center services, pay per use public services			- biogas sold to some nearby actors - aims to commercialize fertilizer and biogas production (NGO1) (Umande, 2016b)
F6: resource mobilization	- funding from water board (NGO1) (Binale, 2011; Wamuchiru, 2015) - venturing into a social enterprise, to attract investors (Umande, 2016b) (NGO1) - funding from international donors (NGO1, NGO2)		- funding from water board - funding from international donors	
F7: legitimation creation	- local acceptance through active involvement local community groups (NGO1, NGO3) (Binale, 2011; Otsuki, 2016; Umande, 2016b; Wamuchiru, 2017) - bio-center accepted as a sanitation model by local government (NGO1, NGO3, GOV5) - MOU with public utility (Wamuchiru, 2015)		- anaerobic digestion accepted as a treatment technology by utility, local government and local communities (NGO1, NGO3)	- use of biogas accepted by many local communities, but still sensitization activities necessary for the acceptance using biogas made from human waste (NGO1, NGO3)

Table 5 in detail

Biodegradable bags approach				
	User interface & storage	**Conveyance**	**Treatment**	**Use and/or safe disposal**
F1: entrepreneurial activities	- development biodegradable bag - in the process to set-up a local production plant to produce bags (iNGO6)	- experimentation different manual & mechanical collection models in the past (SE8) (Wirseen et al., 2009)	- composting biodegradable bags 6 weeks (SE8)	- usage bags as fertilizer on farms outside Nairobi (SE8)
F2: knowledge development	- developed biodegradable bag design as a new toilet option - research on producing different types, cheaper of bags (SE8)		- research on composting biodegradable bags (SE8)	- research on fertilizer quality from biodegradable bags to develop potentially homogeneous fertilizer product (SE8)
F3: knowledge diffusion	- collaboration with international researchers (SE8, iNGO6) - education about WASH in schools (SE9) - pilots in several countries around the word, in slums and after emergencies (Patel et al., 2011; Wirseen, 2013; Peepoople, n.d.)		- collaboration with local universities and international researchers (SE8, iNGO6)	- collaboration with local universities and international researchers (SE8, iNGO6)
F4: guidance of search				
F5: market formation	- various models for selling (in 2014 sold 80k bags per month) & giving away biodegradable bags to schools and households (SE8, SE9) (Wirseen, 2013; Graf et al., 2014)			- aims to sell fertilizer, needs to receive the necessary licenses from KEBS (iNGO6)
F6: resource mobilization	- received donor funding to develop biodegradable bag in the past (SE8)			
F7: legitimation creation	- planning to lobby to let the government take-up biodegradable bags as a viable solution for schools (iNGO6) - sensitization to create social acceptance biodegradable bags as a toilet (SE8, SE9, iNGO6)	- borrowing trucks that are licensed by NEMA to transport human waste (SE9)		- sensitization to overcome taboos of using biodegradable bags waste as a fertilizer (SE8, SE9, iNGO6)

Table 6 in detail

CBS approach				
	User interface & storage	**Conveyance**	**Treatment**	**Use and/or safe disposal**
F1: entrepreneurial activities	- development and installment of 1134 CBS toilets (Sanergy, 2018) - experimentation with new in-home toilet (SE1, SE4) - improvements construction of the CBS toilet (lighter, smaller) (SE6)	- experimenting with different collection models (SE6)	- co-composting in full treatment plant outside Nairobi 2467 metric tons of waste treated in 2017 (Sanergy, 2018) - Black solider flies tests (SE2) (Auerbach, 2016) - Urine nutrients recovery experiments (Sanergy, 2016)	- development fertilizer and animal feed product - experimenting with liquid fertilizer and biochar (Auerbach, 2016)
F2: knowledge development	- developing new type in-home CBS toilet (SE1, SE4) - research on converting pit latrines to CBS toilets (SE1)	- research on more efficient collection models (SE6)	- research on different treatment technologies (SE2)	- research on usage and quality different reused products (SE2)
F3: knowledge diffusion	- collaboration with international researchers (SE2) - participation international workshops on CBS (SE4) - education about sanitation in communities (SE5)		- collaboration with international researchers (SE2)	- collaboration with international researchers (SE2)
F4: guidance of search				
F5: market formation	- brand development for the container toilets - franchise network of toilet operators that offer pay-per-use public sanitation services (Auerbach, 2016)			- sales fertilizer and animal feed (Auerbach, 2016)
F6: resource mobilization	- R&D funded through grant capital (Auerbach, 2016) - international donors & investors		- R&D funded through grant capital - international donors & investors	- R&D funded through grant capital (Auerbach, 2016) - international donors & investors
F7: legitimation creation	- sensitization to create social acceptance UDDTs and CBS (SE5)	- successful lobby to handle human waste at various Ministries and Regulators (SE3) - trucks licensed by NEMA to transport human waste (SE3) - brand development “Fresh Life” for collection services (SE6)	- successful lobby to handle human waste at various Ministries and Regulators (SE3)	- branding of fertilizer as organic and not human based (Farmstar, 2016) - brand development for animal feed and fertilizer (Farmstar, 2016) - lobby for permissions and certificates to sell products (SE3)

Table 7 in detail
Summary TIS analysis of the on-site sanitation chain in Nairobi 2016

Complete TIS				
	User interface & storage	**Conveyance**	**Treatment**	**Use and/or safe disposal**
F1: Entrepreneurial activities	- Many new toilet designs developed and produced - Various pilots and experiments	- Few experiments - Use of conventional pick-up trucks	- Many different technologies used - Various pilots and experiments	- Various different products are being developed - Reused products are developed, used and some sold
F2: Knowledge development	- Research into users preferences	- Some research on improving efficiency collection	- Research into various new technologies	- Research on quality and usage reused products
F3: Knowledge diffusion	- Few Nairobi specific exchanges, many international meetings & networks		- Few Nairobi specific exchanges, many international meetings & networks	- Few Nairobi specific exchanges, many international meetings & networks
F4: guidance of search	- Several innovative on-site sanitation options recognized in new KESH policy 2016 -international standards & development goals		-international standards & development goals	- Mentioned in several Kenyan vision/strategy documents
F5: market formation	- Demand for hygienic sanitation services - Market to pay for sanitation exists, TIS services take part in this market			- Start of sales fertilizer and animal feed in existing markets, licensing approved - Some sales of biogas
F6: resource mobilization	- Local Water Board financed some bio-centers - Several int. donors and investors interested in development of new types of toilets		- Some international donors and investors interested in development new treatment technologies	- Some international donors and investors interested in development new types of reused products
F7: legitimation creation	- Among users acceptance and status of on-site sanitation options is increasing because they are clean and well-managed - Among officials, bio-centers are officially accepted and the legitimation of CBS and bags is mixed	- Manually handling human waste is a taboo, needs to be overcome to collect containers	- Handling human waste is a taboo, but treatment of waste is seen as important	- Taboo vs. attractive potential of reusing human waste

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