Generation and evaluation of sanitation options for urban planning: systematic consideration of technology innovations and sustainability criteria

Doctoral Thesis

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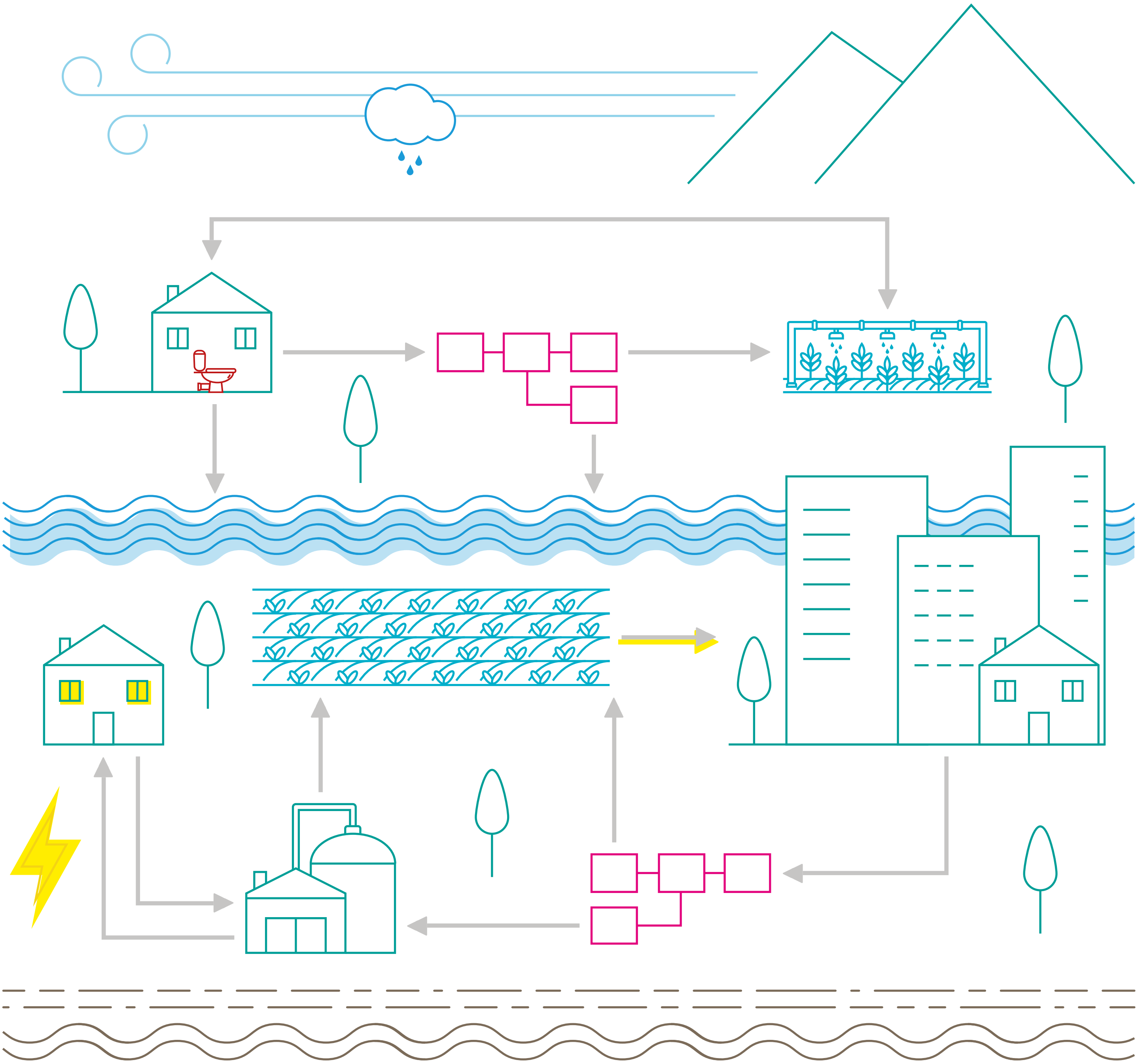
Publication date:
2020-05

Permanent link:
https://doi.org/10.3929/ethz-b-000444234

Generation and evaluation of sanitation options for urban planning

Systematic consideration of technology innovations and sustainability criteria

Dorothee Spuhler • April 2020



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DISS. ETH NO. 26812

Generation and evaluation of sanitation options for urban planning: systematic consideration of technology innovations and sustainability criteria

A thesis submitted to attain the degree of

DOCTOR OF SCIENCES of ETH ZURICH

(Dr. sc. ETH Zurich)

presented by

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2020

Summary

Motivation. It is particularly challenging to reach SDG 6.2, access to sanitation for all, in urban areas of developing countries, where most of the current global population growth is taking place. Traditionally, urban sanitation planning is based on top-down, one-size-fits-all approaches. This has often led to inappropriate technology choices and failing projects worldwide, particularly in urban areas of developing countries. Conventional centralized sanitation is often inappropriate in these areas because it depends on capital-intensive sewer networks, large quantities of water, stable institutions with adequate capacities, and long planning horizons. Increasing investments in the development of novel technologies (e.g. urine separation) and system configurations (e.g. container-based sanitation) have been the result. These innovations can be more appropriate (independent from sewers, water and energy) and sustainable (adaptable to changing environmental and socio-demographic conditions, and saving/recovering water, nutrients, and energy).

Research need. While novel technologies and system configurations potentially enhance sustainability, they also increase planning complexity. Structured decision-making (SDM) has been found to assist the planning process, by combining decision analysis with engineering, and balancing opposing interests in a facilitated framework that embraces all relevant steps. To support the application of SDM, several frameworks were developed over the past decades (e.g. Community-led Urban Environmental Sanitation, CLUES, or Sanitation21). Yet, they are rarely used in practice. Recent research focuses on developing tools that operationalize the different planning steps, but these tend to prioritize methods for understanding the problems (e.g. Shit Flow Diagrams, SFDs), or for the selection of preferred options (e.g. multi-criteria decision analysis), assuming that the options to choose from are given. However, the currently available technologies result in an unmanageable number of possible system configurations (>100’000). The present technological development requires methods that generate a manageable number of locally appropriate sanitation decision options and that are systematic and can deal with the growing portfolio of technologies and sustainability criteria. Moreover, there is a lack of generic methods to quantify the performance of novel sanitation system configurations at the scale of an entire city. The identification of options and their comparison is further hampered by the lack of knowledge or data, particularly for novel options.

Research objectives. The objective of this thesis is to develop systematic and generic methods to identify locally appropriate sanitation system options and to evaluate their performance in terms of resource efficiency. The aim is to use these results as an input into the decision-making process. The methods shall: (i) consider entire sanitation systems from the toilet to reuse or disposal; (ii) be applicable to a large and diverse range of technologies and system configurations; and (iii) integrate criteria from all sustainability dimensions. Given the context of expanding urban areas and the focus on novel technologies, the methods should also be able to deal with uncertainties. The thesis covers three specific objectives: (I) methods for sanitation system options generation; (II) methods to quantify resource recovery potentials of entire systems as a performance indicator for the evaluation of their sustainability; and (III) a procedure for the integration of the methods in SDM and their practical application. The third objective also includes the analysis of the implementation of practical applications in Nepal, Ethiopia, South Africa, and Peru.

Generation of locally appropriate sanitation system options. To provide a systematic method that can deal with a large and diverse set of technology and system options, a computer model was developed that contains three algorithms for: (i) the evaluation of technology appropriateness based on a number of non-negotiable screening criteria (e.g. water availability, socio-cultural acceptance); (ii) the generation of all valid system configurations from the appropriate technologies; and (iii) for the selection of a set of locally appropriate sanitation system options, which is diverse but of manageable size. The diversity of the options is defined by 19 system templates, categories of

systems based on technological characteristics (e.g. onsite simple, urine diversion, biofuel systems, or blackwater). A technology library compiles the required data for 41 conventional and novel technologies and 27 screening criteria based on international literature and expert judgement. To account for uncertainties related to technology implementation or local contexts, the screening criteria are quantified using probability distributions.

Quantification of resource recovery potentials. To quantify ex-ante substance flows, an additional algorithm was added. The algorithm uses generic transfer coefficients from literature to quantify flows of total phosphorus, total nitrogen, total solids (as indicator for energy and organic matter) and water. These mass flows are then used to quantify resource recovery potentials as well as losses to the soil, surface water, and air. The uncertainty of the transfer coefficient, expressed by the variability of literature data, is modelled using the Dirichlet distribution and Monte Carlo.

Integration with SDM. For the practical application of the software (algorithms + technology library), a procedure for the integration with SDM was developed. The integration requires three elements : (i) a list of screening criteria for the appropriateness assessment; (ii) evaluation data to characterize the application case and technology profile for the screening attributes; and (iii) the desired number of sanitation system decision options. The screening criteria are derived from the decision objectives for sustainable sanitation developed in one or two facilitated stakeholder workshops. The evaluation data is based on secondary literature for the application case and the library for the technology options. The desired and manageable number of decision options depends on the complexity of the methods used for the final selection and lies between 3 and over 50. To support the interaction with the stakeholders, a generic objective hierarchy for sustainable sanitation and a master list of screening criteria was developed based on literature.

Results from the practical applications. The practical applications provided the results to derive a set of sensitive criteria for appropriateness (e.g. water and energy requirements, operation and maintenance frequency and skills, vehicular access, and socio-cultural acceptance), and information on what types of systems are most appropriate in expanding urban areas of low-income countries. It also showed that the system templates effectively describe technological diversity, but they give not sufficient indication on appropriateness or resource recovery. Because of their ability to describe diversity, system templates are however useful to provide sets of options that are balanced, minimising the impact of the screening step on the final decision outcome. The applications of the substance flow model to a representative real-live example allowed for the identification of factors for resource recovery (e.g. number of technologies that make up the system, and level of containment used in the technologies for storage and treatment) as well as recommendations for optimising resource recovery potentials (e.g. shorter systems that integrate fewer technologies, leading to fewer losses, and a combination of valorisation of different product streams, such as transforming urine into fertiliser and solids into energy leads to the highest recovery ratio). However, the thesis was not able to identify a single unequivocal set of factors for appropriateness or resource recovery as both strongly depend on technology interactions and the system configuration. This highlights the needs for such an automated and prospective approach that can deal with many technology options and system configurations at a pre-planning stage. For the integration of the methods with SDM, the main challenges lie in the moderation and facilitation of the interaction with stakeholders in order to obtain suitable input. This aspect requires expert skills and local knowledge that go beyond typical engineering expertise.

Main contributions. The two main scientific contributions are that (1) the methods are generic, and therefore can be applied to almost any thinkable technology, system configuration, product, and decision criteria and (2) they are automated and, thus, can deal with a large and diverse number of sanitation system options simultaneously (typically >100,000 systems for 41 potential technologies).To support the automatization and the application in practice, data based on international literature and knowledge is compiled in a the technology library making this knowledge available to practice on the ground. Moreover, the methods are systematic, and thus reproducible; enforce the consideration of entire sanitation systems; and explicitly consider uncertainties in order to be applicable ex-ante. The two main contributions to practice are that (1) the methods allow to find appropriate and sustainable sanitation systems that one might not have thought of based on experience alone; and that (2) more appropriate and resource efficient options can be given priority threby contributing to a circular economy and sustainable development. Additional contributions include enhanced transparency and more empirical decision making; the elimination of inappropriate options at the beginning; and decision based on strategic objectives rather than on biased expert knowledge. The practical applications also indicated that these methods potentially positively influence the local planning culture by (i) supporting the definition of a joint vision shared by all stakeholders; (ii) bridging area-based screening criteria with citywide decision objectives thereby contributing to Citywide Inclusive Sanitation (CWIS); (iii) structuring stakeholder participation, and (iv) by contributing to organizational and individual capacity development.

Shortcomings. The presented software and integration procedure are not intended to replace the technical expertise required for detailed planning and implementation or of existing planning frameworks for the entire SDM process, such as CLUES. But, the results are intended to enable the systematic consideration of technology innovations and sustainability criteria during the structuring phase. The appropriateness assessment remains sensitive to several aspects, such as the set of potential technologies and the screening criteria, which require expert skills and local knowledge. The decision options for sanitation systems still require a plausibility check and need to be complemented with aspects related to the service models and with additional performance indicators (e.g. costs) for the final evaluation. Furthermore, the methods are based on a number of simplifications (e.g. generic definition of technologies, products, and transfer coefficients) in order to allow for automatization. The consequences of these simplifications are, however, captured in the uncertainty of the transfer coefficients and the resulting resource recovery and loss potentials. In addition, some challenges were not addressed: (i) how the options for different zones within a city interact with each other and with existing infrastructure; and (ii) the synergies with other sectors (e.g. organic solid waste).

Outlook. From a scientific point, the most tangible next step would be to validate the results and potential contributions in more practical applications. These experiences could then be used to develop standardized set of most sensitive criteria appropriate systems for different settings (e.g. a growing small town in Nepal, or an urban neighbourhood in Switzerland) or cases within a setting (e.g. centre or low-income area of a small town). Moreover, the methods could be expanded for additional products (e.g. solid waste), substances (e.g. hygiene indicators), or (novel) technologies along the entire water and nutrient cycle. Specific libraries could also be developed for example for municipal wastewater, drinking water supply, emergency sanitation, etc. Another required next step is the completion of the generated sanitation system decision options with aspects related to the service models (e.g. in a strategy table) and additional performance indicators. Also, system combinations (hybrid systems) should be investigated in order to study how different combinations within a city perform as a whole. The factors for appropriateness and resource recovery could be used to develop performance-based system templates or to guide future research on technology and system development. From a practical point of view, the next step would be to make the results available in an online interactive interface that supports users (e.g. engineering consultants, governmental planners, and NGOs) in the provision of suitable inputs and allows them to browse results interactively. The complementarity of this tool with other currently developed supporting tools for SDM could be investigated (e.g. SFDs) in order to develop an adaptive strategic planning framework for CWIS. Within this more holistic framework, the methods presented here could provide an empirical approach to identify appropriate options for different context along with the required performance indicators for resource recovery potential, thereby contributing to more inclusive and sustainable sanitation worldwide.

Zusammenfassung

Beweggründe. Das Ziel 6.2 für nachhaltige Entwicklung, Zugang zu sanitären Einrichtungen für alle, zu erreichen, ist besonders schwierig in städtischen Gebieten von Entwicklungsländern, wo das derzeitige globale Bevölkerungswachstums stattfindet. Traditionell basiert die städtische Abwasserplanung auf einem Top-down-Ansatz, der eine Standardlösung vorschlägt, die für alle passen soll. Dies hat zur Auswahl von nicht angepassten Technologien und zum Scheitern von Projekten weltweit geführt, insbesondere in städtischen Gebieten von Entwicklungsländern. Konventionelle, zentralisierte Abwassersysteme sind in diesen Gebieten ungeeignet, weil sie von kapitalintensiven Kanalisationsnetzen, großen Wassermengen, stabilen Institutionen mit angemessenen Kapazitäten und langen Planungshorizonten abhängen. Dies führte zu vermehrten Investitionen in die Entwicklung neuer Technologien (z.B. Urinseparierung) und Systemkonfigurationen (z.B. Container-basierte Abwassersysteme). Diese Innovationen sind angemessener für städtische Gebiete in Entwicklungsländern, da sie unabhängig von Kanalisation, Wasser und Energie sind. Sie sind auch allgemein nachhaltiger und zeichnen sich durch höhere Resilienz aus, da sie sich an verändernde Umwelt- und soziodemographische Bedingungen flexibler anpassen können und Einsparung/Rückgewinnung von Wasser, Nährstoffen und Energie ermöglichen.

Forschungsbedarf. Neue Technologien und Systemkonfigurationen können zwar die Nachhaltigkeit verbessern, erhöhen aber auch die Planungskomplexität. Es hat sich gezeigt, dass die Methode der strukturierten Entscheidungsfindung (‚structured decision making' SDM) den Planungsprozess unterstützt, indem sie multikriterielle Entscheidungsanalyse (MCDA) mit Naturwissenschaften kombiniert und gegensätzliche Interessen ausbalanciert in sechs generischen Schritten. Zur Unterstützung der Anwendung von SDM in der Abwasserplanung wurden in den letzten Jahrzehnten mehrere Rahmenwerke entwickelt (z.B. Community-Led Urban Sanitation', CLUES oder Sanitation21). Sie werden jedoch in der Praxis nur selten angewendet. Daher konzentrierte sich die jüngste Forschung auf die Entwicklung von Instrumenten, die die verschiedenen Planungsschritte operationalisieren. Diese Forschung betrifft jedoch hauptsächlich Methoden für das Verständnis der Probleme (z.B. ‚Shit Flow Diagrams',) oder für die Endauswahl einer bevorzugten Lösung, wobei davon ausgegangen wird, dass bereits eine Reihe geeigneter Optionen zur Auswahl steht. Allerdings resultieren die derzeit verfügbaren Technologien in einer unüberschaubaren Anzahl von Abwassersystemoptionen (>100'000). Die aktuelle technologische Entwicklung erfordert Methoden, welche einen überschaubaren Satz an lokal angepasste Optionen generieren kann, und welche systematisch und reproduzierbar sind und mit dem wachsenden Portfolio an Technologien und Nachhaltigkeitskriterien umgehen können. Zudem fehlt es an generischen Methoden, um die Leistung neuartiger Sytemkonfigurationen für ein ganzes städtisches Einzugsgebiet zu quantifizieren. Die Identifizierung von Optionen und deren Vergleich wird durch das Fehlen von Wissen oder Daten, insbesondere bei neuartigen Technologien/Systemen, weiter erschwert.

Forschungsziele. Das Ziel dieser Arbeit ist die Entwicklung systematischer und generischer Methoden, um lokal angepasste Abwassersystemoptionen zu generieren und deren Leistung als Input für den Entscheidungsprozess zu bewerten. Die Methoden sollen: (i) ganze Sanitärsysteme von der Toilette bis zur Wiederverwendung oder Entsorgung berücksichtigen; (ii) für ein großes und vielfältiges Spektrum von Technologien und Systemkonfigurationen anwendbar sein; und (iii) Kriterien aus allen Nachhaltigkeitsdimensionen integrieren. Angesichts des Kontexts der schnell wachsenden städtischen Gebiete und dem speziellen Fokus auf neue Technologien, sollten die Methoden auch mit Unsicherheiten umgehen können. Die Arbeit umfasst drei spezifische Ziele: (I) die Methoden zur Generierung von Abwassersystemoptionen; (II) die Methoden zur Quantifizierung des Ressourcenrückgewinnungspotenzials der Systeme als Leistungsindikator für die Bewertung ihrer Nachhaltigkeit; und (III) das Verfahren zur Integration der Methoden in SDM für die praktische Anwendung.

Generierung von lokal angepassten Abwassersystemoptionen. Um eine systematische Methode bereitzustellen, die mit einem großen und vielfältigen Satz von Technologien und Systemen umgehen kann, wurde ein Computermodell entwickelt, das drei Algorithmen enthält: (i) zur Bewertung der Angemessenheit von Technologien auf der Grundlage einer Reihe von nicht verhandelbaren Screening-Kriterien (z.B. Wasserverfügbarkeit, sozio-kulturelle Akzeptanz); (ii) zur Generierung aller gültigen Systemkonfigurationen aus den entsprechenden Technologien; und (iii) zur Identifizierung einer Reihe von lokal angepassten Abwassersystemoptionen, die zwar vielfältig, aber von überschaubarer Größe sind. Die Diversität der Optionen wird durch19 Systemvorlagen (‚system templates') definiert, Kategorien von Systemen basierend auf technologischen Charakteristiken (z.B. Behandlung vor Ort, Urinsammlung, Biokraftstoffherstellung, Schwarzwasserproduktion, etc.). Eine Technologiebibliothek stellt basierend auf internationaler Literatur und Expertenwissen die erforderlichen Daten für 41 konventionelle und neuartige Technologien und 27 Screening-Kriterien zusammen. Um Ungewissheiten in Bezug auf die Technologieumsetzung oder den lokalen Kontext zu berücksichtigen, werden die Screening-Kriterien anhand von Wahrscheinlichkeitsverteilungen quantifiziert.

Quantifizierung des Ressourcenrückgewinnungspotenzials. Zur Quantifizierung der Ex-ante Stoffströme wurde ein zusätzlicher Algorithmus hinzugefügt. Der Algorithmus verwendet generische Transferkoeffizienten aus der Literatur, um die Ströme von Gesamtphosphor, Gesamtstickstoff, Gesamtfeststoff (als Indikator für Energie und organische Substanz) und Wasser zu quantifizieren. Diese Massenströme werden dann zur Quantifizierung des Ressourcenrückgewinnungspotenzials sowie der Verluste an Boden, Oberflächenwasser und Luft verwendet. Die Unsicherheit des Transferkoeffizienten, ausgedrückt durch die Variabilität der Literaturdaten, wird mit Hilfe der Dirichlet-Verteilung und Monte Carlo modelliert.

Integration mit SDM. Für die praktische Anwendung der Software (Algorithmen + Technologiebibliothek) wurde ein Verfahren für die Integration mit SDM entwickelt. Die Integration erfordert drei Elemente: (i) eine Liste von Screening-Kriterien für die Beurteilung der Angemessenheit; (ii) Bewertungsdaten zur Charakterisierung der Screening-Kriterien für den Anwendungsfall sowie die möglichen Technologien; und (iii) die gewünschte Anzahl von Entscheidungsoptionen. Die Screening-Kriterien werden in einem oder zwei moderierten Stakeholder-Workshops aus den Entscheidungszielen für nachhaltige Sanitärversorgung abgeleitet. Die Bewertungsdaten sind durch Sekundärliteratur für den Anwendungsfall und die Technologiebibliothek für die Technologien gegeben. Die gewünschte und überschaubare Anzahl von Entscheidungsoptionen hängt von der Komplexität der für die endgültige Auswahl verwendeten Methoden ab und liegt zwischen 3 bis über 50. Zur Unterstützung der Interaktion mit den Beteiligten wurde eine generische Zielhierarchie für nachhaltige Sanitärversorgung und eine Masterliste von Screening-Kriterien auf der Grundlage der Literatur entwickelt.

Ergebnisse aus den praktischen Anwendungen. Die praktische Anwendungen in Nepal, Äthiopien, Peru, und Südafrika ermöglichten es, eine Reihe von sensiblen Kriterien für die Angepasstheit zu identifizieren (z.B. Wasser- und Energiebedarf, Betriebs- und Wartungshäufigkeit und -fähigkeiten, sozio-kulturelle Akzeptanz, Zufahrtsmöglichkeiten), und lieferte Informationen darüber, welche Arten von Systemen in expandierenden städtischen Gebieten in Entwicklungsländern angepasst sind. Es zeigte sich auch, dass die Systemvorlagen erfolgreich die technologische Diversität beschreiben, aber sie stehen nicht im Zusammenhang mit der Angemessenheit oder der Ressourcenrückgewinnung. Weil sie aber Diversität beschreiben, können Systemvorlagen helfen, einen ausgewogenen Satz an Optionen auszuwählen, wodurch die Auswirkungen des Screening-Schritts auf das endgültige Entscheidungsergebnis minimiert werden. Die Anwendung des Stoffflussmodells auf einen allgemeinen Fall ermöglichte es, Faktoren für die Ressourcenrückgewinnung (z.B. Länge, Art der Aufbewahrung) sowie Empfehlungen zur Optimierung der Ressourcenrückgewinnung zu ermitteln (z.B. kürzere Systeme führen zu weniger Verlusten, die Kombination der Verwertung verschiedener Produktströme wie die Umwandlung von Urin in Dünger und von Feststoffen in Energie führt zur höchsten Rückgewinnungsraten). Die Arbeit konnte jedoch nicht einen einzigen eindeutigen Satz von Faktoren für die Angepasstheit oder die Ressourcenrückgewinnung identifizieren, da beide stark von den Wechselwirkungen zwischen den Technologien und der Systemkonfiguration abhängen. Dies unterstreicht die Notwendigkeit eines solchen automatisierten Ansatzes. Für die Integration der Methoden mit SDM liegen die Hauptherausforderungen in der Moderation der Interaktion mit den Stakeholdern. Diese Aspekte erfordern Expertenfähigkeiten und lokale Kenntnisse, die über die typische Ingenieurskompetenz hinausgehen.

Beitrag zu Forschung und Praxis. Die beiden wichtigsten wissenschaftlichen Beiträge sind, dass (i) die Methoden generisch sind und daher fast auf jede denkbare Technologie, Systemkonfiguration, jedes Produkt und alle Entscheidungskriterien angewendet werden können und (ii) sie automatisiert sind und daher eine große und vielfältige Anzahl von Abwassersystemoptionen gleichzeitig behandeln können (typischerweise >100.000 Systeme für 41 potenzielle Technologien). Um die Automatisierung und Transparenz zu unterstützen, werden die auf internationaler Literatur und internationalem Wissen basierenden Daten in einer Bibliothek zusammengestellt. Darüber hinaus sind die Methoden systematisch und damit reproduzierbar, erzwingen die Berücksichtigung ganzer Abwassersysteme (nicht nur Toiletten), und berücksichtigen explizit Unsicherheiten, um ex-ante angewendet werden zu können. Die Integration mit SDM verspricht zwei wesentliche potenzielle Mehrwerte: (i) die Identifizierung von Abwassersystemoptionen, die man vielleicht nicht in Betracht gezogen hätte und die potenziell geeigneter und nachhaltiger sind; und (ii) Systeme, die zur Kreislaufwirtschaft beitragen, können vorrangig behandelt werden. Weitere Beiträge zur Praxis sind u.a. eine erhöhte Transparenz und eine empirischere Entscheidungsfindung, die Beseitigung unangemessener Optionen zu Beginn und Entscheidungen, die auf strategischen Zielen und nicht auf verzerrtem Expertenwissen basieren. Die praktischen Anwendungen zeigten auch, dass diese Methoden die lokale Planungskultur potenziell positiv beeinflussen, indem sie (i) die Definition einer gemeinsamen Vision unterstützen, die von allen Beteiligten geteilt wird; (ii) Zonen-bezogene Screening-Kriterien mit stadtweiten Entscheidungszielen verknüpfen und so zur stadtweiten Inklusiven Abwasserversorgung (‘citywide inclusive sanitation’, CWIS) beitragen; (iii) die Beteiligung der Stakeholder strukturieren und (iv) zur organisationellen und individuellen Kapazitätsentwicklung beitragen.

Limitierungen. Die vorgestellte Software und das Integrationsverfahren soll nicht die Detailplanung oder einen existierenden Planungsansatz wie z.B. CLUES ersetzen. Sondern, diese Resultate sollen die systematische Berücksichtigung von Technologieinnovationen und Nachhaltigkeitskriterien in der Strukturierungsphase ermöglichen. Die Bewertung der Angepasstheit bleibt sensibel für mehrere Aspekte, wie z.B. die Menge der potentiellen Technologien und die Screening-Kriterien, die die Fähigkeiten von Experten und lokale Kenntnisse erfordern. Die Entscheidungsoptionen für Sanitärsysteme bedürfen noch einer Plausibilitätsprüfung und müssen um Aspekte ergänzt werden, die mit den Dienstleistungsmodellen zusammenhängen, sowie zusätzliche Leistungsindikatoren (z.B. die Kosten) für die abschließende Bewertung. Darüber hinaus basieren die Methoden auf einer Reihe von Vereinfachungen (z.B. generische Definition von Technologien, Produkten und Transferkoeffizienten), um die Automatisierung zu ermöglichen. Die Folgen dieser Vereinfachungen werden jedoch in der Unsicherheit erfasst. Auch wurden noch nicht genügend erforscht, wie die Optionen in verschiedenen Zonen innerhalb einer Stadt miteinander und mit der bestehenden Infrastruktur zusammenspielen; und wie Synergien mit anderen Sektoren (z.B. organische Abfälle) miteinbezogen werden können.

Ausblick. Aus wissenschaftlicher Sicht wäre der greifbarste nächste Schritt die Umsetzung von mehr praktischen Anwendungen, um die Ergebnisse zu validieren. Diese Erfahrungen könnten dann verwendet werden um standardisierte Sätze an sensiblen Kriterien und angepassten Systemen für verschiedene Settings (z.B. wachsende Kleinstadt in Nepal, städtische Nachbarschaft in der Schweiz) oder Zonen (z.B. Zentrum oder einkommensschwaches Gebiet einer Kleinstadt) zu erarbeiten. Darüber hinaus könnten die Methoden für zusätzliche Produkte (z.B. organische Abfälle), Substanzen (z.B. Hygiene-Indikatoren) oder (neuartige) Technologien entlang des gesamten Wasser- und Nährstoffkreislaufs erweitert werden. Für z.B. kommunale Abwässer, Trinkwasserversorgung, Notfallsanierung etc. könnten spezifische Bibliotheken entwickelt werden. Ein weiterer notwendiger nächster Schritt ist die Vervollständigung der generierten Abwassersystemoptionen mit Aspekten, die sich auf die Dienstleistungsmodelle (z.B. in einer Strategietabelle) und zusätzliche Leistungsindikatoren beziehen. Außerdem sollten Systemkombinationen (Hybridsysteme) untersucht werden, um zu untersuchen, wie verschiedene Kombinationen innerhalb einer Stadt insgesamt funktionieren. Die Faktoren für die Angemessenheit und die Rückgewinnung von Ressourcen könnten zur Entwicklung von leistungsbasierten Systemvorlagen oder zur Anleitung künftiger Forschung zur Technologie- und Systementwicklung verwendet werden. Aus praktischer Sicht wäre der nächste logische Schritt, die Ergebnisse in einer interaktiven Online-Applikation zur Verfügung zu stellen, die die Nutzer (z.B. Ingenieurbüros, Regierungsplaner, NGOs) bei der Bereitstellung geeigneter Inputs unterstützt und es ihnen ermöglicht, die Ergebnisse interaktiv zu durchsuchen. Die Komplementarität dieses Werkzeugs mit anderen derzeit entwickelten unterstützenden Werkzeugen für SDM könnte untersucht werden, um einen adaptiven strategischen Planungsrahmen für CWIS zu entwickeln. Innerhalb dieses ganzheitlicheren Rahmens könnten die hier vorgestellten Methoden einen empirischen Ansatz bieten, um geeignete Optionen für unterschiedliche Kontexte zusammen mit den erforderlichen Leistungsindikatoren für die Ressourcenrückgewinnung zu identifizieren und so zu einer inklusiveren und nachhaltigeren Abwasserversorgung weltweit beitragen.

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Abbreviations

AppCase	Application case
ASt,c	Appropriateness Score for criteria c and Tech t
CLUES	Community-Led Urban Environmental Sanitation
CWIS	Citywide Inclusive Sanitation
FG	Functional group. There exist five FGs: U: User interface; S: Collection and storage. C: Conveyance; T: Treatment; and D: Reuse or Disposal. Uadd is a variation of U
H2O	Water
MCDA	Multi-Criteria Decision Analysis
MDG	Millennium Development Goal
Product	Sanitation product
SanSys	Sanitation system
SAS	System Appropriateness Score
SDG	Sustainable Development Goal
SDM	Structured Decision Making
SSA	Strategic Sanitation Approach
ST	System Template
TAS	Technology Appropriateness Score
Tech	Technology option
TN	Total Nitrogen
TP	Total Phosphorus
TS	Total Solids

01 Introduction

— 1.1 MOTIVATION AND PROBLEM STATEMENT

1.1.1 The significance of urban sanitation

Sanitation refers to the provision of facilities and services for the safe management of human excreta (WHO, 2018). Urban sanitation is vital for human well-being, enabling human and environmental health and laying the foundations for social and economic development (Hutton and Varughese, 2016; WHO and UNICEF, 2000; 2013). The importance of sanitation has been recognized in the Millennium Development Goals, MDGs (UN, 2000a; b) and as a human right (UN, 2010a).

Box 1.1.

The Human Right to Water and Sanitation:

The UN Committee on Economic, Social and Cultural Rights defined the human right to water in General Comment No. 15. On 28 July 2010 the United Nations General Assembly through Resolution A/RES/64/292 declared safe and clean drinking water and sanitation a human right essential to the full enjoyment of life and all other human rights. Human rights criteria (availability, quality, acceptability, accessibility and affordability) and human rights principles (non-discrimination, access to information, participation, accountability and sustainability) precise the content and scope of the right and guide its implementation process. Source: (UN, 2010b)

Despite these efforts, 55% of the global population did not use safely managed[1] sanitation services in 2017 (UN, 2019). Currently, 80% of wastewater globally is released into the environment without adequate treatment (WWAP, 2017). One of the reasons for the high share of the population not having access to safely managed sanitation is that the unprecedented growth in urban areas of development countries (informal settlements, slums, and small towns) often exceeds the capacities of administrations (Lüthi et al., 2012; Lüthi et al., 2010; UN-HABITAT, 2003). Pressure will most likely increase in the future, as 70% of the world population is projected to live in urban areas by 2050 and over 90% of urban growth will take place in developing countries (Birch et al., 2012; Dodman et al., 2013; UNFPA, 2007). In rapidly growing areas of developing countries, challenges of sanitation provisions are exasperated by high density, informality, and a lack of administrative and financial capacities for planning, implementing, and operating safe sanitation (Dodman et al., 2013; Dodman et al., 2017; Isunju et al., 2011; Ramoa et al., 2014; Tremolet et al., 2010; UN-HABITAT, 2012).

Even though there is less open defecation in urban than in rural areas (1% as compared to 18%, WHO and UNICEF, 2019), systematic and safe collection and treatment of sanitation products downstream is more often lacking (47% as compared to 43%, WHO and UNICEF, 2019). Existing sanitation services, especially in low-income areas are limited to latrines or septic tanks without appropriate effluent treatment or emptying (Strande, 2014; WSP, 2014).

[1] Safely managed: Use of improved facilities which are not shared with other households and where excreta are safely disposed in situ or transported and treated off-site. **Improved sanitation facilities** are those designed to hygienically separate excreta from human contact. https://washdata.org/monitoring/sanitation [Access: 31.03.2020]

Only 18% of the products from domestic on-site sanitation facilities are treated worldwide (UN-WATER, 2018). Safe sanitation requires to address the entire system, from the toilet, to containment and storage/treatment onsite, or conveyance, treatment and eventual safe end use or disposal off-site. The impacts of unsafe sanitation is intensified in urban areas with high population density and little environmental adsorption capacity. Unsafely managed urban sanitation systems are a major contributor to the discharge of untreated wastewater making, creating hotspots of environmental degradation and public health hazards worldwide (Lüthi and Narayan, 2018).

Figure 1.1: Typical simple pit latrine often seen in the peri-urban area of Arba Minch, Ethiopia. Source: M. Rath 2015

Figure 1.2: Semi-functional constructed wetland for decentralized wastewater treatment in Thimi Municipality, Nepal. Source: D. Spuhler 2015

1.1.2 A strategic approach to sanitation planning

Historically, the provision of urban sanitation was based on top-down master planning and driven by a centralized approach. Such a centralized approach is commonly based on sewer systems, transporting sewage from households and industry with the aid of gravity (or pumping) and flushing water to centralised treatment facilities (Mara, 2018). Such an approach has been highly effective to protect the human health. But it relies on costly sewer networks, large quantities of water, stable institutions, and long-term planning, and are therefore not viable in the high-density, fast-growing, and poor urban areas of developing economies (e.g. Schertenleib, 2005). The conventional approach to urban sanitation provision has failed to address the current challenges in many developing urban areas and the abandonment or breakdown of centralized sanitation infrastructures is a common phenomenon (Barnes and Ashbolt, 2006; McConville, 2010).

Already in the 80's the World Bank (WB) launched a research project into low-cost technologies (1976-1980) and initiated the Low-cost Water Supply and Sanitation Project - Technical Advisory Group, the precursor of the Water and Sanitation Programme (WSP). Their criticism on the status quo was that the conventional sewer-based solutions were (i) not adapted to local skills and materials, (ii) capital intensive; and (iii) required imports from donor countries, leading to solutions that were not affordable (Iwugo, 1979; Kalbermatten et al., 1980; Menck, 1973). The main conclusion was that there are many technologies that are more appropriate, providing a socially and environmentally acceptable level of service, at affordable cost (Kalbermatten, 1982; Kalbermatten et al., 1980; Middleton and Kalbermatten, 1990). The project resulted in recommendations compiled in several document under advocating a more "Strategic sanitation approach" (SSA, e.g. Kalbermatten and Middleton, 1999; Middleton and Kalbermatten, 1990; Wright, 1997). The aim was to move away from a top-down centralized approach, towards engagement of the community and an interactive planning processes with minimal external assistance (Kalbermatten, 2009; Kalbermatten and Middleton, 1999). The main innovation were defined in four principles still relevant today: SSA (i) is a multi-technology approach, providing a mixture of on-site and centralized solutions appropriate for different urban realities; (ii) is multi-professional, including not only sanitary engineers, but also economists, behavioural scientists, and health specialists; (iii) considers multiple criteria, including financial, socio-cultural, institutional, and environmental aspects; and (iv) plans for a flexible phase-wise incremental improvement.

These principles were further developed in the Bellagio Principles for environmental sanitation (Box 1.2) in 2000 confirming the need for appropriate technologies and participation. Moreover, human dignity, quality of life and environmental security at household level were put in the centre in order to resolve sanitation problems at lowest practical levels: household, neighbourhood, community, and city. Additionally, the principles explicitly advocate considering waste as a resource. To implement these principles, the Household-Centred Environmental Sanitation (HCES) approach was formulated (Eawag, 2005; Schertenleib, 2005) and piloted in several cities (Lüthi et al., 2009b). Although the initial idea was a combination of bottom-up and top-down approach, HCES could only be piloted and evaluated for area-based planning focusing on community involvement within one neighbourhood, and therefore the scope of citywide sanitation could not be achieved as initially intended.

Box 1.2

The Bellagio Principles for environmental sanitation (2000):

(1) Human dignity, quality of life and environmental security at household level should be at the centre of the new approach, which should be responsive and accountable to needs and demands in the local and national setting.

(2) In line with good governance principles, decision making should involve participation of all stakeholders, especially the consumers and providers of services

(3) Waste should be considered a resource, and its management should be holistic and form part of integrated water resources, nutrient flow and waste management.

(4) The domain in which environmental sanitation problems are resolved should be kept to the minimum practical size (household, community, town, district, catchment, city) and wastes diluted as little as possible.

These principles were endorsed by the members of the WSSCC during its 5th Global Forum in November 2000 in Iguacu, Brazil. Source: (Schertenleib, 2005)

1.1.3 Sustainable sanitation

The Bellagio principles as well as HCES and SSA clearly showed that conventional systems are unsustainable in many ways. Therefore, and in preparation of the United Nations International Year of Sanitation in 2008, an informal independent alliance was formed in order to align the various organizations efforts for pushing a more sustainable approach. In 2008, the Sustainable Sanitation Alliance (SuSanA) put forward its vision based on the previous experiences and defined five criteria for sustainable sanitation (Box 1.3). According to this definition, sustainable sanitation not only protects human health by providing a clean environment, it is also economically viable, socially acceptable, and technically and institutionally appropriate, and protect the natural resources (SuSanA, 2008). The definition emphasizes the need to shift the focus from end-of-pipe treatment towards the consideration of human waste as a resource in order to close nutrient and water cycles (Figure 1.4). SuSanA also introduced the systems approach, acknowledging that providing toilet infrastructure alone does not improve public and environmental health conditions. A sanitation system was defined as a combination of compatible technologies from the point of generation to a final point of reuse or disposal for safe management (Maurer et al., 2012; Tilley et al., 2014b; Zurbrügg et al., 2009). The “sanitation service chain” or “sanitation value chain” systematises this approach using five functional groups (Figure 1.3) and considers not only appropriate technologies for those, but also services and business model around required for operation and maintenance.

Box 1.3

The five sustainability criteria for sanitation:

The main objective of a sanitation system is to protect and promote human health by providing a clean environment and breaking the cycle of disease. In order to be sustainable a sanitation system has to be not only economically viable, socially acceptable, and technically and institutionally appropriate, but it should also protect the environment and the natural resources. According to the Sustainable Sanitation Alliance, when improving an existing and/or designing a new sanitation system, sustainability criteria related to the following aspects should be considered (SuSanA, 2008):

(1) Health aspects include the risk of exposure to pathogens and hazardous substances that could affect public health at all points of the sanitation system. The topic also covers aspects such as hygiene and nutrition, as well as downstream effects.

(2) Environment and natural resource aspects involve the required energy, water and other natural resources for construction, operation and maintenance of the system, as well as the potential emissions to the environment resulting from use. It also includes the degree of recycling and the effects of these.

(3) Technology and operation aspects incorporate the functionality and the ease with which the system can be constructed, operated and monitored using the available human resources. It also concerns the robustness of a system, its vulnerability towards disasters, and the flexibility and adaptability of its technical elements to the existing infrastructure, to demographic and socio-economic developments and climate change.

(4) Finance and economic issues relate to the capacity of households and communities to pay for sanitation, including the capital and operation and maintenance costs. It also considers the economic benefits that can be obtained from the production of the recyclables, employment creation, increased productivity through improved health and the reduction of environmental and public health costs.

(5) Socio-cultural and institutional aspects consider the acceptance and appropriateness of the system, convenience, system perceptions, gender issues and impacts on human dignity, the contribution to subsistence economies and food security, and legal and institutional aspects

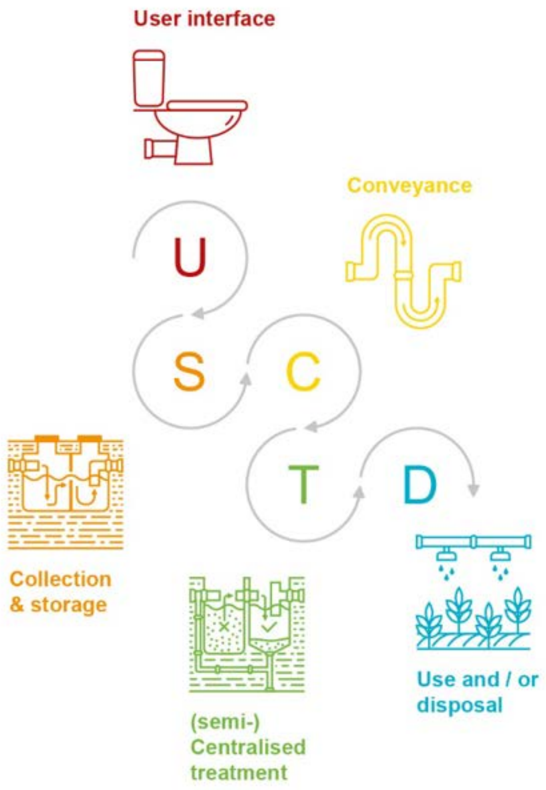

Figure 1.3: A Sanitation System is a context-specific series of technologies and services for the management of human wastes (or resources), from the point of generation to the point of reuse or disposal. This includes five functional groups: the user interface (U), the collection and storage (S), conveyance (C), treatment (T), and final reuse or disposal (D). Sources: (Maurer et al., 2012; Spuhler et al., 2018; Tilley et al., 2014b; Zurbrügg et al., 2009).

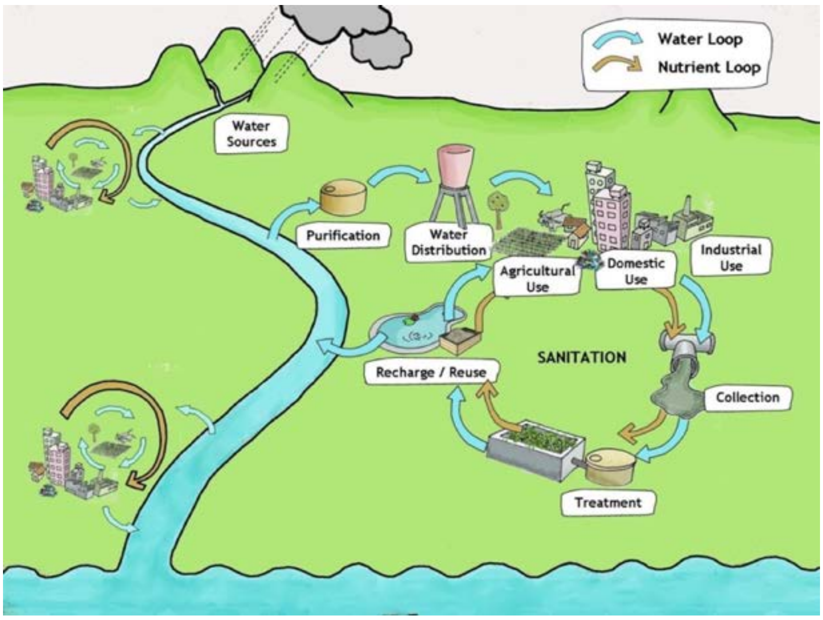

Figure 1.4: Sustainable sanitation addresses the entire cycle from the toilet to the collection, treatment, and reuse, and closes water and nutrient cycles in order to protect natural resources and people downstream. Picture: (Conradin et al., 2010).

The call for ‘community participation’, ‘appropriate technologies’, ‘management of the entire nutrient and water cycle’, and ‘resource efficiency’ was formally recognized by the global community in the Sustainable Development Goals (SDGs), in particular SDG 6.2, sanitation for all (Box 1.4, UN, 2014). Moreover, SDG 11 on sustainable cities further emphasizes on the importance ‘inclusivity’ to reach social equity.

Box 1.4

Sustainable Development Goal 6: Ensure availability and sustainable management of water and sanitation for all

- 6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all
- 6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations
- 6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
- 6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity
- 6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate
- 6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes
- 6A By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies
- 6B Support and strengthen the participation of local communities in improving water and sanitation management

Sustainable Development Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable

- 11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums
- 11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons
- 11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries
- 11.4 Strengthen efforts to protect and safeguard the world’s cultural and natural heritage
- 11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations
- 11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management
- 11.7 By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities

Source: (UN, 2015)

1.1.4 Innovations and novel sanitation solutions

To reach SDG 6 by 2030 one million people have to get access to sanitation each day (Mara and Evans, 2018), half of them in urban areas of developing countries (WHO and UNICEF, 2019). This has triggered massive investments in the development of novel technologies (e.g. urine diversion dry toilets, composting toilets, briquetting) and system configurations (e.g. container-based sanitation) providing solutions for non-sewer sanitation and faecal sludge management. Being independent from energy, water and sewer networks, these innovations are potentially more appropriate for developing urban areas. They also have the potential to enhance sustainability and resilience by reducing water requirements, being more adaptable for socio-demographic and environmental changes, and allowing recovery of nutrient, energy, and water resources (Drechsel et al., 2011; Larsen et al., 2016; Tilmans et al., 2015; Tobias et al., 2017). They also expand opportunities for private sector involvement in the collection and safe reuse of resources (Diener et al., 2014; Evans et al., 2013; Langergraber, 2014b; Lüthi et al., 2009a; Murray and Ray, 2010; Parkinson and Tayler, 2003; Schertenleib, 2005). The "reinvent the toilet challenge" (Box 1.5) has massively influenced the sanitation sector and the potential of novel sanitation has also been recognized in high-income countries, where the focus is on optimising aging infrastructure. Although there are little to no full-scale implementation examples of those innovations, there exists today a global consensus that sanitation technology and system innovations need to find their way into practice (Larsen et al., 2016).

Box 1.5

The Reinvent the Toilet Challenge aims to create a toilet that:

- Removes germs from human waste and recovers valuable resources such as energy, clean water, and nutrients.
- Operates "off the grid" without connections to water, sewer, or electrical lines.
- Costs less than US$.05 cents per user per day.
- Promotes sustainable and financially profitable sanitation services and businesses that operate in poor, urban settings.
- Is a truly aspirational next-generation product that everyone will want to use—in developed as well as developing nations.

Source: (BMGF, 2013)

Figure 1.5: Absence of sanitation lead to degradation of hygiene and the environment ,Kibera Slum, Nairobi, Kenya. Source: SuSanA 2015

Figure 1.6: Today it is possible to foresee decentralized wastewater treatment systems in urban areas where the blackwater is reclaimed for fertilizer production and the greywater is treated locally. Source: P. Jenssen, Oslo, Norway, 2010

1.1.5 Making modern sanitation available to practice

To take into consideration the call for a more ‘inclusive’ approach (UN, 2014) the Manila Principles of Citywide Inclusive Sanitation (CWIS) were defined (Gambrill et al., 2019; Narayan and Lüthi, 2019b; Schrecongost et al., 2020). The CWIS principles (Box 1.6) try to take up the concepts defined in the past, framing them specifically to address ‘inclusivity’ in various ways: encompassing informal and peri-urban areas, sewer and non-sewer technologies, the entire sanitation value chain, all stakeholders, larger urban goals, and all groups of society, without marginalisation based on gender, disability, or income (Narayan and Lüthi, 2019a).

Box 1.6

Citywide Inclusive Sanitation is an approach to urban sanitation, where all members of the city have equitable access to adequate and affordable improved sanitation services through appropriate systems of all scales (sewered & non-sewered), without any contamination to the environment along the entire sanitation value chain. Principles:

- **Equity:** everyone in an urban area, including communities marginalised by gender, social and economic reasons, benefit from equitable, affordable and safe sanitation services.
- **Environmental and public health:** human waste is safely managed along the entire sanitation service chain, starting from containment to reuse and disposal.
- **Hybrid technologies:** variety of sewered and non-sewered sanitation solutions coexist in the same city, depending on contextual appropriateness and resource recovery potential.
- **Comprehensive Planning**: planning is inclusive and holistic with participation from all stakeholders including users and political actors, with short- and long-term vision, incremental perspective and synergistic with other urban development goals.
- **Monitoring and Accountability:** authorities operate with a clear, inclusive mandate, performance targets, monitoring requirements, human and financial resources, and accountability.
- **Mix of business models:** Sanitation services are deployed through a range of business models, funding sources, financial mechanisms to reach all members equitably.

Source: (Narayan and Lüthi, 2019b)

However, there is still a lack of implementation of such principles that have evolved over the past decades, into practice. Currently, few cities are prepared to invest time and resources in sanitation planning. Missing leadership and lack of knowledge of new approaches leads to the propagation of outdated solutions which do not meet the needs of the people (Kennedy-Walker et al., 2014; Lüthi and Kraemer, 2012; McConville, 2010).

> *The current technological innovation provides a unique opportunity, especially for developing urban areas, to leapfrog the world's stagnant end-of-pipe approach to sanitation, and to implement CWIS. First, novel sanitation solutions potentially provide appropriate solutions to city areas were sanitation was seen too complex to be addressed in the past (e.g. slums). Second, novel solutions potentially enhance sustainability and resilience, as they are more adaptable to changing environmental and socio-demographic conditions, and allow for resource recovery. Third, these solutions are more flexible providing opportunities for community and private sector engagement and trying out new business models at each stage of the sanitation value chain.*

— 1.2 RESEARCH GAPS AND STATE-OF-THE-ART

While sanitation technology and system innovations potentially enhance appropriateness for difficult urban settings and contribute to sustainable development, they also increase planning complexity.

The experience of the past decades demonstrates, that reaching SDG 6.2, sustainable sanitation for all, cannot be achieved by one-size-fits-all solutions. Rather a more strategic approach to planning is required that considers a diverse portfolio of technology and system options, multiple criteria from all sustainability dimensions and specifically responds to the needs and preferences of local stakeholders (Figure 1.7).

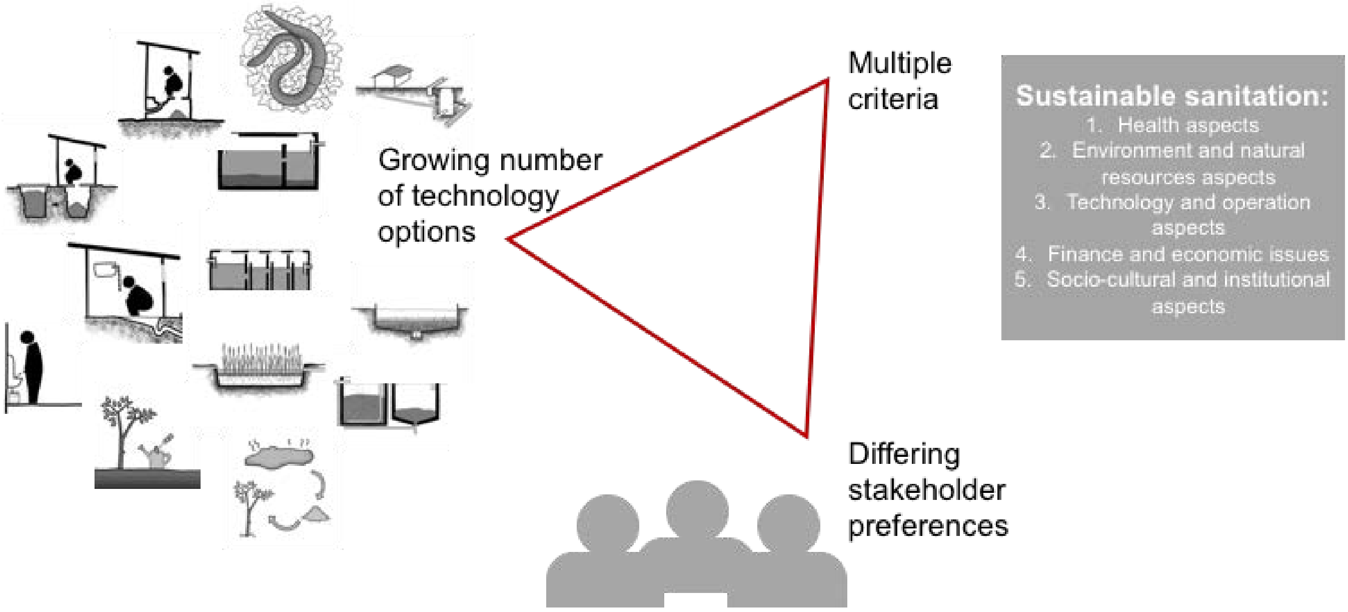

Figure 1.7: From a decision-making viewpoint, selecting a locally appropriate and sustainable sanitation system and its corresponding technologies is a complex multi-criteria decision-making problem involving multiple sustainability criteria (see also Box 1.3) large number of technology options (see also Box 1.5) and often differing stakeholder preferences. Source: D. Spuhler

1.2.1 Structured decision making (SDM) to tackle a complex multi-criteria problem

From a decision-making viewpoint, selecting a locally appropriate and sustainable sanitation system and its corresponding technologies is a complex multi-criteria decision-making problem. Structured decision making (SDM) can help to tackle such problems by systematically comparing decision options regarding the objectives and criteria in order to reveal trade-offs and balance for opposing interests. The facilitated participatory framework covers at least six steps (Gregory et al., 2012): (1) clarification of the decision context; (2) definition of objectives, indicators and stakeholder preferences; (3) development of decision options; (4) evaluation of decision consequences; (5) selection of preferred decision option; and (6) implementation and monitoring. Environmental science provides the information for step 3 and 4, while Multi-Criteria Decision Analysis (MCDA) provides the methods to combine this expert knowledge with the objectives and preferences of stakeholders (step 5). MCDA uses systematic analytical methods and thus enhances the transparency and accountability of the process (Linkov and Moberg, 2011; Linkov et al., 2004). It complements other methodologies such as (Finnveden et al., 2007; Motevallian and Tabesh, 2011; Starkl et al., 2005) Life-cycle Costing, LCC (Burr and Fonseca, 2011; Langergraber, 2014a; Maurer, 2013; von Sperling and Salazar, 2013) or Life Cycle Assessment, LCA (Lundin et al., 1999a; Pasqualino et al., 2009; Renou et al., 2008; Suh and Rousseaux, 2002).

1.2.2 SDM for urban sanitation

SDM and MCDA are widely applied for water management as exemplified by Table 1.1. To implement SDM for urban sanitation, various planning frameworks have been developed including Community-Led Urban Environmental Sanitation (CLUES, Lüthi et al., 2011a; Lüthi and Parkinson, 2011; Sherpa et al., 2012), Sanitation 21 (Parkinson et al., 2014), or City Sanitation Planning (CSP, GoI, 2008; MOUD, 2008). However, despite the continuous development of these theoretical foundations over the past decades, there is a lack of applying them in practice, one reason being the significant technical and financial support required (Kennedy-Walker et al., 2014; Ramôa et al., 2018; Starkl et al., 2013). In developing urban areas, there is a capacities for planning are often lacking, leading to a situation, where unsystematic decision-making allows to push for decisions based on political and hardly rational reasons. To operationalise SDM in these areas, recent research has focused on the development of methods and tools to operationalize the different planning steps. Yet, most of the research focuses on the understanding of the problem (e.g. Peal et al., 2014a; Robb et al., 2017; Strande et al., 2018) or the selection of a preferred option (e.g. Schütze et al., 2019), assuming that a set of appropriate decision options are already given (Hajkowicz and Collins, 2007). But every decision support approach is only as good as the decision options presented. Typically, the creation of sanitation system options (step 3 of SDM) and the evaluation of options (step 4) is done separately by engineers who lack data and reproducible methods for considering the entire spectrum of technologies and sustainability criteria.

Table 1.1: Literature examples of the application of Structured Decision Making (SDM) and Multi-criteria Decision analysis (MCDA) for wastewater management and sanitation planning.

SDM for sustainable water infrastructure planning in Switzerland:	(Borsuk et al., 2008; Larsen et al., 2010; Lienert et al., 2015)
Specific MCDA methods for environmental management:	(Hajkowicz and Collins, 2007; Huang et al., 2011)
MCDA for water and sanitation planning in developing countries:	(Hendriksen et al., 2012; Loetscher and Keller, 2002; Malekpour et al., 2013)
Multi-criteria evaluation of sanitation options in developing countries:	(Agudelo et al., 2007; De Silva, 2007; Kalbar et al., 2012; Katukiza et al., 2010; Makropoulos et al., 2008; Nayono, 2014; Olschewski, 2013; van Buuren and Hendriksen, 2010)
Identification of sustainability criteria for water or sanitation planning:	(Balkema, 2003; Chen and Beck, 1997; Dunmade, 2002; Foxon et al., 2002; Hellström et al., 2000; Hoffmann et al., 2000; Kvarnström et al., 2004; Kvarnström and Petersens, 2004; Muga and Mihelcic, 2008; Murphy et al., 2009; NETSSAF, 2006; Palme et al., 2005; Sahely et al., 2005; Singhirunnusorn and Stenstrom, 2009; Tilley et al., 2010)

1.2.3 Step 3: generation of sanitation system decision options

In order to fill in this gap, Maurer et al., (2012) have proposed a structured and formal approach for the generation of sanitation system options from basic technologies. The methodology draws from the field of product development and applies a novel compatibility assessment procedure that identifies compatibility relationships among technologies inspired by methods from product development (Singhal and Singhal, 2002; Singhal, 1978). The approach is capable of systematically producing a large variety of sanitation system decision options. The

Compendium of Sanitation Systems and Technologies (Tilley et al., 2014b) puts this into practice by providing an overview on 55 sanitation technologies and nine examples of how they could be combined in entire system templates.

> *However, the system templates are not systematically covering the entire option space and the number of options is still too large in order to be manageable in a planning situation. To comprehensively combine 50 technologies into entire systems would result in several 100'000 of possible options. A more systematic approach to system generation and an additional step to reduce the number of options is needed.*

The number of options that can be managed in a decision-making processes varies with the model complexity of methods used in steps 4 and 5 of SDM (e.g. more than 50 with multiple−attribute value theory, or multiple−attribute utility theory, or six to eight according to Gregory et al., (2012). Common methods to decrease the option space are Pareto optimality or dominance e.g. (Chen et al., 2008), sequential screening in combination with subset selection (Kilgour et al., 2004), and screening by restriction and aspiration levels (Eisenführ et al., 2010). The problem with these methods is that they require information on both the preferences of the stakeholders and the performance of options. However, this information is typically unavailable at the structuring phase of decision-making for the entire spectrum of technology options and criteria.

1.2.4 Step 5: evaluation of options regarding main decision criteria

In order to define decision criteria for sustainable sanitation (step 2 of SDM), many examples exist from literature and practice (e.g. Kvarnström et al., 2004; Kvarnström et al., 2011; Murphy et al., 2009; NETSSAF, 2006; SuSanA, 2008; Tilley et al., 2010). However, to quantify these criteria in order to evaluate different sanitation system options (step 4 of SDM) is often underestimated, because each and every criteria requires its specific indicator and method to quantify those.

One generic methodology applied in environmental engineering is material flow analysis MFA and substance flow modelling (SFM). It is a type of system analysis based on the principles of mass balances providing indication of material use, emissions, and costs. The nature of the system is captured in a mathematical model. Analytical methods quantify flows and stocks of resources and/or materials, which are transformed or consumed related to a given service within the system boundaries (Baccini and Brunner, 2012; Brunner and Rechberger, 2004). MFA/SFM are widely applied for environmental management, see examples in table.

Table 1.2: Literature examples of the application of Material Flow Analysis (MFA) and Substance flow modelling (SFM) in waste- and wastewater management and sanitation planning.

Waste- and wastewater management in Europe:	(Beretta et al. 2013, Binder et al. 2010, Binder and Mosler 2007, Binder et al. 2009, Cooper and Carliell-Marquet 2013, Finnveden et al. 2007, Huang et al. 2012, Huang et al. 2007, Lang et al. 2006, Lederer and Rechberger 2010
Nutrient management related to sanitation:	(Do-Thu et al., 2010; Gumbo, 2005; Montangero and Belevi, 2007)
Environmental sanitation planning:	(Jain 2012, Koffi et al. 2010, Meinzinger 2009, Montangero and Belevi 2008, Montangero et al. 2007, Sinsupan et al. 2005, Wang 2013, Yemaneh 2009)

The problem with MFA/SFM models is, that they are generally too complex to rely on empirical experience alone, and therefore various simulation tools have been implemented (e.g. Assefa et al., 2005; Dahlmann, 2009; Finney and Gearheart, 2004; Jeppsson et al., 2005; Makropoulos et al., 2008; Mitchell and Diaper, 2006; Robleto et al., 2010; Robleto et al., 2011; Schütze and Alex, 2014).

> *However, most of these models are designed for conventional centralized systems and do not allow to compare a large and diverse set of different sanitation systems simultaneously.*

One recent exception is SampSONS, that includes novel technologies and distributed systems along with sewer-based options (Campos, 2013; Ormandzhieva et al., 2014; Schütze et al., 2019). However, so far only a prototype is available containing building blocks for a few selected technologies, which have not been validated with real data.

1.2.5 Research gap: lack of reproducible methods and data

There exists currently a lack of reproducible methodologies that systematically identify sanitation system options for a given application (step 3 of SDM) and can deal with the large and diverse portfolio of currently available technologies and multiple sustainability criteria. Moreover, there is a lack of generic methods to quantify the performance of a large and diverse set of sanitation system configurations (step 4 of SDM) at the scale of a city. Additionally, the identification of options and their comparison is further hampered by the lack of knowledge or data, particularly for novel options.

— 1.3 RESEARCH OBJECTIVES AND QUESTIONS

The goal of this thesis is to improve sanitation planning practice by providing the methods to implement more sustainable sanitation solutions. The main research questions address the difficulty of making an optimal infrastructure choice in sustainable sanitation planning under uncertainty: how can the growing portfolio of technologies be considered when generating sanitation system decision options appropriate for a given case? And how can relevant sustainability indicators such as resource recovery and losses be quantified?

> *The main aim of this thesis is to develop systematic and generic methods to identify locally appropriate sanitation system decision options and to evaluate their performance as an input into the decision-making process.*

The term ‘systematic’ refers to transparent and reproducible methods that consider the entire option space. The term ‘generic’ refers to the potential consideration of almost any thinkable past, present, or future sanitation technology or system configurations. Furthermore, the methods should be applicable for a large and diverse range of technologies and system configurations simultaneously; and integrate criteria from all sustainability dimensions (see Box 1.3). Given the context of expanding urban environments and the focus on novel technologies, the methods should also be able to deal with uncertainties. To achieve the aim stated above, three specific objectives were defined and are briefly described in the following.

Objective I: To develop a systematic method for the generation of locally appropriate sanitation system decision options at the structuring phase of the decision-making process.

For this objective, I build on methods from previous work using a system approach with five functional groups (Tilley et al., 2014b) and methods from product development (Maurer et al., 2012). Crucial are two steps: (1) the identification of locally appropriate sanitation technologies, and (2) the generation of entire sanitation systems from the combination of compatible technology components. Each technology is characterised for these criteria, providing the technology appropriateness profile that can be matched to each application cases profile. The set of potential technologies and systems is given by the “Compendium of sanitation technologies and systems” (Tilley et al., 2014b). The core of the procedure is the development of the generic set of attributes and its definition for all potential technologies. Based on this data, the comparison of the appropriateness profiles can be automatized. The set of attributes is obtained using literature review, expert interviews, as well as the analysis of attribute sensitivity in different application cases. The method should be flexible enough in order to align the main method parameters (set of potential technologies and criteria) to the local conditions. The sanitation system options are characterized using the system approach and the system templates as defined by Tilley et al. (Tilley et al., 2014b). To consider the uncertainty related to technologies or the local context, I use probability theory and a novel approach comparing for each criteria the conditional probability of the requirements (given either by the technology or the application case) with the probability density of the condition (given by either the case or the technology).

Objective II: To develop a generic method for the quantification of resource recovery potentials suitable for the comparison of a diverse and large range of sanitation systems.

For this objective, I use a simplified substance flow modelling approach (e.g. Baccini and Brunner, 2012; Montangero and Belevi, 2007; Ormandzhieva et al., 2014) based on the previously defined technologies as building blocks and input and output products to define flow paths. The substances of primary focus are nutrients (phosphorus, nitrogen), water, and total solids (as an indicator for energy and organics). To make the model applicable ex-ante and to automatize the process, I develop generic transfer coefficients based on literature considering their uncertainties related to technology implementation, inflow quality, and environmental conditions (e.g. temperature). Monte Carlo is used to propagate uncertainties and to simulate the uncertainty of the model outcomes (Montangero and Belevi, 2008).

Objective III: To develop a standardized procedure for the integration of the methods with structured decision-making in expanding urban areas and to evaluate their contribution.

To test the developed methods and their contribution, I develop a standardized procedure for the integration with SDM and apply it practically in different urban settings in four countries: Nepal, Ethiopia, South Africa, and Peru. The procedure for integration of the methods is given by the six steps of SDM. To implement the different steps in the application cases, I work together with local partners that use methods from CLUES (Lüthi et al., 2011a; Lüthi and Parkinson, 2011; Sherpa et al., 2012), Sanitation 21 (Parkinson et al., 2014), or CSPs (GoI, 2008; MOUD, 2008). The core of the integration method is the adaption of the input parameters (potential technologies, screening criteria, substance inflows) to the local context engaging with stakeholders. The community engagement is achieved in facilitated workshops that use methodologies based on CLUES (Lüthi et al., 2011a), experiences from Eawag (Haag et al., 2019; Marttunen et al., 2019), and literature (Bond et al., 2008). Data collection is based on secondary literature (e.g. baseline reports, reports from previous projects), expert interviews, and field visits).

— 1.4 RELEVANCE

In this chapter we provide a brief overview on the relevance of the here presented work. A detailed description of the contributions of this thesis to science and practice is provided in chapter 8, section 8.3.

1.4.1 Relevance for science

There is a clear gap in literature and academic knowledge of systematic evaluation methods for considering the entire spectrum of available technologies and sustainability criteria. This lack of suitable methods introduces a whole range of shortcomings for practice, such as insufficient knowledge and data, particularly for novel options, leading to bias, opaque pre-selection processes, and preferences for available or personally preferred systems. Moreover, the lack of systematic methods that can consider a diverse and large range of options hampers the transfer of technology and system innovations form science to practice leading to limited uptake and of innovations and a lack of successful implementation examples at scale. The current rapid technological development in the field of sanitation requires a more systematic and generic methods. This thesis provides such methods for (1) the systematic assessment of the appropriateness of technologies for a given context based on objective screening criteria; (2) the generation of all valid sanitation system configurations; (3) the selection of a set of appropriate systems which is of manageable size; and (4) the quantification of resource recovery potentials of all systems. The methods are automatized in order to enable the consideration of a diverse and large set of technologies and systems (i.e. including onsite/offsite, sewer/off-the-grid, nature-based/high-tech, novel/conventional options). This automatization also enforces the consideration of entire and valid systems only (from the use to reuse of disposal). The appropriateness assessment considers indicators from all sustainability dimensions which are fixed and independent from stakeholder preferences and therefor useful for screening. The set of appropriate options is not only of manageable size, but also diverse in order to reveal relevant trade-offs and to minimise the impact on the final decision. The resource recovery potentials provide the indicators for a detailed sustainability evaluation of the appropriate options. The developed methods are generic and therefore remain applicable for future technology innovations. Currently, there exists little to no methods for planning sanitation systems other than classical sewers at the scale of an urban catchment. The here presented methods will enable the consideration of technology and system innovation in strategic sanitation planning in the future.

1.4.2 Relevance for policy and practice

The current number of available technologies leads to an overwhelming number of sanitation system planning options. The work presented here can help to streamline the planning process by providing reproducible methods to focus on the most appropriate systems only. The methods are based on a set of screening criteria that includes technical requirements, physical, demographic, socio-cultural conditions, and aspects related to capacity and skills. A compilation of international data is made available in a library as input into the appropriateness assessment. As international literature data and expert knowledge is matched to the local context, more empirical decision making is enabled in consideration of local stakeholder preferences as outlined in SDG 6b. The suggested procedure for integrating the methods with SDM fills in major methodological gaps in existing planning frameworks and also helps to close the capacity gap in planning practice. Its application in Nepal and Ethiopia provides options appropriate to different zones within a city supporting to more citywide inclusive sanitation (CWIS). The methods presented here enable the consideration of environmental sustainability in decision-making by quantifying resource recovery and loss potential. The application to a representative real-life case provides resource recovery and loss potentials for more than 100’000 sanitation system options that can be reused in any other decision-making process or that can be used to inform about the potential contribution of modern sanitation to circular economy. As novel technologies are developed and added to the already large portfolio, the methods presented here will become an essential tool for operationalizing CWIS and for achieving SDG 6, sanitation and water for all, and SDG 11, inclusive, sustainable and circular cities for all.

— 1.5 THESIS OUTLINE

In the remaining chapters of this thesis, five individual publications are presented, which address different research objectives relating to the main research question of identifying more appropriate and sustainable sanitation system options. The scientific publications are presented in order of the argumentation. Chapter 2 is a detailed analysis of existing methods and the gap. Chapter 3 addresses the research objective I. Chapter 4 and 5 address the research objective II, and chapter 6 addresses the research objective III. As this doctoral thesis is a cumulative dissertation and all main chapters can be read individually, some lines of thought and arguments are repeated in the different chapters.

Three publications have been published or submitted to the academic journal Water Research with the aim of connecting the international knowledge about the performance of different technologies with modelling and planning. One publication has been submitted to the Journal of Water, Sanitation and Hygiene for Development in order to contribute to the ongoing debate about more citywide inclusive sanitation planning. The last chapter publication is submitted to the Journal of Environmental Management in order to present the potential of the methods to improve current sanitation management practice.

Chapter 2 presents an overview on strategic planning approaches from a structured decision-making perspective. It describes in detail the lack of suitable methods and tools to identify sanitation technology and system options and to compare their performance regarding multiple sustainability criteria. It answers the question of what features a method for step 3 and 4 of SDM should embrace, in order to be capable of addressing the current urban sanitation challenges and to operationalize CWIS. The content of chapter 2 has been published as:

> *Spuhler, D. and Lüthi, C. 2020. Review of frameworks and tools for urban strategic sanitation planning: considering technology innovations and sustainability. Journal of Water Sanitation and Hygiene for Development. DOI: 10.2166/washdev.2020.062.*

Chapter 3 presents a systematic procedure for (1) the evaluation of the appropriateness of sanitation options considering novel technologies and uncertainties; (2) for the generation of entire systems; and (3) for the selection of a sub-set of options that is diverse and suitable for the decision-making process. It addresses the question of how to consider the growing number of conventional and novel technologies and system options at the structuring phase of SDM. The content of Chapter 3 has been published as:

> *Spuhler, D., Scheidegger, A. and Maurer, M. 2018. Generation of sanitation system options for urban planning considering novel technologies. Water Research 145, 259-278. DOI: 10.1016/j.watres.2018.08.021.*

Chapter 4 presents a generic substance flow model for the quantification of resource recovery potentials and losses as an input into the comparison of different sanitation system decision options. The content of chapter 4 has been published as:

> *Spuhler, D., Scheidegger, A. and Maurer, M. 2020. Ex-ante quantification of nutrient, total solids, and water flows in sanitation systems. Submitted to Journal of Environmental Management. Preprint available in the associated data package: https://doi.org/10.25678/0000HH.*

Chapter 5 (Spuhler et al., 2020b) presents the application of this model to a representative real-life case and for four substances (phosphorus, nitrogen, total solids, water) that allow to derive system characteristic that influence on resource recovery and recommendations for future system design. Chapter 5 together with chapter 4 address the question of how to quantify ex-ante key performance indicators for a diverse and large range of sanitation technologies and systems at the scale of an urban catchment. The content of chapter 5 has been published as:

> *Spuhler, D., Scheidegger, A. and Maurer, M. 2020. Comparative analysis of sanitation systems for resource recovery: influence of configurations and single technology components. Water Research 186. DOI: 10.1016/j.watres.2020.116281.*

Chapter 6 presents in detail the procedure to integrate the methods in an SDM process. It addresses the question whether and how the methods contribute to sustainable sanitation planning in urban areas of developing countries. The content of chapter 6 has been published as:

Spuhler, D., Germann, V., Kassa, K., Ketema, A.A., Sherpa, A.M., Sherpa, M.G., Maurer, M., Lüthi, C. and Langergraber, G. 2020. Developing sanitation planning options: a tool for systematic consideration of novel technologies and systems. Journal of Environmental Management 271. DOI: 10.1016/j.jenvman.2020.111004.

In **Chapter 7**, the main findings, recommendations, and shortcomings are discussed.

Chapter 8 concludes with answers to the research questions initially outlined in the research plan for each of the three objectives described above. The chapter also provides a more detailed description of the relevance and the contributions to science and planning practice, the implications, and the potential generalisation of the results of this thesis. Finally, an outlook towards future research activities and practical applications is presented.

— 1.6 DECLARATION OF PERSONAL CONTRIBUTION

This doctoral thesis is a cumulative thesis and therefore based on publications which were written together with different co-authors. Dorothee Spuhler is the first author of all included publications and the main contributor with the greatest intellectual and analytical contribution. The personal contribution of Dorothee Spuhler towards this dissertation principally includes the following according to CRediT – Contributor Roles Taxonomy:

- Conceptualization – Ideas; formulation or evolution of overarching research goals and aims.
- Data curation – Management activities to produce and maintain research data (including software code) for initial use and later re-use.
- Formal analysis – Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data.
- Funding acquisition – Acquisition of the financial support for the project leading to this publication.
- Investigation –Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection.
- Methodology – Development or design of methodology; creation of models.
- Project administration – Management and coordination responsibility for the research activity planning and execution.
- Software – Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components.
- Supervision – Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team.
- Validation – Verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs.
- Visualization – Preparation, creation and/or presentation of the published work, specifically visualization/data presentation.
- Writing – original draft – Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation).

- Writing – review & editing – Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages.

However, most of the creative thinking as well as the implementation of software was heavily supported by Andreas Scheidegger. Moreover, Prof. Dr. Max Maurer, Dr. Christoph Lüthi, and Dr. Günter Langergraber took on the role of principal investigators, supervising and contributing accordingly in terms of ideas and intellectual guidance, steering the overall writing and formation process of this thesis and the included publications. All publications have been written together, including framing the storyline, polishing the manuscripts with multiple revision rounds (also additionally based on feedback of anonymous reviewers). Max Maurer was particularly involved in crafting Chapter 3, 4, 5, Christoph Lüthi in chapter 2, and Günter Langergraber in chapter 6. The practical applications were made possible through local partners including ENPHO and 500B in Nepal, and the University and the Town Municipality of Arba Minch. These organisation and the people behind contributed mainly to the methodology design and its validation. Most of them also were involved in crafting chapter 7, namely Dr. Kinfe Kasse, Dr. Atekelt A. Ketema, Dr. Minga Sherpa, Anjali Sherpa, and Verena Germann. Agnès Montangero from Helvetas enabled additional field testing in Nepal and provided extra feedback. The framing of this thesis (chapters 1, 7 and 8) were written by Dorothee Spuhler with feedback from supervisors and colleagues, such as Max Maurer, Christoph Lüthi, Günter Langergraber, Lena Mutzner, Andreas Scheidegger, Abishek Sankara Narayan, Samuel Renggli, Barbara Jeanne Ward, and Philippe Reymond.

02 Review of frameworks and tools for urban strategic sanitation planning: considering technology innovations and sustainability

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Publication version Preprint (submitted 31.07.2020). Spuhler, Dorothee and Lüthi, Christoph. 2020. Review of frameworks and tools for urban strategic sanitation planning: a structured decision-making perspective. Journal of Water Sanitation and Hygiene for Development.

Supplementary material Summary of literature review: https://iwaponline.com/washdev/article/doi/10.2166/washdev.2020.062/76656/Review-of-frameworks-and-tools-for-urban-strategic

- **Provides a historical review of frameworks for strategic sanitation planning**
- **This reveals a lack of systematic tools to identify suitable planning options considering innovations**
- **Compares how 15 tools for option selection address the current urban sanitation challenge**
- **Compiles eight qualities from this analysis that could improve any future tool**
- **Most important qualities are the ability to deal with the growing portfolio of novel technologies, multiple criteria, and uncertainties**

Author contributions: D.S. and C.L. conceptualised this review together. D.S. was responsible for data curation, formal analysis, funding acquisition, investigation, and the methodology. D.S. also wrote the original draft and visualized the results. C.L. supervised the process.

ABSTRACT

To achieve citywide inclusive sanitation in developing countries, a strategic sanitation planning approach (SSA) needs to provide a variety of technical solutions that respond to different urban realities. Despite the development of various SSA frameworks, sanitation planning still often follows a “one-size-fits-all” approach. Structured decision making (SDM) can help by balancing trade-offs among different solutions. But SDM requires a set of appropriate sanitation options to choose from. Because conventional sewer-based sanitation is often inappropriate, many novel technologies and systems have been developed (e.g. container-based sanitation). While these innovations enhance sustainability, they also increase planning complexity.

In this review, we look at available frameworks and tools for SSA and discover a lack of systematic tools for the identification of planning options that are able to consider the growing portfolio of available solutions and multiple sustainability criteria. Therefore, we critically compare 15 tools from which we compile eight qualities that could help any future tool address the current sanitation challenge: it should be comprehensive, automated to deal with a large number of options, systematic, flexible towards future innovation and should consider all sustainability dimensions, make a contextualized evaluation, allow for participation, and consider uncertainties to be applicable ex-ante also for novel technologies.

— 2.1 INTRODUCTION

Safe sanitation services are a precondition for healthy people and a healthy environment and thus also for social and economic development (Hutton and Varughese, 2016; WHO and UNICEF, 2000; 2013). Still in 2017, only 45% of the global population used safe sanitation, leaving the rest of the world at high risk for diseases and death (UN, 2019). To reach the Sustainable Development Goal (SDG) 6 by 2030, each day an additional one million people have to get access to safe sanitation (Mara and Evans, 2018). Half of those that need access live in urban areas of developing countries where most current population growth is taking place (Dodman et al., 2013; UNDESA, 2014) (WHO and UNICEF, 2019). Even though there is less open defecation in urban than in rural areas (1% as compared to 18%, WHO and UNICEF, 2019), safe collection and treatment downstream is more often lacking (47% as compared to 43%, WHO and UNICEF, 2019). Only 18% of the products from domestic on-site sanitation facilities are treated worldwide (UN-WATER, 2018). High density and low absorption capacity in the urban environment further increase the impact of unsafe sanitation. Climate change exasperates the problem (World Resources Institute, 2020). Unsafely managed urban sanitation creates hotspots of environmental degradation and public health hazards worldwide (Lüthi and Narayan, 2018). Rapid unprecedent population growth, high density, and the lack of financial and human resources in many developing urban areas make it extremely difficult to address this problem (Dodman et al., 2013; Dodman et al., 2017; Isunju et al., 2011; Ramoa et al., 2014; Tremolet et al., 2010; UN-HABITAT, 2012).

Conventional approaches to urban sanitation are top down and technology driven and have often failed to address the current urban sanitation challenge. Already in the 80's, it was recognized that improving access to sanitation in urban areas of developing countries requires a strategic sanitation planning approach (SSA). Such an approach is multi-technology, multi-criteria, multi-professional and allows for incremental improvement by engaging with the community (Kalbermatten, 1982; Kalbermatten et al., 1982; Kalbermatten and Middleton, 1999; Lüthi et al., 2009a; Middleton and Kalbermatten, 1990; Reymond et al., 2016; Scott et al., 2017; Tayler et al., 2000; 2003; Wright, 1997). Since then, various SSA frameworks have been developed including for instance Household-centred Environmental Sanitation (HCES) or Sanitation21 (Eawag, 2005; Parkinson et al., 2014). Despite these efforts, sanitation planning in urban settings of developing countries still tends to follow a "one-size-fits-all" approach today. This leads to inappropriate technology choices, lack of ownership, and many failing projects world-wide (e.g. (Brunson et al., 2013; Jurga, 2009; Kvarnström et al., 2011; Lüthi et al., 2010; Montgomery et al., 2009; Starkl et al., 2013; Tilley et al., 2014a). One main reason for failure is the lack of political will to invest time and human and financial resources for long-term strategic planning. Another reason is that planners lack the knowledge and experience concerning viable solutions for high-density low-income areas where water, energy, space, and land tenure are often lacking.

This has triggered the development of many novel sanitation technologies and system configurations and options for faecal sludge management (FSM) as alternatives to the sewered centralised solution. Examples include urine diversion dry toilets or container-based sanitation (e.g. Tilmans et al., 2015; Tobias et al., 2017). These options are often more appropriate for developing urban areas because they are independent from sewer, energy, and water supply. The innovations are also potentially more sustainable because they can adapt to changing environmental or socio-demographic conditions and allow for resource recovery and reuse opening up opportunities for private sector engagements (e.g. Diener et al., 2014; Evans, 2013; Hoffmann et al., 2020; Larsen et al., 2016; Russel et al., 2019).

Current technological innovation provides a unique opportunity, especially for developing urban areas, to bypass the unsustainable conventional end-of-pipe approach to sanitation. This has also been recognized in the most recent urban strategic sanitation planning approach: Citywide Inclusive Sanitation, CWIS (Gambrill et al., 2019; Lüthi and Narayan, 2018; Schrecongost et al., 2020).

But while technology and system options potentially enhance appropriateness, sustainability, and inclusiveness, they also increase planning complexity. This can be illustrated by a simple mathematical example: considering 5 interchangeable technologies along the 5 functional groups of the sanitation chain, thus in total 25 technologies, results already in 3,125 possible system configurations. How can we consider them all and evaluate their suitability for a given planning context?

Structured decision making (SDM) is a generic planning framework that can help in such complex situations by systematically comparing several decision options regarding the decision objectives. It combines decision analysis with engineering methods in six steps that are generic to any decision-making process (Gregory et al., 2012): (1) understanding the decision context; (2) defining decision objectives and criteria; (3) identifying decision options/alternatives; (4) evaluating of consequences of the options regarding the decision objectives; (5) discussing the trade-offs and selecting the preferred options, and (6) planning, implementation and monitoring. SDM helps reveal trade-offs and balance opposing interests and differing stakeholder preferences. In recent years, a variety of tools have been developed to put strategic planning into practice following the SDM frameworks. Examples include Community-led Environmental Sanitation (CLUES, Lüthi et al., 2011a), the five criteria for sustainable sanitation (SuSanA, 2008), or Shit Flow Diagrams (Peal et al., 2014b). But most current research focuses on understanding the context or the selection of a preferred option, assuming that a set of appropriate sanitation planning options is already available. Still, every decision support is only as good as the options presented. The current sanitation challenge requires a tool that enables engineers and planners to consider the growing portfolio of technology options and the multiple sustainability criteria when providing suitable planning options.

— 2.2 AIM OF THIS PAPER

In this paper, we attempt to answer three questions:

1. What frameworks and tools for strategic sanitation planning in developing urban areas have been developed over the past 40 years and what can we learn from them by taking an SDM perspective?

2. What tools do we have for the identification of sanitation system planning options (step 3 of SDM) and to what extent do they help address the current sanitation challenge?

3. What are the qualities that a tool for option selection should embrace in order to address the current sanitation challenge?

To answer these questions, we start with a description of the current sanitation challenge. Secondly, we provide a review of SSA frameworks and tools that evolved over the past 40 years from an SDM perspective. Thirdly, we systematically compare 15 tools for the identification of sanitation system decision options (step 3 of SDM) in order to evaluate how they address the current sanitation challenge. For this, we are mainly interested in the capability to consider (i) the growing portfolio of available sanitation technologies and system configurations; (ii) multiple sustainability criteria; and (iii) uncertainties related to the local context or novel technologies.

— 2.3 METHODS

This publication is based on a review of a broad range of literature (academic publications, project reports, grey literature, and practice-oriented publications) collected and analysed within the GRASP project (GeneRation and Assessment of Sanitation options for Planning). GRASP was carried out at Eawag from 2015 to 2020 in collaboration with Arba Minch University (Ethiopia), University of Natural Resources and Life Sciences BOKU (Vienna, Austria), the Environmental and Public Health Organisation (ENPHO) and 500B Solutions (Nepal). The literature review covered two main topics:

1. Frameworks for strategic sanitation planning: Frameworks included 'principles' such as defined in the strategic sanitation approach (Middleton and Kalbermatten, 1990); 'frameworks' such as Sanitation21 (Parkinson et al., 2014); detailed 'guidelines' such as CLUES (Lüthi et al., 2011a); as well as 'approaches' such as CWIS (Schrecongost et al., 2020).

2. Tools to put these concepts into practice: Tools included any decision support for sanitation planning such as 'decision trees', 'computer models', and 'information packages'. Particular attention was given to tools supporting the identification of sanitation system decision options (step 3 of SDM).

Literature was collected through (i) targeted research using databases such as Science Direct or Scopus, as well as through (ii) expert interviews for specific recommendations. To organize and compare the collected literature, the structured decision making (SDM) approach (Gregory et al., 2012) was chosen, as it embraces all relevant steps for any generic decision-support process.

The literature review revealed a lack of systematic tools that allow for the consideration of the growing number of technology options and decision criteria when generating sanitation decision options (step 3 of SDM). Therefore, we systematically and critically compared 15 tools that can support step 3 of SDM and identified qualities that such a tool should embrace to address the current sanitation challenge.

— 2.4 THE CURRENT SANITATION CHALLENGE

The world has not achieved the Millennium Development Goals (MDG) for sanitation and is not on track to reach the SDG 6.2 (UN, 2019), i.e. sanitation to all. While the MDGs aimed for improved access to toilets, the SDG extended the demand for toilets with a call for a looking at entire systems, considering sustainable sanitation, and providing appropriate options for inclusive services.

The idea of appropriate technology initially evolved in the 1970s in order to promote an alternative to the capital-intensive technology of modern industry (Schumacher, 1973). Appropriate sanitation services require a mixture of technologies that are adapted to (i) local skills and materials; (ii) capital resources; (iii) physical conditions such as topography, soil type, water availability; (iv) and socio-demographic conditions such as population density, user preferences, and affordability (Iwugo, 1979; Kalbermatten et al., 1980; Menck, 1973; Reymond et al., 2016; Spuhler et al., 2018).

The five criteria for sustainable sanitation have been laid out by the Sustainable Sanitation Alliance in 2008 (SuSanA, 2008). To be sustainable sanitation systems must not only provide appropriate technologies that are socially acceptable and institutionally and financially viable – they must also protect the environment by saving/recovering natural resources. Social acceptance here, not only refers to user preferences regarding e.g. squatting or sitting or the reuse of human waste, but also integrates aspects related to gender issues and the inclusion of marginalized groups. The definition of sustainable sanitation challenged the sector to shift the focus from end-of-pipe treatment towards approaches that integrate resource recovery and reuse. As cities are responsible for the largest component of global energy, water, and food consumption, as well as related wastewater and organic waste production, this is a promising approach in regard to sustainable development (Lüthi and Narayan, 2018; Schuetze et al., 2013). The need for resource efficiency was also reconfirmed by SDG 6 (UN, 2014) and reflected in a new functional sanitation ladder that defines the quality of sanitation not by the technology of choice, but by the functions that can be fulfilled (Kvarnström et al., 2011).

Moreover, for SDG 6.2, the focus is not only on toilet access, but for the first time also on the management of the entire sanitation value chain or sanitation service chain. The sanitation service chain refers to the system approach introduced by the Compendium of Sanitation Systems and Technologies (Tilley et al., 2014b). A sanitation system is a set of compatible technologies, which in combination, safely manage human excreta and wastewater along five functional groups: user interface, containment and emptying, transport, treatment and safe reuse or disposal (Maurer et al., 2012; Spuhler et al., 2018; Tilley et al., 2014b). The sanitation value chain refers to the technologies in place, and to the quality of services. Service provision requires institutional arrangements that fit a given technology combination. Sewer systems are one type of sanitation system that are appropriate in well-planned central areas. These conventional solutions are however often not viable in fast-growing low-income areas because they rely on large quantities of water, costly sewer networks, stable institutions, and long planning horizons (Larsen et al., 2016). The increasing recognition of a need for more appropriate and sustainable solutions has led to important investments in the development of innovations for non-sewered sanitation and Faecal Sludge Management (FSM). These innovations consider both novel technologies and system configurations. Examples include urine diversion dry toilets (Tobias et al., 2017), briquetting (Jones, 2017; Septien et al., 2018b), or container-based sanitation (Tilmans et al., 2015). The innovations are more appropriate for urban areas in developing countries because they are independent from energy, water, and sewer networks. They are potentially also more sustainable because they reduce water requirements, are more adaptable to demographic and environmental changes, and allow for resource recovery and reuse (e.g. phosphorus and nitrogen, biofuel, heat, (Drechsel et al., 2011; Larsen et al., 2016; Tilmans et al., 2015; Tobias et al., 2017). They also expand the possibilities for private sector involvement in the collection and safe reuse of resources in order to complement often lacking public services (Diener et al., 2014; Evans et al., 2013; Langergraber, 2014b; Lüthi et al., 2009a; Murray and Ray, 2010; Parkinson and Tayler, 2003; Schertenleib, 2005). The "reinvent the toilet challenge"[2] has significantly influenced the sanitation sector and the potential of novel sanitation solutions has also been recognized in high-income countries, where the focus is on optimising aging infrastructure.

The current urban sanitation challenge can be described as a combination of challenging factors. These factors include rapidly changing demographics based on unprecedented growth, lack of political will, the paucity of human and financial capacities, failure of conventional sewer infrastructure, and high uncertainty related to local socio-demographic and environmental conditions as well as novel technologies and systems.

To address the current urban sanitation challenge, the Manila Principles of Citywide Inclusive Sanitation (CWIS) are presently being framed (BMGF, 2017; Gambrill et al., 2019; Lüthi and Narayan, 2018; Narayan and Lüthi, 2019a;

[2] https://www.gatesfoundation.org/Media-Center/Press-Releases/2018/11/Bill-Gates-Launches-Reinvented-Toilet-Expo-Showcasing-New-Pathogen-Killing-Sanitation-Products Access: 29.05.2019

Schrecongost et al., 2020; Scott and Cotton, 2020). These principles advocate an approach to urban sanitation, where all members of the city have equitable access to affordable sanitation services that incorporate a safe and complete sanitation service chain and consider effective resource use and diverse sanitation services (BMGF, 2017; Narayan and Lüthi, 2019a). Many of the principles for which CWIS is advocating have been put forward previously e.g. through the Bellagio Principles in Urban Environmental Sanitation Planning (Schertenleib, 2005). The difference between the two approaches hinges on the term inclusive. This term encompasses several elements: all urban realities (e.g. centre, informal, peri-urban), different sanitation solutions appropriate to these different realities, multiple criteria, the entire sanitation value chain, all stakeholders, larger urban goals, and marginalised group (e.g. gender, disability, low-income level, etc.), (Narayan and Lüthi, 2019a).
Today, there is growing global agreement that sanitation innovations need to find their way into practice in order to achieve the SDGs and CWIS (e.g. (Andersson et al., 2018; Davis et al., 2019; Davis et al., 2014; Drangert et al., 2018; Guest et al., 2009; Hoffmann et al., 2020; Larsen et al., 2016; Orner and Mihelcic, 2018; Trimmer et al., 2019; Willetts et al., 2010). But while sanitation innovations potentially enhance appropriateness for difficult urban settings and sustainability in general, they also increase planning complexity. How compatible are technologies and how can they be assembled into entire systems? And, how appropriate and sustainable are those systems for a given urban area? These are questions that sanitation planners are increasingly struggling with.

— 2.5 STRATEGIC SANITATION PLANNING FROM AN SDM PERSPECTIVE

From a decision-making viewpoint, selecting locally appropriate and sustainable sanitation planning options is a complex multi-criteria decision-making problem involving a large and diverse range of technologies, multiple sustainability criteria, and often divergent stakeholder preferences (Bracken et al., 2005; Kvarnström and Petersens, 2004; Lienert et al., 2015; Zurbrügg et al., 2009). SDM can help with such complex situations by combining engineering expertise with Multi-Criteria Decision Analysis (MCDA). This leads to enhanced transparency and more empirical decision making while taking stakeholder preferences into consideration. The aim is not only to elicit "better" (more rational) decisions, but also more accepted decisions.

Over the past 40 years, various frameworks have been developed for SSA in urban areas. All of them provide a more or less structured framework and/or methodology covering several steps of SDM. And each of them captures a current trend and provides an additional element based on lessons learned from previous efforts (see Table 2.1 and supplementary information SI-A).

The basis for **SSA** was prepared in 1976 when John Kalbermatten set up the World Bank project looking at low-cost sanitation. SSA suggests that problems need to be addressed through (Kalbermatten, 1982; Kalbermatten et al., 1982; Middleton and Kalbermatten, 1990): (i) a *multi-technology* approach providing a mixture of on-site and centralized solutions appropriate for different urban realities; a (ii) a *multi-professional* approach, including not only sanitary engineers, but also economists, behavioural scientists, and health specialists; (iii) a *multiple criteria* approach including not only technical, but also health, costs, socio-economic, socio-cultural, institutional, and environmental factors; and by (iv) allowing for flexible solutions and phase-wise *incremental* improvements. These key principles were the basis for moving away from a top-down, technology-centred approach towards engagement of the community and interactive planning processes that identify locally *appropriate technologies* considering multiple criteria. In 1997, **"Towards a Strategic Sanitation Approach"** was published, operationalizing many of the ideas behind SSA. It advocates for (Wright, 1997): (i) paying attention to the preferences of users and their *willingness to pay*; (ii) unbundling sanitation services into discrete parts (such as household services and trunk services) and providing these components in user preferred sequence; and (iii) involving the creative use of both formal and informal institutions to co-produce services. SSA was tested in several cities, including Kumasi, Ouagadougou, and Bharapur and was critically reviewed in the publication by Tayler (Tayler et al., 2003). One of the main challenges in implementing the SSA was the significant technical and financial support required, due to the multi-sectoral complexity and scope. Many multilateral agencies were not prepared to invest the required time and resources for such an approach at that time.

The **Household-Centred Environmental Sanitation (HCES)**, (Eawag, 2005) approach was formulated as guidelines for implementing the Bellagio Principles in Urban Environmental Sanitation Planning (Schertenleib, 2005). HCES was based on four core principles: (i) *households* should be at the centre of the planning process; (ii) *bottom-up planning should be combined with a top-down* approach considering multiple actors and multiple sectors; (iii) cities should be divided into spatial *zones* (household, neighbourhood, local government etc.), with systems that emphasizes reuse and recycling within these zones in order to solve the problems nearest to where they arise; and (iv) focus should be given to the *enabling environment*. The HCES approach was tested, piloted, and evaluated in seven cities (Lüthi et al., 2009b). The focus was mainly on community involvement within one zone independently, rather than looking at the zones jointly. Therefore, the scope of citywide sanitation was not achieved as initially intended.

In 2008, SuSanA laid out its vision in which **five criteria for sustainable sanitation** were defined: health and hygiene; environment and natural resources; technology and operation; financial and economic issues; social and institutional aspects (SuSanA, 2008). SuSanA also introduced the systems approach and the sanitation value chain, acknowledging that providing toilet infrastructure alone does not improve public and environmental health conditions, but may only help export problems to the next zone. The formulation of the five criteria as a directive allowed **multi-criteria analysis** to become operational (Kvarnström et al., 2004; Spuhler et al., 2018), as exemplified by Open Planning for Sanitation (Kvarnström and Petersens, 2004).

In 2010, the **Human Right to Water and Sanitation (HRWS)** was declared, calling not only for increased participation, but also for improved accountability and equity and consideration of marginalized groups (UN, 2010a). In parallel, various **City Sanitation Planning (CSP)** frameworks were developed (GoI, 2008; MOUD, 2008; Walther, 2016; WSP, 2010). A very similar approach was also developed for French speaking areas, i.e. Concerted Municipal Strategy (CMS), (LeJallé et al., 2012). The main three contributions of CSP are the detailed guidance provided for (i) the creation of a shared vision among all the actors; (ii) the consideration of all segments of the population including marginalized groups; and (iii) the joint consideration of liquid and solid waste streams.

In 2011, the **Community-Led Urban Environmental Sanitation (CLUES)** guidelines were presented as a follow-up concept to the HCES concept, making it more actionable (e.g. reducing the 10 steps to 7), and focusing on the community level instead of making the household level the centre of action (Lüthi et al., 2011a). The main innovation of CLUES is the prominence given to the importance of the enabling environment. Furthermore, a set of tools was provided to put each planning step into practice. Several NGOs and institutions have validated and adopted the

CLUES approach including among others WSUP (Water and Sanitation for the Urban Poor) and Helvetas Swiss Intercooperation.

The **Sanitation21** framework (Parkinson et al., 2014) was intended to be complementary to CLUES addressing the challenge of citywide sanitation. Sanitation21 does not provide planning steps, but highlights five features that should be covered: (1) build institutional commitment for planning; (2) understand the existing context and define priorities; (3) develop system options; (4) develop models for service delivery; and (5) prepare for implementation. The main contribution is the focus on planning objectives rather than technology options. However, there was a lack of funds for broad testing and it always remained an abstract framework. Nevertheless, the guidelines were instrumental in moving away from traditional, physically-focused master plans to today’s more contemporary thinking on inclusive, multi-stakeholder sanitation planning.

In 2015, the World Health Organisation published new guidelines for **Sanitation Safety Planning** (WHO, 2015). Sanitation Safety Planning provides a step-by-step approach that assists risk assessment at the local level for each element of a sanitation system. Starting with the idea that all sanitation systems should protect human health, Sanitation Safety Planning focuses on the identification of hazardous events and risk exposure as well as the assessment and prioritisation of control measures. The main contribution of this risk assessment tool is that it links systematic health risk assessment at the local level with citywide hygiene conditions. The SaniPath Rapid Assessment Tool is a related example that helps assess exposure to faecal contamination in low-income urban settings (Robb et al., 2017).

Despite the efforts described above, the challenges for a citywide approach for sanitation are still not being addressed sufficiently. At the same time, the roles of on-site and non-sewered sanitation and faecal sludge management are recognized as part of urban sanitation solutions. Today, it is widely acknowledged that technical solutions exist that can be integrated into urban planning at scale to address areas which have been neglected so far and have relied on informally built and maintained onsite solutions. This together with the Sustainable Development Goals (SDG 6 and SDG 11), prepared the ground for **the Citywide Inclusive Sanitation approach (CWIS)**. This approach is still under development (see ‘current sanitation challenge’). But, there is broad agreement on a number of key principles, including: safe and equitable service delivery, resource efficiency (water, nutrients, and energy), a mix of technologies and business models, and planning and accountability (Narayan and Lüthi, 2019a).

Table 2.1: Historical overview of selected strategic sanitation planning frameworks broadly following a structured decision making (SDM) and their contribution to address the current sanitation challenge. Source: authors; details provided in SI-A.

SDM framework	Main innovation/contribution
Framework	**Main innovation/contribution**
Strategic Sanitation Planning (SSP) (Kalbermatten, 1982; Kalbermatten et al., 1982; Kennedy-Walker et al., 2014; Middleton and Kalbermatten, 1990)	Multi-professional; multi-criteria (not only technical and financial, but also social and environmental); community participation, considering user preferences to provide appropriate technologies; unbundling services and allowing for incremental improvement; combining informal and formal institutions (co-creation)
Strategic Sanitation Approach (SSA) (Tayler et al., 2003; Wright, 1997)	Community participation; willingness to pay; capacity development; market-based approach.
Household-Centred Environmental Sanitation (HCES) (Eawag, 2005)	Combination of bottom-up and top-down approach using a multi-actor and multi-sector approach; prioritisation of circular systems that consider waste as a resource and work within different city zones ; focus on the enabling environment; not only a framework but a 10-step implementation methodology.
City Sanitation Planning (CSP) (GoI, 2008; Walther, 2016; WSP, 2010)	Consideration of marginalized groups; comprehensive planning that considers all solid and liquid waste streams.
Community-led Urban Environmental Sanitation (CLUES) (Lüthi et al., 2011a)	Further fostering enabling environment; empowering communities; 7-step methodology and a choice of tools that helps to put the methodology into practice.
Sanitation21 (Parkinson et al., 2014)	Pulls together key elements of good planning seen across the range of other planning tools/frameworks; focuses on objectives rather than technologies; citywide approach; emphasizes importance of institutional partnerships.
Concerted municipal strategy (CMS) (LeJallé et al., 2012)	Specifically, for French-speaking areas; framework for inclusion of local actors; detailed guidance available; several case studies documented.

— 2.6 TOOLS TO MAKE PROCESS GUIDES OPERATIONAL

Despite the continuous development of theoretical foundations over the past decades, these theoretical well-planned participatory approaches are rarely used in practice (Kennedy-Walker et al., 2014; Ramôa et al., 2018). This is due to various practical challenges (Barnes and Ashbolt, 2006; McConville, 2010; Ramôa et al., 2018). One key constraint is that cities and development agencies are not prepared to invest time and resources in planning (Tayler and Parkinson, 2005). And even when planning is undertaken, capacity and skill gaps persist (Kennedy-Walker et al., 2014; Lüthi and Kraemer, 2012). One of these gaps consists of the lack of knowledge about new approaches and their potential to reply to local needs (Kennedy-Walker et al., 2014; Lüthi and Kraemer, 2012; McConville, 2010).

And even if knowledge would be available, planners are often confronted with an existing system that is overly constraining, making it difficult to think outside the box. To motivate and build capacity of the different stakeholders to productively participate in a structured planning process could be a first step towards improvement (Lüthi and Kraemer, 2012). To go in this direction, recent research has focussed on the development of various methods and tools to put the different planning steps in to practice.

In the table in SI-B, we provide an overview of tools that we know and believe to be useful for making SSA operational. As shown in this overview, tools exist for most of the SDM steps. Most recent and prominent examples include Sanitation Safety Planning (WHO, 2015), excreta or Shit Flow Diagrams (SFDs), (Peal et al., 2014a), SaniPath (Robb et al., 2017), and Quantity and Quality of Faecal Sludge (Strande et al., 2018). However, most current research focuses on understanding the current situation (e.g. diagnostic tools such as SFDs) and on selecting a preferred option (Schütze et al., 2019), assuming that an appropriate set of sanitation system decision options is already available. The identification of locally appropriate sanitation system planning options is most often left to engineering consultants. This leads to a number of shortcomings such a knowledge bias. Consultants are often not familiar with novel options, lack data on their performance, and are overwhelmed when asked to consider a large and diverse range of sanitation technologies and systems. The situation is further complicated by the multiple criteria that should be looked at from a sustainability perspective, the preferences of different stakeholder regarding those criteria, and a high uncertainty regarding the future. Criteria that should be analysed include all dimension of sustainable sanitation: health, protection of the environment and natural resources, technical and institutional appropriateness, financial viability, and socio-cultural acceptance. Stakeholders should include all levels from the community to the city or regional government and civil society as well as private and public sector actors. Uncertainties are due to the difficulty of predicting socio-demographic and environmental conditions in the future as well as the performance of novel technologies.

— 2.7 IDENTIFYING APPROPRIATE SANITATION PLANNING OPTIONS (SDM STEP 3)

Option generation approaches that have been applied to sanitation include: cause-effect analysis, creativity-based techniques, such as brainstorming, and mixed approaches, such as decision matrices and strategy tables (e.g. Eisenführ et al., 2010; Gregory and Keeney, 2017; Keeney, 1996; Larsen et al., 2010; Mara et al., 2007; McConville et al., 2014; Tilley et al., 2014b). Other popular and well-recognized support tools are structured compilation of information (‘information packages’) such as the ‘Compendium of Sanitation Systems and Technologies’ or the ‘Philippines Sanitation Sourcebook and Decision Aid’ (e.g. Tilley et al., 2014b; WSP, 2007). However, the results of these procedures rely heavily on available knowledge and are, therefore, also somewhat arbitrary. The systematic identification of sanitation system options is currently one of the biggest weaknesses in SDM for water and sanitation (Gregory et al., 2012; Hajkowicz and Collins, 2007; Spuhler et al., 2018).

To address the current sanitation challenge, tools for the identification of sanitation system options have to consider (i) the growing portfolio of available sanitation technologies and system configurations, (ii) multiple sustainability criteria; and (iii) uncertainties related to the local context or novel technologies. To better understand the extent to which existing tools cover these features, we critically compared 15 methods and tools that can be categorised into three types of approaches: decision trees, scoring or ranking using software support, and information packages (see Figure 2.1). For the evaluation we only looked at the hardware aspect of 'systems' and did not include different institutional arrangements. We acknowledge that institutional arrangements depend on stakeholder preferences and involve trade-offs and therefore deserve to be dealt with once detailed planning is being undertaken (step 6 of SDM).

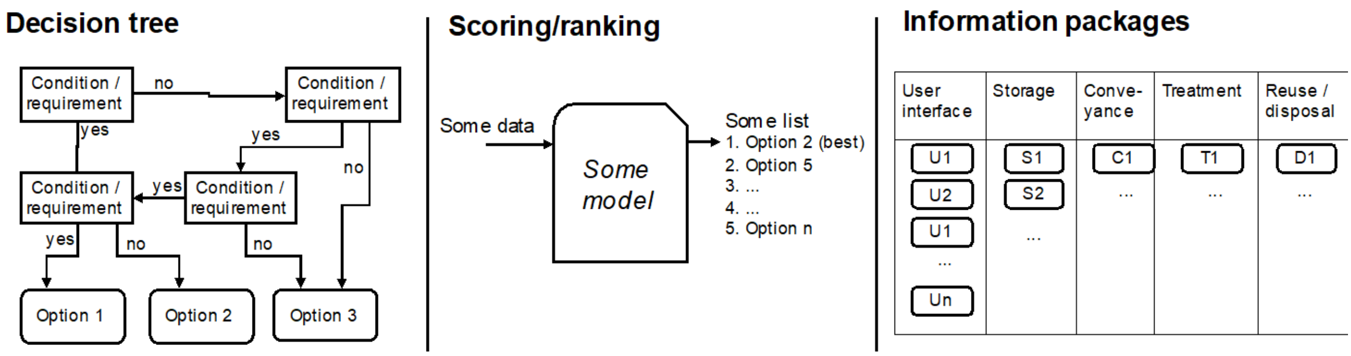

Figure 2.1: Types of decision support tools and approaches currently available for the generation of sanitation system options as an input into structured decision making (SDM). Source: authors.

We compared the tools in relation to eight identified qualities. These eight qualities are based on our historical review of SSA frameworks: (1) the use of a systematic evaluation method; (2) comprehensiveness regarding the entire system, (3) comprehensiveness regarding the diversity of technical options; (4) appropriateness of technologies; (5) consideration of uncertainty related to technology performance or the context; (6) participation of local actors; (7) consideration of multiple criteria from all sustainability dimensions; (8) and flexibility towards future technology innovations. The detailed evaluation is available in SI-C. Table 2.2 provides a compact overview of the results. None of the analysed tools embrace all of the eight features. Three groups of tools could be distinguished:

I. Tools being systematic (transparent assessment), but not entirely comprehensive (both for all potential technologies, and for entire systems), such as Kalbermatten, (1982); Loetscher, (1999); Nayono, (2014); Olschewski, (2013), leading to the risk of omitting valid options by not considering them (Keeney, 1996; Siebert and Keeney, 2015).
II. Tools being comprehensive, but not systematic, such as the information package 'Compendium' or the 'Philippines Sourcebook' (Tilley et al., 2014b; WSP, 2007), leading to transparency issues (Olschewski et al., 2011; Ramôa et al., 2018).
III. A third group of tools were systematic and comprehensive, but not flexible for novel technologies nor automated for comprehensive system generation (Ketema and Langergraber, 2016; Langergraber et al., 2015).

Furthermore, while only two tools consider uncertainties, most of the tools allow for stakeholder participation and provide a contextualized appropriateness assessment. Nine of the 15 tools consider all sustainability dimensions and eight of them are flexible, and can accommodate future technology innovation. A typical example of a flexible tool is the 'Compendium of Sanitation Systems and Technologies', which is an information package developed to support the informed creation of sanitation systems from a set of potential technology options (Tilley et al., 2014b). However, it results in an unmanageable number of system configurations that cannot be dealt with manually (typically more than 100'000 for 40 technologies). This underlines the need for an automated approach.

Table 2.2: Critical review and systematic comparison of different tools and methods assisting in the generation of sanitation technology and system decision options (step 3 of structured decision making, SDM). The tools are compared regarding eight features. Detailed results from the evaluation are available in the supplementary information.

Name	Short description	Systematic: transparent and reproducible assessment	Comprehensiveness: novel and conventional technologies	Comprehensiveness: entire systems	Contextualised: considering specific local conditions	Can deal with uncertainty (related to technology and	Allows for stakeholder participation and an informed	Considering all sustainability dimensions	Flexible to accommodate future technology innovation	Score: number of feature out of the eight
Decision trees										
Algorithm for the selection of sanitation technology (AST) (Kalbermatten, 1982)	Decision tree that allows the choice of a locally appropriate technology based on a fixed set of technical options and criteria.	Y	Y	N	Y	N	Y	Y	N	5/8
Algorithm for the selection of sustainable sanitation arrangement (ASSA) (Mara et al., 2007)	Same concepts as AST, but the set of technology options is broadened to also consider ecological sanitation and low-cost sewerage. Criteria are based on health, affordability, environmental sustainability, and institutional appropriateness.	Y	Y	N	N	N	Y	N	N	3/8
A guide to sanitation selection (ASS) (Franceys et al., 2013; Pickford, 1991)	Relatively complex yes/no algorithm based on the methods of anal cleansing, population density, affordability, demand for reuse, land availability, soil conditions and user acceptance.	Y	N	N	Y	N	Y	N	N	3/8
Technology selection scheme for FSM (TSS for FSM) Reymond, P in (Strande et al., 2014)	Designed for the identification of a combination of technologies to treat faecal sludge based on characterisation and quantification of sludge.	Y	N	N	Y	N	N	N	N	2/8
Scoring/ranking										
SANEX (Loetscher, 1999; Loetscher and Keller, 2002)	Software to assist (1) in the evaluation of a fixed set of technology alternatives using 20 mainly technical criteria; (2) the Multi-attribute Utility Technique (MAUT) to assess the feasibility ; and (3) a model to quantify the costs of those.	Y	N	Y	Y	N	Y	N	N	4/8

Open planning (Kvarnström and Petersens, 2004)	An overview of criteria for the evaluation of sanitation technologies, using function requirements and the five sustainability criteria.	N	N	N	N	Y	Y	Y	Y	4/8
Water and Wastewater Treatment Technologies Appropriate for Reuse (WAWTTAR) (Finney and Gearheart, 2004)	Similar to SANEX, but covers water *and* wastewater treatment processes and designed for the Swedish context. The aim is pre-selection and not final evaluation.	Y	N	N	Y	N	N	Y	N	3/8
SANitation CHoice Involving Stakeholders (SANCHIS) (van Buuren, 2010; van Buuren and Hendriksen, 2010)	A participatory methodology based on multi-criteria decision analysis designed to enable experts and non-experts to connect local experience with systemic knowledge. The set of technologies and criteria are fixed.	Y	N	Y	Y	N	Y	Y	Y	6/8
Technology selection method (TSM) (Katukiza et al., 2010)	A multi-criteria concept for a technology selection method for urban slums.	N	N	N	Y	N	Y	Y	Y	4/8
Technology Applicability Framework (TAF) (Olschewski, 2013; Olschewski and Casey, 2015)	A simple multi-dimensional scoring matrix to assess the requirements for successful introduction of a new technology into a given context.	Y	Y	N	Y	N	Y	Y	Y	6/8
Sustainability-based Sanitation Planning Tool (SusTA) (Nayono, 2014)	A concept for a sustainability-based planning tools including the multi-criteria evaluation of technology appropriateness.	Y	N	N	Y	N	Y	Y	Y	5/8
The CLARA simplified planning tool (CLARA STP) (Ketema and Langergraber, 2016; Langergraber et al., 2015)	Excel spreadsheet to compare the costs of different system combinations in a given context.	Y	Y	Y	Y	Y	N	N	N	5/8
Information packages										
WSP's Philippines Sanitation Sourcebook and	Reference collection of different sanitation and drainage technologies and data to compare them in ters of restricting variables (e.g. water	N	Y	Y	Y	N	Y	Y	Y	6/8

Decision Aid (WSP, 2007)	supply) and influencing variables (technical and socio-cultural).									
Compendium of Sanitation Systems and Technologies (The Compendium) (Tilley et al., 2014b)	Contains: (1) an overview of the currently most common types of sanitation systems (system templates); and (2) an almost comprehensive collection of technology information sheets. The document helps to understand different technologies and know how to combine them into entire systems.	N	Y	Y	Y	N	Y	Y	Y	6/8
How to select? (Monvois et al., 2012)	Describes a three-step procedure for the selection of an appropriate technology: characterizing the town, determining a sanitation chain (on-site, small-piped, or conventional), and selecting appropriate technologies. It also contains a compilation of factsheets on the treatment trains and technologies.	Y	Y	N	Y	N	N	N	N	3/8

— 2.8 KEY FACTORS FOR IMPROVED OPTION SELECTION

To address the current urban sanitation challenge, there are three main features that need to be considered when developing planning options. First, we need to be able to consider the growing portfolio of available sanitation technologies and system configurations. Second, while selecting from all these options, we need to consider multiple criteria from all sustainability dimensions. And third, given the fast-changing socio-demographic and environmental conditions and the lack of knowledge specifically for novel options, we need to consider uncertainties. Based on the evaluation of the 15 tools we define eight qualities that would provide an opportunity for significant improvement of any future tool:

1. **Comprehensive:** In order to avoid bias based on expert knowledge or opinion, there is a need to consider, if possible, the entire option space including novel options. Moreover, there is also a need to look at entire systems when comparing options because the performance of a system always depends on technology interactions. To be comprehensive requires that the needed information is available. This can be achieved by compiling international data and information in such a way, that it can easily be adapted to the local context.

2. **Automated:** Because the currently available portfolio of options is so large and diverse it cannot be dealt with manually. For instance, a set of 40 technologies can lead to over 100’000 possible system configurations as shown in (Spuhler et al., 2020a). Obviously, not all of them are appropriate for a given setting, which confirms the need for a systematic approach for their evaluation (Spuhler et al., 2018). Automatization would allow unorthodox and innovative options to be generated that are said to be potentially more appropriate and sustainable, and allow option generation to be more comprehensive.

3. **Flexible:** This quality is required to account for any future technology and system innovations. It could be achieved by providing a tool that can be easily extended by the users themselves.

4. **Systematic:** Providing a systematic approach would enhance transparency and reproducibility while being comprehensive. This could be achieved by using a clearly defined set of objective pre-selection criteria and by evaluating these in a given context for each and every technology with a quantitatively and qualitatively transparent method.

5. **Inclusive of all sustainability dimensions:** This is obviously required in order to be in line with the SDGs. It could be achieved by using a multi-criteria decision analysis (MCDA) approach that can deal with the very different scales and metrics of different criteria (e.g. socio-cultural acceptance and costs).

6. **Encourages participation of all relevant stakeholders:** Implementation and operation and maintenance of any technology or system will always depend on the stakeholder in charge of it. Participation should be well structured and specific in order to streamline the process and avoid endless discussion while enhancing accountability. This can be achieved by integrating the tool with an SDM framework and by including stakeholder preferences in the evaluation of options.

7. **Contextualized appropriateness assessment:** The performance of a technology or system highly depends on specific local conditions (centre, low-income dense, peri-urban). Contextualization could be achieved by providing a methodology for the appropriateness assessment that can be easily replicated for different areas within a city or for different cities all over the world.

8. **Considers uncertainties**: There is no single best solution but there might be an optimal solution given the currently available knowledge and data and local stakeholder preferences. The capacity to consider uncertainties would also allow the tool to be applied ex-ante and to produce useful input for strategic planning. Uncertainties that need to be considered are related to: (i) local conditions (e.g. water availability, temperature, and population growth); (ii) knowledge about a technology (e.g. nitrogen degradation in a septic tank), and (ii) technology implementation (e.g. hydraulic retention time); or (iv) ignorance, particularly concerning novel technologies and their implementation at scale.

These qualities are not intended as a precondition but are intended to provide guidance to improve the capability of future tools in addressing the current urban sanitation challenge. Moreover, it remains clear that even a tool with all these qualities will not provide the solution to the sanitation crisis but will only provide one piece of the puzzle. Any planning process depends first and foremost on political will and local leadership backed up with sufficient time and human and financial resources for strategic sanitation planning. The greatest challenge in sanitation planning lies in institutions laying out the responsibilities and resources for developing and implementing urban sanitation plans.

— 2.9 LIMITATIONS

This paper is based on the analysis of a broad range of literature that was collected over several years while paying attention to comprehensiveness. However, there is a strong risk for cognitive bias related to the GRASP project and the experts involved. There are, of course, other resources for supporting SSP. Because of this, there is a limitation in the empirical data, underlying the conclusions, giving it a speculative character. Nevertheless, despite these limitations we feel that the identified research challenges are generalizable for the sanitation sector and can provide guidance for more effective strategic planning and structured decision making for urban sanitation in the future.

— 2.10 CONCLUSIONS

This paper provides an overview of the current sanitation challenge and of existing strategic sanitation planning frameworks from a structured decision-making (SDM) perspective. It seeks to identify research needs for making strategic sanitation planning operational in practice.

The paper looks in detail at one need which is the availability of systematic tools, or lack thereof, for the identification of sanitation system planning options (step 3 of SDM). Existing tools do not fully address the current urban sanitation challenge. The growing portfolio of available sanitation technologies and system configurations is not sufficiently taken into account. Systematic evaluation of available options considering multiple sustainability criteria is also lacking. Existing tools are either: (i) systematic, but not comprehensive (about all potential technologies, and about entire systems); (ii) comprehensive, but not systematic; or are (iii) both systematic and comprehensive, but not flexible enough to include future technologies and innovations, nor automated to deal with the very large number of existing system configurations.

Future decision-making support tools for the identification of sanitation options for strategic planning could be improved and better address the current urban sanitation challenge. Future tools would benefit from being comprehensive, systematic, and flexible. This could be achieved by using automatization for the consideration a large and diverse portfolio of technologies and systems. Additionally, a method would be required that allows systematic evaluation of all these options for multiple criteria, from all sustainability dimensions, and that considers uncertainties related to the local conditions and novel technologies. This would enhance transparency and reproducibility of the pre-selection of options. Integrating the tool in a participatory SDM framework would enhance accountability.

Better decision-making and planning approaches are urgently needed to achieve safely managed sanitation in the rapidly developing cities of the global South. Providing sanitation options that are appropriate for the different areas within a city that can deal with current challenges related to population growth, climate change, and resource depletion is an important step towards more citywide inclusive sanitation planning. However, it is only one piece of the puzzle and needs to come with political will and human and financial resources not only for planning, but also for implementation and maintenance in the long term.

— 2.11 ACKNOWLEDGEMENTS

This PhD is funded by the Sawiris Foundation for Social Development through the Engineering for Development (E4D) programme of the Swiss Federal Institute for Technology (ETH) Zurich.

03 Generation of sanitation system options for urban planning considering novel technologies

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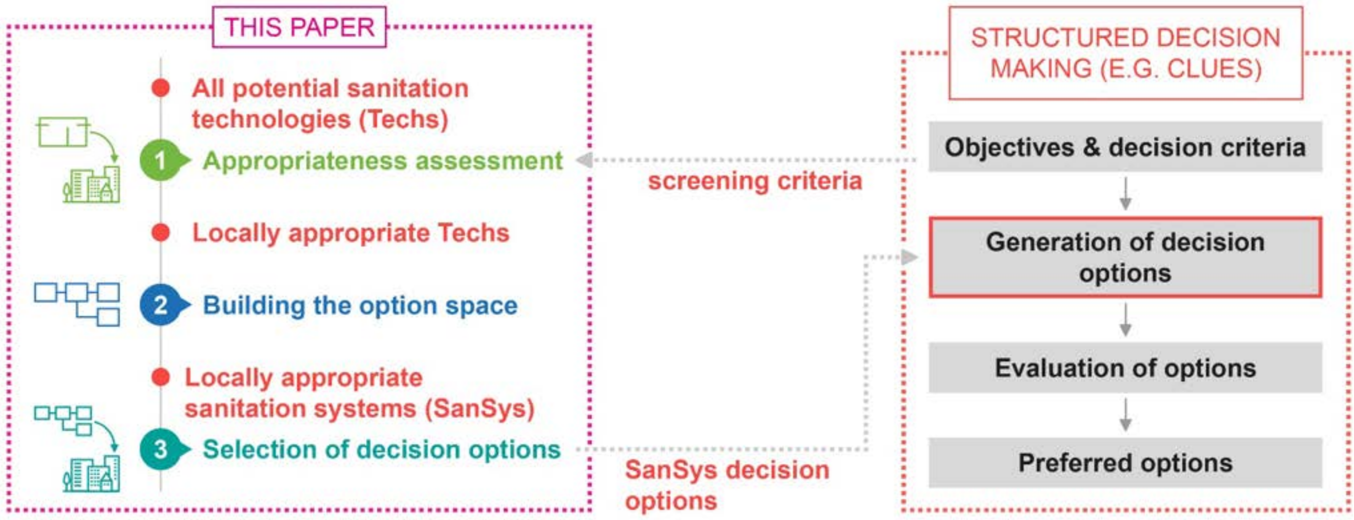
Publication version Postprint (accepted 8. August 2018). Adaptions: figure formatting; new legend for Figure 3.13; data package transferred from zenodo (10.5281/zenodo.1092686) to ERIC, the Eawag Research Data Institutional Repository.
Spuhler, Dorothee, Scheidegger, Andreas and Maurer, Max. 2018. Generation of sanitation system options for urban planning considering novel technologies. Water research 145: 259-278. https://doi.org/10.1016/j.watres.2018.08.021

Supplementary material Data package including a supplementary information document: https://doi.org/10.25678/0001PH

- → **Automatic generation of all sanitation systems considering novel technologies.**
- → **The most appropriate and diverse subset of sanitation systems is selected.**
- → **The size of the subset is defined by the decision-making process.**
- → **Uncertainties relating to the technologies and local conditions are considered.**
- → **A sensitivity evaluation shows the robustness of the suggested procedure.**

Author contributions: .D.S., A.S., and M.M. conceptualized this publication together and jointly managed reviewing and editing. D.S. was responsible for data curation, formal analysis, investigation, and validation. The methodology and software were developed jointly by D.S. and A.S.. D.S. also wrote the original draft and visualized the results. A.S. and M.M. supervised the process. D.S. and M.M. were responsible for funding acquisition. Mingma and Anjali Sherpa (550B solutions, Nepal) and Bipin Dangol (Enironmental and Public Health Organization, Nepal) provided resources for acquiring data and validate the methods as well as for the development of the methodology. Fridolin Haag, Dr. Mika Marttunen and Dr. Christoph Lüthi (all Eawag) also provided input for the methodology (decision objectivise, screening criteria). Judith Lienert contributed to the methodology with knowledge on structured decision making and multi-criteria decision analysis. Joel Gundlach and Maria Rath validated the developed software in the field. Agnes Montangero (Helvetas) and her colleagues from the Swiss Water and Sanitation Consortium and the inhabitants of Katarniya provided their project as an application case.

ABSTRACT



The identification of appropriate sanitation systems is particularly challenging in developing urban areas where local needs are not met by conventional solutions. While structured decision-making frameworks such as Community-Led Urban Environmental Sanitation (CLUES) can help facilitate this process, they require a set of sanitation system options as input. Given the large number of possible combinations of sanitation technologies, the generation of a good set of sanitation system options is far from trivial.

This paper presents a procedure for generating a set of locally appropriate sanitation system options, which can then be used in a structured decision-making process. The systematic and partly automated procedure was designed (i) to enhance the reproducibility of option generation; (ii) to consider all types of conventional and novel technologies; (iii) to provide a set of sanitation systems that is technologically diverse; and (iv) to formally account for uncertainties linked to technology specifications and local conditions.

We applied the procedure to an emerging small town in Nepal. We assessed the appropriateness of 40 technologies and generated 17,955 appropriate system options. These were classified into 16 system templates including on-site, urine-diverting, biogas, and blackwater templates. From these, a subset of 36 most appropriate sanitation system options were selected, which included both conventional and novel options.

We performed a sensitivity analysis to evaluate the impact of different elements on the diversity and appropriateness of the set of selected sanitation system options. We found that the use of system templates is most important, followed by the use of a weighted multiplicative aggregation function to quantify local appropriateness. We also show that the optimal size of the set of selected sanitation system options is equal to or slightly greater than the number of system templates.

As novel technologies are developed and added to the already large portfolio of technology options, the procedure presented in this work may become an essential tool for generating and exploring appropriate sanitation system options.

— 3.1 INTRODUCTION

3.1.1 The global sanitation crisis

Sanitation is crucial for human and environmental health as well as social and economic development (WHO, 2013). Its critical role for development was recognized in the Millennium Development Goals (MDG, UN, 2000a) and was taken further in the Sustainable Development Goals (SDGs) for 2030 (UN, 2015). Despite these efforts, the world has fallen short of its MDG sanitation target, leaving 2.3 billion people without access to basic sanitation facilities and even more (WHO and UNICEF, 2017) without integration into a fully functioning sanitation system. The situation is particularly challenging in the urban areas of developing countries, where most current population growth is taking place (UNFPA, 2007). These areas are characterized by high population densities, the low financial power of their citizens, and a predominantly informal sanitation sector (Dodman et al., 2013; Isunju et al., 2011; Ramôa et al., 2016; Tremolet et al., 2010). If sanitary facilities exist, they are often only basic systems such as pit latrines and septic tanks (Munamati et al., 2017). Systematic collection and safe disposal of wastewater and sludge are often missing (Strande, 2014; WSP, 2014), leading to 90% of urban wastewater globally being discharged without appropriate treatment (UNW-DPC, 2013).

3.1.2 Failure of conventional approaches

The abandonment or breakdown of sanitation infrastructures in developing urban areas is a common phenomenon (Barnes and Ashbolt, 2006), which indicates the failure of conventional approaches to sanitation planning and service provision (McConville, 2010). Planning approaches have a tendency to be top-down, technology-driven, and focussed on implementations of technology or regional master plans. This has led to inappropriate technology choices for local physical and social environments and the often-limited available human and financial resources for maintenance and operation (Kalbermatten et al., 1980; Kvarnström et al., 2011; Menck, 1973; Starkl et al., 2013; Tilley et al., 2014a).

3.1.3 Sustainable sanitation systems planning

It is now widely accepted that sanitation planning should consider the entire sanitation chain and rely on the principles of sustainability. Sustainable sanitation systems not only protect and promote human health; they also protect the environment and natural resources and are economically viable, socially acceptable, and technically and institutionally appropriate (Kvarnström et al., 2004; SuSanA, 2008). A sanitation system is a set of technologies which in combination treat and manage human waste and wastewater from the source of generation to the final point of reuse or disposal. This includes five functional groups (FGs): the user interface, collection and storage, conveyance, semi-centralized treatment, and reuse or disposal (Tilley et al., 2014b). Each technology should be appropriate to the context-specific health, environmental, economic and financial, socio-demographic, and institutional conditions. This strongly highlights the multicriteria aspect of sanitation systems planning (Zurbrügg et al., 2009) and the importance of trade-offs and stakeholder preferences (e.g. Lennartsson et al., 2009; Motevallian and Tabesh, 2011; Willetts et al., 2013).

3.1.4 Available planning frameworks

Several sanitation system planning frameworks have been proposed (e.g. Ashley et al., 2008; Bracken et al., 2005; Hendriksen et al., 2012; Kvarnström et al., 2011; Kvarnström and Petersens, 2004; Lennartsson et al., 2009; Lundie et al., 2006; Lüthi et al., 2011a; Nayono, 2014; Parkinson et al., 2014; Tilley et al., 2010; van Buuren and Hendriksen, 2010). Many of them use structured decision-making (SDM) in combination with multicriteria decision analysis (MCDA). SDM helps to structure the decision-making process and to deliver insights about what matters to diverse stakeholders and how well various objectives may be satisfied by different decision options (Gregory et al., 2012; Marttunen et al., 2017). Well-known SDM frameworks for sanitation planning in urban areas of developing countries include Community-Led Urban Environmental Sanitation, CLUES (Lüthi et al., 2011a; Lüthi and Parkinson, 2011; Sherpa et al., 2012), and Sanitation 21 (Parkinson et al., 2014).

3.1.5 Lack of adequate decision options creation

Planning and decision-making in developing urban settings still face various practical challenges (Barnes and Ashbolt, 2006; McConville, 2010; Ramôa et al., 2018). Amongst these, the systematic generation of decision options is one of the more substantial weaknesses (Hajkowicz and Collins, 2007). In particular, the diversity of available technologies, the multiple sustainability dimensions, and their corresponding criteria are often not sufficiently considered.

Approaches to option generation that have been applied to sanitation include cause-effect analysis, creativity-based techniques such as brainstorming, and mixed approaches such as decision matrices and strategy tables (Eisenführ et al., 2010; Gregory et al., 2012; Keeney, 1996; Larsen et al., 2010; McConville et al., 2014; Tilley et al., 2014b). The results of these procedures rely strongly on the available expertise and are therefore somewhat arbitrary.

To overcome this disadvantage, the Compendium of Sanitation Systems and Technologies (Tilley et al., 2014b) presents a compilation of available technologies and thus enables the systematic creation of sanitation system options by combining compatible technologies. The disadvantage of this approach is that it results in several hundred thousand potential options for sanitation systems.

Option generation is complicated by the emergence of many novel technologies in the recent years, especially for on-site sanitation and semi-centralized systems (e.g. Amoah et al., 2016b; Larsen et al., 2016; Parker, 2014; Tilmans et al., 2015; Tobias et al., 2017). While novel technologies increase engineering flexibility and allow resource recovery, they also substantially increase the complexity of creating decision options.

Decision-making processes require a manageable number of options. In reality, it is often hard to consider more than several dozen decision options in an SDM process (e.g. with multiple−attribute value theory, MAVT, or multiple−attribute utility theory, MAUT) or six to eight according to (Gregory et al., 2012) chap. 7). Common methods to decrease the option space are Pareto optimality or dominance (e.g. Chen et al., 2008), sequential screening in combination with subset selection (Kilgour et al., 2004), and screening by restriction and aspiration levels (Eisenführ et al., 2010). The problem with these methods is that they require information on both the preferences of the stakeholders and the performance of options. However, this information is typically unavailable at the structuring phase of decision-making. Moreover, screening carries the risks that good options are discarded and that the criteria used imply value trade-offs (Gregory et al., 2012; Keeney, 2002). Therefore, screening procedures need to carefully consider uncertainties and use criteria that can be exogenously defined and are independent of stakeholders (Eisenführ et al., 2010; Gregory et al., 2012).

3.1.6 Aim of this paper

The aim of this methodological paper is to present and exemplify a systematic procedure designed to generate a set of sanitation system options that can be used in a structured decision-making process (Figure 3.1). The procedure is able to:

- systematically include all types of conventional and novel technologies for building entire sanitation systems;
- provide a limited set of sanitation system options that (i) are appropriate to a given application case and (ii) incorporate diverse technologies and system configurations; and
- consider the uncertainties relating to the technology properties and local conditions.

The procedure only generates technical options and does not include financing or maintenance schemes. It is targeted at planners and engineers and intended as support for the structuring phase of a decision-making process, as Figure 3.1 explains.

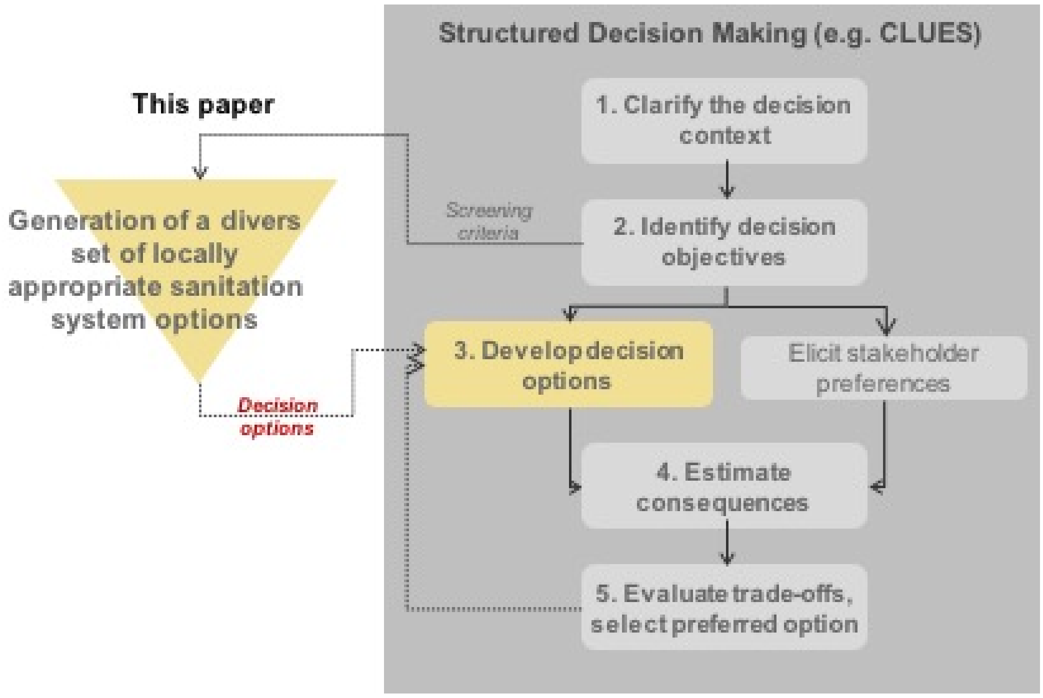


Figure 3.1: Schematic illustration of the wider structured decision making (SDM) framework in which the procedure presented here is integrated. The procedure is intended to generate a limited and diverse set of locally appropriate sanitation system options as an input into the SDM process and is targeted at planners and engineers. The schematic of the SDM process was adapted from (Schuwirth et al., (2012) and Lüthi et al., (2011a).

— 3.2 MODEL DEVELOPMENT AND METHODS

3.2.1 Overview of the procedure

The procedure is designed to generate a set of decision options as an input into the SDM process. Decision options, also called decision alternatives, are possible actions designed to address the *decision objectives*. Decision objectives describe a goal that should be achieved with one of the decision options. In other words, decision objectives describe what matters to the decision-makers and stakeholders (Gregory et al., 2012). In this paper, we use the definition of sustainable sanitation as a proxy for typical urban sanitation planning decision objectives (Kvarnström et al., 2004; SuSanA, 2008). The final decision entails the selection of a single decision option from a given set of decision options. In sanitation planning, a decision option generally consists of a sanitation system (see below) complemented by other aspects. In this paper, the term decision option always refers only to the technical part of a sanitation system. The procedure consists of three major steps; see Figure 3.2.

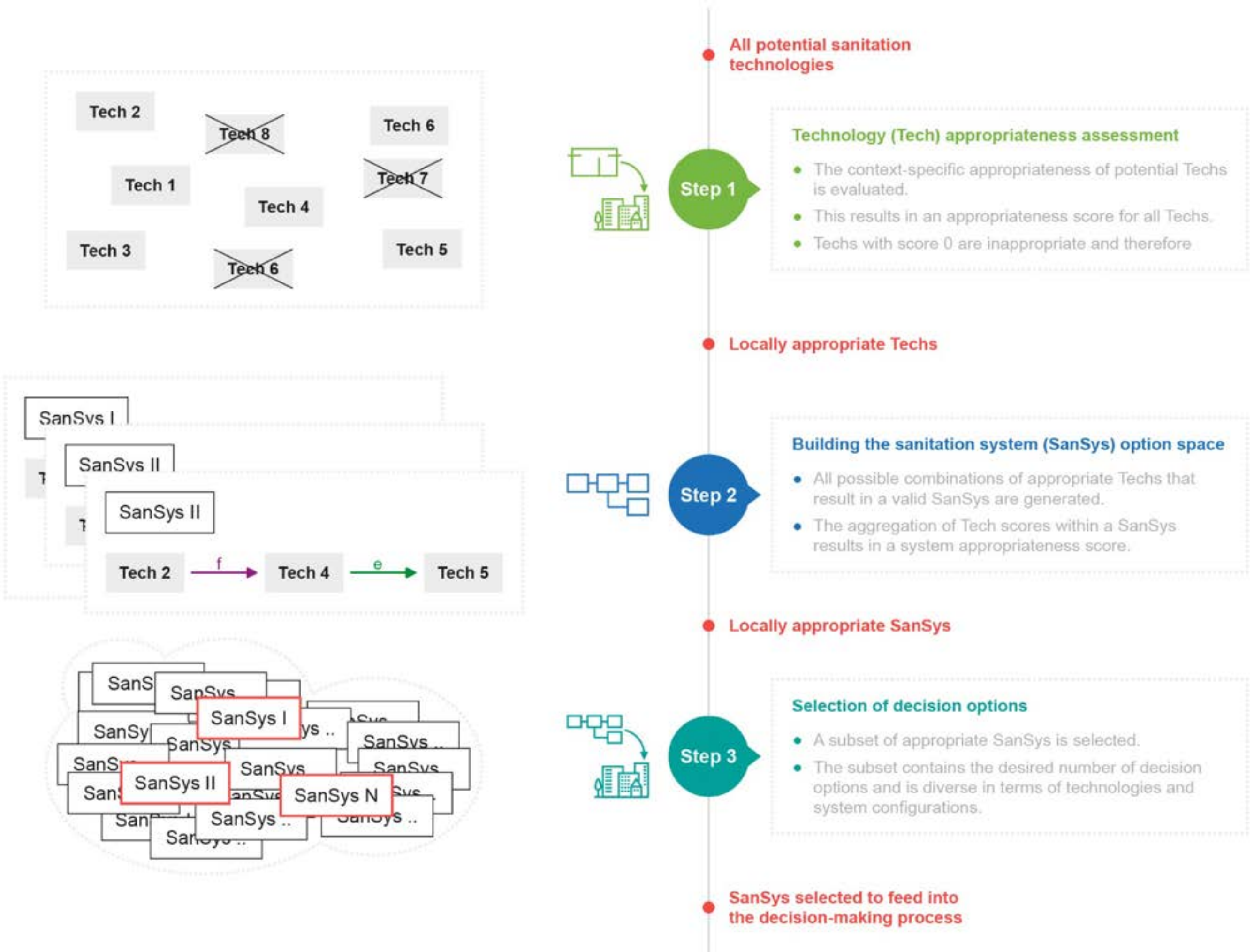


Figure 3.2: Detailed overview of the presented procedure. The procedure consists of three steps. In step one, the context-specific appropriateness of a set of potential technologies (Techs) is evaluated. In step two, all possible sanitation system (SanSys) options are generated by the combination of compatible Techs. In step 3, a subset of most appropriate and most diverse SanSys is selected to be used in the structured decision making (SDM) process.

3.2.2 Step 1: Appropriateness assessment of Techs

The goal of this first step is to identify those technologies among all potential ones that are appropriate for a specific application case. A technology *(Tech)* is defined as any process, infrastructure, method or service that is designed to contain, transform or transport sanitation products (Maurer et al., 2012; Tilley et al., 2014b). The application case (*AppCase*) is the case study or context in which the presented procedure is applied. For example, if a Tech requires a water supply, and the provision of water is not possible in the AppCase, this Tech can be excluded immediately.

Most Techs can have multiple input and output products in different configurations. Sanitation *products* are materials that are generated either directly by humans (e.g. urine, faeces, greywater), the urban environment (e.g. stormwater), or by the Techs (e.g. sludge, blackwater, biogas). We use a standardised set of products based on the definition of (Tilley et al., 2014b) (see also Figure 6). For instance, a septic tank can have blackwater and greywater as an input, or blackwater alone.

3.2.2.1 Identification of screening criteria

The appropriateness of Techs is evaluated on the basis of screening criteria derived from the overall decision objectives for sustainable sanitation as defined by (SuSanA, 2008). Based on this definition, a sustainable sanitation system not only has to protect and promote human health by providing a clean environment and breaking the cycle of disease but also has to be economically viable, socially and institutionally acceptable, technically appropriate, and protective of the environment and natural resources. We translated this definition into five main decision objectives: (1) protection of human health, (2) financial and economic viability, (3) social and institutional acceptance, (4) technical functionality, and (5) protection of the environment and natural resources. We then established an overall objective hierarchy for sustainable sanitation planning: we compiled the lower level objectives for each of the five main decision objectives and listed the corresponding quantitative and qualitative attributes based on existing literature (e.g. Balkema et al., 2002; Chen and Beck, 1997; Dunmade, 2002; Krebs and Larsen, 1997; Kvarnström et al., 2004; Larsen and Gujer, 1997; Lennartsson et al., 2009; Lundin et al., 1999b; Palme et al., 2005; Sahely et al., 2005). Attributes measure how well an option performs with respect to a decision objective. Other terms used for attributes are ‘performance measures’ and ‘objective variables/functions’ (Eisenführ et al., 2010). A summary of the literature review, the objective hierarchy, and the corresponding attributes are available in SI-A.

We then compiled a master list of screening criteria (see Table 3.1) by identifying decision objectives and corresponding attributes that fulfil three requirements: (i) they can be defined exogenously (they are ‘fixed’); (ii) they do not involve trade-offs that might be weighted differently by different stakeholders; and (iii) they can be evaluated on the basis of the information and data generally available in the structuring phase of decision-making (i.e. baseline reports, local and regional statistics). The set of screening criteria contained in the master list overlap with the concept of appropriate technology (see Figure 3.3), which is a sub-domain of sustainable sanitation that evolved earlier (Bouabid and Louis, 2015; Goldhoff, 1976; Iwugo, 1979; Kalbermatten et al., 1980; Loetscher, 1999; Magara et al., 1986; Menck, 1973; Schumacher, 1973; Singhirunnusorn and Stenstrom, 2009). The master list of screening criteria should be adapted to the local preferences in an AppCase. This contextualization is also important, as the requirements used for the identification of screening criteria can vary in different contexts. For instance, legal aspects are generally recognized as fixed (defined exogenously) in Switzerland but are seen as flexible in Nepal. Another example is that of financial criteria: in some cases, they are perceived as stakeholder-independent killer criteria, even though they involve major trade-offs.

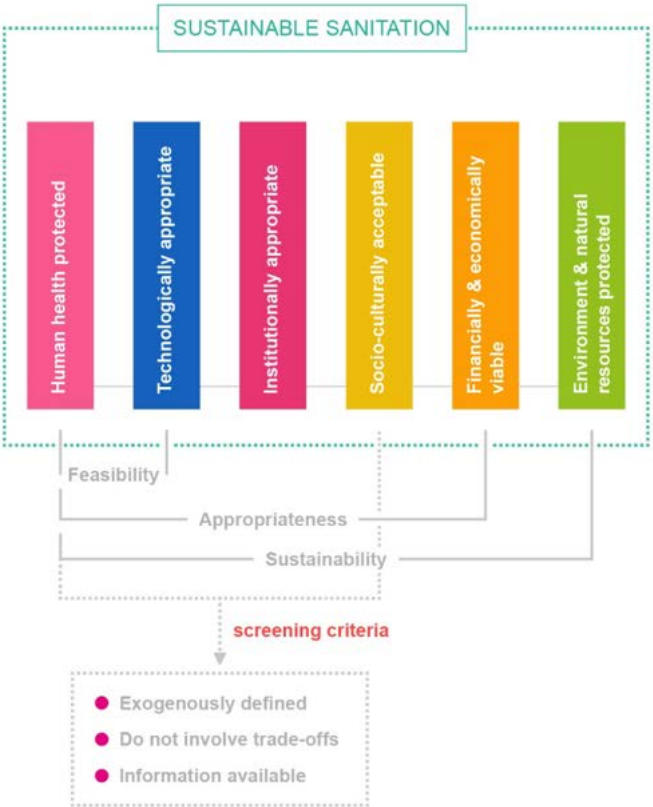


Figure 3.3: Dimensions of sustainable sanitation and overlap with other commonly defined concepts used to evaluate sanitation infrastructures. Screening criteria were derived from all sustainable sanitation criteria based on three factors:(i) they can be defined exogenously (ii) they do not involve trade-offs; and (iii) they can be evaluated on the basis of the information and data generally available at the structuring phase of decision making (i.e. baseline reports, local or regional statistics). The identified set of screening criteria overlaps with the concept of appropriate technology, which is a sub-domain of sustainable sanitation.

Table 3.1: Master list of screening criteria used to assess the local appropriateness of technologies (Techs). To improve readability, we grouped the criteria into legal, technical, physical, demographic, socio-cultural, capacity and managerial, and financial aspects. Each screening criterion is further specified by an attribute for the Tech and one for the AppCase (see also Figure 3.4). Possible metrics for the evaluation of the attributes are also given. By matching the Tech attribute to the AppCase attribute, the appropriateness score for the given criterion can be evaluated. (Nb=number).

Nb	Screening criteria	*Tech* attribute	Possible evaluation metrics	*AppCase* attribute
Legal				
1.	Effluent	Effluent quality	Microbial quality (faecal coliforms, helminths, viruses) Chemical quality (toxic substances, Nitrogen, Phosphorus, total solids, biological oxygen demand, chemical oxygen demand)	Legal requirement for the effluent
2.	Solid residue	Solid residue quality	Microbial quality (faecal coliforms, helminths, viruses) Chemical quality (toxic substances, Nitrogen, Phosphorus, total solids, biological oxygen demand, chemical oxygen demand)	Legal requirement for the solid residues

Technical				
3.	Water	Water requirements	Litre per capita per year	Water availability
4.	Energy	Energy requirements	Kilowatt-hours per capita per year	Energy availability
5.	Water stability	Vulnerability to water supply disruption	Hours per day	Frequency of water supply disruption
6.	Energy stability	Vulnerability to energy supply disruption	Hours per day	Frequency of energy supply disruption
7.	Construction material	Construction material requirements	Pipes, pumps, concrete	Construction material available
8.	Spare parts	Spare parts requirements	Ladder	Spare parts supply
9.	Chemicals	Chemicals requirements	Ladder	Chemicals supply
10.	Operation and maintenance (O&M)	Frequency of O&M requirements	Hours or event per capita per year	O&M capacity
Pyhsical				
11.	Climate	Climate type requirements	Category: tropical, dry, temperate, cold	Type of climate
12.	Temperature	Temperature requirements	Celsius	Temperature range
13.	Flooding	Flooding tolerance	Days of flooding per year accepted (scale to be defined)	Flooding occurrence
14.	Area	Plot area requirements	Meter square per person	Average free area available per person
15.	Vehicle access	Access requirements	Per cent (m^2 of buildings/m^2 of total area)	Accessibility of households

16.	Slope	Slope requirements	Per cent	Slope distribution
17.	Soil type	Soil type / soil permeability range tolerated	cm/hours	Soil type occurrence
18.	Groundwater depth	Groundwater depth requirements	Meter	Groundwater depth occurrence
19.	Excavation	Excavation requirements	Constructed scale	Ease of excavation
Demographic				
20.	Population	Size of population that can be served	Number of capita per household or volume of flow stream	Service capacity requirements
21.	Population density	Range of population density tolerated	Capita per kilometre square	Current population density
22.	Volume stability	Potential to accommodate changing water volumes	Litre per capita per day	Expected wastewater flows at the end of project design life
23.	Pollution stability	Potential to accommodate higher pollution loads	Milligram of biological oxygen demand per capita and day	Expected BOD5 load at the end of project design life
Socio-cultural				
24.	Religious constraints	Compatibility with religious constraints	Ladder or range	Socio-cultural requirements
25.	Cultural constraints	Compatibility with cultural constraints	Ladder or range	Cultural requirements
26.	User awareness	User awareness requirements	Ladder	Range, to be defined
Capacity and managerial				
27.	Construction skills	Construction skills requirements	Ladder, e.g. from 0 to 4: none, mason, specially trained mason, implementation engineer, supervisor	Construction skills availability

28.	Design skills	Design skills requirements	Ladder, e.g. from 0 to 5: none, unskilled labour, mason, specially trained mason, planning engineer, supervisor	Design skills availability
29.	Management	Required management level	Low, medium, high household, shared, city	Preferred management level
Financial				
30.	Investment costs	Investment costs requirements	Dollar per person	Available investment capital
31.	Annual costs	Annual costs requirements	Capital expenditures and operational expenditure in dollar per person per year	Available funds for operation

3.2.2.2 Evaluation of screening criteria and attributes

The evaluation of screening criteria is also highly context-dependent (Hoffmann et al., 2000). Therefore, each screening criterion consists of a pair of Tech and AppCase attributes, which characterize the Tech and the AppCase respectively (see Figure 3.4). To account for uncertainties, we use probability functions to parametrize the attributes. Each pair of Tech and AppCase attributes consists of one probability density or distribution function (e.g. the water availability for a given AppCase, p($water\ availability$)) and one conditional probability (e.g. the performance of a Tech given a certain water availability $P(performance|water\ availability)$), varying between 0 and 100%. Whether the density or the conditional probability is used for the AppCase or the Tech is not important as long as both types of functions are always represented for one criterion.

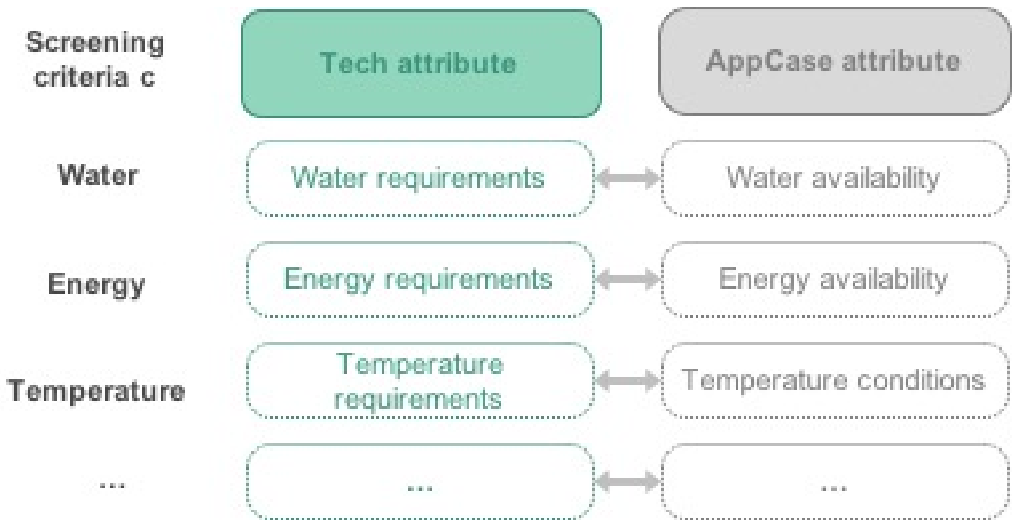


Figure 3.4: Examples of screening criteria and corresponding attributes used to assess the appropriateness of a set of potential technologies (Techs) for a specific application case (AppCase). For example, if a Tech has a high water requirement, but the water availability in the AppCase is very low, this Tech has limited appropriateness.

3.2.2.3 Quantifying technology appropriateness

The match of the Tech attribute with the AppCase attribute for a Tech t and a criterion c defines the appropriateness score, either as

$$AS_{t,c} = P(p) = \int P(p|c)\, p(c)\, dc\,, \qquad \text{Equation 3-1}$$

if p(c) is a probability density function, or

$$AS_{t,c} = P(p) = \sum_{c\prime \in \Omega} P(p|c)\, p(c') \qquad \text{Equation 3-2}$$

if $P(c)$ is a probability distribution function.

If a Tech t has multiple criteria, the scores must be aggregated. The aggregation results in the technology appropriateness score (TAS):

$$TAS_t = \sqrt[n]{\prod_{c=1}^{n} AS_{t,c}} \qquad \text{Equation 3-3}$$

It is important to note that screening criteria are different from performance criteria in SDM and MCDA, as they are used to quantify the suitability of an option in a given context and not to identify the best option (Eisenführ et al., 2010). Consequently, screening criteria do not necessarily apply to all options under assessment, whereas performance criteria must do so. For instance, water availability should not influence the TASt of a Tech t that operates completely independently of the water availability. However, the TASt of this Tech t can still be compared to the TASx of another Tech x which is water-reliant. Therefore, the aggregation function should allow for different numbers of criteria. We also require it to be equal to zero if at least one ASt,c is zero. The geometric mean (see Equation 3-3) fulfils these requirements (Langhans et al., 2014; Pollesch and Dale, 2015; Rowley et al., 2012).

3.2.2.4 Removing inappropriate Techs

Techs with a TAS = 0 are totally inappropriate for the given AppCase and are therefore excluded.

3.2.3 Step 2: Building the *SanSys* option space (*SanSys* builder)

3.2.3.1 Building all possible sanitation systems from Techs

A sanitation system (*SanSys*) is defined as a set of Techs which, in combination, manage sanitation products from the point of generation to a final point of reuse or disposal (adapted from Maurer et al., 2012 and Tilley et al., 2014b). The Techs contained in a SanSys can be organized in functional groups (FGs). We use the following FGs: toilet user interface (U), on-site storage (S), conveyance (C), transport (T), and reuse or disposal (D). A Tech belonging to U is always a source, while a Tech belonging to D is always a sink. Additional sources, such as tabs or drainage, are assigned to a sub-group of U called U_{add}. Each SanSys comprises at least one source and one sink and a number of compatible Techs in such a way that all products end up in another Tech or in a sink. The set of all valid SanSys is constructed on the basis of the appropriate Techs, as illustrated in Figure 3.5. A SanSys is valid if it fulfils the following criteria:

i. every output product of each Tech must be connected to another Tech that can take this product as its input,
ii. no Tech has inputs that are not connected to the output of another Tech.

These rules allow loops in a SanSys. However, loops between Techs are practically only possible if the infrastructures are situated close to each other. This leads to the additional constraint that

iii. loops are only allowed for the FG S or T either at the level of the premises (onsite) or at semi-centralized treatment facilities (offsite).

The same product may occur onsite or offsite. In this case, it is treated as two different products for the generation of SanSys. For example, blackwater that is produced onsite (e.g. by a 'septic tank'), cannot feed into a centralized Tech (e.g. 'activated sludge'); it must first be transported by a transport Tech (e.g. 'conventional sewer'). For the generation of SanSys we distinguish between products and transported products in building the systems (i.e. 'blackwater' and 'transported blackwater').

The generation of SanSys requires some assumption and simplifications to be automated and generic enough to deal with all potential sanitation technologies. The main simplifications concern the way how the input and output streams are related to each other. Some Techs of the FG C take a varying number of input products that are then mixed together. To take this fact into consideration, the model defines a hierarchy of products according to their degree of pollution. When different products enter into such a Tech, the resulting output corresponds to the product which is defined to be the most polluted. For example, a conventional sewer fed with greywater and blackwater will produce blackwater. The same Tech fed with blackwater will also produce blackwater.

Another simplification concerns the generation of different Tech variations. The relations of different in- and out-products to each other is defined as either (i) any possible combination ('OR'), (ii) their mutual exclusion ('XOR'); or their compulsory co-existence ('AND'). For example, a septic tank can have the following in-products: 'blackwater' OR 'greywater'; and has the following out-products: 'sludge' AND 'effluent'. This results in three possible combination of in- and out-products: (i) blackwater, greywater -> effluent, sludge; (ii) blackwater -> effluent, sludge; (iii) greywater -> effluent, sludge. For the generation of SanSys we treat each of these possible combinations as a distinct Tech variation (see also supporting information B, SI-B).

Creating all possible combination of Techs is not feasible as a very large number of combinations exist (see SI-B). Moreover, only a very small fraction of these possible combinations are valid SanSys. The SanSys builder we propose here provides an efficient heuristic designed to create all valid SanSys (see details in the SI-B). The functioning of the algorithm is illustrated in Figure 3.5.

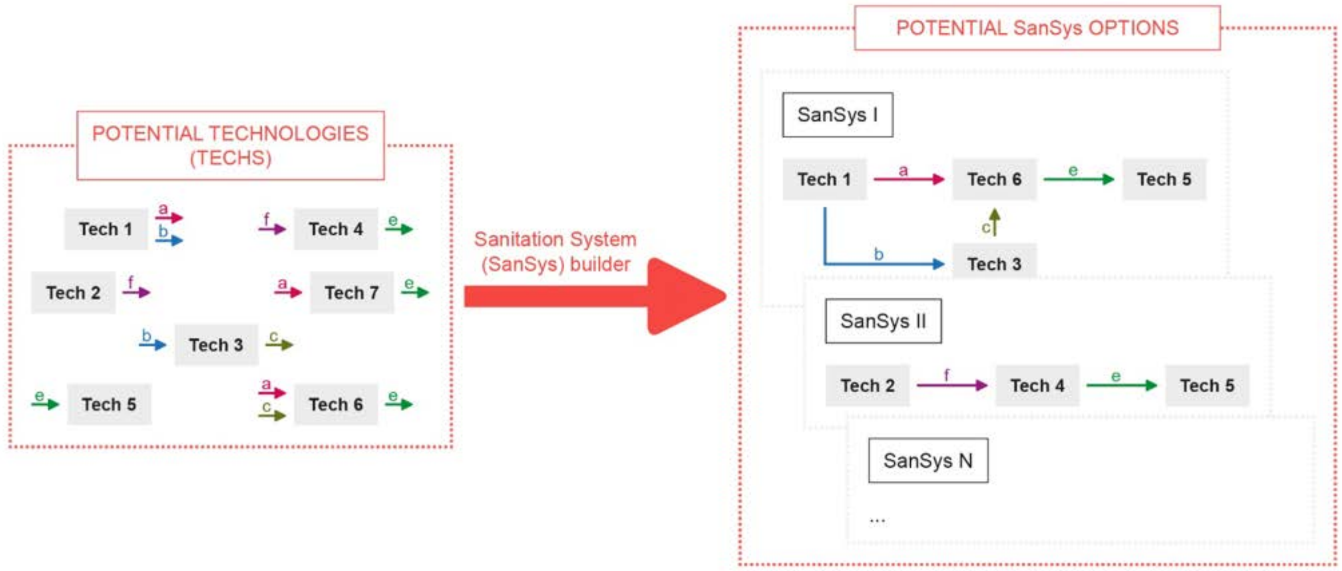


Figure 3.5: Concept underlying the efficient heuristic designed to build almost all valid sanitation systems (SanSys). The aim is to combine the set of appropriate technology options (Techs) in such a way that valid SanSys are generated (see text for the definition of valid SanSys).

3.2.3.2 Quantifying system appropriateness

The SanSys appropriateness score (*SAS*) is calculated by aggregating the *TAS* of every Tech of the system. Any aggregation function could be used. We propose a function that can either mimic the product of all *TAS*, the geometric mean, or a compromise between both:

$$SAS_S = \prod_{i=1}^{n.tech} TAS_t^{\frac{1}{\alpha\,(n.tech-1)+1}}$$ Equation 3-4

where $n.tech$ is the total number of *Techs* in a given system, and $\alpha \in [0,1]$.

A purely multiplicative aggregation ($\alpha = 0$) systematically penalizes SanSys with a large number of Techs. This contradicts the principle of allowing a broad range of SanSys in the decision option set. Using the geometric mean ($\alpha = 1$) is often not desirable neither, because a simple system should be preferred over a complex (long) one with the same performance. The smaller the factor α that is chosen, the more are the SanSys (i.e. SanSys with many Techs) are penalized.

3.2.4 Step 3: Selection of decision options

The set of all possible SanSys created in Step 2 may contain ten or even a hundred thousand systems. From these, we must select a subset Q of potentially applicable decision options that will serve as an input for decision-making. We define two key characteristics for Q:

1. The set contains the desired number of decision options. The absolute number of decision options depends on the specific SDM process and its ability to handle small or larger numbers of decision options.
2. The set entails a diverse range of options. The integration of a high variability of different options opens up the decision space for the stakeholders and therefore increases the probability of finding a sustainable solution.

In a first step, the SanSys are grouped according to their system templates. A *system template* (ST) defines a class of SanSys with similar conceptual characteristics (see also Table 3.5). Then, the SanSys within each ST are assigned to clusters. For clustering, we use properties such as the number of technologies per SanSys and the K-medoids algorithm (e.g. Hastie et al., 2009). This algorithm is similar to the k-means but also allows non-Euclidian distance measures to be used. Finally, the SanSys with the highest score of each cluster is selected for Q. The number of clusters per ST is controlled by the number of options to be selected from an ST.

3.2.5 User and stakeholder involvement

The procedure is intended to be used by experts for identifying decision options in an SDM procedure such as CLUES. This includes data collection, the application of the appropriateness assessment, the system builder, and the identification of the set of selected decision options. The stakeholder involvement is particularly relevant for (i) the identification of screening criteria; (ii) the definition of potential Techs; (iii) the definition of system templates; (iv) and the definition of properties used to identify the selected set of options. The master list of screening criteria and the Tech database can be used as a point of departure (see also next section or directly ERIC: https://doi.org/10.25678/0001PH).

3.2.6 Implementation and data linking

The assessment of the appropriateness of the Tech (section 3.2.2) was implemented in R (R Development Core Team, 2015). The code is freely accessible at https://github.com/Eawag-SWW/TechAppA (v1.0). For the generation of the possible SanSys (section 3.2.3) and selection of Q (section 3.2.4), Julia was chosen for performance reasons (Bezanson et al., 2017). The code is freely accessible at https://github.com/Eawag-SWW/SanitationSystemBuilder.jl (v1.0). The data used and generated for this article is available at ERIC: https://doi.org/10.25678/0001PH. The database contains a set of 43 Techs and corresponding attribute functions. The database is a simple comma-separated text file and can be easily extended with any Tech as long as their inputs and outputs are known and information regarding the relevant screening criteria are available.

3.2.7 Model sensitivity

3.2.7.1 Goal

We perform a sensitivity analysis for the appropriateness assessment of Techs (step 1) and the selection of decision options (step 3). The generation of SanSys (step 2) does not require relevant parameters and is therefore not considered. The application in Katarniya (see section 3) is used as baseline scenario.

3.2.7.1.1 Step 1: Appropriateness assessment of technology options

The aim here is to see how the choice of screening criteria and attributes impacts the *TAS* and the corresponding ranking of Techs per FG. For example, criteria related to 'operation & management' or 'skills' are often neglected. For this purpose, we perform the appropriateness assessment with different sets of screening criteria and compare the outcome with the baseline. Table 3.2 summarizes the changes in the set of criteria performed for the four runs presented.

Table 3.2: Overview of different computational runs implemented to evaluate the sensitivity of Step 1. Run 1.1 corresponds to the baseline scenario (application in Katarniya). Each run 1.2 to 1.4 corresponds to the removal of one or several criteria compared to the baseline. "✔" indicates that the criteria are included for the evaluation of the TAS, while "-" indicates that the criteria were not considered.

Run #	Name	Criterion management	Criteria related to available skills (construction, O&M, and design skills)	Criteria related to O&M (frequency of O&M, O&M skills)
1.1	Baseline	✔	✔	✔
1.2	No institutional aspects	-	✔	✔
1.3	No capacity aspects	✔	-	✔
1.4	No O&M aspects	✔	✔	-

Table 3.3: Overview of the computational runs implemented to evaluate the sensitivity of Step 3. The columns show the numerical variations and model elements used for the generation of the set of selected sanitation system (SanSys) also called Q. "✔" indicates that the model element is included, while "-" indicates the element was not used.

Run #	Name	Size of *Q* (number of selected SanSys options)	α used to compute the *SAS*	Clustering (according to number of Techs and number of connections per SanSys)	Classification to STs	Selection based on highest SAS
2.1	Baseline	36	0.5	✔	✔	✔
2.2	Baseline (size of Q = 8)	8	0.5	✔	✔	✔
2.3	α =0	36	0	✔	✔	✔
2.4	α =1	36	1	✔	✔	✔
2.5	No clusters	36	0.5	-	✔	✔
2.6	No system templates	36	0.5	-	-	✔
2.7	Random within templates	36	0.5	-	✔	-
2.8	Baseline (size of Q = 4)	4	0.5	✔	✔	✔
2.9	Baseline (size of Q = 64)	64	0.5	✔	✔	✔

3.2.7.1.2 Step 3: Identification of decision options

The aim here is to evaluate how different elements of Step 3 impact the median *SAS* and the diversity of ***Q***. The diversity of Q is characterized by the average of the number of different STs, the number of different sources, the different numbers of Techs per SanSys, and the different numbers of connections per Tech within ***Q***. The investigated elements are:

- the size of Q,
- α used to compute the *SAS*,
- the clustering based on structural properties (numbers of Techs and number of connections per Tech per SanSys),
- the classification according to STs,
- the appropriateness assessment, and the resulting *SAS.*

— 3.3 EXAMPLE APPLICATION

To demonstrate the application, we selected a real case in Nepal. However, the case is not presented in its entire complexity.

3.3.1 Application case

3.3.1.1 Description

We applied our model to a water and sanitation project in Katarniya, a small town in the mid-western region of Nepal. Katarniya is very typical of an emerging small town in Nepal. It is characterized by rapid and unplanned growth, a weak institutional setting, and a lack of human and financial resources. Basic sanitation elements such as toilet infrastructure are present, but full sanitation systems are mostly absent. The project was planned and implemented by three partners of the Swiss Water and Sanitation Consortium (SWC). The aim of the project was to improve access to water and environmental sanitation for the central part of the town with about 1000 inhabitants. In order to improve the town's sanitation situation, an environmental sanitation plan was developed using CLUES (Lüthi et al., 2011a).

3.3.1.2 Data collection

As model input data, we use the results from a household survey and an interaction workshop with the local community, both of which were conducted by the project in 2016. We complement this data with information that we collected during a field visit in May 2017.

3.3.2 Step 1: Appropriateness assessment

3.3.2.1 Potential Techs

Figure 3.6 illustrates all potential Techs used for the assessment. We rely on a restricted list of Techs for illustration purposes. Theoretically any number of Techs could be used as a point of departure. We have taken the list of potential Techs from the *Compendium of Sanitation Systems and Technologies* (Tilley et al., 2014b). To showcase the integration of novel options, we added 'vermi-composting' (Amoah et al., 2016b; Lalander et al., 2013), 'struvite precipitation', and 'struvite application' (Dalecha, 2012) to the list. These technologies have been tested in similar regions and shown to be promising.

3.3.2.2 Identification of screening criteria and attributes

The screening criteria for the application case are derived from the master list in Table 3.1. First, we validated this list by conducting a workshop with experts in Kathmandu in 2015. We noted very little disagreement between the locally brainstormed list and the master list provided. Second, based on individual consultations with some key workshop participants, we removed some criteria from the master list because they were either not relevant or contradicted the conditions listed in section 3.2.2.1. These criteria from Table 3.1 were removed:

- Nb. 11 : not relevant.
- Nb. 1, 2, 24, 25, 26, 30, and 31: involving major trade-offs which should be discussed among stakeholders.

- Nb. 5, 6, 7, 9, 14, 20, 21, 22 and 23: Not enough information available either for the AppCase or the Techs.

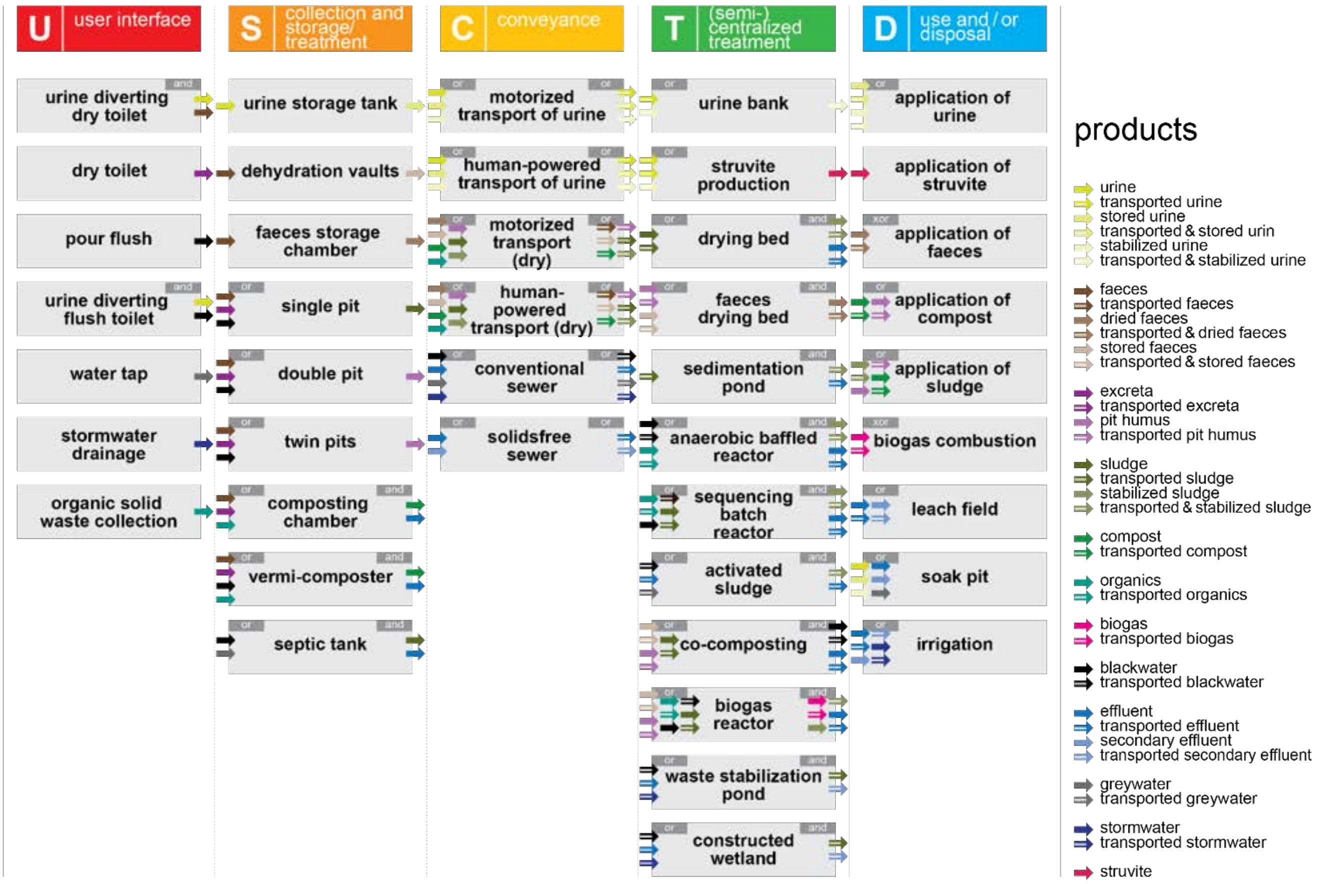


Figure 3.6: Overview of the sanitation technologies, products and functional groups (FGs) used in the example application in Nepal. Notes: (i) Storage (S) may also include (partial) treatment; (ii) Treatment (T) technologies may be applicable on-site (no transport required) or offsite; (iii) the model can also include non-toilet sources which allows the system boundaries to be extended (water tap, stormwater drainage, organic solid waste collection).

3.3.2.3 Quantification of screening attributes

To quantify the screening criteria, a pair of probability density and conditional probability functions is needed for each pair of Tech and AppCase attribute (see also section 3.2.2.2). These functions describe the requirements and the conditions that have to be matched. In principle, any uncertainty model and corresponding probability function could be used. However, the choice of probability function can have an impact on the model output and should be purely data-driven to represent the state of knowledge available at the structuring phase. The data sources generally available at the structuring phase include baseline reports, semi-structured interviews, reports from previous projects, and regional and national statistics. In the application case presented here, we found little information in these documents and therefore used rather simple probability functions: triangular, trapezoid, uniform, and categorical distributions. Based on similar experiences in other case studies (not presented here), we recommend working with such simple functions except where good reason or data exists to use more sophisticated models (e.g. a normal or beta distribution). Expert knowledge is required to identify a probability function that embraces all relevant data sources considering their potential inconsistency. Here we provide some examples how the functions are applied based on available input data. The categorical function is a non-continuous function. It is best applied when the data contains categories and a value for each category is available: e.g. 30% of population have low access to water, 50% have moderate access, and 20% have high access (categorical density function). The uniform function is the simplest model and requires only an upper and lower level: e.g. Tech X has a performance of 100% between 5˚C to 35˚C (conditional uniform probability function). The triangular function requires a minimum, maximum, and a mean value: e.g. the temperature in the AppCase varies between 5 and 42˚C with a mean at 28˚C (triangular density function). The trapezoidal function requires four values including the minimum, the maximum, and the two modes in between: e.g. the performance of a Tech Y starts at -5˚C, is 100% between 5 and 25˚C and then decreases until 50˚C (trapezoidal conditional probability function).

Table 3.4 shows the final list of screening criteria, the corresponding attributes, and the type of probability function used in the application in Katarniya for each attribute. The use of 'd-' at the beginning of the function name refers to the density function, 'p-' refers to the conditional probability, 'cat' stands for a categorical function, 'triangle' refers to a triangular distribution, 'range' refers to a uniform distribution, and 'trapez' refers to a trapezoidal distribution. All the AppCase data and the Tech data are available in the associated data (ERIC: https://doi.org/10.25678/0001PH).

Table 3.4: Overview of screening criteria, corresponding attributes and the type of uncertainty functions used to quantify the attributes.

Screening criteria	Tech attribute and probability function		AppCase attribute and probability function	
Water supply	Water requirements	pcat	Water availability	dcat
Energy supply	Energy requirements	ptriangle	Energy availability	drange
Frequency of O&M	Frequency of O& M	dtrianlge or drange	O & M capacity	prange
Temperature	Temperature requirements	prange, ptrapez, or ptriangle	Temperature range	dtriangle
Flooding	Flooding tolerance	ptrapez	Flooding occurrence	drange
Vehicular access	Access requirements	ptrapez or prange	Accessibility of households	dtrapez
Slope	Slope requirements	ptrapez	Slope distribution	dtriangle
Soil type / hydraulic conductivity	Soil type requirements	pcat	Soil type occurrence	dcat
Groundwater depth	Groundwater depth requirements	prange, or ptrapez	Groundwater depth occurrence	dtrapez
Excavation	Excavation requirements	pcat	Ease of excavation	dcat
Construction skills	Construction skills requirements	dtriangle	Construction skills availability	ptrapez
Design skills	Design skills requirements	dtriangle	Design skills availability	ptrapez
O&M Skills	O&M skills requirements	dtriangle	O&M skills availability	ptrapez
Management	Required management level (household, shared, public)	pcat	Preferred management level	dcat
Spare parts	Spare parts requirements	dcat	Spare parts supply	pcat

3.3.2.4 Quantifying TAS

The AppCase attributes and corresponding functions in Table 3.4 were parametrized with the data collected in Katarniya (see 3.3.1.2 Data collection). The Tech attributes for all Techs in Figure 3.6 were quantified on the basis of the literature and our own expert estimations.

3.3.3 Step 2: Generation of sanitation systems

We use 37 Techs from the 43 shown in Figure 3.6 to build the SanSys option space. We have excluded some Techs from the system generation in order to limit the size of the option space and to make the example application more illustrative. The excluded Techs are all Techs from the FG U_{add}, as well as the Techs struvite production, struvite application, and irrigation. To compute the *SAS*, we use $\alpha = 0.5$.

3.3.4 Step 3: Selection of decision options

3.3.4.1 Classification into system templates

Table 3.5 shows the properties and *STs* which we use for classifying the SanSys. The *Compendium of Sanitation Systems and Technologies* (Tilley et al., 2014b) serves as the inspiration for the STs used. However, we defined the STs provided further by specifying distinctive profiles and refining some STs. For sixteen STs sorted into four groups, we use nine properties.

Table 3.5: System templates (ST) used to characterize the sanitation system (SanSys) option space. The STs are adapted from (Tilley et al., 2014b). Each of the 16 ST has a unique profile defined by a value for the nine properties. ‘1’ means that the property applies (e.g. 'the systems do have dry material production”); 0 means that the properties do not apply (e.g. “there is no dry material”); and ‘not defined’ (n.d.) means that the property does not apply to this ST.

Nb	Group of ST	STs	ST profiles									
			Property / detailed description of ST	*Dry material (pit humus, compost, dried or stored faeces)*	*Onsite sludge production*	*Urine*	*Black water*	*Transported black- or brown-water*	*Effluent transport*	*Biogas*	*Transported biogas*	*With a single pit onsite*
ST.1	Onsite simple	Dry onsite storage without treatment	*This includes simple onsite storage of dry or wet toilet products with sludge production such as a single pit or a single ventilated improved pit latrine (VIP)*	n.d.	1	n.d.	n.d.	0	n.d.	0	0	1
ST.2	Onsite simple	Dry onsite storage and treatment	*Excreta are stored onsite and transformed to either pit humus or compost.*	1	0	0	0	0	n.d.	0	0	0
ST.3	Urine	Dry onsite storage without sludge with urine diversion	*Mainly urine diversion dry toilets (UDDTs) or dry composting systems with urine diversion.*	1	0	1	0	0	n.d.	0	0	n.d.
ST.4	Urine	Onsite blackwater without sludge and with urine diversion	*Mainly onsite composting systems with urine diversion*	1	0	1	1	0	n.d.	0	0	0
ST.5	Urine	Offsite blackwater treatment with urine diversion	*Sewer systems with urine diversion*	n.d.	n.d.	1	1	1	n.d.	0	0	n.d.
ST.6	Biogas	Onsite biogas with effluent infiltration	*Biogas reactor where effluent goes to onsite infiltration (soak pit).*	n.d.	n.d.	n.d.	n.d.	0	0	1	0	n.d.
ST.7	Biogas	Onsite biogas with effluent transport	*Biogas reactor where effluent goes to a simplified sewer.*	n.d.	n.d.	n.d.	n.d.	0	1	1	0	n.d.
ST.8	Biogas	Offsite biogas without blackwater transport	*This mainly concerns the transport of pit humus or sludge (e.g. from septic tanks) to a (semi-)centralized co-digestion facility*	n.d.	n.d.	n.d.	n.d.	0	n.d.	1	1	n.d.
ST.9	Biogas	Offsite biogas with blackwater transport	*Co-digestion of blackwater collected through sewer lines*	n.d.	n.d.	n.d.	1	1	n.d.	1	1	n.d.
ST.10	Blackwater	Onsite blackwater without sludge and with effluent infiltration	*Blackwater is stored, dewatered, and transformed to compost or pit humus (e.g. twin-pits); effluent goes to a soak pit or similar.*	1	0	0	1	0	0	0	0	0
ST.11	Blackwater	Onsite blackwater without sludge and with effluent transport	*Blackwater is stored, dewatered and transformed to compost or pit humus (e.g. twin pits); effluent goes to a simplified sewer or similar.*	1	0	n.d.	1	0	1	0	0	0
ST.12	Blackwater	Onsite blackwater with sludge and effluent infiltration	*Mainly septic tank or similar options (which are not just for storage but also involve some sort of basic treatment); effluent goes to a soak pit or similar.*	n.d.	1	n.d.	1	0	0	0	0	0
ST.13	Blackwater	Onsite blackwater with sludge and effluent transport	*Mainly septic tank or similar options (which are not just for storage but also involve some basic treatment); effluent goes to a simplified sewer or similar.*	n.d.	1	n.d.	1	0	1	0	0	0
ST.14	Blackwater	Onsite blackwater treatment with effluent infiltration	*Concerns compact onsite wastewater treatment units such as SBR; effluent goes to a soak pit or similar.*	0	0	n.d.	1	0	0	0	0	0
ST.15	Blackwater	Onsite blackwater treatment with effluent transport	*Concerns compact onsite wastewater treatment units such as SBRs; effluent goes to a simplified sewer or similar.*	0	0	n.d.	1	0	1	0	0	0
ST.16	Blackwater	Offsite blackwater treatment	*Everything goes to a (semi-)centralized system through sewer lines.*	n.d.	0	0	1	1	n.d.	0	0	0

3.3.4.2 Clustering

For clustering within the STs, we use two properties: (i) the number of Techs per SanSys, and (ii) the mean number of connections per Tech within a SanSys as a measure of complexity.

3.3.4.3 Selection of SanSys options

We define the number of SanSys in Q as 36 and distribute these 36 options across the STs. The distribution is proportional to the 90% quantile of *SAS* within each ST under the condition that each ST is represented at least once in $\boldsymbol{Q}$.

3.3.5 Results of the application case

3.3.5.1 Step 1: Appropriateness assessment

The histogram of the *TAS* per FG may be seen in Figure 3.7: It shows that for this case the selection of Tech in the FG C and T is most relevant, while all Techs in U, S, and D perform similarly well. None of the Techs perform very badly because those selected have already been shown to be applicable in similar regions.

It is illustrative to identify those criteria that influence the *TAS* the most. Figure 3.8 shows the distribution of the $AS_{t,c}$ grouped per FG. From a visual analysis, we can see that the management and to a lower extent construction skills, temperature range, and slope are the most variable criteria and are therefore mainly responsible for the diversity of TAS shown in the previous figure (Figure 3.7).

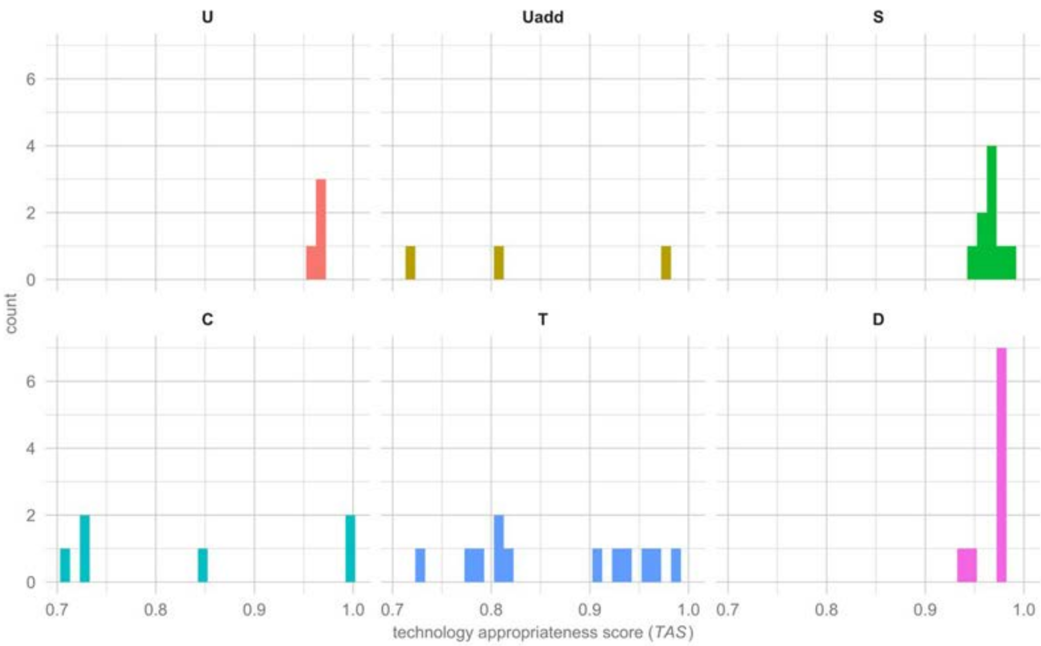


Figure 3.7: Histogram of technology appropriateness scores (TAS) grouped per functional group (U: user interface; Uadd: user interface other than toilet; S: collection and storage; C: conveyance; T: (semi-)centralized treatment; D: reuse or disposal). Please be aware that the abscissae start at 0.7 and not at the origin.

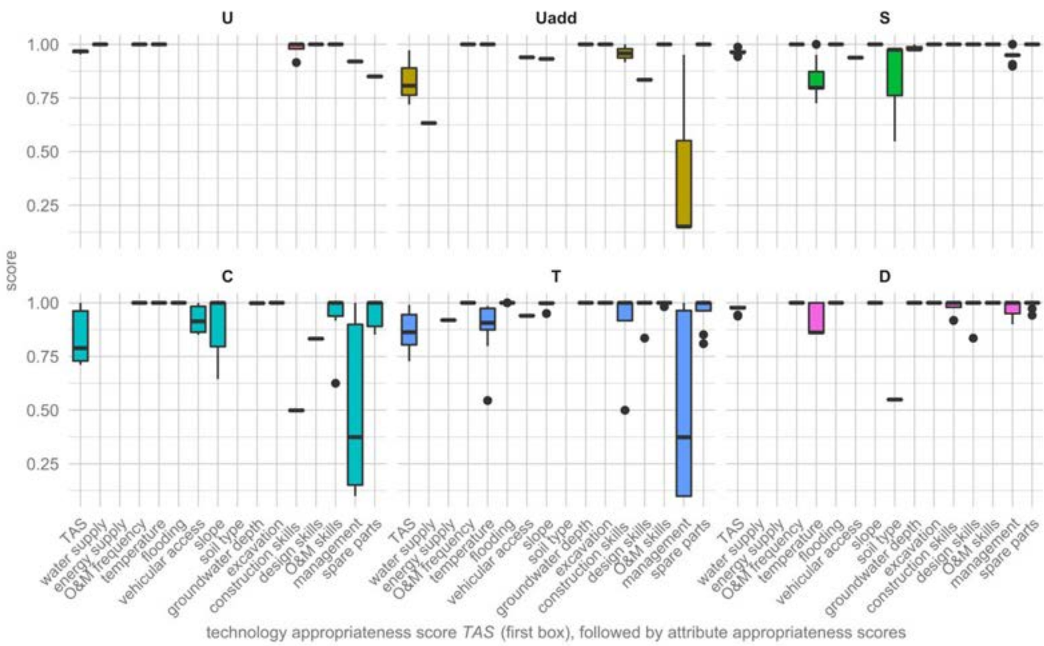


Figure 3.8: Boxplot of technology appropriateness scores (TAS) and criteria appropriateness scores (ASt,c) grouped per functional group (FG, U: user interface; Uadd: user interface other than toilet; S: collection and storage; C: conveyance; T: (semi-)centralized treatment; D: reuse or disposal). The first box in each FG always corresponds to the TAS and the subsequent boxes to the ASt,c. A higher wider box indicates a higher variability of the TAS, respectively the i. The figure allows to visually identifying those FGs with more variability in terms of TAS, and to identify those ASt,c that can be accounted for this higher variability.

3.3.5.2 Step 2: System generation

In total, 17,955 possible SanSys can be generated. These are distributed as follows: 2,166 SanSys for the urine diversion dry toilets (UDDTs), 380 for dry toilets, 1,531 for pour flush toilets and 13,878 for urine diversion flush toilets (UDFTs). UDDTs and UDFTs have more SanSys because these sources generate two output products (urine and faeces or blackwater), which greatly increases the number of Techs per SanSys and consequently the number of possible combinations. The computation time on an average desktop computer was approximately 14 minutes.

The number of Techs per SanSys varies between 3 and 14. Different numbers of Techs per SanSys are represented in all *SAS* ranges, indicating that $\alpha = 0.5$ is probably a reasonable choice. In the case of higher α (e.g. $\alpha = 1$, no penalization of length), we would have more long systems with a higher *SAS* and for a lower α (e.g. $\alpha = 0$) we would mainly see short systems with a high *SAS*.

3.3.5.3 Step 3: Option selection

The histograms of all SAS grouped according to the system templates (STs, see Table 3.5) are shown in Figure 3.9. The figure illustrates how the total number of SanSys per ST varies. This number depends on the Techs available for a given ST and on the number of products arising from these Techs. Both have an effect on the number of possible Tech combinations and thus on the number SanSys variations.

We distribute the 36 options to be selected among the STs proportional to the 90% quantile of *SAS* within each ST under the condition that each ST is represented at least once in S. The 90% quantile of *SAS* within each ST is illustrated by the red line in Figure 3.9. From the STs with a higher 90% quantile, three SanSys are selected (ST.2, ST.4, ST.6, and ST.10). Only two SanSys are selected from all other STs.

In Figure 3.10 we show the number of Techs per SanSys and the number of connection per Tech. SanSys with similar characteristics are grouped in clusters of same size within a ST (see also section 3.2.4). These clusters are indicated by the different colours. The SanSys with the best *SAS* in each cluster is selected to be in ***Q*** (marked by a cross).

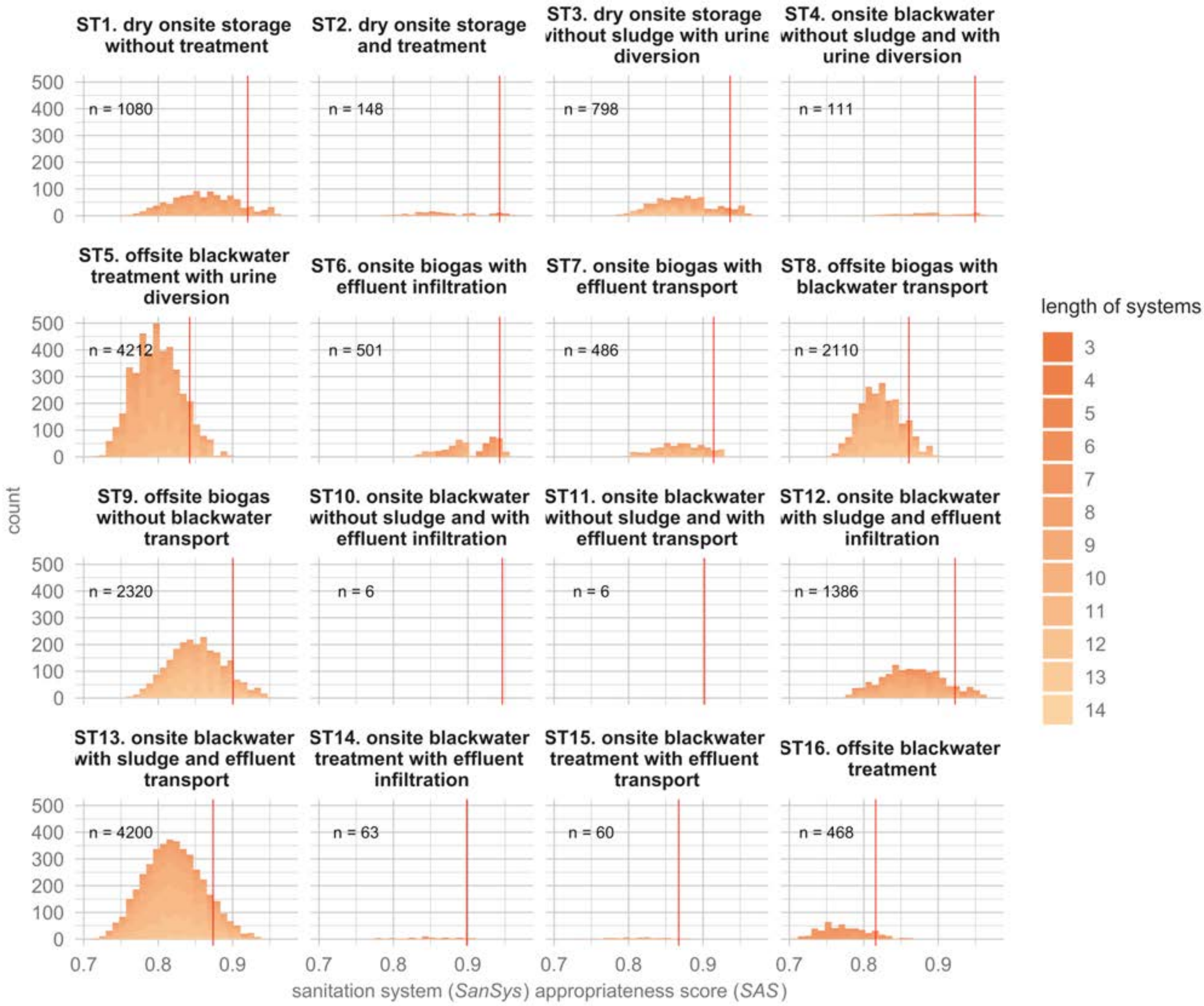


Figure 3.9: Histogram of sanitation system (SanSys) appropriateness scores (SAS) grouped per system template (ST). The numbers of SanSys per ST are also indicated (n). The 90% quantile of SAS within each ST is used to distribute the total number of SanSys to be selected and is indicated by the red line.

Figure 3.10: Count plot of the number of Techs per SanSys and the number of connection per Tech of all sanitation system (SanSys) options grouped per system template (ST). SanSys with similar characteristics are grouped in clusters of same size within an FG (indicated by the different colour). The size of the circles indicates the number of SanSys with exactly the same characteristics. The system with the best SAS (the most appropriate SanSys) in each cluster is selected to be used in the decision-making process (marked by a cross).

Four examples of selected SanSys are illustrated in Figure 3.11 (see SI-C for the others). The systems (a), (b), and (c) are examples of SanSys that have been successfully implemented in the region of the case study. The systems are diverse, as (a) is onsite and dry, (b) onsite wet, producing biogas, and (c) is an offsite wet blackwater system involving centrally-managed natural wastewater treatment. The SanSys given in (d) is a novel option for the context of Nepal. It combines onsite vermi-composting with urine diversion and centralized urine treatment and allows recovery of nutrients and organic matter in the form of stabilized urine and compost. This system has shown high potential in similar regions (Amoah et al., 2016b), and it is therefore highly appropriate to include it in the set of decision options.

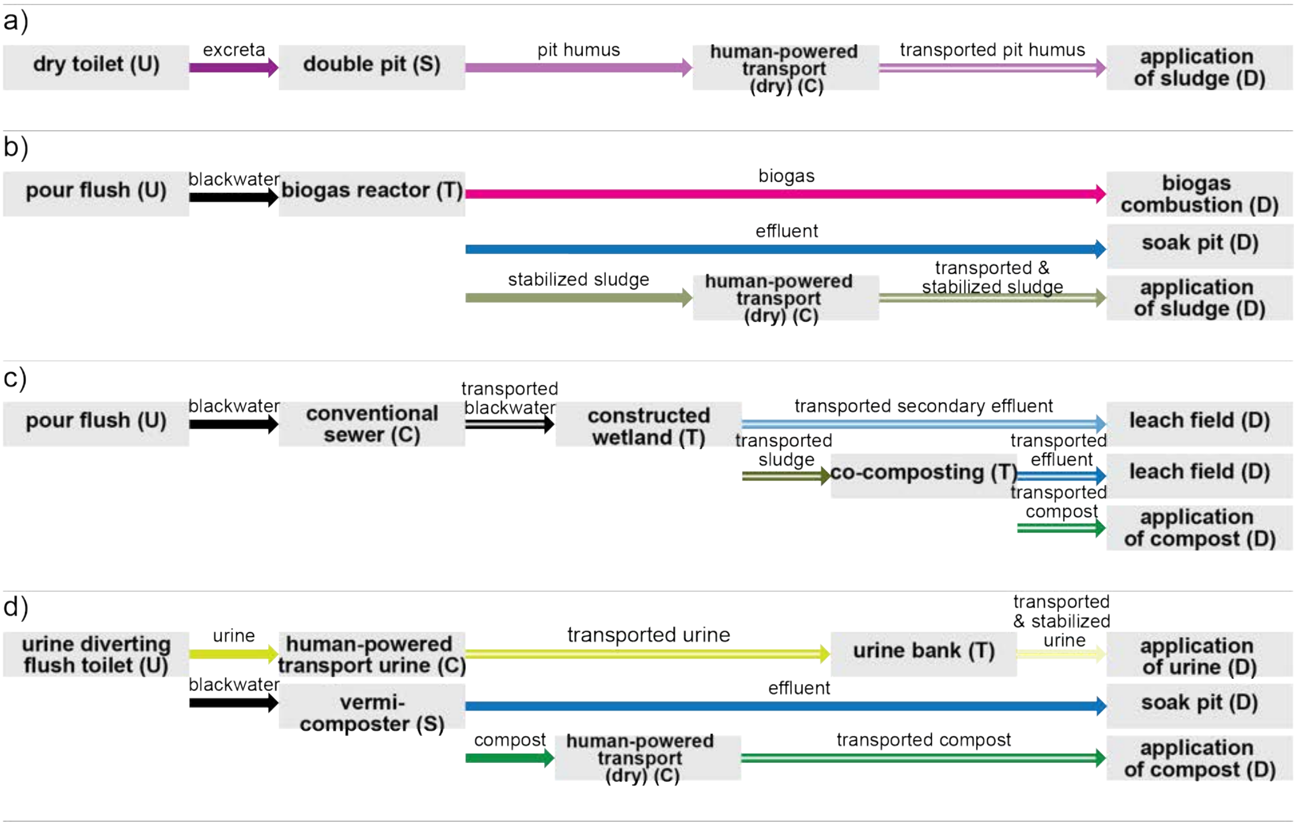


Figure 3.11: Four examples of sanitation systems (SanSys) selected for use in the decision-making process (from a total of 36; see supporting information for the others). Each box represents a technology (Tech). The arrows indicate the sanitation products. The letter in the parenthesis indicates the functional group. Systems (a), (b), and (c) are very different but are all quite common in the region. System (d) is a novel system based on vermi-composting. (a) System template 2 (ST.2): dry onsite storage and treatment), SAS=0.966; (b) ST.6 onsite biogas with effluent infiltration, SAS=0.938; (c) ST.16 offsite blackwater treatment, SAS=0.857; (d) ST.4 onsite blackwater without sludge and with urine diversion, SAS=0.958.

3.3.6 Results of sensitivity evaluation

3.3.6.1 Step 1: Appropriateness assessment of technology options

The omission of some criteria influences the ranking of the Tech as the impact on the *TAS* is not the same for different Techs. To quantify the change in the ranking, we counted the number of Techs that either moved up or down compared to the baseline (run 1.1). Table 3.6 shows the count of changes per FG and in total. The results are analysed separately for each FG, as only Techs within the same FG are true alternatives to each other. There is a total of 26 changes for run 1.2 (without management), 22 for run 1.3 (without criteria related to skills), and 8 for run 1.4 (without criteria related to O&M). The results compare well with Figure 3.8, showing the high impact of the management screening criterion (run 1.2) and the criteria related to skills (construction, O&M, and design skills, run 1.3). The omission of the criteria frequency of O&M and O&M skills also has an impact, although this is much lower (Table 3.6, run 1.4). The criteria relating to O&M also have an impact, but it is rather lower. The removal of the management criterion (run 1.2) also resulted in a lower variance of the *TAS* (not shown in the table, see associated data at ERIC: https://doi.org/10.25678/0001PH for full results), showcasing the importance of this criteria to enhance the significance of the rankings.

Table 3.6: Results from the sensitivity analysis of runs 1.2 to 1.3. Run 2.1 serves as a baseline (not shown). The results are shown as changes in position of the ranking of the Techs within a functional group (FGs) according to their technology appropriateness score TAS. The results are analysed separately for each FG, as only Techs within the same FG are true alternatives to each other.

FG	Number of Techs	Run		
		1.2	1.3	1.4
		Without management	Without construction skills, O&M skills, and design skills	Without criteria related frequency of O&M, and O&M skills
U	4	0	4	0
S	9	5	3	2
C	6	3	1	3
T	12	3	5	3
D	9	7	8	2
Total	**43**	**26**	**22**	**8**

3.3.6.2 Step 3: Option selection

The five elements that were varied in the analysis (see section 3.2.7.1.2) have different impacts on ***Q***. Table 3.7 shows the characteristics of the ***Qs*** generated in the runs 2.1 to 2.7. The ***Qs*** are evaluated by the median *SAS*, the diversity as a function of number of different sources within ***Q***, the number of different STs, the number of different numbers of technologies per system, and the number of different numbers of connections per Tech (see also section 3.2.7.1.2). Figure 3.12 highlights the diversity and the median *SAS* of the ***Qs*** obtained with the different runs. Figure 3.13 highlights the impact of the size (number of selected SanSys) on the diversity of ***Q***. In the following, we discuss the influence of all five evaluated elements on the median *SAS* and the diversity.

3.3.6.2.1 Size of Q

The baseline (run 2.1) has a size of ***Q*** = 36 compared to 8, 4, and 64 for runs 2.2, 2.8, and 2.9 respectively. The SanSys are selected in decreasing order of *SAS,* so that a smaller ***Q*** will always result in a higher median *SAS* (Figure 3.12). As shown in Figure 3.13, the diversity increases with the size of ***Q***. The benefit of a large ***Q*** for diversity tempers as soon as the size of the ***Q*** exceeds the total number of STs defined (16 STs in our case, see also Table 3.5).

3.3.6.2.2 α

A small α penalizes long systems, so that $\alpha = 0$ (run 2.3) results in a lower number of different numbers of Techs (see SI-D). This is reflected in the diversity which is 9.75 for $\alpha = 0$ (run 2.3), 10.5 for $\alpha = 0.5$ (run 2.1), and 10.75 for $\alpha = 1$ (run 2.4, Figure 3.12). The term α also shifts the scale of the *SAS* to lower values, so that the median SAS is not directly comparable. It is interesting to note that the decrease in diversity, as well as the shifting effect are both more pronounced if α is reduced from 0.5 to 0, compared to an increase from 0.5 to 1. This indicates that $\alpha = 0.5$ provides a good balance between the penalization of long systems and maintaining high diversity.

3.3.6.2.3 Clustering to structural properties

The clustering itself, as shown by run 2.5, has little impact on the diversity or the median of *SAS.*

3.3.6.2.4 Classification to system templates

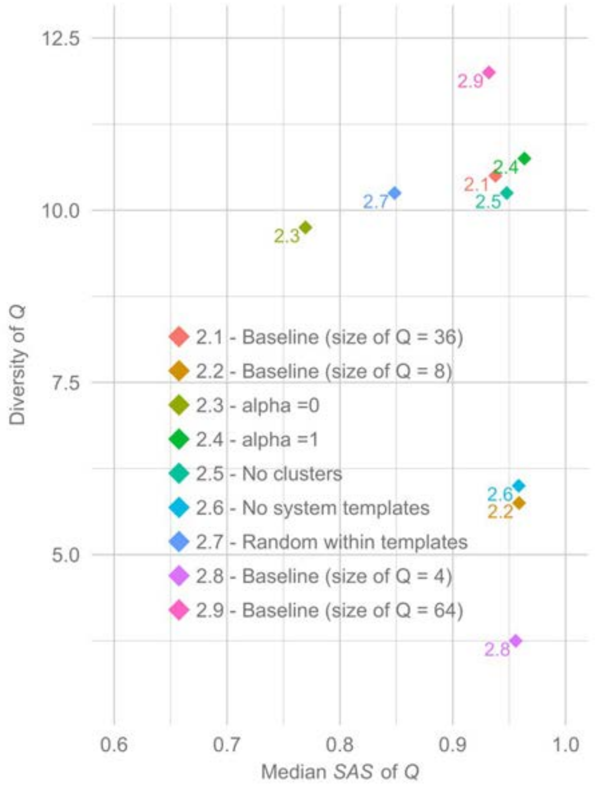
In run 2.6, we select the 36 SanSys with the highest *SAS,* ignoring the STs and without clustering. This obviously results in a higher *SAS* (Figure 3.12), although the impact is small. On the other hand, the diversity is strongly impacted, as only five STs remain represented in ***Q***.

3.3.6.2.5 Use of the SAS

In run 2.7, we use STs to classify and then randomly (independently of *SAS*) select the number of options from each ST. This has a high impact on the median *SAS* (Figure 3.12), whereas the decrease of diversity is negligible.

Table 3.7: This table shows the characteristics of diversity and the median system appropriateness score (SAS) of the sets of selected sanitation systems (SanSys) Q resulting from runs 2.1 to 2.7 of the sensitivity analysis of step 3. The characteristics of the different runs are shown in section 3.2.7.1.2). In summary, the highest impact on the diversity and median SAS of Q can be observed by the size of Q, the use of STs (all except run 2.6), and the use (or not) of the SAS (all except run 2.7).

Characteristics		**Run**								
		2.1 (base-line)	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**
Size of ***Q*** (number of selected *SanSys* options)		36	8	36	36	36	36	36	4	64
α		0.5	0.5	0	1	0.5	-	0.5	0.5	0.5
Other elements						No clusters	No system templat es	No SAS		
Quality	Diversity	10.5	6	9.75	10.75	10.25	6	10.25	3.75	12
	Median of *SAS*	0.938	0.959	0.769	0.964	0.948	0.958	0.848	0.956	0.932



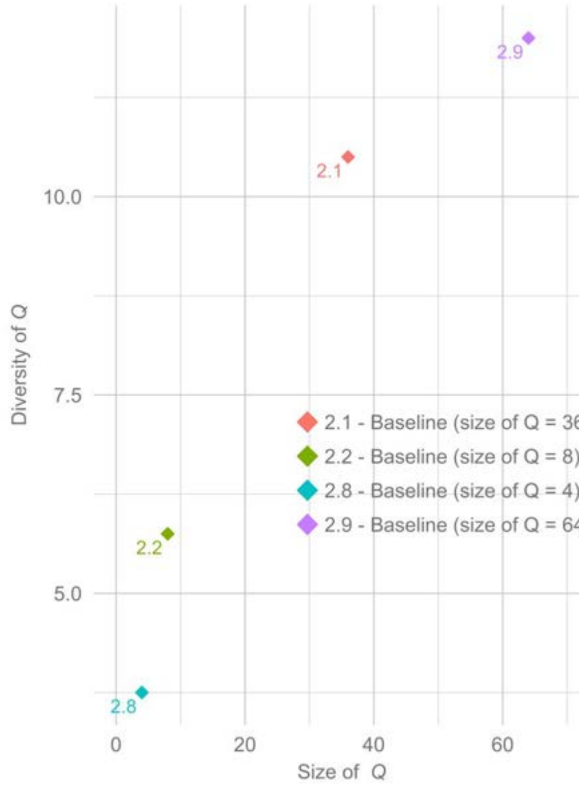


Figure 3.12: Characteristics of the set of selected sanitation systems (SanSys) Q for nine different runs for Step 3 (see also Table 3.3). The diversity is plotted against the median SanSys appropriateness scores (SAS). Note that runs 2.3 and 2.4 have different α, so that their median SAS are not directly comparable.

Figure 3.13: Diversity of the set of selected sanitation systems (SanSys) Q for four different runs (2.1, 2.2, 2.8, and 2.9) as a function of the size of Q (see also Table 3.3). The diversity increases with the size of Q. The benefit of a large Q for the diversity tempers after the size of Q exceeds the total number of system templates.

— 3.4 DISCUSSION

The procedure presented here systematizes the generation of a diverse but manageable set of locally appropriate sanitation system options. The core purpose is to break down the typically opaque option generation step into smaller more reproducible elements. It is by no means intended to replace the technical know-how required for detailed planning and implementation but serves to help integrate the growing number of decision criteria and technological options into the decision-making process.

In addition, some elements in the procedure still require some degree of judgement. These include (1) the identification of a set of potential technologies; (2) the case-specific choice of the set of screening criteria; (3) the definition of the screening criteria attributes and corresponding uncertainty models; (4) the aggregation method for the *TAS* and *SAS* appropriateness scores; (5) the checking of the final set of sanitation system options from a process engineering point of view; and (6) the definition of the system templates and the number of selected options (size of ***Q***).

In the following, we discuss these elements in more detail and argue that, despite these subjectivities and the need for expert judgement, the increased transparency and the formal structure of our approach still offers substantial advance over the currently used approaches.

3.4.1 Identification of potential technologies

The main decisive element of the presented procedure is that it shifts the burden of choosing complete sanitation systems to selecting potential technologies. As this requires no local expertise, we believe that it is easier to compile a comprehensive list of potential technologies (Techs) from literature or experience and then to identify a set of appropriate and complete sanitation systems (SanSys). This is also emphasized by the huge number of potential SanSys, as demonstrated in this paper, compared with the rather limited number of potential Techs. We provide a list of potential Techs based on the literature (Tilley et al., 2014b) and corresponding model input data in the linked dataset for reuse in other applications of the procedures (ERIC: https://doi.org/10.25678/0001PH).

3.4.2 Choosing a set of screening criteria

A second decisive element of the procedure is the use of screening criteria to eliminate inappropriate options at the beginning and to streamline the decision-making process. Obviously, which screening criteria are used has an impact on the outcome of the screening procedure. Because no trade-offs are discussed at the screening stage, screening criteria should be exclusively exogenous and as independent of stakeholder preferences as possible. However, in practice the lines are not always clear. Legal directives, cultural constraints, and available skills are often seen as exogenously fixed. However, these might represent current or past stakeholder preferences, such as in the case of legal directives, and can be changed or ignored by the stakeholders. Therefore, the choice of screening criteria relies on the expert in charge of the procedure and will thus imply a certain level of subjectivity about how adaptable they are.

In the example application, we have shown a pathway for structuring the selection of screening criteria as transparently as possible. We provide a carefully assembled master list of possible screening criteria (see Table 3.1 and SI-A). We then propose involving the stakeholders in selecting case-specific screening criteria.

Because the screening criteria are derived from the overall objective hierarchy of sustainable sanitation, some of them might also be relevant later in the SDM process. For example, a common screening criterion is water use; a potential technology should not exceed the amount of water available in the application case. Nevertheless, the decision-maker still might want to prefer among the appropriate Techs, those with lower water use.

3.4.3 Quantifying attributes and their uncertainty

A third decisive element of the procedure is the use of attributes for the calculation of appropriateness scores for every technology and sanitation system. Their quantification is based on probability functions characterizing the screening criteria for the technology (Tech attribute) and the application case (AppCase attribute). The selection and quantification of probability function should be mainly data driven and based on data available at the structuring phase of decision making (e.g. household survey, official statistics, baseline reports, former project reports). The uncertainty model for each attribute can then be derived from the data available using the simplest model that describes the data sufficiently (e.g. triangular distribution). The supporting information in SI-A and the data (ERIC: https://doi.org/10.25678/0001PH) provide a good starting point for this step.

We are well aware that the detailed choice of attribute and corresponding probability function for each screening criterion might have a substantial impact on the outcome of the analysis (see e.g. section 3.3.6.1). This step of the procedure depends strongly on the experts in charge of the procedure and therefore also implies a certain level of subjectivity. However, this is a system-immanent problem that many value-focussed SDM procedures face (see e.g. Keeney and Gregory, 2005) and not a problem specific to the procedure proposed here.

In the application case, we present a stakeholder-oriented approach, agreeing with them not only about the case-specific screening criteria (see 3.4.2) but also the attributes by which these are evaluated.

3.4.4 Quantifying appropriateness scores *TAS* and *SAS*

A fourth decisive element of the procedure is the technology and system appropriateness scores (*TAS* and *SAS*). They express the confidence in how appropriate the technologies and sanitation systems are for a given application case. The appropriateness scores on their own are not sufficiently robust to identify a single most appropriate solution (as shown in the sensitivity analysis in 3.3.6.1), but they are very well able to show whether any options are significantly more or less promising than others for a specific application case. It therefore acknowledges that hardly any Tech is 100% appropriate and thus reduces the risk of eliminating options too early. However, it is important to note that the *TAS* and *SAS* cannot provide information on the real performance of the technologies and systems in the future. The real performance depends not only on the aspects covered by the screening criteria but also on many other factors such as implementation, influent quality and quantity, and operation and maintenance.

For the quantification of the technology appropriateness score, *TAS,* we aggregate the match of the Tech attribute and the AppCase attribute for all screening criteria. The geometric mean aggregation function satisfies our requirements of allowing different numbers of criteria and turning equal to zero if at least one element is zero (see 3.2.2.3). However, this aggregation model also implies that the number of criteria used is relevant; the more criteria are used, the less relevance any single criterion has to the overall score. The selection of case-specific criteria from the master list involving stakeholders as described in 3.4.2 can help to limit the set of screening criteria used to the most relevant. If the list of screening criteria remains long (e.g. greater than 15), we recommend the use of hierarchical structures and of sub-level aggregation, as aggregation via the geometric mean is not an associative function (Grabisch et al., 2011).

To quantify the system appropriateness scores, *SAS*, we propose a weighted multiplicative aggregation model that allows us to define how much long SanSys should be penalized. The main argument here is that the appropriateness of long systems with many technological steps might be judged to be less appropriate than that of shorter and therefore less complex systems with technological elements of same appropriateness. In the application case presented in this paper, we show that the chosen value for $\alpha = 0.5$ (see 3.3.6.2.2) leads to a well-balanced behaviour that penalizes very long systems but still allows high diversity in the final set of SanSys.

3.4.5 Generation of the sanitation system option space

A fifth decisive element of the procedure is the automatic generation of all possible system combinations. The application example showed that the systematic option generation allows the diversity of the option space to be expanded, as it also results in *SanSys* options that are not widely applied (see Figure 3.11c). This enhances the probability that innovative or unusual options find their way into the decision-making. The innovation can lie in how technologies are combined (e.g. combining a urine-diverting toilet with vermi-composting) or in the integration of novel technology options. For instance, the model could provide all possible sanitation systems that can be realized with the blue diversion toilet (Larsen et al., 2015). An added benefit of this systematic process is the creation of truly comparable alternatives that incorporate everything from user interface to disposal.

To balance the comprehensiveness of the SanSys option space with the computational efforts required, we used a semi-acyclic algorithm that allows loops only the functional groups storage and treatment (S) and (semi-)centralized treatment (T). If there are no computational limitations, the fully cyclic algorithm could be used (see SI-B).

It is important to emphasize that the procedure provides generic SanSys including the technologies and the type of products that flow between them. However, it does not provide (i) detailed characteristics of input or output quantities or qualities or (ii) any spatial information. For example, the semi-centralized composting system displayed in Figure 11c could consist either of one central large co-composting site or several smaller ones in different areas of the town.

The SanSys builder is based on a series of simplifications and assumptions. For instance, it requires a standardized set of products and is not able to generate new products, as the model does not have any process engineering knowledge. As a consequence, when different products are mixed together in a conveyance technology, the output product will always be that with the highest degree of pollution. For example, a conventional sewer fed with greywater and blackwater will produce blackwater. The same sewer fed only with blackwater will also produce blackwater. It is clear that the degree of dilution of a certain product might influence the performance of the subsequent treatment step. Another simplification concerns the relationship between the input and output products by 'AND', 'OR', or 'XOR'; this does not allow special cases to be described. For example, a biogas reactor can have dried faeces OR sludge as an input product, but from an engineering perspective dried faeces as the only input does not make too much sense. Therefore, one must assume that some of the permutations might not be sensible from a purely process engineering perspective. This can easily be rectified by checking the set of SanSys selected in step 3 of the procedure before passing them on to the SDM process. Moreover, the SDM process will probably also include a detailed performance evaluation of the SanSys options, where their technical performance can be compared to other decision objectives.

3.4.6 Selection of the final set of SanSys options as an input into SDM

A sixth decision element is the systematic selection of a final set of SanSys. This step is designed to reduce the overwhelming number of SanSys options to a limited number that can be managed by an SDM or MCDA process. The requirements for the algorithm are that (i) the diversity of the set of SanSys is maintained*;* and (ii) the most appropriate options are selected. The algorithm has four key parameters: (i) the aggregation function used to compute the *SAS*; (ii) the size of the final set of options ***Q***; (iii) the system templates (STs); and (iv) the characteristics used for clustering. We showed that the size of ***Q*** and the system templates have the highest impact on the diversity of ***Q***. The use of the *SAS* guarantees that only the most appropriate options are selected.

The size of ***Q*** depends on the capability of the SDM methodology chosen to treat various numbers of decision options. We show that the diversity increases with the size of ***Q*** while the median *SAS* of ***Q*** decreases. The increase in diversity is only relevant until the size of ***Q*** exceeds the total number of system templates (see Figure 3.13). Increasing the size of ***Q*** any further then mainly leads to a decrease of the median *SAS* as an increasing number of less appropriate SanSys are included in ***Q***. This shows that there exists a quasi-optimal size of ***Q*** even if the SDM methodology were able to manage very high number of options. This optimal size is equal to or slightly higher than the number of defined system templates.

The way system templates are defined also influences how much weight different groups of system templates might gain in Q. In the example application, we decomposed the group of blackwater system templates into seven sub-templates (see Table 3.5), compared to only two sub-templates for the onsite simple, thus giving blackwater systems a higher weight. We argue that the number of Techs available is higher in the blackwater group and that the diversity of these options should be accounted for. However, other definitions might be more suitable for other decision contexts. There is some subjectivity in how the system templates are defined; however, this is also the case for the diversity of decision options that may be requested (Gregory et al., 2012; Keeney, 1996). We here suggest verifying the choice of system templates with the stakeholders in an application case.

3.4.7 Limitations and outlook

The main limitations of the procedure presented here lie in the experts' skills and local knowledge to provide suitable inputs. In the future, this procedure could therefore be more strongly adapted to different settings so as to connect it more intimately with existing planning procedures. Good results might be achieved by using the proposed procedure to generate technology profiles and system option compendiums. Specialized knowledge and available sanitation-relevant data could be used to characterize the technology profiles. The SanSys builder could be used to generate the corresponding system compendium. These products could then be used in local sanitation planning processes to identify appropriate technology profiles and system options as input for local decision-making (e.g. CLUES). This would allow a standardized approach that combines in-depth expert knowledge about potential technologies with local data and preferences. The appropriateness assessment based on the technology profiles can be discretized, which would make it independent of modelling software. As much of the system generation and option selection procedures are algorithms, the system compendium could be implemented as a web-based service that centralizes in-depth technical know-how and provides the user with localized options. In addition, specific technology profiles and system compendiums could be generated for typical regions and settings. The system templates could be defined in a way to correlate with appropriateness ranges for different regions, which would further facilitate the integration of the approach into the local sanitation planning process.

An interesting extension of the SanSys builder would be the addition of a material flow analysis module. This would allow for the quantitative estimation of the performance of entire sanitation systems including nutrient, water, or solids recovery potentials as additional indicators that can be used by the decision-making process.

— 3.5 CONCLUSIONS

We present a codified and therefore reproducible procedure to identify an initial set of SanSys decision options as an input into a structured decision making (SDM) process such as CLUES, a strategic sanitation planning guideline developed for urban settings in the global South (Lüthi et al., 2011a). The procedure is not meant to identify the best option, because this is what SDM does. Instead, it focusses on potentially appropriate options while maintaining high conceptual diversity. Furthermore, it is meant not to replace but to support engineering know-how in an SDM process. It provides a series of advantages over currently used empirical methods:

- It is automated and thus allows very large numbers of technology and system options to be dealt with;
- It makes technical suggestions for each and every product and therefore enforces the consideration of entire sanitation systems;
- it is systematic and thus enhances the reproducibility and transparency of option generation;
- it explicitly considers uncertainties relating to local conditions and technology options and thus can work with data and information generally available at the structuring phase, also in developing urban areas; and
- it can include novel technologies and therefore generates options that have not yet been widely applied but are nevertheless realistic (as shown in the application case). The hope is that such novel options have the potential to be more sustainable than conventional ones in developing urban areas because of e.g. their greater flexibility to demographic changes and the opportunities for resource recovery (e.g. nutrients, energy, or water).

The procedure remains sensitive to several parameters that should ideally be defined together with local stakeholders: the definition of potential technologies; the set of screening criteria, attributes, and uncertainty models; and the system templates. Moreover, the procedure is generic and can be extended to integrate other parts of urban water systems (e.g. stormwater) and applied to other complex infrastructure problems, such as solid waste management. The procedure is sufficiently systematic that it could be standardized for regional or national planning procedures and provide low-level support for local decision-making and planning procedures.

— 3.6 ACKNOWLEDGMENTS

The authors gratefully acknowledge Mingma and Anjali Sherpa and Bipin Dangol for providing inputs on the practical application of the method. The inputs from Fridolin Haag, Dr. Mika Marttunen and Dr. Christoph Lüthi helped us to define decision objectives and to develop a method for identifying screening criteria. Judith Lienert's inputs on SDM helped us to improve the methodological approach. The authors also thank Joel Gundlach and Maria Rath for reviewing and testing the models. Furthermore, the authors gratefully thank Agnes Montangero and her colleagues from the Swiss Water and Sanitation Consortium and the inhabitants of Katarniya for providing their project as an application case.

This work was supported by the Engineering for Development (E4D) programme of the Swiss Federal Institute for Technology (ETH) Zurich. The programme is funded through the Sawiris Foundation for Social Development.

04 Ex-ante quantification of nutrient, total solids, and water flows in sanitation systems

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Publication version Preprint (submitted 24.07.2020).
Spuhler, Dorothee, Scheidegger, Andreas and Maurer, Max. 2020. Ex-ante quantification of nutrient, water and total solid flows in sanitation systems. Submitted to Journal of Environmental Management.

Supplementary material Data package 1 (code, modelling input/results, and supplementary material): https://doi.org/10.25678/0000HH
Data package 2 (Sanitation technology library):
https://doi.org/10.25678/0000ss

→ **The model quantifies ex-ante nutrient, water and solid flows for entire systems**

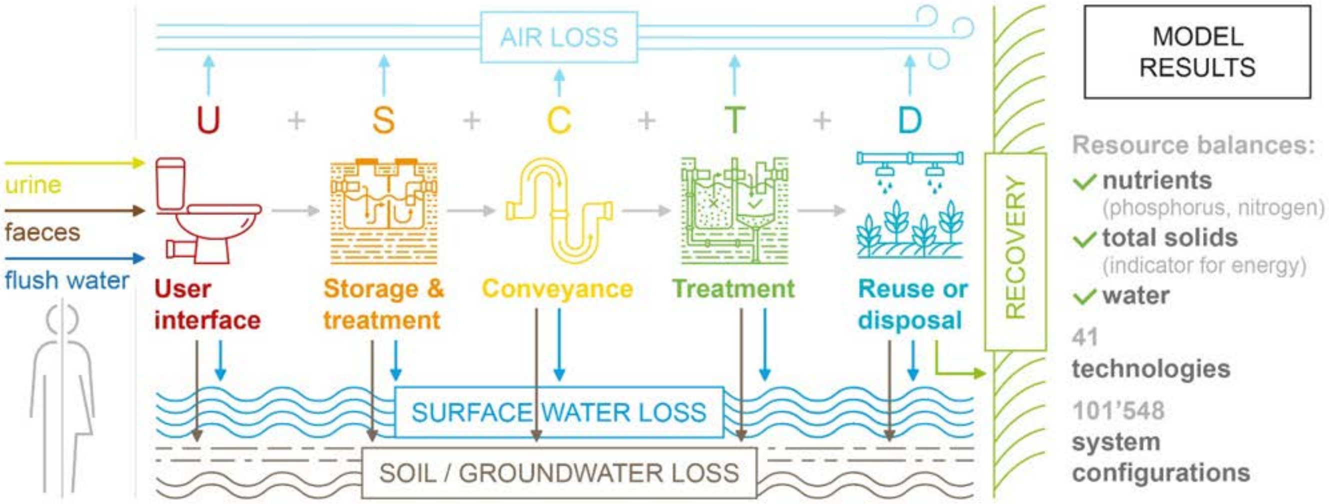
→ **Uncertainties for novel and conventional technologies are systematically considered**

→ **An extensive literature-based library provides transfer coefficients for 41 technologies**

→ **Application examples shows the relevance of such a model supported approach**

Author contributions: D. S., A.S., and M.M. conceptualised this publication together and jointly managed reviewing and editing. D.S. was responsible for data curation, formal analysis, investigation, and validation. The methodology and software were developed jointly by D.S. and A.S.. D.S. also wrote the original draft and visualized the results. A.S. and M.M. supervised the process. D.S. and M.M. were responsible for funding acquisition. Resources (primary literature data) were collected by Leandra Roller.

ABSTRACT



To prioritise sustainable sanitation systems in strategic sanitation planning, indicators such as local appropriateness or resource recovery have to be known at the pre-planning phase. The quantification of resource recovery remains a challenge because existing substance flow models require large amounts of input data and can therefore only be applied for implemented options. This paper aims to answer two questions: How can we predict resource recovery and loss ratios of sanitation systems ex-ante at the pre-planning phase? And how can we do this efficiently to consider the entire sanitation system option space?

The approach builds on an existing model to create sanitation systems from a set of conventional and emerging technologies and to evaluate their appropriateness for a given application case. It consists of a Substance Flow Model (SFM) complemented with transfer coefficients from a technology library to quantify nutrients (phosphorus and nitrogen), total solids (as an indicator for energy and organics), and water flows in sanitation systems ex ante. The transfer coefficients are based on literature data and expert judgement. Uncertainties resulting from the variability of literature data or ignorance of experts are explicitly considered, allowing to assess the robustness of the model output. Any (future) technologies or additional products can easily be added to the library.

The model is illustrated with a didactic example showing how 12 valid system configurations are generated from nine technologies, and how substance flows, recovery ratios, and losses to soil, air, and water are quantified considering uncertainties. The recovery ratios vary between 0-28% for phosphorus, 0-10% for nitrogen, 0-26% for total solids, and 0-12% for water. The uncertainties reflect the high variability of the literature data but are but comparable to those obtained in studies using a conventional post-ante material flow analysis (max 28%). Because the model is fully automated and based on literature data, it can be applied ex-ante to a large and diverse set of possible sanitation systems as shown with a real application case. From the 41 technologies available in the library, 101,548 systems are generated and substance flows are modelled. The resulting recovery ratios range from almost nothing to almost 100%.

The two examples also show that recovery ratios depend on technology interactions and has therefore to be assessed for all possible systems and not on single technology level only. The examples also show that there exist trade-offs among different types of reuse (e.g. energy versus nutrients) or different sustainability indicators (e.g. local

appropriateness versus resource recovery). This highlights the need for such an automated and generic approach that provides recovery ratio data already at the pre-planning phase.

The approach presented enables to integrate transparently the best available knowledge for a growing number of sanitation technologies into a planning process. The resulting resource recovery and loss ratios can be used to prioritise resource efficient systems in sanitation systems at the pre-selection phase or during the detailed evaluation of options using e.g. MCDA. The results can also be used to guide future development of technology and system innovations. As resource recovery becomes more relevant and novel sanitation technologies and system options emerge, the approach presents itself as a useful tool for strategic sanitation planning.

— 4.1 INTRODUCTION

If there is one thing important for health and environmental protection, and thus for social and economic development, it is good sanitation. In most of high-income countries, we benefit from great sanitation services and make great efforts to treat wastewaters and to prevent environmental pollution.

The importance of sanitation has been acknowledged in the human right to water and sanitation (UN, 2010). That sanitation should also be sustainable has been recognized by the Sustainable Development Goals SDGs 6 (UN, 2015). Despite these efforts, the situation has not been improving much recently. One reason for this is, that conventional sanitation solutions are not appropriate and thus not viable in fast growing urban areas, where most of the current population growth is taking place (Dodman et al., 2017; Isunju et al., 2011; Tremolet et al., 2010; UNDESA, 2014). This is due to their e requirements for large amounts of water and energy, expensive infrastructure, and long planning horizons (Davis et al., 2019). Sustainable sanitation systems not only to protect the human health and are technically and institutionally appropriate; they are also economically viable, and socially acceptable, and protect natural resources by closing water and nutrient loops at the lowest possible level (SuSanA, 2008).

This has triggered the development of many novel sanitation technologies and system configurations such as urine diversion toilets or container-based sanitation (Tilmans et al., 2015; Tobias et al., 2017). Many of these innovations are independent from sewers, water, and energy and therefore more appropriate for developing urban areas. They are also potentially more sustainable because they often allow for the recovery of resources such as nutrients, water, and energy (e.g. Andriessen et al., 2019; Chen and Beck, 1997; Cofie et al., 2009; Daigger, 2009; Davis et al., 2014; Evans et al., 2013; Harder et al., 2019; Langergraber and Masi, 2018; Rao et al., 2017; Trimmer et al., 2019; Udert and Wachter, 2012). Also, the flexibility to cope with changing environmental and socio-demographic conditions further enhance their sustainability (Hoffmann et al., 2020; Larsen et al., 2016).

While innovation potentially enhance sustainability, they certainly enhance planning complexity. The currently available portfolio of technologies leads to an overwhelming number of possible system configurations. To consider them all in a strategic planning process is extremely difficult. The two main challenges are (1) the lack of knowledge what options exists and how appropriate they might be in a given context; and (2) data about the performance of these options regarding the multiple sustainability criteria. The sustainability criteria are given by the five objectives for sustainable sanitation laid out by the Sustainable Sanitation Alliance (SuSanA, 2008): health and hygiene, economic viability, socio-cultural acceptance, technical and institutional appropriateness, and protection of the environment and natural resources. Because sustainability requires multiple dimensions to be considers, trade-offs are to be expected and a multi-criteria decision approach such as structured decision making is needed. (Gregory et al., 2012). Spuhler et al., (2018) addressed the first point by presenting a model that builds all valid sanitation system configuration from a set of potential technologies, and pre-select a small set of options that are locally appropriate given technical, legal, socio-socio-cultural and institutional criteria. This manuscript describes a model to compute performance indicators on resource recovery and provides a technology library containing international data and knowledge needed for this task.

Only if practitioners have the knowledge and data about the resource recovery and loss ratios of the various sanitation systems they can consider environmental protection when planning for sustainable sanitation. Hence this knowledge and data are needed ex-ante, at the pre-planning phase. Unfortunately, in the absence of infrastructure in place and few full-scale implementation examples of novel technologies and systems, we cannot measure this data. Thus, a modelling approach is required. Resource recovery and loss ratios can be modelled using substance flow modelling (SFM) based on material flow analysis (MFA), (e.g. Baccini and Brunner, 2012; Huang et al., 2012; Mehr et al., 2018). Unfortunately, existing models require detailed knowledge about the technology implementation and large amount of data (e.g. Espinosa and Otterpohl, 2014; Montangero and Belevi, 2008; van der Hoek et al., 2016; Yoshida et al., 2015). Therefore, they can be applied for a few options only post-ante (e.g. Dahlmann, 2009; Meinzinger et al., 2009; Montangero et al., 2007; Ormandzhieva et al., 2014; Schütze and Alex, 2014; Ushijima et al., 2012; Woltersdorf et al., 2016; Yiougo et al., 2011). Moreover, most of the existing models are designed for conventional systems and are not easily applicable for innovations. To our knowledge, there is currently a complete lack of generic methods to model substance flows of a large and diverse range of sanitation systems at the scale of an entire city.

4.1.1 Aim

To help solve these problems we will address two questions in this paper:

1. How can we predict resource recovery and loss ratios of sanitation systems ex-ante at the pre-planning phase?
2. And how can we do this efficiently to consider the entire sanitation system option space?

To answer these questions, we present two elements. First, we present a method to model substance flows that is generic to any system and can be applied automatically for many sanitation systems. Second, we provide the required a priori data to apply this model for four substances and a large and diverse set of conventional and emerging technologies ex-ante. The four substances cover nutrients (nitrogen and phosphorus), organics and energy (total solids), and water. Because the a priori data is highly variable depending on the technology implementation, the quality and quantity of flows, and the local context, we also calculate the uncertainties of the results. To exemplify the model and its outputs we present a didactic case and some snapshots of a full-scale application of 41 technologies resulting in 101,548 valid system configurations.

— 4.2 METHODS

4.2.1 Overview

The quantification of recovery ratios of sanitation systems automatically, for many options simultaneously, and ex-ante, requires three elements: a **generic** description of the systems; a method to **model** the substance flows within these systems, and the **data** on transfer coefficients and inflowing masses. Additionally, we need a way to consider the **uncertainties** related to the data of transfer coefficients as those data are based on prediction and not on in-situ measurements.

Spuhler et al., (2018) provides an automated system builder that allows to systematically build all valid system options from a set of technologies. We extended this model with a substance flow model and the technology library with the required data: transfer coefficients and their uncertainties. The only additional input is the masses per person and year entering a system. Figure 4.1 provides an overview on the required model and data elements. The substance modelling aspects are described in this method sections. The required a priori data is provided in the results section.

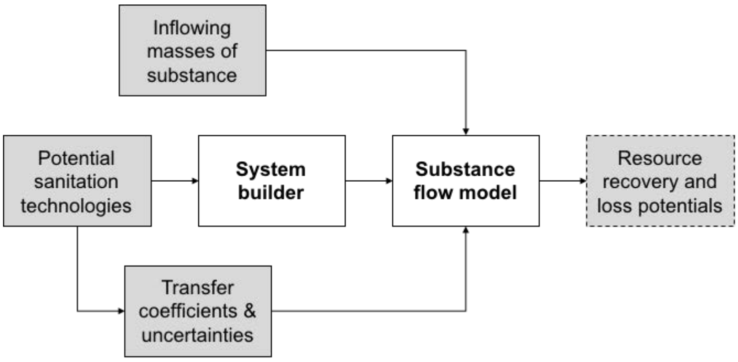


Figure 4.1: Overview of the required elements to quantify resource recovery and loss ratios ex-ante for a large and diverse set of sanitation systems. The system builder and the substance flow models are described in the methods. The data elements required for the model are in grey and provided in the results section. The model output are the resource recovery and loss ratios.

4.2.2 Sanitation technologies and system builder

The sanitation system builder defines a sanitation system (*SanSys*) as a set of compatible sanitation technologies (*Techs)* which in combination transport, transform, or separate sanitation products from their point of generation to the final point of reuse or disposal(Maurer et al., 2012; Spuhler et al., 2018; Tilley et al., 2014b). This definition is generic and could be applied to any unit process, infrastructure, or service. Sanitation *products* are materials that are generated either directly by humans (e.g. urine, faeces, greywater), the urban environment (e.g. stormwater), or by some Techs (e.g. sludge, biogas). Each Tech is defined by the possible input and output products and the stage within a system (*functional group*) it can apply to (see Figure 4.2). Sources could be toilets, handwashing stations, stormwater collection tanks, organic solid waste bins but in this paper, we focus on toilet sources only.

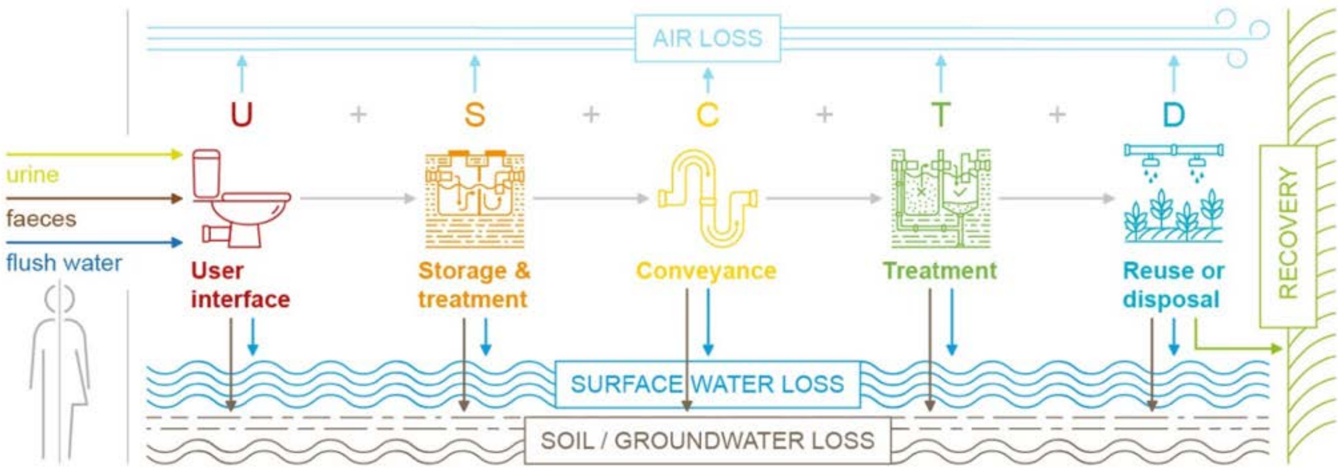


Figure 4.2: A valid sanitation system is a set of technologies which in combination manage sanitation products from the point of generation to a final point of reuse or disposal. Technologies contained in a system can be organized in five functional groups (FGs): source/ toilet user interface (U), on-site storage and treatment (S), conveyance (C), (semi-)centralized treatment (T), and reuse or disposal (D). Technologies belonging to U are sources, technologies belonging to D are sinks. To quantify resource recovery and loss ratios, substance flows are modelled along the system allowing to then quantify how much of inflowing mass of substance is either lost, transferred, or can be recovered.

4.2.3 Substance flow modelling

The product connections between the technologies in each sanitation system define the flow paths of the substances (see also Figure 4.2). Transfer coefficients (TCs) define how much of substance entering a technology is transferred to one of the output products, or lost to the environment. These TCs and the connections can be expressed in a matrix P, where $P_{i,j}$ is the fraction of the substance leaving Tech i that is transferred to Tech j. Additionally, we define a row vector $F^{ext}(t)$, where the i-th element represents the external inflow to Tech i at time t (e.g. the dry toilet Tech receives 0.548 $kgyear^{-1}$ of phosphorus per one person). Based on this information, we can calculate the total inflow into Tech i at time t. We define a row vector $F(t)$ where the i-th element represents the sum of all inflows to Tech i at time t (e.g. the amount of phosphorus entering a single pit through excreta).

The mass flows at time $t + 1$ are obtained by

$$F_{t+1} = F_t \cdot P + {F^{ext}}_{t+1}, \qquad \text{Equation 4-1}$$

If we assume a constant inflow $F^{ext}(t) = F^{ext}$, we have a steady state flow F that is calculated by

$$F = F \cdot P + F^{ext}, \qquad \text{Equation 4-2}$$

$$F = F^{ext} \cdot (\mathrm{I} - P)^{-1}, \qquad \text{Equation 4-3}$$

The flow at steady state from node i to node j is consequently defined as

$$flow_{i,j} = F_i \cdot P_{i,j}, \qquad \text{Equation 4-4}$$

The recovery ratios are defined only by the sinks. The total losses are obtained by summing all the losses from all Techs within a SanSys. Because we have different external inflows and transfer coefficients for each substance, the calculations are repeated separately for each substance that is to be modelled.

4.2.4 Transfer coefficients

Each technology needs to be characterised with a TC for each output flow and substance of interest. For a given substance, the TC for the i-th output flow of a technology (TC_i) is the fraction of the sum of the input flows that leave the technology through outflow i:

$$TC_i = \frac{out_i}{\sum_{j=1}^{n} in_j}, \qquad \text{Equation 4-5}$$

where n is the total number of inputs to this Tech. We assume a system with no biological fixation and three explicit losses - to air, soil/groundwater, and surface water. Therefore, the sum of all TCs of a Tech must always be 1 and all TCs positive.

where n is the total number of inputs to this technology. The output flows are the output products as well as the losses to the environment - to air, soil/groundwater, and surface water. Input flows are defined only by the input products as we assume a system with no biological fixation. Thus, the sum of all TCs of a technology must always be 1 and all TCs positive.

Three types of TCs can be distinguished:

- Input-output TCs. For every output a TC needs to be defined; the number of outputs depends on the Tech.
- Input-loss TCs. Quantifying the fraction of substances transferred to air, soil or groundwater, and surface water. We only consider the losses (e.g. leaching of phosphorus from a single pit into the soil) and not the subsequent interactions (e.g. transfer of the same phosphorus from the soil to the surface water).
- Recovery TCs. Besides losses, sink technologies also have a TC to quantify the fraction of a substance that can be recovered (e.g. over 90% of phosphorus is recovered through the sink ‘application of stored urine’).

Figure 4.3 provides an example of the flows and the TCs for the technology single pit and the substance total phosphorus (TP). The example also shows the high variability of the data found in literature. Therefore, we need a systematic method to consider and model this uncertainty.

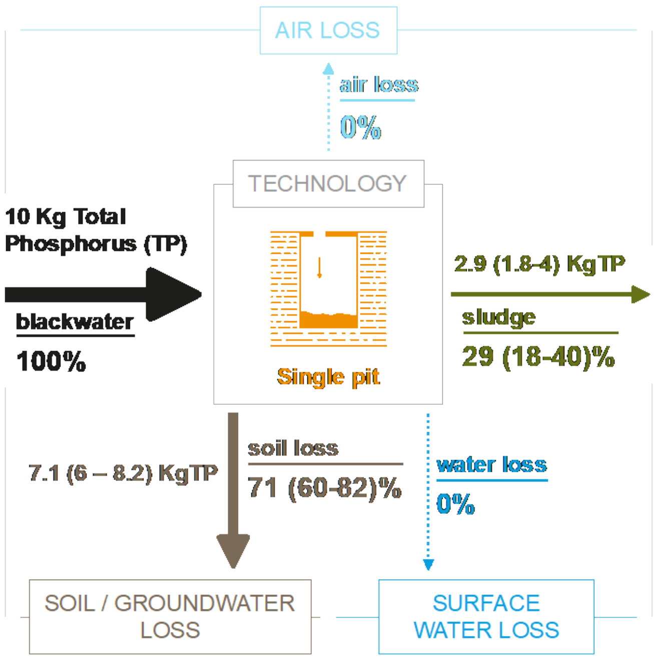


Figure 4.3: Illustration of the approach used to quantify transfer coefficients (TCs) using the example of total phosphorus (TP) pathways in a single pit. The TCs are estimated based on literature values in mass and in percentage as mean values. In parenthesis we provide the variability range resulting from the literature data points. From the 100% of phosphorus entering the single pit via blackwater, 29% are transferred to sludge and 71 % are lost to the soil. But these values can vary as much as between 18 to 40 and 60 to 82 % respectively.

4.2.4.1 Estimation of transfer coefficients and their uncertainty

We use two different ways to determine transfer coefficients. If literature data was available, we defined the expected value μ_i for TC_i as the median of the data points collected from the literature. In absence of literature data, we used expert judgement. For expert judgment we collected information on the chemical and physical processes to make a best guess or contacted colleagues directly involved in the development of the technology to do that for us.

Because TCs depend on the environmental conditions, the design and implementation of a technology, the qualities and quantities of inputs, and ignorance (especially for novel technologies), exact definition is not possible. It is therefore important to consider uncertainties attached to the TCs. A suitable model is the Dirichlet distribution as it encodes the sum constraint. Thus, the probability density of the transfer coefficients $TC = [TC_1 \ldots TC_n]$ of a given Tech is:

$$TC \sim f(x) = \frac{1}{B(\alpha)} \prod_{i=1}^{n} x_i^{\alpha_i - 1}, \qquad \text{Equation 4-6}$$

where B is the Beta function and n is the number of TCs for a given Tech (Johnson et al., 1995). We define $\alpha_i = \mu_i \cdot k$, where μ_i is the expected value of TC_i and k is the concentration describing the variability range r_i of the TCs. The smaller the k, the larger the standard deviation of the observations. For a very small k, the marginal distributions become bimodal. The effect of k is visualized in Figure 4.4.

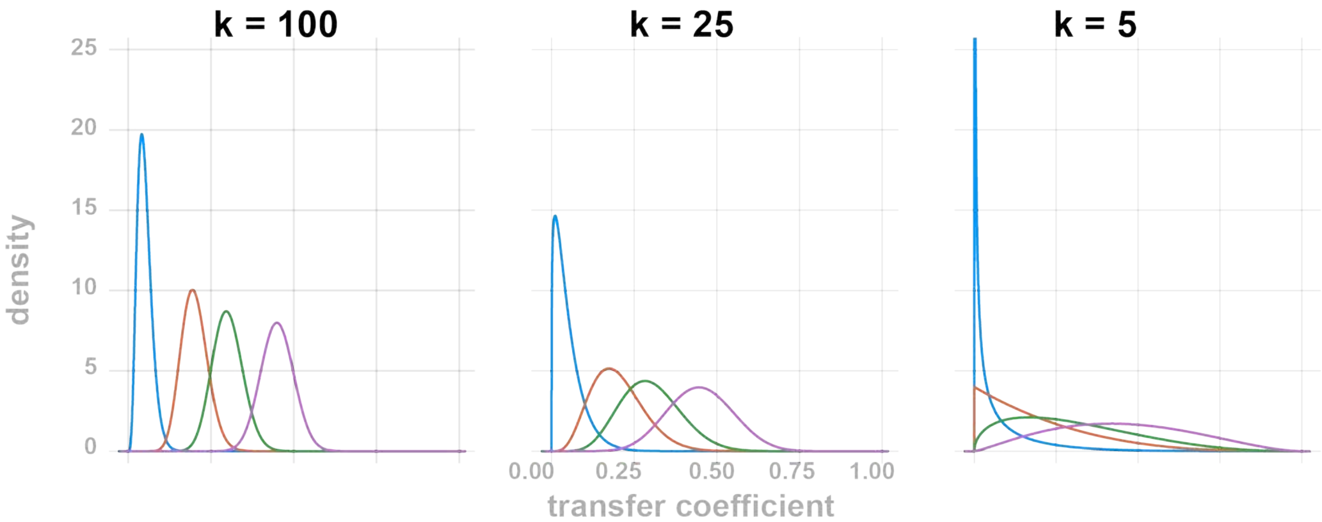


Figure 4.4: Three examples of concentration factors k for a set of four transfer coefficients (0%, 20%, 30% and 45%). For k = 100, the distributions are relatively narrow (small variability range of up to 10%). For k = 5, the variability ranges are up to 40%.

To simplify the application of the approach, we define six generic values for $\boldsymbol{k}$ and use two different approaches to define $\boldsymbol{k}$ for a given TC: one for the case when literature data is present based on the observed data variability; and one for the case of expert judgement based on the confidence in the judgement.

Concentration factors k based on literature observation: The range between the lowest and the highest values of all data points, the variability range $\boldsymbol{r_i}$, is determined and used to define the concentration factor $\boldsymbol{k}$ with the help of Table 4.1. In the example presented in Figure 4.3, total phosphorus transferred to sludge in a single pit, we found TC values in the literature between 18 % and 40 %, resulting in $\boldsymbol{r_i}$ = 0.40-0.18 = 0.22 and thus $\boldsymbol{k}$ = 5. As the $\boldsymbol{r_i}$ for different $\boldsymbol{TC_i s}$ of one Tech are not identical, we use the largest $\boldsymbol{r_i}$ to define $\boldsymbol{k}$. Table 4.1 shows the $\boldsymbol{k}$ associated with each variability range $\boldsymbol{r_i}$. The values are based on an approximation using 45 possible scenarios of TCs sets and their variability ranges (details are provided in supplementary information SI-A).

Table 4.1: Six standardized intervals are used to translate the variability of ranges observed in literature into the concentration factor k. The variability range of a transfer coefficient i (TC_i) is defined by the range between the lowest and the highest value data points reported in literature.

Observed variability ranges in literature data	Concentration factor for the Dirichlet distribution (k)
[0, 0.1] (0-10%)	100
]0.1, 0.2] (10-20%)	25
]0.2, 0.4] (20-40%)	5
]0.4, 0.6] (40-60%)	2
]0.6, 0.8] (60-80%)	1
]0.8, 1] (80-100%)	0.5

Concentration factors k for TCs defined by expert judgement: We define the concentration factor $\boldsymbol{k}$ as a statement of the experts' confidence in two dimensions: (i) confidence in knowledge about the technology, and (ii) confidence in knowledge about the specific substance, as shown in Table 4.2. The knowledge about the technology is defined by the readiness level and its complexity. The knowledge in the substance is defined by a judgement how well the substance behaviour can be predicted.

Table 4.2: Experts' knowledge about the technology and confidence in the substance are used to define the concentration factor k for transfer coefficients based on expert judgement. Confidence in the technology depends on different factors such as its development stage and the process used. Nitrogen and total solids have lower confidence, while phosphorus and water have medium and high confidence.

Concentration factor used in the Dirichlet distribution (k)		Confidence in knowledge about technology		
		low	medium	high
Confidence in substance	low	1	2	5
	medium	2	5	25
	high	5	25	100

4.2.5 Uncertainty propagation

Monte Carlo simulations are used to propagate the uncertainty of the TCs through the substance flow model and to quantify their effect on the resource recovery and loss ratios. The TCs for each Tech are sampled from their Dirichlet distribution and used to compute the mass flow of the entire SanSys in repeated runs. We used a total of 300 runs which proved to be sufficient for stable results (see SI-B).

4.2.6 Integration in the planning process

The approach from (Spuhler et al., 2018) and the extension presented here are designed to provide input to strategic planning. As strategic planning framework, we use structured decision making (SDM) which covers six steps generic to any decision-making process (Gregory et al., 2012) as shown in Figure 4.5. The integration of our methods into a regular SDM planning process happens at steps 2, 3 and 4. In (Spuhler et al., 2020a) we detailed the procedure and the requirements for this integration. Here we shortly explain how the appropriateness of sanitation system can be evaluated and how this can be used to pre-select a set of sanitation system planning options that is not only locally appropriate, but also of manageable size.

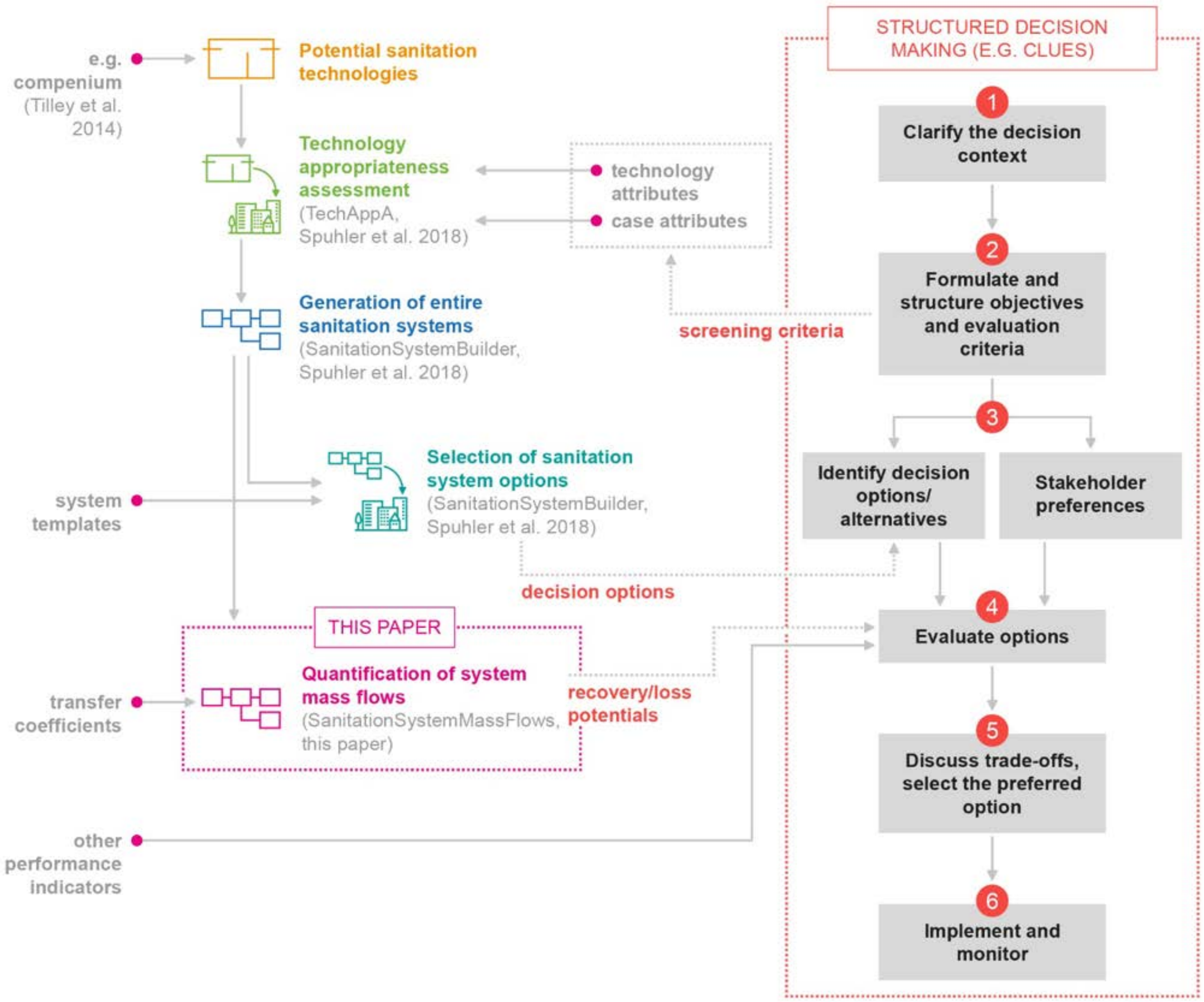


Figure 4.5: Overview of the methods developed in Spuhler et al., (2018) and the expansion presented in this paper and how they are integrated into a structured decision-making (SDM) framework. Spuhler et al., (2018) provides the procedure to generate sanitation system options. In this paper we present an approach that supports step 4 consisting in the automatic evaluation and comparison of nutrient, solids and water recovery and loss ratios of the sanitation systems.

The main input for the approach are: (1) a set so screening criteria that can be used to evaluate the appropriateness of a given technology; (2) the data describing the local conditions; and (3) the number of options that should be pre-selected.

The screening criteria are obtained together with stakeholders and based on the definition of sustainable sanitation including technical, legal, socio-socio-cultural and institutional aspects. In order not to bias the final decision, only criteria which are agreed on by all stakeholders and are not expected to involve trade-offs can be used for pre-selection. Typical screening criteria are e.g. groundwater table, water availability or availability of spare parts. Each technology is characterised for these criteria with data in the technology library. The data for the local conditions is provided by the SDM process. By matching the technology data to the local conditions, a technology appropriateness score (TAS) is calculated. By aggregating all TAS within a system, the system appropriateness scores (SAS) is obtained. The SAS that varies between 0 and 100% and expresses the confidence in the suitability of the system for the local conditions (Spuhler et al., 2018).

The appropriateness assessment is not enough to limit the options to a manageable number (e.g. something between three and 50 options). Thus, an additional step is required. This step consists in selecting a set of options which is appropriate but also diverse in order to further avoid bias. The diversity of the option space is defined by system templates (Spuhler et al., 2018; Tilley et al., 2014b). Using nine binary conditions, we define 19 templates as shown in Table 4.3. By selecting the most appropriate sanitation system from each of the system templates, a set of sanitation system planning options is obtained which is locally appropriate, of manageable size, and diverse.

Table 4.3: System templates (ST) used to characterize the sanitation system (SanSys) options. The STs are adapted from Spuhler et al., (2018). Each of the 19 STs has a unique profile defined by a value for the nine properties. '1' means that the property applies; 0 means that the property does not apply; and 'ND' (not defined) means that the property does not apply to this ST.

Name	System template profiles		Dry material (pit humus, compost, dried or stored faeces)	Onsite sludge production	Urine	Blackwater	Transported black- or brown water	Effluent transport	Biogas, biochar or briquettes	Transported biogas, biochar, or briquettes	Onsite single pit
Onsite simple											
ST1	**Dry onsite storage with sludge production without effluent transport**	Onsite single pits with sludge production.	ND	**1**	**0**	ND	**0**	**0**	**0**	**0**	**1**
ST2	**Dry onsite storage with sludge production with effluent transport**	Onsite single pits with sludge production and with effluent transport.	ND	**1**	0	ND	0	1	0	0	1
ST3	**Dry onsite storage and treatment without sludge production**	Onsite storage of excreta and transformation to either pit humus or compost.	**1**	**0**	**0**	**0**	**0**	ND	**0**	**0**	**0**

Urine											
ST4	**Dry onsite storage without treatment with urine diversion without effluent transport**	Simple onsite storage of dry or wet toilet products with sludge production (e.g. single pits, double pits, twin pits) with onsite effluent management (e.g. soak pits).	ND	**1**	**1**	ND	**0**	**0**	**0**	**0**	**1**
ST5	**Dry onsite storage without treatment with urine diversion with effluent transport**	Simple onsite storage of dry or wet toilet products with sludge production (e.g. single pits, double pits, twin pits) with effluent transport to offsite management.	ND	**1**	**1**	ND	**0**	**1**	**0**	**0**	**1**
ST6	**Dry onsite storage and treatment with urine diversion**	Urine diversion dry toilets (UDDTs) or dry composting systems with urine diversion.	1	0	1	0	0	ND	**0**	**0**	**0**
ST7	**Onsite blackwater without sludge and with urine diversion**	Onsite composting systems with urine diversion.	1	0	1	1	0	ND	**0**	**0**	**0**
ST8	**Offsite blackwater treatment with urine diversion**	Sewer systems with urine diversion.	ND	ND	**1**	**1**	**1**	ND	**0**	**0**	ND
Biofuel											
ST9	**Onsite biogas, biochar, or briquettes without effluent transport**	Biogas reactors or other fuel producing technologies (e.g. ladepa) with onsite effluent management (e.g. soak pit).	ND	ND	ND	ND	**0**	**0**	**1**	**0**	ND
ST10	**Onsite biogas, biochar, or briquettes with effluent transport**	Biogas reactors or other fuel producing technologies (e.g. ladepa) where effluent goes to simplified sewer.	ND	ND	ND	ND	**0**	**1**	**1**	**0**	ND
ST11	**Offsite biogas, biochar, or briquettes without blackwater transport**	Offsite production of biofuel from pit humus or sludge (e.g. from septic tanks).	ND	ND	ND	ND	**0**	ND	**1**	**1**	ND
ST12	**Offsite biogas, biochar, or briquettes with blackwater transport**	Offsite co-digestion of blackwater collected through sewer lines.	ND	ND	ND	**1**	**1**	ND	**1**	**1**	ND
Blackwater											
ST13	**Onsite blackwater without sludge and without effluent transport**	Blackwater stored, dewatered, and transformed to compost or pit humus (e.g. twin-pits), onsite effluent management (e.g. soak pit).	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**

ST14	**Onsite blackwater without sludge and with effluent transport**	Blackwater stored, dewatered, and transformed to compost or pit humus (e.g. twin-pits), effluent goes to simplified sewer or similar.	**1**	**0**	ND	**1**	**0**	**1**	**0**	**0**	**0**
ST15	**Onsite blackwater with sludge without effluent transport**	Storage technologies including some basic treatment (e.g. septic tank) with onsite effluent management (e.g. soak pit).	ND	**1**	ND	**1**	**0**	**0**	**0**	**0**	**0**
ST16	**Onsite blackwater with sludge and effluent transport**	Storage technologies including some basic treatment (e.g. septic tank) with effluent going to simplified sewer or similar.	ND	**1**	ND	**1**	**0**	**1**	**0**	**0**	**0**
ST17	**Onsite blackwater treatment without effluent transport**	Compact onsite wastewater treatment units (e.g. SBR) with onsite effluent management.	**0**	**0**	ND	**1**	**0**	**0**	**0**	**0**	**0**
ST18	**Onsite blackwater treatment with effluent transport**	Compact onsite wastewater treatment units (e.g. SBR) with effluent going to simplified sewer or similar.	**0**	**0**	ND	**1**	**0**	**1**	**0**	**0**	**0**
ST19	**Offsite blackwater treatment**	(Semi-)centralized sewer system.	**0**	**0**	ND	0	**1**	**1**	ND	**0**	**0**

4.2.7 Implementation

All algorithms used in this paper are implemented in Julia (Bezanson et al., 2017) and available for download as a package at https://github.com/Eawag-SWW/SanitationSystemMassFlow.jl (v1.0). A newer version can be accessed at https://github.com/santiago-sanitation-systems/Santiago.jl. Case specific scripts are not included but can be shared upon request. The technology appropriateness model is separately implemented in R (R Development Core Team, 2018) and can be used independently. It is accessible at https://github.com/Eawag-SWW/TechAppA (v1.0).

Data and code used for the didactic application are available in the associated data package 1: https://doi.org/10.25678/0000HH ([dataset] Spuhler, 2020c)). The input data contains the definition of Techs including their transfer coefficients and appropriateness profiles. The output data contains plots of all systems, a csv table with the characteristics and mass flow results of all systems, and a Julia database to load and work with the data interactively.

The technology library including the TCs, a detailed description of each technology, and instructions how to add or modify technologies is provided in in the associated data package 2: https://doi.org/10.25678/0000ss ([dataset] Spuhler and Roller, (2020) and in Spuhler and Roller, (2020). The data package also contains a csv file for more convenient adaption and which can be directly read by the models.

— 4.3 RESULTS

To use the developed substance flow model, we require the a priori data on the transfer coefficients and their uncertainties, and the masses per person and year entering a system. To exemplify the use of the model and its outputs we present a didactic case. To illustrate the entire potential of the model we apply it to all 41 technologies resulting in 101,548 valid system configurations. To show the relevance for strategic planning and implications for practice we use the case of a rapidly growing small town in Nepal previously presented in Spuhler et al., (2018).

4.3.1 Technology library

The aim of the technology library is to cover a large and diverse set of conventional and emerging technologies. To select the technologies we used as starting point the list of technologies provided by Spuhler et al., (2018) and Tilley et al., (2014b). We complement this list with five novel technologies: liquid urine fertilizer (aurin) production and application (Bonvin et al., 2015; Etter et al., 2015b; Fumasoli et al., 2016), briquetting based on the process implemented by Sanivation in Naivasha (Jones, 2017), and latrine dehydration and pasteurization, ladepa pelletizing (Septien et al., 2018b). The resulting 41 technologies currently available in the technology library are shown in Figure 4.6.

This technology library has two important features:

1. First, it covers a set of technologies which is able to represent the entire system option space including different concepts (dry, wet, urine diversion, biofuel product) and degrees of centralisation (from onsite to decentralized, centralized, and hybrid systems). This is illustrated by the system templates as described in section 4.2.2 and used in the full-scale example application (section 4.3.6).
2. Second, using the generic definition, the library can easily be extended with any (future) technology.

Figure 4.6: Overview of the set of sanitation technologies currently available in the technology library for five functional groups. Each box represents a technology. The arrows represent the input and output products. So far only toilet sources are implemented, although greywater, stormwater, and organic waste sources can also be considered by the model.

4.3.2 Substances: total phosphorus, total nitrogen, total solids, and water

For every technology we added the transfer coefficients for four substances with different properties: Total Phosphorus (TP), Total Nitrogen (TN), Total Solids (TS) and water (H2O). TP and TN are both important macronutrients with significant environmental pollution potential and at the other hand predicted to deplete soon. TS can be used as a proxy for energy, for example in the form of briquettes or biochar (e.g. Andriessen et al., 2019; Motte et al., 2013), and for organic matter that can be used in soil amendment (e.g. Diener et al., 2014; Septien et al., 2018a). Water in many urban areas is under increasing pressure and has become a scarce commodity. For TN and TS, the behaviour is also more difficult to predict than for TP and water. Water is also a special case because the inflowing masses vary significantly depending on the system and from a sustainability perspective, both the requirement and the recovered masses are interesting. A more detailed description of the four substances and their relevance can be found in the technology library ([dataset] Spuhler and Roller, 2020).

4.3.3 Transfer coefficients (TC)

The literature review and collection of expert knowledge resulted in the definition of transfer coefficients for the 41 technologies and the four substances. For the literature review, preference was given to peer-reviewed literature, but other literature such as project reports, factsheets, and books were also considered. In absence of literature data, we either made a best guess ourselves or contacted colleagues directly involved in the development of the technology (e.g., for aurin production, briquetting, and ladepa pelletizing). The detailed list of all TCs and corresponding literature references are available in the SI-D and in ([dataset] Spuhler and Roller, 2020).

Because this data is generic and could be used for any other application, we present an overview Figure 4.7. Each bar corresponds to a technology and the colours represent the fraction of a substance which is either transferred, lost to air, soil, or water, or recovered. This figure also indicates some pattern that are confirmed by the analysis of recovery ratios from the full-scale application:

- The functional groups storage and treatment (FG S) and (semi-)centralized treatment (FG T) contribute significantly to losses.
- Second, recovery can only occur in the sink technologies (FG D) and many of the sink technologies provide either almost 100% recovery (recovery sinks) or 100% losses (disposal sinks).

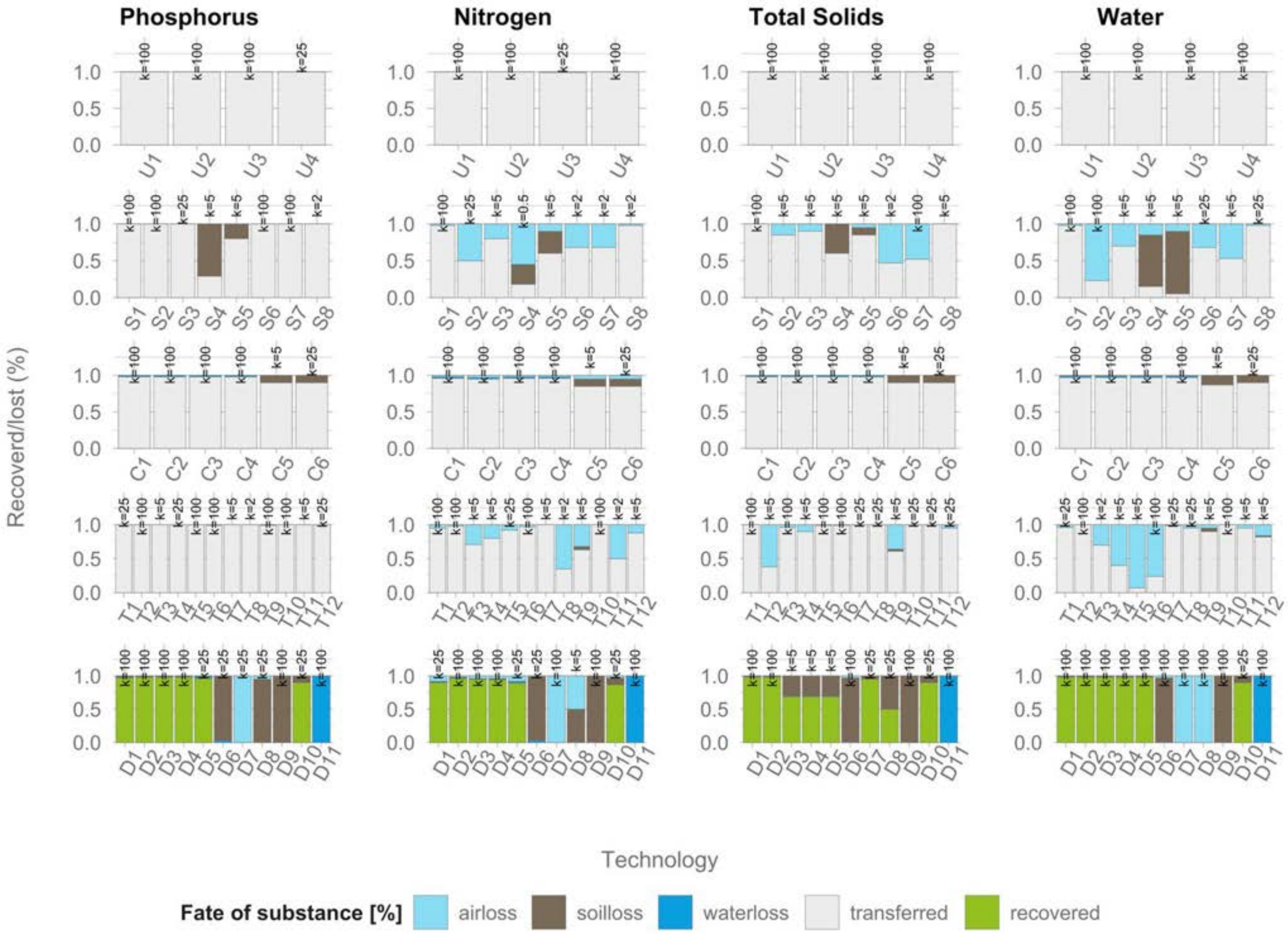


Figure 4.7: Overview of losses, transfers, and recoveries for all four substances and 41 technologies. Each bar represents a technology, the colours indicate the fate of the substances which is either lost, transferred, or recovered. From top to bottom the technologies are grouped by functional group (rows). U: user interface, S: storage and treatment, C: conveyance, T: (Semi-)centralized treatment, D: reuse or disposal. The k is the concentration factor indicating the uncertainty. A low k means high uncertainty. See Figure 4.6 for the technologies behind the labels (e.g. T9 = Co-composting).

4.3.4 Inflows

We used literature data to provide the inflowing masses for the four substances for one person and year (e.g. Lohri et al., 2010; Rose et al., 2015). Although the masses vary depending on the diet of people, the inflow masses presented in Table 4.4 provide an estiamte that can be applied to any case in the absence of more detailed knowledge. Details on the underlying calculations are provided in SI-B. As the current version of the technology library only considers toilet sources, the inflowing mass is equal to the mass of substance contained in the urine, faeces, and flushing water. The values can be scaled using the number of inhabitants within an area or adapted if local data is available.

Table 4.4: Overview of estimated inflow substance masses based on international literature per person and year. TP: total phosphorus, TN: total nitrogen, TS: total solids, H2O: water. The amount of TP, TN, and TS are the same for all sources; only water inflow masses depend on the flush volume. The assumed amount of flushing water is 2L/day/person for the pour flush toilet and 60 L/day/person for the cistern flush toilet. Details on the assumptions and literature references are provided in SI-B.

	Substance	U1. cistern flush toilet	U2. pour flush toilet	U3. dry toilet	U4. Urine diversion dry toilet (UDDT)
Inflows in kg year^{-1} for 1 person equivalent	TP	0.548			
	TN	4.550			
	TS	32.12			
	H2O	22447	1277	547	

4.3.5 Didactic application

This simple didactic application helps to illustrate the substance flow model, the mass flow calculations, the estimations of resource recovery and loss ratios, and the consequences of the TC uncertainties. The results are fairly straightforward and intended to demonstrate that the fully automatic procedure is capable of producing reasonable outcomes. The example is based on only nine technologies for which we also provide the detailed data for the TCs in Table 4.5.

Table 4.5: Summary of raw data used for the estimation of transfer coefficients (TCs) for the technologies used in the didactic application. TP: total phosphorus, TN: total nitrogen, TS: total solids, H2O: water. A more detailed description is available in the associated data package 2 ([dataset] Spuhler and Roller, 2020). EJ: expert judgement.

Tech	Subs-tance	Transfer Coefficient to…				Concentration factor *k*	References
U2. pour flush toilet		Black-water					
	TP	1				100	EJ
	TN	1				100	EJ
	H2O	1				100	EJ
	TS	1				100	EJ
S4. single pit		Sludge	Air loss	Soil loss	Water loss		
	TP	0.29 (0.18 - 0.4)	0	0.71 (0.6 - 0.82)	0	5	(Montangero and Belevi, 2007)
	TN	0.18 (0.09-0.27)	0.55 (0 - 0.8)	0.27 (0.01-0.91)	0	0.5	(Jacks et al., 1999; Montangero and Belevi, 2007; Nyenje et al., 2013)

	H2O	0.15 (0.05-0.25)		0.15 (0.05-0.25)	0.7 (0.5 – 0.9)	0	5	EJ
	TS	0.6 (0.5 - 0.7)		0	0.4 (0.3-0.5)	0	5	(Montangero and Belevi, 2007)
C4. human transport of dry material		Faeces		Air loss	Soil loss	Water loss		
	TP	0.98		0	0	0.02	100	EJ
	TN	0.96		0.02	0	0.02	100	(Udert et al., 2006)
	H2O	0.97		0.01	0	0.02	100	EJ
	TS	0.98		0	0	0.02	100	EJ
T3. sludge drying bed		Dried Sludge	Effluent	Air loss	Soil loss	Water loss		
	TP	0.62 (0.48 - 0.7)	0.38 (0.3 - 0.52)	0	0	0	5	(Kuffour, 2015; Nikiema et al., 2014)
	TN	0.53 (0.5-0.7)	0.37 (0.2 - 0.6)	0.1	0	0	5	(Cofie et al., 2006; Kuffour, 2015; Montangero and Strauss, 2002; Nikiema et al., 2014; O'Shaughnessy et al., 2008; Ryan and Keeney, 1975))
	H2O	0.31 (0.14-0.79)	0.39 (0.22-0.7)	0.3	0	0	100	(Montangero and Strauss, 2002; O'Shaughnessy et al., 2008; Strande et al., 2014)
	TS	0.75	0.21	0.04	0	0	2	(Cofie et al., 2006; Montangero and Strauss, 2002)
T9. co-composting		Compost		Air loss	Soil loss	Water loss		
	TP	0.99		0	0.01	0	100	(Belevi, 2002; Leitzinger, 2001; Meinzinger, 2010)
	TN	0.63 (0.3-0.69)		0.32	0.04	0	5	(Belevi, 2002; Heinonen-Tanski and van Wijk-Sijbesma, 2005; Leitzinger, 2001; Meinzinger, 2010)
	H2O	0.9		0.05	0.05	0.01	5	EJ
	TS	0.61		0.36	0.03	0	5	(Belevi, 2002)
T12. horizontal subsurface flow constructed wetland		Sludge	Effluent	Air loss	Soil loss	Water loss		
	TP	0.41 (0.3 - 0.5)	0.59	0	0	0	25	(Conradin et al., 2010; Vymazal, 2007; 2010)
	TN	0.26	0.62 (0.57-0.85)	0.12 (0.07-0.16)	0	0	5	(Conradin et al., 2010; Poach et al., 2002; Vymazal, 2007; 2010)
	H2O	0.02	0.8 (0.71-0.95)	0.16 (0.03-0.27)	0.02	0	25	(Consoli et al., 2018; Headley et al., 2012)
	TS	0.32 (0.29-0.37)	0.63	0.05	0	0	5	(Conradin et al., 2010; Vymazal, 2007)

D4. application of compost/ pit humus		Reco-vered	Air loss	Soil loss	Water loss 0.01 0.01		
	TP	0.98	0	0.01	0.01	100	EJ
	TN	0.94	0.04	0.01	0.01	100	EJ based on (He et al., 2003)
	H2O	0.98	0	0.01	0.01 0.01	5	EJ
	TS	0.69	0	0.3		100	(Lima et al., 2009)
D6. surface solids disposal		Reco-vered	Air loss	Soil loss	Water loss		
	TP	0	0	0.97	0.03	25	EJ
	TN	0	0.01	0.96	0.03	25	EJ
	H2O	0	0.03	0.96	0.01	100	EJ
	TS	0	0.03	0.96	0.01	100	EJ
D10. irrigation		Reco-vered	Air loss	Soil loss	Water loss		
	TP	0.9	0	0.1	0	25	(Odindo et al., 2016)
	TN	0.87	0.03	0.1	0	25	(Odindo et al., 2016)
	H2O	0.9	0	0.1	0	25	(Odindo et al., 2016)
	TS	0.9	0	0.1	0	25	(Odindo et al., 2016)

4.3.5.1 Overview on results

The nine technologies can be combined into 12 systems listed in Table 4.6. All of them are valid according to our definition and very plausible from a practical point of view (see supplementary information SI-E and in the associated data package 1, [dataset] Spuhler, 2020c)). The mass flow calculations provide the flows in each technology, as well as the losses to air, soil, and surface water. These flows and losses allow to calculate the recovery and loss ratios for the four substances for the entire systems. The recovery and loss ratios can be calculated as mass or as ratio in percentage. Both results include the uncertainties of the transfer coefficients that can be expressed as standard deviation.

Table 4.6: Characteristics of systems generated in the didactic application. Only the mass flow results for total phosphorus (TP) are shown and expressed in % of entered substances. The full results are provided in the associated data package 1 ERIC: https://doi.org/10.25678/0000HH ([dataset] Spuhler, 2020c) and in SI-E. ID: unique identification number: Length: number of technologies contained in the system. The value in parentheses "()" represents the standard deviation (SD) resulting from the Monte Carlo simulation.

ID	Length	TP recovery ratio [%]	TP air loss [%]	TP soil loss [%]	TP water loss [%]
1	6	10 (9)	0	89 (9)	1 (1)
2	9	10 (8)	0	89 (9)	1 (1)

3	9	6 (5)	0	93 (6)	1 (1)
4	5	28 (17)	0	71 (18)	1 (1)
5	5	0	0	99 (1)	1 (1)
6	**7**	**7 (7)**	**0**	**91 (7)**	**1 (1)**
7	6	10 (10)	0	89 (10)	1 (1)
8	5	10 (9)	0	89 (9)	1 (1)
9	5	28 (18)	0	71 (18)	1 (1)
10	5	0	0	99 (2)	1 (2)
11	4	**28 (18)**	0	72 (18)	0
12	**4**	**0**	**0**	**99 (1)**	**1 (1)**

In Figure 4.8, we present three SanSys in more detail:

- ID-12 is the simplest system possible with the nine technologies. But this system provides no phosphorus recovery, as it contains only a disposal sink.
- ID-6 is the most complex system which also integrates loops.
- ID-11 is similar to ID-12 but contains a recovery sink (‘the application of compost’) and is therefore the system with the highest resource recovery ratio for phosphorus.

For ID-11 we provide in details the flows for phosphorus. This is interesting, because it shows that the recovery ratio is mainly influenced by one technology: the single pit where 72% of phosphorus is lost to soil. For total nitrogen (TN) and total solids (TS), more significant losses occur in the co-composting process to the air. Not only the losses, but also the uncertainties are dominated by the single pit where the standard deviation for the TP to soil is 18% (Table 4.6).

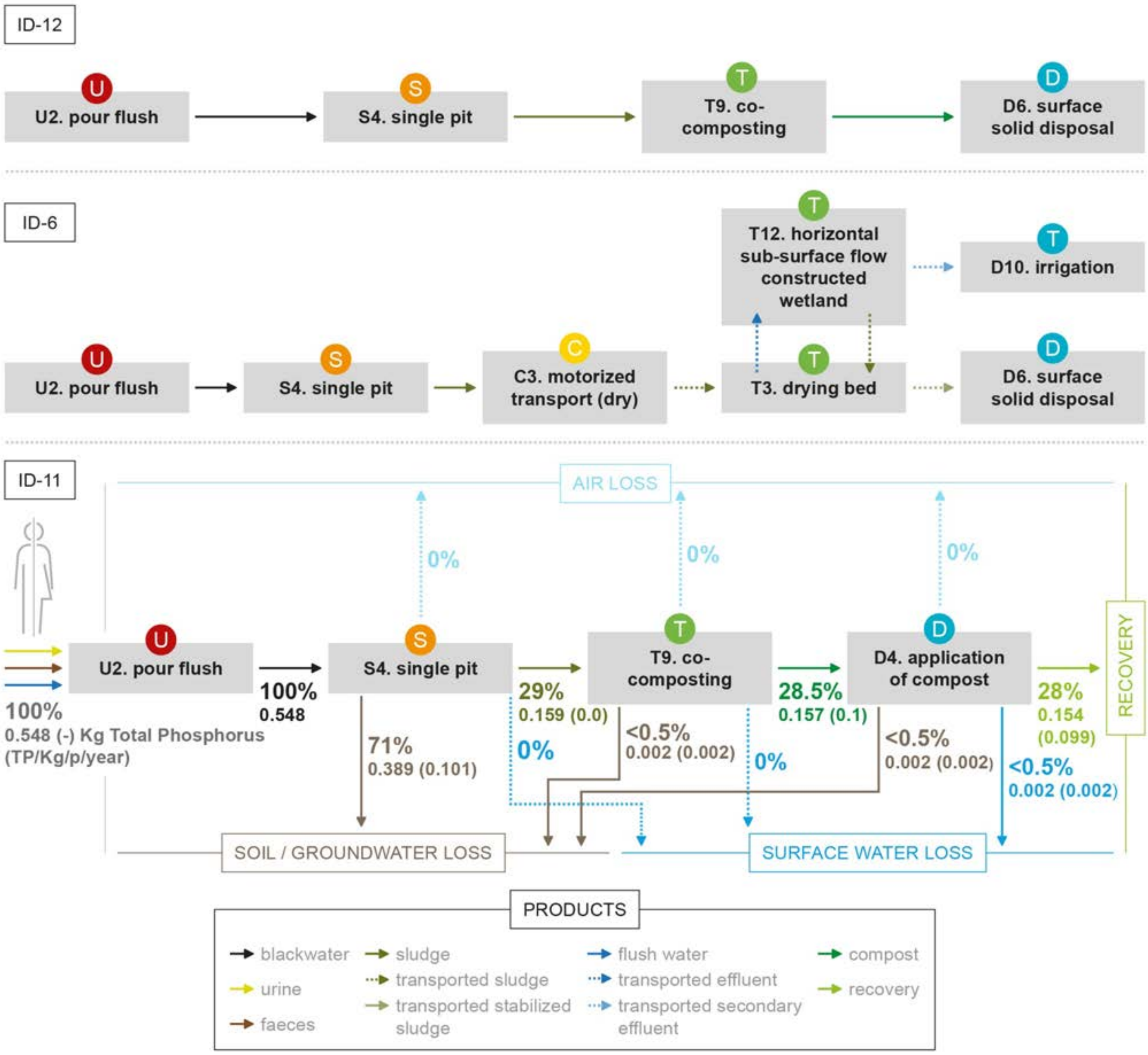


Figure 4.8: Three systems resulting from the didactic application. ID-12 is the least complex system; ID-6 is the most complex system, integrating loops; and ID-11 is a system with very high phosphorus recovery. For SanSys-ID11 we provide all flows for total phosphorus (TP). All numbers are either in kg $person^{-1}year^{-1}$ or %. The standard deviations (SD) resulting from the uncertainties of the transfer coefficient (TCs) are given in parentheses. ID: unique identification number.

Analysing the results of all 12 system we can identify three groups. Group 1 includes systems with recovery sinks (co-composting and application of compost, ID4, ID9, ID11) and high phosphorus recovery ratios. Group 2 includes systems with both loss sinks (sludge drying beds and surface solids disposal) and recovery sinks, ID1, ID2, ID3, ID6, ID7, and ID8) and low phosphorus recovery ratios. Group 3 includes systems with only loss sinks (ID5, ID10 and ID12) and no phosphorus recovery at all.

In summary we learn from this didactic example four things:

- The model is capable of creating reasonable system configurations and automatically calculating reasonable mass flows through the systems.
- Resource recovery depends on the technology interaction. For instance, the fraction of inflowing mass that can be recovered in a sink depends on how much losses occur on the way.
- There are some key technologies that have a major impact on the recovery ratios and the uncertainties (single pit in this example). Thus, in some instances, the recovery ratio can be significantly enhanced or reduced by exchange only one technology elements.
- Knowing uncertainties allows to assess the robustness of the results. The uncertainties obtained by the model are substantial, but comparable to those obtained in studies using a conventional post-ante material flow analysis (e.g. (Montangero and Belevi, 2008).

4.3.6 Full-scale application

Using all the 41 technologies from the library, the system builder generated 101,548 valid SanSys of 17 system templates as defined in Table 4.3. No system from ST7 and ST8 was formed because the urine diversion flush toilet was not considered. The substance flows were modelled for 1000 people equivalent (corresponding to a larger neighbourhood) and for all 101,548 systems and four substances total phosphorus (TP), nitrogen (TN), total solids (TS), and water (H2O).

4.3.7 Resource recovery ratios

In Figure 4.9 we show the results of the resource recovery ratios grouped by system template as defined in Table 4.3 which are indicated in the x-axis. Each dot represents one of the 101,548 systems. The colour represents the source of this system which is either a cistern flush toilet, pour flush toilet, dry toilet, or urine diversion dry toilet. Because the results are shown in percentage and not in masses, the recovery ratios for the cistern flush and pour flush toilet are identical and therefore overlap (only light blue dots visible). The y-axis shows the recovery ratio between 0 and 100%.

As expected across the more than 100,000 systems, all four substances showed recovery ratios from nothing to almost 100% even within the same templates. The only exceptions are the simple onsite templates (ST1 and ST2) with exclusively low recovery ratios. This shows that system templates are not enough indicator for resource recovery. The Figure 4.9 provides additional information:

- For phosphorus recovery, the simple onsite blackwater systems (ST13 and ST14) have the highest mean recovery ratio. Thus, if you would be interested in high phosphorus recovery, you would probably go for a system from one of these two templates.
- But for the accumulated recovery ratio, the results are different. Urine diversion templates (ST4 to ST6) show the highest mean accumulated recovery, followed by the biofuel STs (ST9 to ST12) and some blackwater STs (ST14, ST16). Thus, if the objective is resource recovery in general, you would prioritise the templates ST4 and ST5.
- However, if you are not interested in the templates, but are interested in the optimised recovery of phosphorus, then you would choose one of the systems at the upper edge of ST 3 (onsite composting) or ST14 (onsite

blackwater systems). These systems include few treatment steps and are therefore particularly short. Urine diversion systems are generally longer (more products, more bifurcation) and losses are generally high for very long systems. Short systems reduce the risk for losses but can also result in very low effluent quality (e.g. direct irrigation after a septic tank).

- If you are independently of the templates interested in optimising accumulated recovery (not only phosphorus), then the choice would be one of the systems at the upper edge of ST9 which combines urine diversion with the production of biofuel.

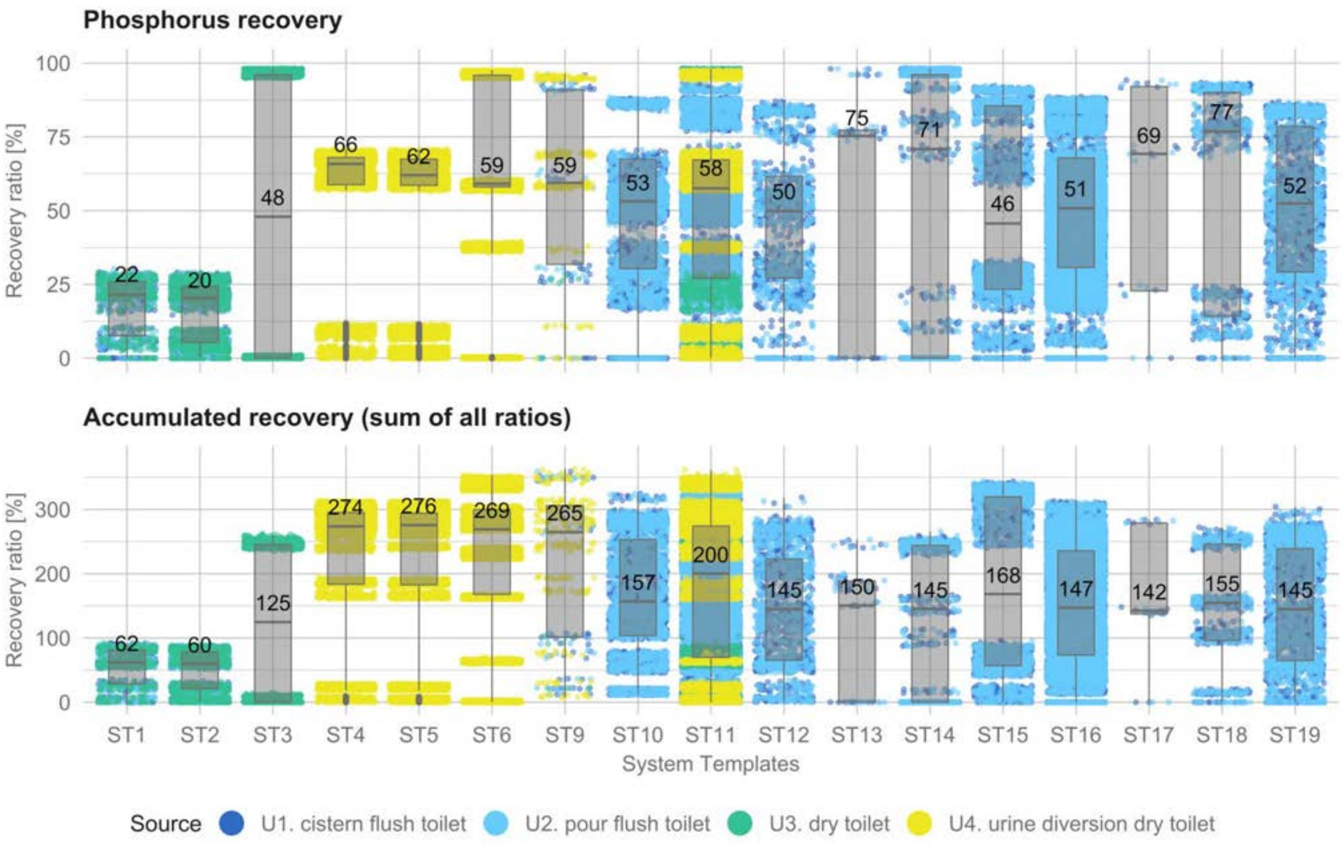


Figure 4.9: Recovery ratios of all sanitation system options for total phosphorus and accumulated for all four substances. The accumulated recovery corresponds to the sum of the ratio for phosphorus (TP), nitrogen (TN), total solids (TS), water (H2O). The y-axis shows the recovery ratio. The x-axis shows the system templates STs (no system from ST7 and ST8 was generated). Each dot represents a system. The colour represents the source of the system which is either a cistern flush toilet, pour flush toilet, dry toilet, or urine diversion dry toilet. Because the results are shown in percentage and not in masses, the recovery ratios for the cistern flush and pour flush toilet are identical and therefore only light blue dots are visible The grey box represents a boxplot of the same data with the line being the mean value. The figure shows that system templates are no indicator for the recovery ratio and that therefore it is important to know the recovery ratios of all possible systems. To optimise recovery, one of the systems at the upper edge of ST9 should be selected which combine urine diversion with biofuel production.

4.3.8 Dependencies with other sustainability criteria

To illustrate the integration with the planning process and the dependencies with other sustainability criteria we use the case of Katarniya, a rapidly growing small town in Nepal already used in Spuhler et al., (2018). In this case, 15 screening criteria including water and energy availability, skills requirements, and operation and maintenance requirements and the data from the library ([dataset] Spuhler and Roller, 2020) are used to calculate the sanitation system appropriateness scores SAS. To preselect options, the 17 systems with the highest SAS from each system template are selected. In Figure 4.10 we plot again all systems but this time comparing the resource recovery ratio with the SAS. For TP, TN, and TS we show the ratio in percentage. For water, we provide the absolute volume [$m^3 year^{-1}$], as this is the more relevant information for comparing different systems. The coloured dots indicate the selected systems. They are distributed over the entire range of recovery confirming that that templates are no indicator for resource recovery (see previous Figure 4.9). Thus, there exists a high probability that systems could be found that are both, appropriate and recovery at least for some templates such as ST3 or ST 19. But there exists also a high probability that for some templates, a trade-off between appropriateness and recovery exist. Similar trade-offs would be expected for other sustainability indicators such as costs. Additionally, there exists also some systems that have a high recovery ratio for one substance but not for another implying that there exist also trade-offs among different types of reuse (e.g. energy versus nutrients).

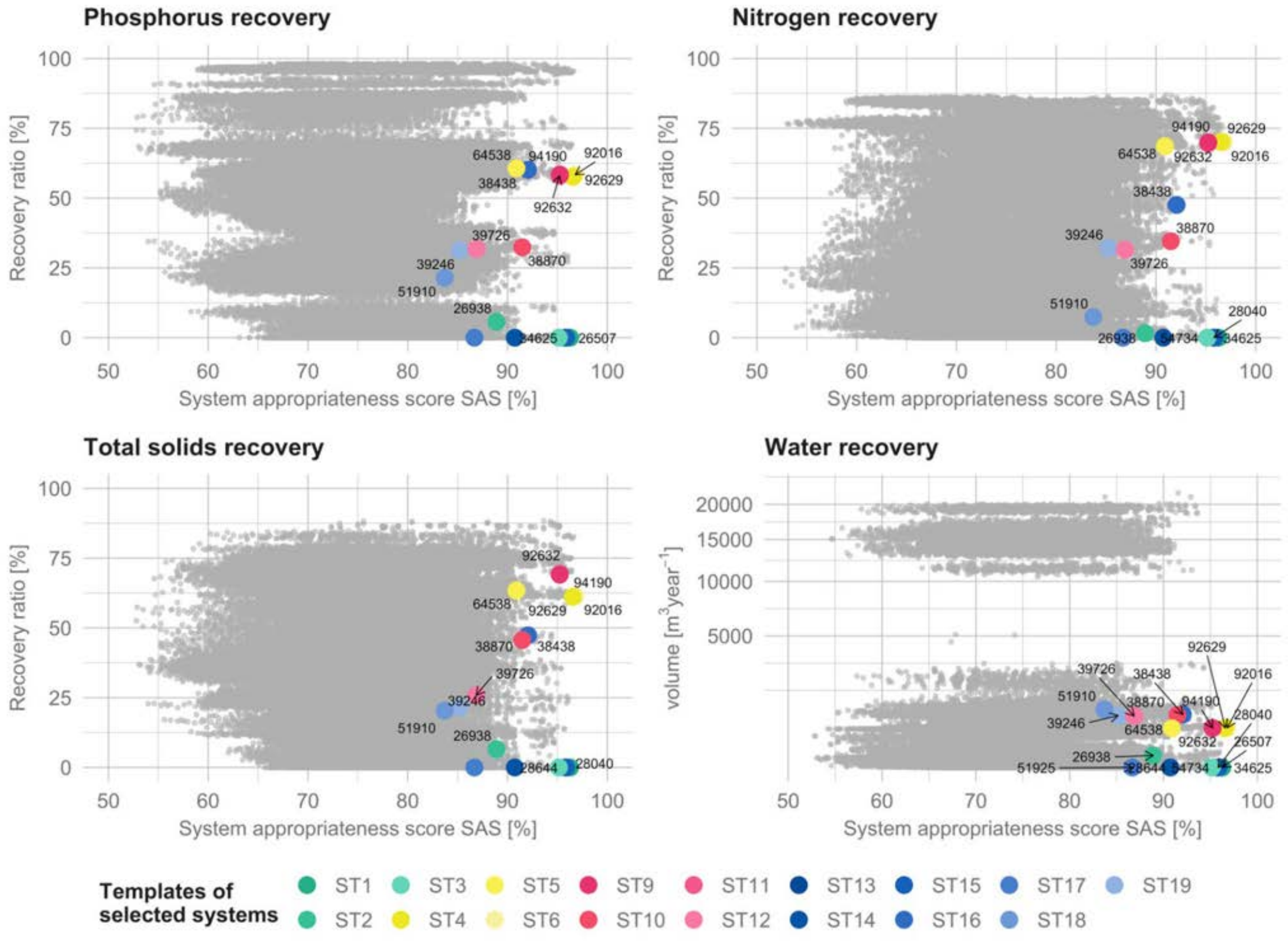


Figure 4.10: Point plots of recovery ratios of all sanitation systems compared to the system appropriateness scores. For water, we provide the absolute volume [$m^3 year^{-1}$], as this is the more relevant information for comparing different systems. The selected systems (highest SAS) from each system template (ST) are shown as coloured dots and marked with the system ID. The templates are described in detail in Table 4.3. The figure shows that some of the appropriateness show low recovery ratio, confirming that templates are a good indicator for diversity. However, given that almost all templates also include systems with high recovery ratio, there exists a high probability that systems with both high recovery and high SAS could be found.

In Figure 4.11 we show three examples of selected systems in more detail. All selected systems have a high appropriateness as this was a precondition for selection but not all of them have a high recovery. The examples are exemplary for three groups:

- Group 1 is illustrated by ID-92016 from ST6 and combines different types of recoveries such as urine transformation, biofuel, and/or sludge reuse. This results in high recovery ratios for TP, TN, and TS, and moderate water recovery.
- Group 2 is illustrated by ID-38870 from ST10 which is a blackwater production and reuse of the effluent in irrigation. This results in moderate recovery ratios for TP, TN, and TS, and potentially high volumes of water recovery.
- Group 3 is illustrated by ID-26507 from ST1 and includes almost exclusively disposal sinks and therefore show only minor recovery ratio.

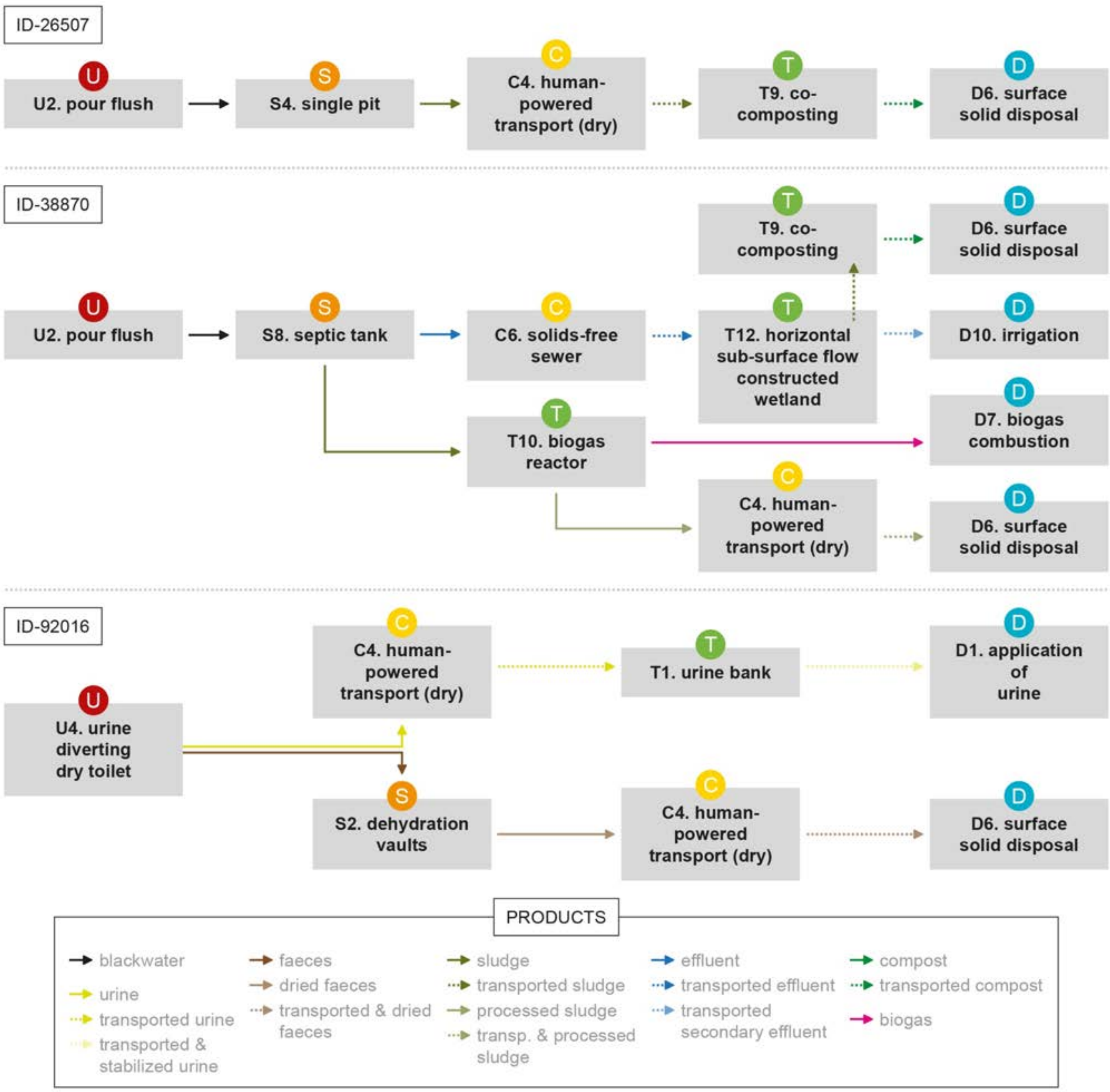


Figure 4.11: Three examples of selected sanitation systems. SanSys ID-26507 is from the system template ST1 (dry onsite storage with sludge production) and shows almost no recovery ratio, meaning that almost all nutrients, total solids, and effluents are lost to the environment. ID-38870 is from ST10 (offsite biogas system) and shows moderate nutrient and total solids recovery and high water recovery. SanSys ID-92016 is from ST6 (offsite urine diversion system) and shows high nutrients and total solids recovery ratios and moderate water recovery (from urine).

In summary we learn from this full-scale example two things:

- First, system templates are good to define diversity but are no good indicator for resource recovery.
- Second, there exist no clear “winners” solutions. Recovery ratio and appropriateness can be both high or completely diverging. Similar trade-offs ware also observed among recovery of different substances and expected to exist for other sustainability criteria such as costs.

These result highlight the need for an automated model that enables the consideration of resource recovery ratios already at the pre-selection phase.

— 4.4 DISCUSSION

4.4.1 Lessons from the model applications

The application of the model provided us with following insights:

- The amounts of resources potentially recovered in sinks designed for reuse is limited by the resources that are lost on the way. This is a simple example showing the importance of technology interactions on system level for resource recovery and cannot be evaluated based on single technology alone.
- Some system characteristics, like the integration of a specific technology or the length (number of technologies) can provide hints on the potential resource recovery, but no reliable guidance.
- There are trade-offs between different potentially recovered resources (e.g. phosphorus and water). Only some systems such as from ST9 manage to combine different reuse optimising the accumulated recovery ratios. There are similar trade-offs among other sustainability criteria such as appropriateness and costs. Because there are no clear predefined winners or losers, it is important to know the resource recovery ratios of all systems options. This allows to consider recovery already at the pre-selection phase but also as input into multi-criteria decision analysis where different criteria are evaluated, weighted, and trade-offs are balanced.

The relevance of technology interaction shows that an automated approach that can look at all possible systems instead of single technologies is useful. Because of the trade-offs, the model must be applicable ex-ante in order to support strategic planning.

4.4.2 Advantage and novelty of the approach

The presented approach integrates algorithms, literature data and expert knowledge into a systematic tool. This provides three main advantages:

- First, the model it is generic and thus can be easily extended to accommodate new technologies or products.
- Second, the model is automated. This allows an application to a diverse and large range of sanitation technologies and systems simultaneously with minimal manual labour.
- Third, all the data to apply the model ex-ante are available.

In the following, we discuss some of the aspect that allow the ex-ante application in more detail.

Integration of literature data: A major strength of our approach is the quantitative integration of data from literature. The data in the associated data package 2 at ERIC: https://doi.org/10.25678/0000ss ([dataset] Spuhler and Roller, 2020) are based on an extensive literature research, are complemented with expert knowledge, and present a compact and accessible overview of the currently available knowledge on the performance of conventional and emerging technologies. Confidence in knowledge about the performance of a specific technology is reflected in the defined uncertainties. This large body of independent knowledge is integrated to the local planning process through the model results.

Automation: the generic definition of technologies and systems enabled the automation which increases the likelihood for applications. This generalisation brings however also a number of limitations which are discussed below.

Uncertainty estimations: For each recovery and loss ratio, the model also quantifies the uncertainties arising from the transfer coefficient uncertainties. For instance, in the didactic application the mean phosphorus recovery ratio is 0.154 kg per person and year (see Figure 4.4) with a standard deviation of 0.099 kg (the uncertainty is relatively high due to the single pit). The detailed interpretation of these uncertainties is not trivial, as they aggregate different types of uncertainties: (i) related to local environmental conditions, (ii) specific to the implementation of a technology, (iii) related to the technology in general, and (iv) related to ignorance, particularly of novel technologies and their implementation at scale. However, this interwoven mix of uncertainty sources is certainly. not unique for this model. Once the uncertainties are quantified, the data can be used to evaluate the robustness of each result and to test the robustness of the MCDA outcome. In the full-scale application, we observed overall uncertainties of maximally 28% (standard deviations for the recovery ratio of TN). This accuracy is comparable to other studies using classical ex-post material flow analysis (Keil et al., 2018; Meinzinger et al., 2009; Montangero et al., 2007).

4.4.3 Limitations

The approach presented here cannot replace a detailed mass flow analysis for existing systems (ex-post analysis). It is intended for automated ex-ante analysis to provide guidance based on the limited knowledge. Other limitations are important:

- How technologies are defined has an impact on the modelling results and should be carefully verified for a specific case. An example is the very generic definition of a single pit, which allows all sorts of input. As a consequence, this Tech dominates the uncertainties and also in some cases the losses of a system (especially for phosphorus). However, local experience with specific implementations, which would provide additional data, can decrease the uncertainty and provide a better estimation of the transfer coefficient.
- Similarly, transfer coefficients are designed to be generic and therefore ignore many factors such as size of the Tech or ambient temperature. This is compensated partly by the uncertainties.
- The third simplification with a similar effect concerns the definition of 'products'. The model uses a standardized set of products based on (Tilley et al., 2014b). The purpose of which is to define the compatibility of two technologies (Maurer et al., 2012). It might be required to integrate context-specific information (e.g. quantity and quality of products, legal requirements), to validate systems from an engineering perspective (Spuhler et al., 2018).
- Another limitation is the requirement that the sum of all TCs for every substance of a Tech is equal one. This boundary condition enables the modelling of steady states but also excludes the generation of a substance through biological fixation. For many cases this is not very relevant and can therefore be neglected.

Importantly, these simplifications allow the automation and generalization of the model application. Consequences of the simplifications are captured in the uncertainty calculations. The user is free to be more specific in the Tech and product definitions or to use more complicated TC models if more accuracy is needed.

4.4.4 Implications for practice

The main intention of the substance flow model is to provide information for the strategic planning in order to enable the prioritisation of resource efficient systems. The approach complements the systematic generation of sanitation system options from Spuhler et al., (2018) by quantifying relevant indicators for resource efficiency and environmental protection in an ex-ante analysis. This enables to consider resource efficiency and environmental protection in strategic planning using any SDM framework such as CLUES (Lüthi et al., 2011a) or Sanitation21 (Parkinson et al., 2014). The information can be integrated at two levels:

- It can be used to compare different selected systems and to select the preferred option using any multi-criteria decision analysis (MCDA) method. It is obvious that additional information, such as costs and value functions, would be required in the MCDA for different stakeholders (e.g. phosphorus recovery might not have the same value for a given stakeholder as costs). The uncertainty ranges provided by the model can be used to evaluate the robustness of the final ranking of the options (e.g. Scholten et al., 2015). If MCDA is not the preferred evaluation method, the results could also be fed into life cycle analysis (LCA).
- The information could already be used at the pre-selection stage. A possible example would be to make the low nutrient losses a precondition for appropriateness in the case of the presence of highly sensitive surface waters. Another example would be, to make optimised resource recovery as a precondition. This could be the case for instance if based on the SDG 6 resource recovery is defined as a non-negotiable criterion.

The results could also be used for research. Either one could check the resource recovery ratio of newly developed technologies when integrated into entire systems. Or the full-scale application results could serve to identify system characteristics for resource recovery and guide future technology and system configurations. The full-scale application showed for instance, that some key technologies, mainly from the functional group S (storage) and T (treatment) have a mayor influence on losses. Moreover, we observed that the combination of different reuse pathways allows to optimise recovery.

It is also important to note, that in principle, our model could be applied for any substance. We have chosen the substances which are most relevant to the discourse on sustainable sanitation, water management, and resource recovery. Implementing the model for additional substances should be straightforward, as the substances already calculated exhibit very different properties.

4.4.5 Outlook

Generic results: The here presented full-scale application is, except for the appropriateness assessment based on generic information. As a result, the relative resource recovery ratios are independent of the inflow masses and therefore fully transferrable. Compiling these data into a catalogue would allow to make it available as a low-level planning support.

Detailed evaluation of the full-scale results: As the full-scale case is representative for many cases, a detailed analysis of the results could allow better understanding about how some system characteristics relate to resource recovery. System templates, for instance, proved to be insufficient predictors for resource recovery. On the other hand, the type of source, the type of sinks, the type of storage or treatment technologies (e.g. single pit), or the length of a system provide information on resource recovery. An interesting next step would be the further analysis of these results in order to investigate how these characteristics could guide the development of future technology or system innovations.

Integration into an accessible tool: We also see an interest in making the algorithms and the data available as user-friendly software. Such a support tool would provide a much-needed complement to decision-making tools such as the Excreta Flow Diagrams (Peal et al., 2014a), Sanipath (Robb et al., 2017), and Quantity and Quality of Faecal Sludge (Strande et al., 2018), and it would close an important gap for implementing SDM procedures such as Sanitation 21 and CLUES.

Technology library expansion: The technology library cold also be adapted to capture future technology innovations and improved knowledge (local and international) about the performance and transfer coefficients of the technologies. A straightforward extension would be the addition of other technologies specific to a certain context (e.g. emergency sanitation) or other products such as organic solid waste and stormwater for a more holistic urban planning support.

— 4.5 CONCLUSIONS

Currently, we observe a development of novel sanitation technologies and system configurations and an increased attention to sustainability in the sanitation sector). We provide a method to systematically evaluate resource recovery and losses of the increasingly larger and more diverse range of sanitation systems early in the planning process.

- The approach allows to model substance flows to quantify resource recovery and loss ratios for nutrients (phosphorus and nitrogen), total solids (as an indicator for energy and organics), and water. It builds on and complements the previously published tool that generates a diverse set of locally appropriate sanitation systems (Spuhler et al., 2018).
- The main advantages of the approach are that is generic, automated, and considers uncertainties in order to be applied ex-ante for the entire option space build from a large and diverse set of conventional and emerging technologies.
- The resulting recovery ratio enable the prioritisation of resource efficient sanitation systems in strategic planning.
- At the core there is a technology library that provides a priori data for transfer coefficients for the four substances and 41 technologies that can be combined in 101,548 systems. This library is flexible and can be expanded with any (future) technology.
- Uncertainties are included as a means of capturing the diversity in knowledge and performance ranges. This enables the robustness of the results to be tested and used in formal decision support methodologies such as MCDA.
- Important limitations of the approach are the simplifications and generalization in the technology and product definitions and the linearity of transfer coefficients. These simplifications enable generalization and automation and their consequences are captured in the uncertainty. For a specific case study, the technologies and products can be adapted with available detailed specifications.

- The application to a didactic case shows that the model can generate plausible results, and that the resource recovery depends on technology interactions and therefore has to be evaluated for all possible systems and not on single technology level. The full-scale application provides substance flows and resource recovery ratios for over 101,548 valid system configurations. These results show that there exist trade-offs among different types of reuse (e.g. energy versus nutrients) or different sustainability indicators (e.g. local appropriateness versus resource recovery). This highlights the need for such an automated and generic approach that provides the recovery ratio data already at the pre-planning phase.
- As resource recovery becomes more relevant and novel sanitation technologies and system options emerge, the approach presents itself as a useful tool for strategic sanitation planning.

— 4.6 ACKNOWLEDGEMENTS

This work is funded by the Sawiris Foundation for Social Development through the Engineering for Development (E4D) programme of the Swiss Federal Institute for Technology (ETH) Zurich. The authors are very grateful to the inhabitants of Katarniya, Mingma and Anjali Sherpa from 500B solutions, and Agnes Montangero from the Swiss Water and Sanitation Consortium for enabling field testing of our methods. We also gratefully acknowledge the contributions of Leandra Roller for the collection of raw data, the estimation of transfer coefficients, and the analysis of preliminary results.

05 Comparative analysis of sanitation systems for resource recovery: influence of configurations and single technology components

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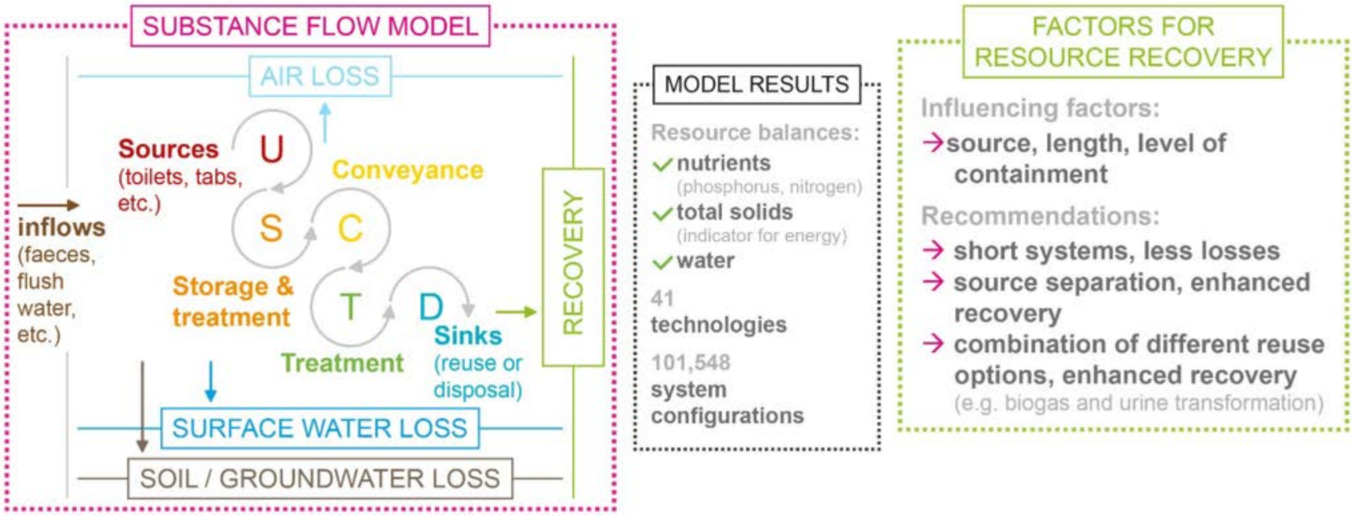
Pubilshed in Revised preprint (submitted 17.07.2020).
Spuhler, D., Scheidegger, A. and Maurer, M. 2020. Comparative analysis of sanitation systems for resource recovery: influence of configurations and single technology components. Water Research 186. DOI: 10.1016/j.watres.2020.116281.

Supplementary material Data package including supplementary material:
https://doi.org/10.25678/0001TN

- → **41 sanitation technologies are combined to form 101,548 different sanitation systems**
- → **Phosphorus, nitrogen, total solid, and water flows are quantified considering uncertainty**
- → **Resource recovery and loss potentials of all systems are compared**
- → **Factors influencing recovery are identified: the source, length, and storage and treatment**
- → **Results are generic and can be used to orient technology development or planning**

Author contributions: D.S., A.S., and M.M. conceptualized this publication together. D.S. was responsible for data curation, formal analysis, investigation, and validation. The methodology and software were developed jointly by D.S. and A.S.. D.S. also wrote the original draft and visualized the results. A.S. and M.M. supervised the process. D.S. and M.M. were responsible for funding acquisition. Resources (primary literature data) was collected by Leandra Roller.

ABSTRACT



Resource recovery and emissions from sanitation systems are critical sustainability indicators for strategic urban sanitation planning. In this context, sanitation systems are the most often structured using technology-driven templates rather than performance-based sustainability indicators. In this work, we answer two questions: Firstly, can we estimate generic resource recovery and loss potentials and their uncertainties for a diverse and large set of sanitation systems? And secondly, can we identify technological aspects of sanitation systems that indicate a better overall resource recovery performance? The aim is to obtain information that can be used as an input into any strategic planning process and to help shape technology development and system design for resource recovery in the future.

Starting from 41 technologies, which include novel and conventional options, we build 101,548 valid sanitation systems. For each system we quantify phosphorus, nitrogen, total solids, and water flows and use that to calculate recovery potentials and losses to the environment, i.e. the soil, air, or surface water. The four substances cover different properties and serve as a proxy for nutrient, organics, energy, and water resources. For modelling the flows ex-ante, we use a novel approach to consider a large range of international literature and expert data considering uncertainties. Thus all results are generic and can therefore be used as input into any strategic planning process or to help guide future technology development.

A detailed analysis of the results allows us to identify factors that influence recovery and losses. These factors include the type of source, the length of systems, and the level of containment in storage and treatment. The factors influencing recovery are related to interactions of different technologies in a system which shows the relevance of an modelling approach that allows to look at all possible system configurations systematically. Based on our analysis, we developed five recommendations for the optimization of resource recovery: (i) prioritize short systems that close the loop at the lowest possible level; (ii) separate waste streams as much as possible, because this allows for higher recovery potentials; (iii) use storage and treatment technologies that contain the products as much as possible, avoid leaching technologies (e.g. single pits) and technologies with high risk of volatilization (e.g. drying beds); (iv) design sinks to optimise recovery and avoid disposal sinks; and (v) combine various reuse options for different side streams (e.g. urine diversion systems that combine reuse of urine and production of biofuel from faeces).

— 5.1 INTRODUCTION

Sanitation protects human health and the environment and thereby promotes social and economic development. Sustainable sanitation also protects natural resources by closing material cycles. The aim is to reduce the net consumption of water and nutrients, and to prevent pollution and accumulation of emerging pollutants (Andersson et al., 2018; Nikiema et al., 2014; Rao et al., 2017; SuSanA, 2008). Sustainable sanitation that allows for resource recovery has the potential to contribute to circular economies and green cities (e.g. Kisser et al., 2020), sustainable food chains (e.g. Wielemaker et al., 2018), renewable energy (e.g. Gold et al., 2018), and new business models for private sector involvement (e.g. Otoo et al., 2015). This has been recognized by the United Nation's Sustainable Development Goal 6, safe water and sanitation for all (UN, 2014).

The call for more sustainable sanitation solutions has triggered substantial investments in the development of novel technologies and system configurations such as urine diversion or container-based sanitation (Tilmans et al., 2015; Tobias et al., 2017). Such innovations have the potential to enhance sustainability and resilience by reducing water requirements, being more adaptable for socio-demographic changes and environmental changes, and allowing for recovery of nutrient, energy, and water resources (e.g. Diener et al., 2014; Larsen et al., 2016; Tilmans et al., 2015; Tobias et al., 2017). Being independent from energy, water and sewer networks, these innovations are also more appropriate for developing urban areas (e.g. Evans, 2013; Hoffmann et al., 2020; Larsen et al., 2016; Russel et al., 2019) where most current population growth is taking place (Dodman et al., 2013; UNDESA, 2014). Today, it is widely recognized that substance flows and resource recovery potentials are highly relevant performance indicators for sustainability evaluations of different sanitation systems (e.g. Ashley et al., 2008; Drangert et al., 2018; Harder et al., 2019; Orner and Mihelcic, 2018). They serve as input for comparisons, using methods such as Multi-criteria Decision Analysis (Schütze et al., 2019), Life-cycle Analysis (Pasqualino et al., 2009), or Cost-Benefit Analysis (Balkema et al., 2002; Döberl et al., 2002).

Currently, the sanitation system options space is, however, mostly structured based on technologies and their characteristics but not on their functions and performance characteristics related to sustainability. This is reflected in the sanitation system templates (Spuhler et al., 2018; Tilley et al., 2014b) or the sanitation ladder used by the Joint Monitoring Programme (WHO and UNICEF, 2017). To consider resource recovery in line with SDG 6 (UN, 2014), a more functional approach to characterise sanitation systems is required as suggested by the functional sanitation ladder (Kvarnström et al., 2011).

One of these functions is the protection of the environment and natural resources (Kvarnström et al., 2011; SuSanA, 2008). The most straightforward attribute that allows to evaluate this this objectives is the knowledge how much pollutants are lost to the environment and how much of resources can be recovered (e.g. Lienert et al., 2015; McConville et al., 2014; Spuhler et al., 2020a). Interestingly, for sanitation systems, many of occurring substances such as nutrients or organic matter are both, potential pollutant and resource for agricultural or energy production. Therefore, a typical method to quantify resource recovery and loss potentials is material flow analysis (MFA), also known as substance flow modelling (SFM). It is a type of system analysis based on the principles of mass balances providing indication of material use, emissions, and costs. The nature of the system is captured in a mathematical model. Analytical methods quantify flows and stocks of substances and/or materials, which are transformed or consumed within the system boundaries (Baccini and Brunner, 2012; Brunner and Rechberger, 2004). MFA/SFM are widely applied for waste- and wastewater management in Europe (Beretta et al., 2013; Binder, 2007; Binder et al., 2010; Binder et al., 2009; Cooper and Carliell-Marquet, 2013; Finnveden et al., 2007; Huang et al., 2012; Huang et al., 2007; Lang et al., 2006; Lederer and Rechberger, 2010); specifically nutrient management (Do-Thu et al., 2010; Gumbo, 2005; Montangero et al., 2007) or environmental sanitation planning (Harder et al., 2019; Jain, 2012; Koffi et al., 2010; Meinzinger, 2009; Montangero and Belevi, 2008; Montangero et al., 2007; Ormandzhieva et al., 2014; Schütze et al., 2019; Sinsupan et al., 2005; Ushijima et al., 2012; Wang, 2013; Yiougo et al., 2011).

Various simulation tools have been implemented to support these quantifications. E.g.: (i) static modelling of costs and contaminant for treatment units (e.g. WAWTTAR, Finney and Gearheart, 2004); (ii) dynamic modelling for urban water flows (e.g. UWOT, Makropoulos et al., 2008), or the LiwaTool (Robleto et al., 2010; Schütze and Alex, 2014; Schütze et al., 2011); and (iii) dynamic modelling for energy, costs and emissions of entire systems, (e.g. ORWARE (Assefa et al., 2005), URWARE (Dahlmann, 2009; Jeppsson et al., 2005). More recently, also a simulation software that potentially could be applied for novel sanitation systems has been developed (Schütze et al., 2019). Unfortunately, all these models require detailed knowledge about technologies and how they connect together as well as available data or in-situ measurements to quantify transfer coefficients. The data requirements make it very demanding to use SFM at a pre-planning stage. Consequently, they most existing studies apply SFM to a few technologies and systems in a specific context only (e.g. Montangero and Belevi, 2007). The increasing number of technologies and corresponding system configurations increase the complexity further. As shown in Spuhler et al., (2020c), a set of over 40 technologies can be combined to over 100'000 plausible system configurations due to combinatorial explosion. Little knowledge exists about which combination might be the most performant for a given case. Moreover, little or no data exists on novel technologies and systems. Therefore, we have developed a method for the ex-ante quantification of substance flows (e.g. nutrients, water, total solids) of a diverse and large set of sanitation systems which we presented in Spuhler et al., (2020c). This method builds on algorithms that automatically generate sanitation systems (Spuhler et al., 2018). The model uses different technologies as building blocks and products as connectors. Each technology contains transfer coefficients for the substance in question. The flow path of substances is defined by the connections between technologies. The fate of the substances is defined by three loss compartments (air loss, soil loss, and surface water loss) and one recovery compartment. To be applicable ex-ante, the algorithms are complemented with a data library that provides transfer coefficients based on international literature and expert knowledge ([dataset] Spuhler and Roller, 2020). Additionally, uncertainties are modelled to express the variability of available data and the confidence in the expert opinion. By summing up all losses and recoveries for a system, the overall system resource recovery potentials and their uncertainty can be calculated. These results serve as basis for the performance comparison of the different sanitation systems in question. The experiences from developing this model and its preliminary application to a full-case real example have indicated, that there exists some system characteristics that could help to predict the resource recovery or loss potentials. These predictors could be used to develop a more functional characterisation of the system options at least in relation to resource recovery and loss potentials.

5.1.1 Aim

In this work we aim to answer the following two questions:

1. Can we estimate generic resource recovery and loss potentials and their uncertainties for a diverse and large set of sanitation systems?
2. Can we identify technological characteristics of sanitation systems that indicate a better overall resource recovery performance and therefore can be used as a predictor for resource recovery potentials or to guide future technology and system development?

To answer these questions, we perform a quantitative analysis of the recovery and loss potentials for a diverse and large range of sanitation systems using the model and full-scale application from Spuhler et al., (2020c). This case generated from 41 sanitation technologies 101,548 valid sanitation systems and quantifies the resource recovery and loss potentials for nitrogen, phosphorus, total solids and water.

— 5.2 METHODS

5.2.1 Overview

This paper presents an advanced application of a modelling approach previously presented in Spuhler et al., (2020c). The approach includes two main elements. First, Spuhler et al., (2020c) presents a generic substance flow model to be applied ex-ante and for a large and diverse set of sanitation technologies and systems. And secondly, Spuhler et al., (2020c) also presents transfer coefficients for four substances for 41 technologies. The four substances represent different properties and cover nutrients (phosphorus, nitrogen) total solids (as a proxy for energy and organics) and water. These results are then to be looked at and discussed in regards of the influence of technical aspects such as technology interaction and system configurations on resource recovery and losses. The advanced application requires three steps:

1. The generation of entire system using the *System Builder* (Spuhler et al., 2018).
2. The characterisation of the option space using the *system templates* as defined in Spuhler et al., (2020c).
3. The modelling of *substance flows* in all sanitation systems and the quantification of recovery and loss potentials Spuhler et al., (2020c).

The definition of the technologies and the transfer coefficients are provided in the technology library that is available here: https://doi.org/10.25678/0000ss ([dataset] Spuhler and Roller, 2020). The system builder and the substance flow model are implemented in Julia (Bezanson et al., 2017) and are accessible at https://github.com/Eawag-SWW/SanitationSystemMassFlow.jl (v1.0). A copy of the algorithms as well as all input and output data used for this publication are available in the associated data package at ERIC: https://doi.org/10.25678/0001TN ([dataset] Spuhler, 2020a).

5.2.2 Sanitation system generation

Sanitation system generation is based on the System Builder (Spuhler et al., 2018), which is an algorithm that automatically generates all valid sanitation system configurations from a set of technologies. Here, we provide just a short summary of definitions and the applied methodology.

A sanitation technology (*Tech*) is defined as any process, infrastructure, method or service that contains, transforms or transports sanitation products. It is characterized by its name and the in- and output *products* (e.g. blackwater or greywater -> septic tank -> sludge and effluent) and its functional group (FG): the toilet user interface or source (FG U), on-site storage (FG S), conveyance (FG C), treatment (FG T), and reuse or disposal sinks (FG D). A technology belonging to FG U is always a source, while a technology belonging to FG D is always a sink. In this paper, we focus on toilet sources only.

A sanitation system (*SanSys*) is defined as a combination of compatible technologies which manage sanitation products from the point of generation to a final point of reuse or disposal (Maurer et al., 2012; Spuhler et al., 2018; Tilley et al., 2014b). A sanitation system is valid if it contains only compatible technologies and every sanitation product either finds its way into a subsequent technology or a sink (Spuhler et al., 2018). Two sanitation technologies are compatible if the output product of one can be the input product of the other (Maurer et al., 2012). For each source (FG U), the System Builder tests stepwise which combination of technologies allow treatment of output products and ends when there is no further combination possible. This happens when there is no more output, meaning that a valid system is formed. Or when it results in an open-ended system which is not valid and abandoned. Loops between technologies are only permitted if the infrastructures are situated close enough to each other, which is true for technologies from the functional groups storage (FG S) and treatment (FG T). An example would be a loop between the two technologies wastewater stabilisation pond (WSP) and a biogas reactor (both from FG T). The sludge from the WSP could be circulated to the biogas reactor, while the effluent from the reactor could be circulated back to the WSP.

5.2.3 Characterisation of the option space: system templates

Starting from 41 technologies, typically over 100’000 systems can be automatically generated. To structure and characterize the option space, system templates (STs) are used. The templates characterize technologies in terms of technological features and thereby group them regarding technical concepts (dry or wet, urine diversion, energy recovery, etc.) and spatial concepts (onsite, offsite, decentralized, hybrid). The system templates were first defined in (Tilley et al., 2010) and further detailed in the Compendium of Sanitation Systems and Technologies (Tilley et al., 2014b). This compendium is supported by the ‘The Water Supply & Sanitation Collaborative Council’ and by the ‘International Water Association’; its second edition is published in six different languages. Based on this widespread use (Spuhler and Germann, 2019; Spuhler et al., 2020a; Spuhler and Scheidegger, 2019), we adapted the existing templates to include novel technologies such as the production of liquid urine fertilizer or briquetting (see also section 5.2.6). Here, we use the templates from Spuhler et al., (2020c) which include 19 templates that cover the entire options space, while grouping the options into four categories: simple onsite systems (ST1-ST3), urine diversion (ST4-ST8), biofuel systems (ST9-ST12), and blackwater systems (ST13-ST19). An overview is shown in Figure 5.1 based on [dataset] Spuhler and Roller, (2020).

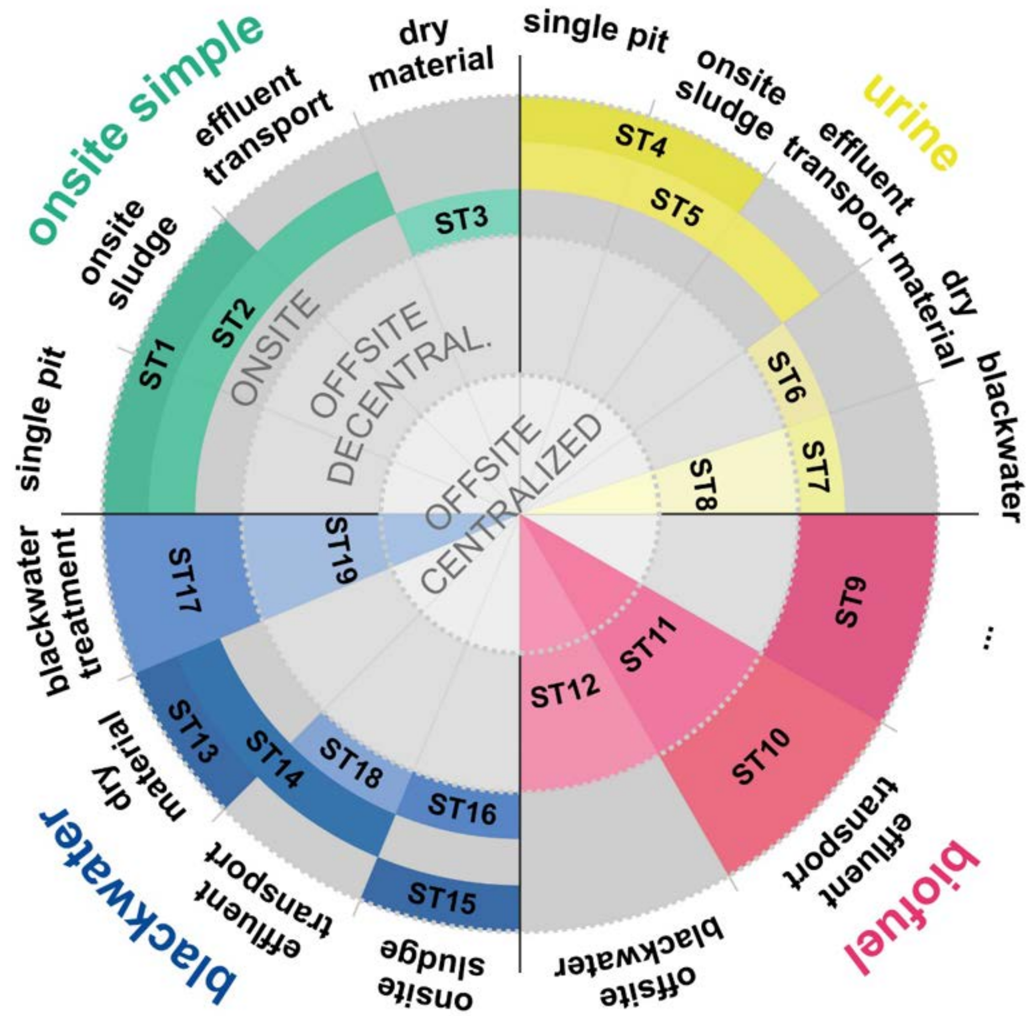


Figure 5.1: To characterise the diversity of the sanitation system option space we used nine binary conditions in order to define 19 different system templates that characterise systems according to different paradigms (onsite simple, urine diversion, biofuel, blackwater) and their degree of centralization. Note that modular systems integrating semi-centralized management of some products are considered as centralized. Source: Spuhler et al., (2020a)

5.2.4 Substance flow modelling

To quantify substance mass flows, transfer coefficients (TCs) for each technology are required. The TCs define how much of an entering substance is either transferred to one of the output products or to the loss compartments air, soil, or surface water. The TCs and the corresponding uncertainties as well as the data used to define them are compiled in the technology library ([dataset] Spuhler and Roller, 2020). The detailed description on how transfer coefficients and their uncertainties are derived can be found in Spuhler et al., (2020c). Here we provide a short overview.

We use two ways to define transfer coefficient. Whenever possible we use literature data from which we selected the median of all data reported and the variability range between the lowest and highest data point to model the uncertainty. In the absence of literature data for example for very novel technologies, we contacted experts involved in the development of the technology. There we elicited the median value for the TC based on the expert's judgement.

To define the variability range we used their confidence in the knowledge about the substance behaviour and the technology readiness level. All variability ranges are expressed as a concentration factor and modelled using a Dirichlet distribution.

Using the transfer coefficients, the inputs are propagated through the systems. This allows to calculate for each technology, the percentage of substance transferred or lost . In the sink technologies, substances are not transferred further but either lost or recovered. By summing up all losses and recoveries within one system, the system's resource recovery and loss potentials can be calculated. The uncertainties are computed by Monte Carlo error propagation and expressed as standard deviations. The standard deviations obtained in preliminary results (Spuhler et al., 2020c) are comparable to those obtained in studies applying a more sophisticated conventional post-ante material flow analysis in sanitation systems (e.g. Montangero and Belevi, 2008). Therefore, we concluded that our approach is capable of providing reasonable results also ex-ante (Spuhler et al., 2020c).

5.2.5 Substances and inflows

So far, we have defined transfer coefficients for four substances that typify different properties: total phosphorus (TP), total nitrogen (TN), total solids (TS), and water (H2O). All four substances are relevant as indicators for resource recovery and pollution potential. Both phosphorus and nitrogen have value and crucial significance: as important macronutrients, there are resources to be recovered; and as environmental pollutants, there are emissions to be minimised. Total solids can be used as a proxy for energy that could be recovered, for example, in the form of briquettes or biochar, as well as for organic matter that could be recovered as soil amendment. If discharged into the environment, total solids also has significant pollution potential. Water is under increasing pressure in many urban areas and has become a scarce commodity which should either be saved or reused.

For these four substances, we also defined fluxes for toilet sources using the values based on international literature (e.g. Lohri et al., 2010; Rose et al., 2015) provided in the technology library. These inflow values are average literature from all over the world and therefore are quite generic. For the application in a specific case, those values could be adjusted to account for the local diet and flush water usages. Because we are more interested in the impact of the technology uncertainty then the uncertainty related to the population specificities in a given case, we did not consider inflow variability in our calculations. However, the variability range of the literature data can be found in the supplementary material of Spuhler et al., (2020c) and in the technology library ([dataset] Spuhler and Roller, 2020).

Table 5.1: Inflow mass for one person equivalent based on international literature and therefore generic for any application. TP: total phosphorus; TN: total nitrogen; TS: total solids; and H2O: water. Note that the amount of TP, TN, and TS are the same for all sources; only water inflow masses depend on the flush volume. We consider 2L/day/person for the pour flush toilet and 60 L/day/person for the cistern flush toilet. Source: Spuhler et al., (2020c).

	Substance	U1. cistern flush toilet	U2. pour flush toilet	U3. dry toilet	U4. Urine diversion dry toilet (UDDT)
Inflows in kg year^{-1} for 1 person equivalent	TP	0.548			
	TN	4.550			
	TS	32.12			
	H2O	22447	1277	547	

5.2.6 Technologies an application case

In collaboration with a Swiss philanthropic organisation and a local organisation, we tested the System Builder from Spuhler et al., (2018) and the SFM model from Spuhler et al., (2020c) in Nepal in 2017. The details for this application case are described in (Spuhler et al., 2018). The characterisation of the technology is independent of the case and are therefore fully transferrable to any case as shown in (Spuhler et al., 2020c). Therefore, the case circumstances are not relevant for the analysis presented in this manuscript.

The 41 sanitation technologies are originally based on the Compendium (Tilley et al., 2014b) and further developed in Spuhler et al., (2018) and Spuhler et al., (2020c). The resulting set includes conventional as well as novel technologies. Examples of such novel technologies include production of liquid urine fertilizer (aurin) and its application (Bonvin et al., 2015; Etter et al., 2015b; Fumasoli et al., 2016), briquetting based on the process implemented by Sanivation in Naivasha (Jones, 2017), and latrine dehydration and pasteurization using ladepa pelletizing (Septien et al., 2018b).

Using these 41 technologies the system builder created automatically 101,548 valid sanitation systems. Valid means they are all able to manage all products from a given source in such a way that no open output remains at the end. The number is so high because of combinatorial explosion. The large number of generated sanitation systems represents almost the entire space of potential solutions – some of them with only minor variations.

It is important to note, that we here only consider toilet sources in order to reduce the complexity of the results. We also did not consider urine diversion flush toilets (and therefore no systems from ST7 and ST8 were formed). However, the underlying models, both the System Builder and the substance flow model, could also accommodate other streams and related technologies such as greywater, stormwater, or organic solid waste.

For the substance flow modelling, we used the transfer coefficients from the library and inflow masses for 1000 person equivalent and a period of one year. This was based on the requirements of our partner organisation that aimed of developing a city sanitation plan for the centre of the small town in Nepal.

5.2.7 Data analysis

To identify the influence of technical aspects such as technology interaction and system configurations on resource recovery and losses we used R for visual data analysis (R Development Core Team, 2018). We also triangulated and reflected the results with data from two other case studies for larger cities. One of this case studies was the city of Arba Minch with 100’000 inhabitants in Ethiopia and another case studies was a low-income settlement of 20’000 inhabitants in Lima, Peru. With visual data analysis we refer to plotting different combinations of results in order to show dependencies between different technical aspects such as for instance the occurrence of urine diversion or the length of a system.

Figure 5.2:Overview of the 41 technologies in this study used to generate sanitation systems and to quantify their substance flows grouped by functional group. Each technology is defined by its name, possible input and output products, and how these products relate to each other (e.g. 'OR' for either one or another, 'AND' if they always arise jointly. Taken from Spuhler et al., (2020c).

— 5.3 RESULTS

5.3.1 Overview

From the 41 Techs, 101,548 valid sanitation systems were generated and the substance flows for total phosphorus (TP), nitrogen (TN), total solids (TS), and water (H2O) were computed, considering the uncertainty of the TCs. Figure 5.3 shows a density plot of the resource recovery of all systems. In the x-axis the recover potential from 0 to 100% is shown and in the y-axis the relative occurrence of systems with a given recovery (density). For TP, TN, and TS we show the ratio [%]. For water, we provide the absolute volume [m^3year^{-1}], as the relative recovery does not provide any useful information (e.g. comparing dry toilets with pour flush). As can be expected, across more than 100,000 systems, all four substances show recovery from nothing to almost 100%. This indicates that the choice of technologies has enough breadth to cover the entire spectrum. However, the maximum recovery ratio for the four substances are different and lower for nitrogen and total solids than for phosphorus and water: 98% for TP, 87% for TN, 88% for TS, and 97% for H2O. Also, the shapes of the profiles differ greatly from each other. But all of them show several peaks, indicating some key characteristics that lead to shifts in the recovery potentials. In the following paragraphs, we look at some of these key characteristics in more detail.

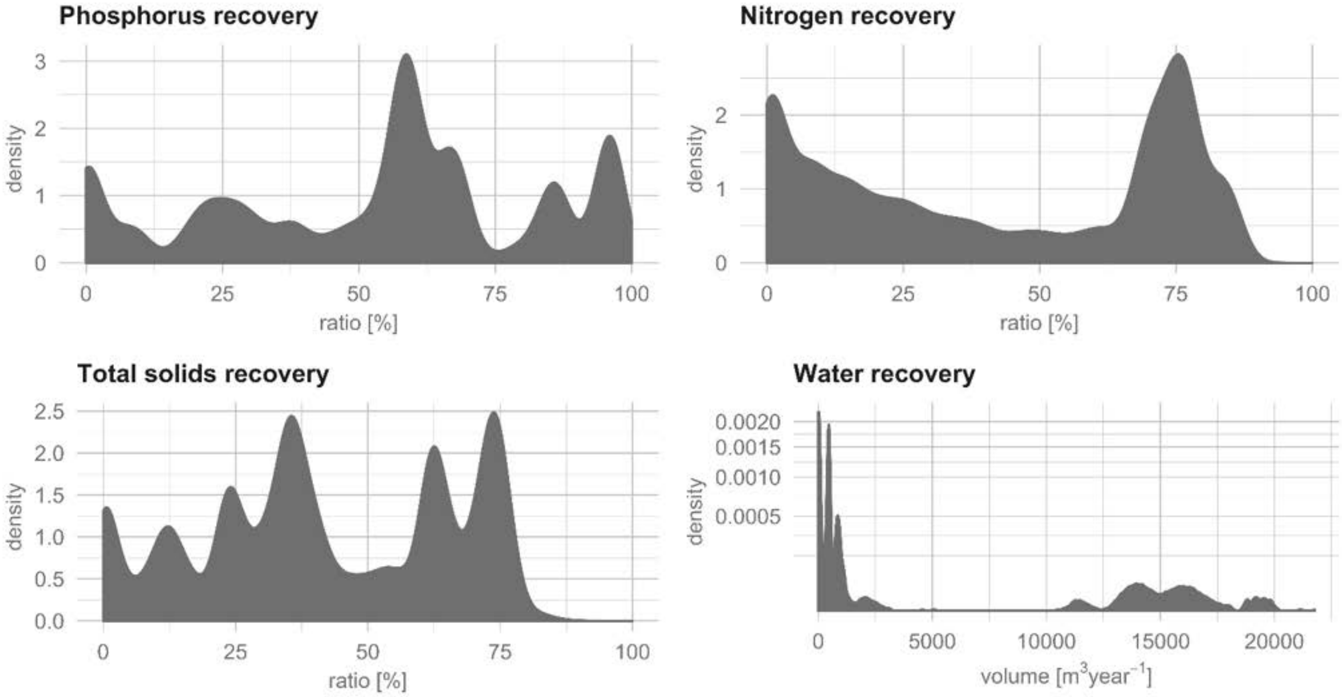


Figure 5.3: Recovery potential profiles of the sanitation system option space for all four substances. The x-axis shows the recovery potential from 0 to 100%. The y-axis shows the density of occurrence of a specific value for the recovery potential among all systems. The is based on kernel density estimate, which is a smoothed version of the histogram. TP: Total phosphorus; TN: total nitrogen; TS: total solids; H2O: water. For TP, TN, and TS we show the recovery ratio [%]. For H2O we show the absolute volume [m^3year^{-1}], as water flow depends on the source used and therefore the relative recoveries cannot be directly compared.

5.3.2 Source technologies (FG U)

The two wet sources (U1. cistern flush and U2. pour flush toilets) generate the same output product, blackwater, and therefore also the same numbers of SanSys (26,124). For dry toilets (U3), the number of valid systems is significantly lower (3,704) because the generated output (excreta) can enter far fewer subsequent technologies and results in fewer partitions. Almost half of all the SanSys generated (45,596) originate from the urine diversion dry toilet (U4), increasing the diversity of the option space. UDDT toilets generate two output products: urine and faeces. The more products occur, the more valid system configurations can be created.

Besides the fact that sources influence the number of system configurations, they also impact the recovery potentials and losses. This is illustrated in Figure 5.4 which shows all resource recovery and loss potentials grouped by the source of the system. Each dot represents a system, the colours represent the sources:

- For phosphorus the median recovery ratio is highest for UDDTs (61%) and lowest for dry toilets (21%). TP losses are dominated by soil loss and significantly higher for dry toilets which show a median soil loss of 75% as compared to 32% and 37% for wet sources and UDDTs respectively. But for wet sources, substantial amounts can also be lost to surface waters.
- A similar but even more pronounced pattern is observed for nitrogen. Again, the highest median recovery which is 75% is observed for UDDT systems and the lowest for dry toilets (4%). Nitrogen losses go also to the soil and are also higher for dry sources (29% for dry toilet, 17% for wet sources, and 5% for UDDTs). What is different for nitrogen is that high amounts are also lost to the air for all sources (59% for dry toilet, 40% for wet sources, and 15% for UDDTs).
- For total solids, the pattern is similar to the nitrogen pattern but less pronounced.
- Water recovery is obviously dominated by cistern flush systems as the water volume entering the system is much higher (0 to 21,773 m3year-1, median of 1687 m3year-1). However, cistern flush systems also have the potential for important losses from all three compartments (3125 m3year-1 to air, 362 m3year-1 to water, and 4021 m3year^{-1} to soil).

In summary, we learn three things from this figure. First, dry toilets result in much higher losses and thus in lower recovery potentials. Secondly, UDDT systems result in low losses and high recovery ratio. And thirdly, most losses occur for nitrogen and total solids.

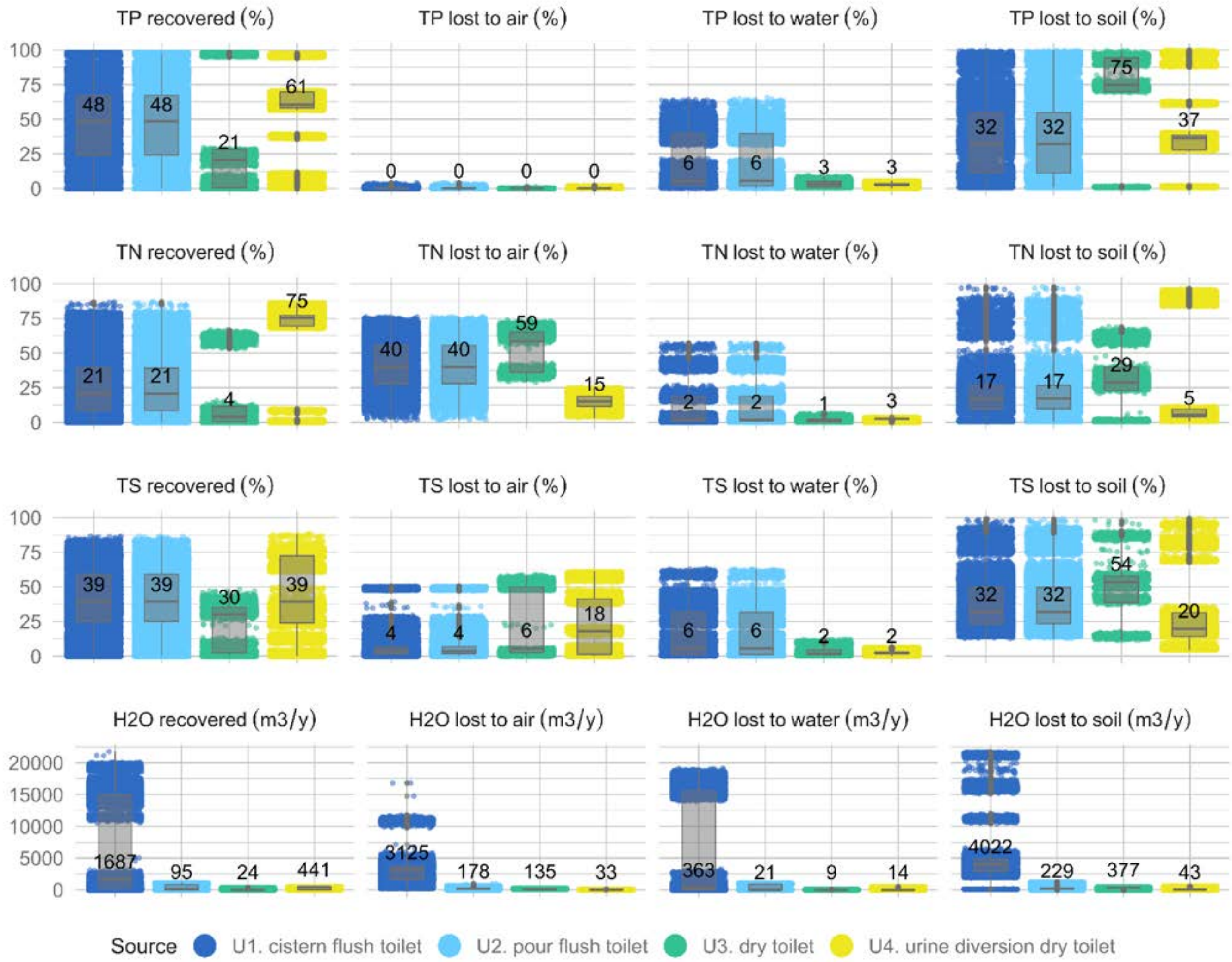


Figure 5.4:Jittered point plots of recovery potentials and losses for all sanitation systems (SanSys) and substances grouped per source. The points are overlaid by boxplots summarizing the results. The middle line of the boxplot represents the median, which is also written on each plot. The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 * IQR from the hinge (where IQR is the inter-quartile range, or distance between the first and third quartiles). The lower whisker extends from the hinge to the smallest value at most 1.5 * IQR of the hinge. Data beyond the end of the whiskers is removed from the plot. The colours correspond to the sources used by the systems. For TP, TN, and TS, we show the ratio [%]; for water we show the absolute amount [$m^3 yr^{-1}$].

5.3.3 System length (number of technologies in a system)

Urine diversion systems are generally longer and more complex (more products, more bifurcations), and onsite dry (ST1 and ST2), biogas, or blackwater (e.g. ST9, ST13, and ST16) systems are shorter. For longer systems, the number of different SanSys and thus the diversity increases illustrated by the high number of UDDT systems. However, this also means that SanSys which are longer are also more similar and therefore have similar resource recovery potentials. This is illustrated in Figure 5.5 showing a clustering of similar recovery potentials to the right. The figure also shows that the median recovery potential increases initially with length, and is maximal at 14 technologies. But there are some very short systems that show extreme values. Either very low what is the case for systems including uncontained storage and a disposal sink. Or very high recovery ratio for systems that include contained storage and a recovery sink. The absolute highest recovery is achieved in short UDDT systems combined with biofuel (again ST9). For longer UDDT systems, recovery is systematically reduced by more possibilities for losses. This shows that the shorter the system the higher the potential for a very high recovery.

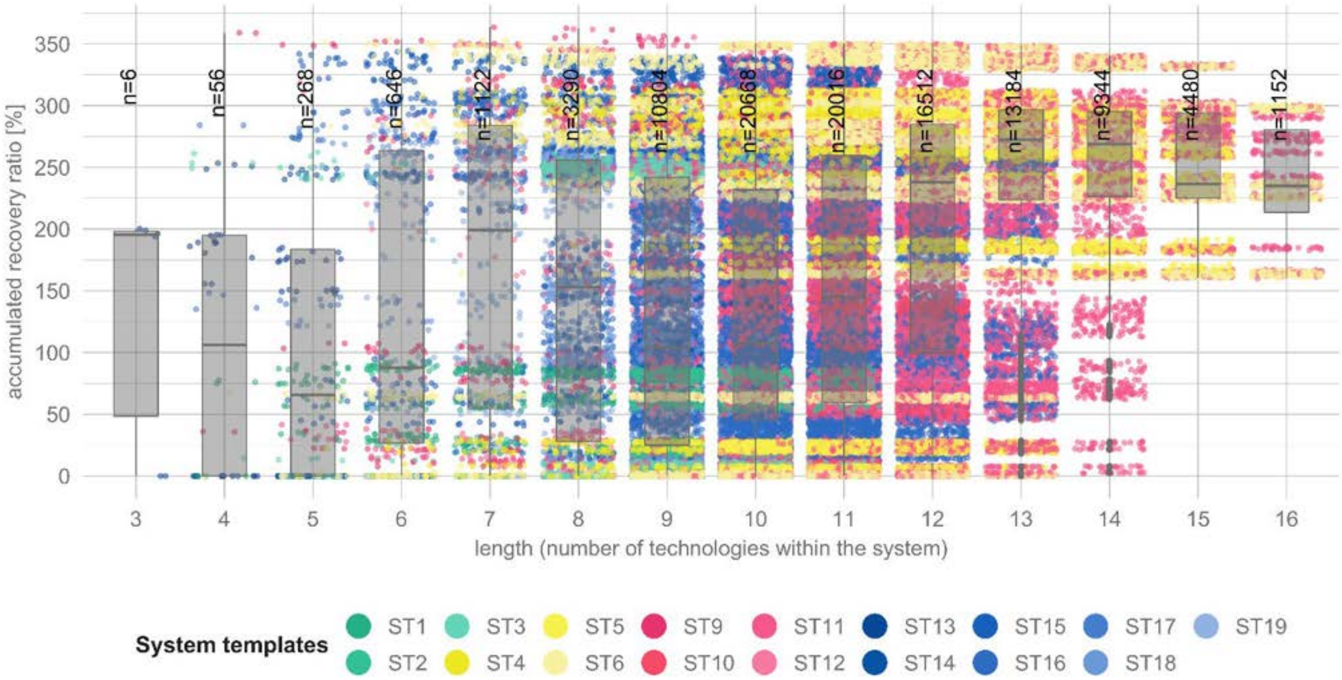


Figure 5.5: Jittered point plots overlaid with boxplots of the accumulated recovery ratios (sum of the ratio for all four substances) and coloured by source. The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value, no further than 1.5 * IQR from the hinge (where IQR is the inter-quartile range, or distance between the first and third quartiles). The lower whisker extends from the hinge to the smallest value, at most 1.5 * IQR of the hinge. Data beyond the end of the whiskers not shown here. Colours correspond to the sources used by the systems. Median length per template is shown in Table 2 in the last column.

5.3.4 Templates

Table 5.2 provides the number of systems per System Template (ST) and the detailed description of each template. there are far fewer onsite simple systems than urine diversion, biofuel, or blackwater systems, mainly because they are simpler and fewer permutations can be generated.

Table 5.2: System configurations per system template (ST). ST7 and ST8 are not represented by any generated sanitation systems because they require a urine-diverting flush-toilet as source. The wet sources (U1. cistern flush and U2. pour flush toilets) occur in all system templates except ST3-ST6 and are the only source represented in templates ST10 and ST12-ST19. The U3. dry toilet is only represented in ST1-ST3, ST9 and ST11, and it is the only source in ST3. UDDT is represented in templates ST4-ST6 (urine diversion templates) but also in the two biofuel templates ST9 and ST11 (if a system integrates both urine diversion and biofuel, it is associated with the biofuel STs from ST 9-ST12).

System template (ST)		Number of generated sanitation systems	Median length per template
Onsite simple	ST1. Dry onsite storage, with sludge production, without effluent transport	1,032	9
	ST2. Dry onsite storage, with sludge production, with effluent transport	3,072	10
	ST3 Dry onsite storage and treatment, without sludge production	1,445	9
Total		**5,549**	
Urine diversion	ST4 Dry onsite storage, without treatment, with urine diversion, without effluent transport	3,832	11
	ST5. Dry onsite storage, without treatment, with urine diversion, with effluent transport	10,432	13
	ST6. Dry onsite storage and treatment, with urine diversion	20,688	13
	ST7. Offsite blackwater, without sludge, with urine diversion	0	
	ST8. Offsite blackwater treatment, with urine diversion	0	
Total		**38,608**	
Biofuel	ST9. Onsite biogas, briquettes or biochar, without effluent transport	328	9

	ST10. Onsite biogas, briquettes or biochar, with effluent transport	3328	11
	ST11. Offsite biogas, briquettes or biochar, without blackwater transport	27,024	12
	ST12. Offsite biogas, briquettes or biochar, with blackwater transport	1,542	10
Total		**31,918**	
Blackwater	ST13. Onsite blackwater, without sludge, without effluent transport	24	5
	ST14. Onsite blackwater, without sludge, with effluent transport	1,656	9
	ST15. Onsite blackwater, with sludge, without effluent transport	2,624	10
	ST16. Onsite blackwater, with sludge, with effluent transport	21,056	10
	ST17. Onsite blackwater treatment, without effluent transport	32	5
	ST18. Onsite blackwater treatment, with effluent transport	768	9
	ST19. Offsite blackwater treatment	2,616	9
Total		**28,752**	

Figure 5.6 shows the recovery potentials for all substances grouped by template and coloured by source. Most templates include systems with both high and low recoveries. Thus, template are not sufficient indicators for resource recovery potentials. Exceptions are ST1 and ST2 with exclusively low recovery rates. The clouds indicate clusters of systems with similar recovery potentials. Some STs show only two clusters of either very high or very low recovery potentials, (e.g. ST3, dry onsite and composting). This distinction is due to only a few products ending up either in a disposal or in a recovery sink. At a first glance the pattern of all four substances looks similar. But there are some differences.

For **phosphorus**, urine diversion templates (ST4-ST6) show the highest median recovery ratio, followed by the biofuel templates (ST9-ST12) and some blackwater templates (ST14, ST16). The five systems with the absolute highest phosphorus recovery ratios are from ST3 (onsite composting) and ST14 (onsite blackwater systems) with fewer treatment steps. This is different for the accumulated recovery ratio which is highest for ST9 as we have shown in the previous paragraph and Figure 5.5.

For **nitrogen and total solids**, urine diversion templates clearly outcompete the other . The five systems with the highest nitrogen recovery ratios are from ST6 (urine diversion and onsite faeces storage) and ST9 (urine diversion and biofuel production). The five SanSys with the highest total solids recovery ratios are also from ST9 and ST11, with exclusively UDDT sources. This also explains why the absolute highest accumulated recovery is achieved in ST9.

For **water**, the recovery ratio in % is not that interesting – as a system with high recovery is similar to a system with low use. Therefore, we look at the absolute amount of water recovered or lost. Higher recovery is obviously obtained in templates with a cistern flush toilet (ST9 to ST 19). The five SanSys with the highest water recovery by mass are again from ST9, followed by a ST11, and ST15 (onsite blackwater system). High water recovery ratios (in %) can also be achieved by dry systems (especially UDDT systems), but are obviously not relevant in absolute terms.

Looking at the accumulated ratios (bottom of Figure 5.6); urine diversion systems clearly perform best especially if combined with biofuel production as it is the case for ST9 (onsite biofuel without effluent transport) or ST11 (offsite biogas without blackwater transport).

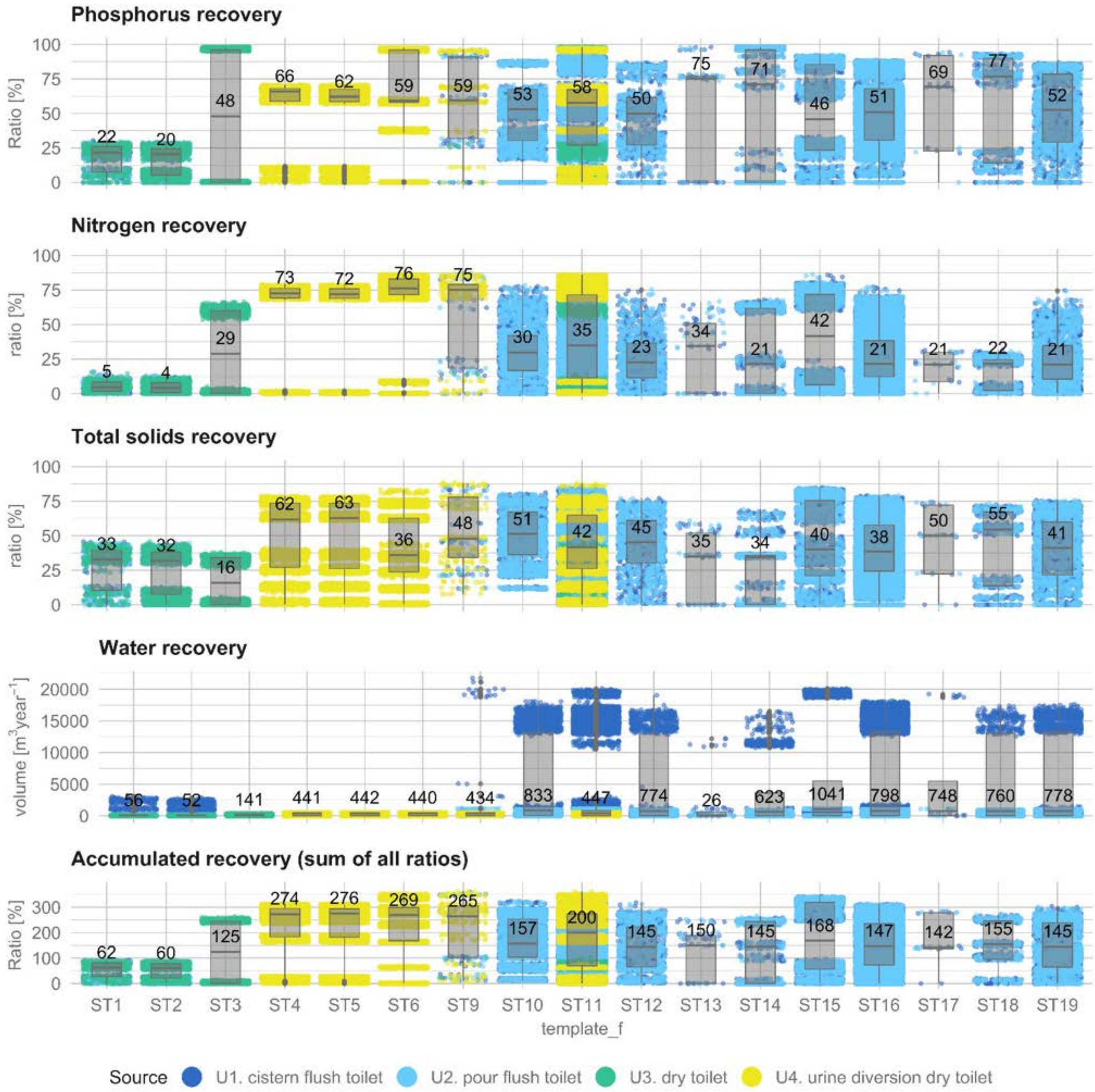


Figure 5.6: Jittered point plots of recovery potentials for all sanitation systems and substances grouped per system template (ST) and coloured by source. A boxplot summarizes the data. The middle line of the boxplot represents the median. The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the largest value no further than 1.5 * IQR from the hinge (where IQR is the inter-quartile range, or distance between the first and third quartiles). TP: Total phosphorus; TN: total nitrogen; TS: total solids; H2O: water. For TP, TN, and TS, we show the ratio, for water we show the absolute volume [$m^3 year^{-1}$]. The accumulated recovery ratio corresponds to the sum of the ratio for all substances. For example, system ID 56423 from ST9 has the absolute highest accumulated recovery ratio corresponding 364% which is the sum of 97 (TP) + 86 (TN) + 88 (TS) + 93 (H2O) %.

5.3.5 Shifting factors and key technologies

The peaks in Figure 5.3 and clusters in Figure 5.6 indicate that key characteristics act as “shifting factors” which are either due to the occurrence of a single technology or a combination of technologies. By analysing the systems that are part of the peaks we identified ten possible “shifting factors”: (1) if a single pit is part of the system; (2) if transport is by pipe; (3) if no transport technology occurs (purely onsite system); (4) if urine source separation occurs (in UDDT); (5) if blackwater occurs; (6) if biofuel production occurs; (7) if toilet producing pit occur (i.e. in twin pits); (8) if composting technologies are used; (9) if surface water discharge is used; and (10) if soak pits are used. We used visual data analysis to better understand the respective influence of these shifting factors. The detailed figures are presented in the supplementary material (SI, Figures 9 to 13), Figure 5.7 summarised the following:

- The single pit and soak pit are clear indicators for losses because of soil infiltration. As they occur in the beginning of the chain, they have increased influence. However, these soil losses are also associated with high uncertainties (quality of inflow, technology implementation).
- Obviously, cistern flush combined with sewers achieve comparatively higher water recovery volumes because inflowing water volumes are also higher. But they also have the potential to lead to more losses (e.g. if effluent is simply discharged).
- Transport technologies (assuming reasonable implementation, operation, and maintenance) have no major impact on resource recovery.
- Composting can lead to high recovery ratios. But major air losses can occur for total solids and nitrogen either in the composting technology itself or during an earlier or later drying or storage step (Benitez et al., 1999; Jönsson et al., 2004; Lalander et al., 2015; Meinzinger, 2010; Yadav et al., 2012).
- Systems producing biofuel achieve high recovery rates only if all side streams are exploited for reuse.
- No imperative trade-offs exist between energy, nutrient, or water recovery because the different recovery pathways can be combined and can help to optimize resource recovery. For example, urine diversion and reuse technologies combined with technologies that transform faeces into biofuel resulted in the highest recovery potentials.

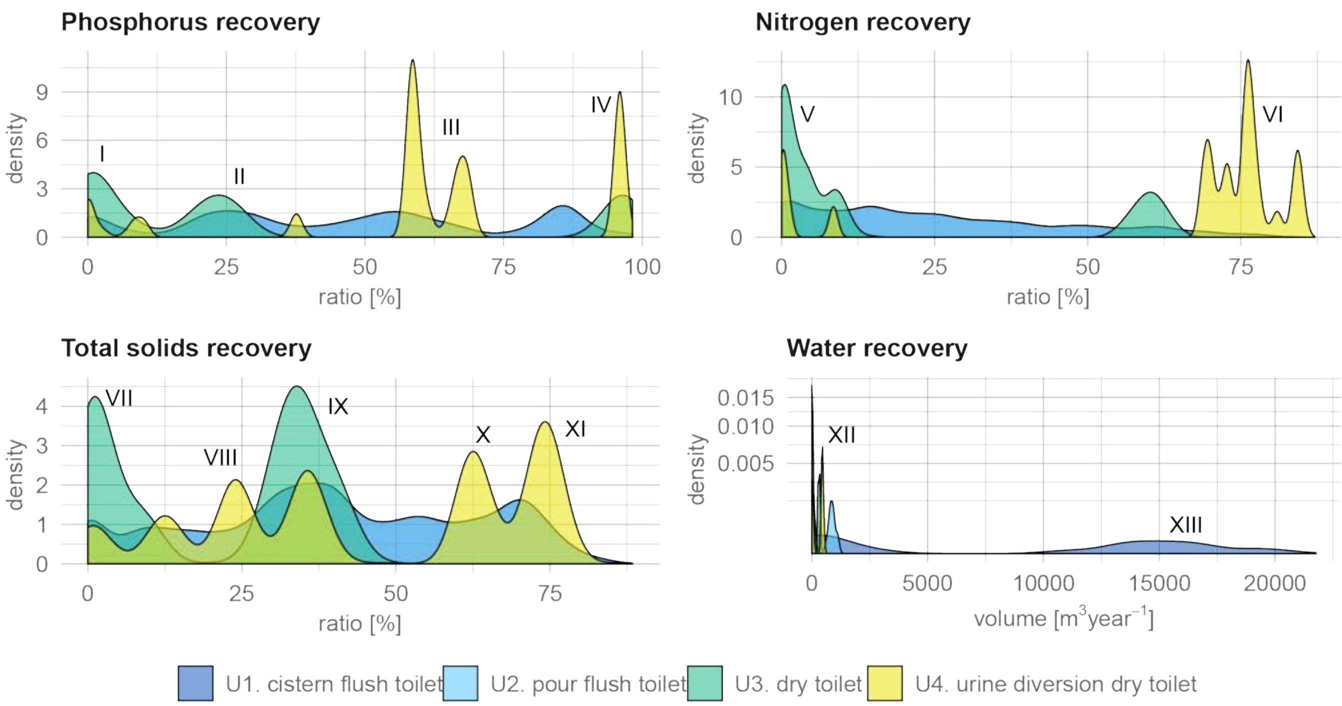


Figure 5.7: Peaks in recovery potentials and shifting factors: (I) dry toilet and UDDT combined with single pit + disposal sink. (II) the first peak is related to the dry toilet combined with some recovery (e.g. irrigation or reuse of sludge); the second smaller peak is related to UDDT combined with reuse of dried faeces + urine disposal in soak pits; (III) UDDT combined with disposal of faeces + reuse of urine; (IV) any source combined with sealed storage and exclusively reuse sinks (e.g. UDDT + reuse of faeces + reuse of urine; dry toilets + reuse of compost or sludge + irrigation with effluent; cistern flush/pour flush + reuse of sludge + irrigation); (V) integration of some disposal sinks; (VI) peaks dominated by urine reuse and reuse of pit humus or compost; (VII) dry toilet and urine diversion but products ending up in disposal sinks; (VIII) two smaller peaks for UDDT (disposal of either urine or solids); (IX) dry toilet + reuse of compost or sludge; (X) and (XI) are dominated by UDDT, same as (III) and (IV) and due to either reuse of urine only or urine and faeces (a substantial mass of TS is contained in urine and not faeces); highest TS recovery rates can be achieved in short water-borne systems (little loss on the way) with reuse of sludge + reuse of effluent (irrigation); (XII) pour flush toilets integrating recovery sinks for water (irrigation); (XIII) dominated by cistern flush systems with recovery sinks.

5.3.6 Functional groups

The shifting factors and key technologies presented in the previous paragraph can clearly be associated with the functional groups user interface (sources, FG U), storage (FG S) treatment (FG T) or reuse or disposal (sinks, FG D). Sources have a direct impact on water volume and thus on the magnitude of losses or recoveries or if urine diversion or blackwater occurs. Transport (FG C) has little influence. To validate these results and be more specific, we looked at the mean recoveries and losses of all systems over the system templates. The results are displayed in Figure 5.8. Obviously, sinks (FG D) have a major impact on recovery ratios as they define whether the final product is reused or lost. However, the storage (FG S) and treatment (FG T) are also relevant because they determine how much is lost before products end up in the sinks. Storage (FG S) losses are mainly to soil and air, and are important for onsite systems without sludge (ST4, ST13, ST14). Treatment (FG T) losses are mainly air losses of TN (and to a lesser extent, TS) and are particularly dominant in onsite blackwater systems with sludge (ST 16 to ST18), offsite blackwater systems (ST19) and biogas systems with effluent transport (ST10, ST11). Storage (FG S) and treatment (FG T) also have high uncertainties. For sinks (FG D), losses are mainly soil losses and relevant for all templates.

Some biogas and blackwater systems with effluent transport (ST10, ST11, ST16) and offsite blackwater systems (ST19) also show substantial water losses.

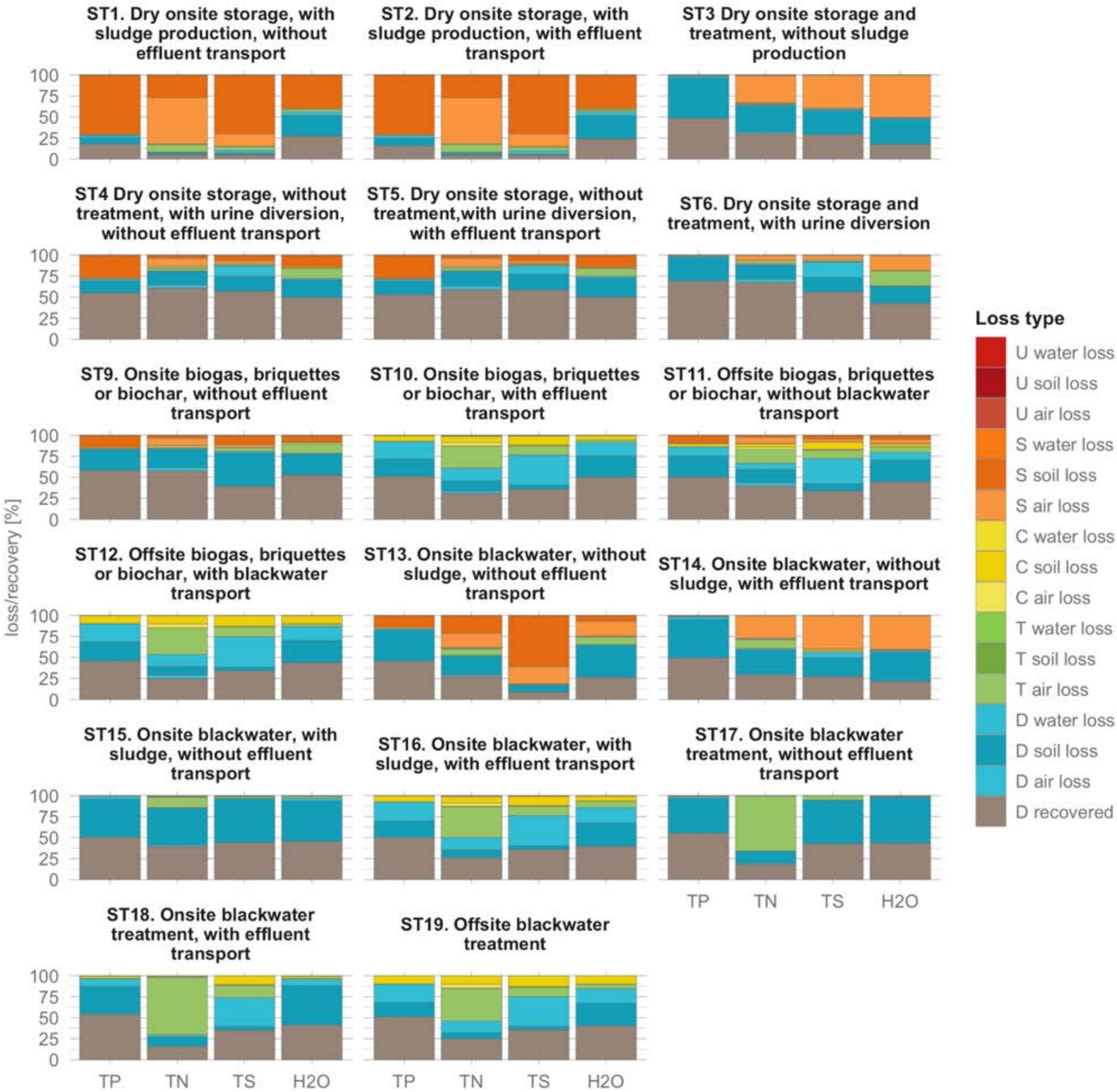


Figure 5.8: Percent of lost substances within a system, showing the mean over all systems within a system template (ST). The losses to the air, soil, and surface water are indicated seperately for each functional group user interface (U), storage and/or treatment (S), conveyance (C), (semi-)centralized treatment (T), and reuse and/or disposal (D). The contribution of the functional group U (toilet sources) to losses is negligible. The functional groups S and T clearly contribute most to the losses. The losses in S go mostly to the soil. The losses in T go mostly to the air. D losses (in blue) refer mainly to the disposal sinks. The number of systems with disposal sinks is approximately equal to half of the systems per template or less. ST1 and ST2 clearly have lower recovery potentials in the mean, while ST4-ST9 clearly have higher recovery potentials than the others.

5.3.7 Uncertainty

In Figure 5.9, we show the simulated standard deviation of all substance recovery potentials. Each dot in a figure represents a system, the colour code shows the system template the system belongs to. The x-axis shows the recovery potential and the y-axis shows the standard deviation. Low and high recovery ratios have lower uncertainties because the TCs cannot vary below 0 or above 100% to conserve the mass balance (Spuhler et al., 2020c).

As shown in Spuhler et al., (2020c) and [dataset] Spuhler and Roller, (2020), the identified uncertainties for each technology can already be quite high as they integrated different aspects such as the quality of inflow, the technology implementation (design and maintenance), environmental conditions, measurement methods, or available knowledge (which is particularly limited for novel technologies). Nevertheless, the maximum standard deviation of the system recovery ratio is 28%, which is comparable to the accuracy of classical material flow analysis (e.g. Montangero and Belevi, 2008). This indicates that the used approach for the ex-ante quantification of resource recovery potentials is capable of producing plausible and thus relevant results for practice. As a consequence, we suggest to use recovery ratios and standard deviations presented in Figure 5.9 as a data pool to guide any strategic sanitation planning case. For instance, the resource recovery potentials can be used to prioritise resource efficient systems already at an early planning phase. Or the recovery ratio are used to compare different options when making a final decision using e.g. multi-criteria decision analysis. This would allow to introduce value functions for different resource recovery pathways (e.g. nutrients versus energy) and the uncertainties could be used to evaluate the robustness of the final outcome.

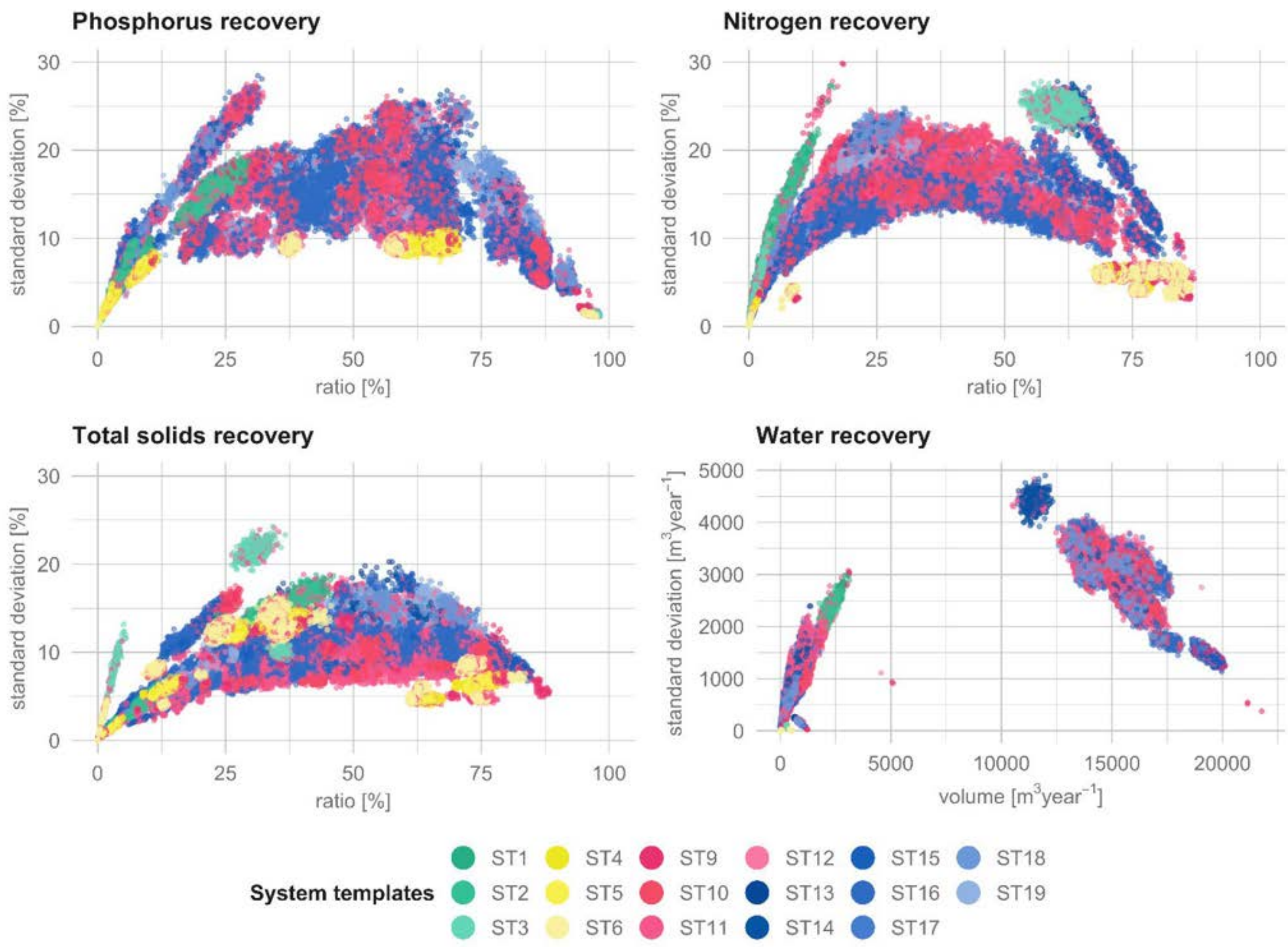


Figure 5.9: Jittered point plots of the recovery potentials mean values (x-axis) and the standard deviation (y-axis). The colours define the system templates (STs). ST1-ST3 are dry onsite systems, ST4-ST7 are urine diversion systems, ST8-ST13 are biofuel systems, and ST14-ST19 are blackwater systems (see Table 5.2 and (Spuhler et al., 2020c) for detailed definitions of STs). The uncertainties are higher for the mean values as there is more room for variability. STs have some influence on the uncertainties as they are related to the technologies within the systems and thus also to the uncertainties defined for those technologies.

— 5.4 DISCUSSION

The quantitative analysis of recovery and loss potentials of four typical substances and over 100’000 sanitation systems contribute to science and practice in two ways. First, most of the input data represents a large body of literature and is therefore generic and could be utilised for other applications. Thus, the resulting recovery and loss potentials and the uncertainty estimations are transferable and could serve as input for the multi-criteria decision analysis or costs-benefit analysis. Second, we were able to identify system characteristics and technology interactions relevant for recovery potentials in order to help shape future technology and system design. In the following two paragraphs, we briefly discuss the main results in order to answer our two main questions. We will start with the discussion of key characteristics that can help to predict resource recovery and guide future technology and system innovations. Secondly, we will discuss the generalisation of the results and their relevance for strategic planning.

5.4.1 Factors influencing resource recovery and losses

By analysing the mass flows for a large number of sanitation systems, we extracted some key characteristics that have a direct impact on the understanding of resource recovery potentials (see also Table 5.3). Most of these influencing factors are related to technology interactions and system configurations. However, we were not able to identify an unequivocal set of factors determining resource recovery or loss, which reveals the need for two considerations. First, performance evaluation, in terms of resource recovery, cannot be based on a single technology but must be based on the analysis of the entire system. Second, the need for a generic and automated model that allows substance mass flows to be quantified, even for large numbers of sanitation systems, is highlighted.

Length: Shorter systems can achieve higher recovery rates due to fewer possibilities for losses. Each additional treatment step potentially contributes to more losses while the recovery only depends on the sinks. Quantitative knowledge about such trade-offs (e.g. treatment quality versus recovery potential) can be used to support the decision-making process.

Source: The system source (functional group FG U) strongly impacts both the system configuration and the recovery potentials. For all four sources studied, TN and TS recovery ratios cannot be as high as for TP and water (more stable substances). But wet systems based on cistern flush and pour flush toilets generally have lower TN recovery potentials than urine diversion systems due to losses to soil and air. However, some systems based on wet sources can achieve very high recovery ratios for all substances if they are short and effluent is reused in irrigation. Obviously, wet systems lead to higher water recovery in absolute terms but also more significantly to higher losses in absolute terms. Dry toilets create systems that perform poorly in recovery, either due to the combination with the single pit (FG S, high soil losses) and/or sludge treatments such as composting and drying beds (FG T, high air losses). However, if dry toilets are linked to pit humus or compost production and irrigation, they can achieve high recovery combined with low water use/loss. Urine diversion systems that integrate recovery sinks clearly show recovery potentials for TP, TN, and TS that are higher than for all other sources.

Other functional groups: Resource recovery is influenced not only by sources (FG U), but also by the sinks, storage, and treatment (FG D) technologies and how these are combined. Obviously, sinks (FG D) have a major impact on recovery ratios as they define whether the final product is reused or lost. However, the storage and treatment technologies define how much of a substance is lost before it enters the sink. Sink (FG D) losses are mainly soil losses and relevant for all templates. Some biogas and blackwater systems with effluent transport (system template ST10, ST11, ST16) and offsite blackwater systems (ST19) also show substantial water losses. Storage (FG S) losses are mainly soil and air losses and are important for onsite systems without sludge (system template ST4, ST13, ST14). Treatment (FG T) losses are mainly air losses of TN (and to a lower extent TS) and are particularly dominant in onsite blackwater systems with sludge (system template ST16 to ST18), offsite blackwater systems (ST19) and biogas systems with effluent transport (ST10, ST11). Storage (FG S) and treatment (FG T) also have high uncertainties (see Spuhler and Roller, 2020; Spuhler et al., 2020c).

System templates: System templates are currently the approach most used to describe the sanitation system option space (see e.g. Gensch et al., 2018; Tilley et al., 2014b; WSP, 2007; Zakaria et al., 2015). System templates are not a sufficient indicator for potential resource recovery. However, different templates lead to different recovery and loss characteristics. Dry onsite systems without sludge templates (ST1 and ST2) mostly include systems with high losses and little recovery. Urine diversion templates (ST4-ST6) have the least number of loss systems and the most recovery systems, followed by biogas templates (ST9-ST12). The blackwater templates (ST13-ST19) integrate systems with mostly moderate losses. However, short blackwater systems with relatively little treatment (e.g. ST 15) can achieve high recovery ratios for all substances. The highest recovery ratios are achieved in urine diversion systems combined with biofuel production (ST9).

Key technologies:

- Single pits and soak pits: Based on the literature data we found, these clearly show high losses of phosphorus and nitrogen (except if urine is separated and recovered), and other substances to a smaller extent. But these high losses are also associated with high uncertainties dependent on contextual conditions.
- Transport generally does not impact recovery potentials
- Cistern flush systems with no sewers achieve higher water recovery, but also potentially higher losses.
- Composting systems show high recovery potentials for TP and TN, but high losses for TS and in some cases also for TN.
- Systems with technologies that produce biofuel achieve high recovery rates, but only if the side products (e.g. sludge from biogas digesters) are also reused (e.g. drying and application to soil).

There is no imperative trade-off between energy, nutrient, and water recovery. The highest recovery is achieved when combining urine diversion and reuse, biogas production from faeces in co-digestion, reuse of sludge for soil amendment, and irrigation with any effluent.

Table 5.3: Factors affecting resource recovery potentials of sanitation systems and level of effect observed in the application case (based on personal judgement). '+', '++', '+++' indicate an enhancing effect and '-', '--', '---' indicate a diminishing effect. TP: total phosphorus; TN: total nitrogen; TS: total solids; H2O: water; ND: not defined.

Affecting factors	Recovery				Loss		
	TP	TN	TS	H2O	To air	To the soil and ground water	To surface water
Length	--	--	--	--	ND	ND	ND
Sources (functional group FG U)	++	+++	++	+++	ND	++	+
Level of containment in storage technology, i.e. how contained is it (FG S, e.g. single pit versus dehydration vault)	--	---	--	--	+++	+++	ND
Level of containment in treatment technology (FG T, e.g. drying bed versus biogas digester)	ND	---	---	ND	+++	+	ND

5.4.2 Relevance of the results

The above findings are based on generic data from the literature and therefore likely to be relevant input for strategic planning in general. Furthermore, they could also contribute to the design of future technologies or to the development of policies and decision support tools. The generic datasets contain the technologies and systems, the considered substances, inflows per capita, and transfer coefficients and their uncertainties.

Technologies and system configurations: The set of technologies covers a broad range of currently available concepts (onsite/offsite/decentralized, nature-based/advanced, dry/wet, etc.). Consequently, the generated system configurations also cover almost the entire diversity defined by the system templates (see also (Spuhler et al., 2018).

System templates: The system templates are efficient in describing the diversity of systems in terms of technological concepts. However, they fail to predict resource recovery. This leads us to ask whether a more performance-based characterisation of systems would contribute to a more streamlined strategic planning process. In this publication, we identify a set of factors for resource recovery which could be used to implement such a performance-based characterisation and to render templates useful for the operationalisation of SDG 6. For instance, the factors would allow groups of templates to be defined based on different types of system requirements (e.g. high freshwater requirements versus low) or more importantly, on different types of recovery (e.g. nutrients versus energy).

Relevance of substances considered: In principle, our model could be extended to any substance. We have chosen substances which we rated as most relevant to the discourse on sustainable sanitation, water management, and resource recovery. Both TP and TN are important macronutrients with significant environmental pollution potential. TS can be used as a proxy for energy, for example, as briquettes or biochar (e.g. Andriessen et al., 2019; Motte et al., 2013), and as organic matter for soil amendment (e.g. Diener et al., 2014; Septien et al., 2018a). Principally, also the chemical oxygen demand (COD) or the exergy flow could be used. However, in most circumstance TS data are more readily available and more frequently used in the available case studies. Water in many urban areas is under increasing pressure and has become a scarce commodity.

Inflows: As for the other input data, we used generic data from literature for a reference case of a city zone of 1000 people to quantify inflows (e.g. centre of an emerging small town in Nepal). These inflows could be adapted to reflect local specifications related to diet (nutrient intake), water volumes used for flushing or the number of inhabitants. However, the mean recovery ratio as well as the standard deviation, would not change and therefore these results can also be reused directly in any other case.

Transfer coefficients (TCs) and uncertainties: A major strength of our approach is the quantitative integration of literature data in the form of TCs. The data in the library are based on an extensive literature research, complemented with expert knowledge. It represented a compact and accessible overview of the currently available knowledge on the performance of diverse set of sanitation technologies and makes it available for almost any application ([dataset] Spuhler and Roller, 2020). Confidence in knowledge about the performance of a specific technology is reflected in the defined variability ranges. This approach has two main advantages. First it allows to use a large body of knowledge. Second, it enables the evaluation of the robustness of the final results based. This can be illustrated with the transfer coefficients for phosphorus and nitrogen in the single pit. Based on our literature data we found a median P loss to soil of 71 % and a variability range of almost 40 %. This high literature data variability is due to the uncertainty about the technology implementation (e.g. how sealed is it?), the local context (e.g. climate) and most importantly the inflowing product (dilution of the products). Considering not only the median but the variability range as well allows to safeguard this knowledge in the simulation. The uncertainty reflects in the standard deviations of the resource recovery of the entire systems which in this case are almost as high as the recovery ratio itself. This was shown for system 11 in a didactic example presented in Spuhler et al., (2020c). Nevertheless, it is important to note that the coefficients presented here may not be fully representative of all possible conditions in the world, especially for complex processes that can vary greatly depending on context.

Due to the generic approach, both the resource recovery potentials and the key influencing factors generalize well. We see three possible use for the results in practice:

1. As an input into strategic sanitation planning either to pre-screen for resource efficient systems or systems with low emissions during the pre-planning phase. For instance, if sensitive urban water bodies require protection, systems with high nitrogen or phosphorus water losses could be eliminated from the beginning. Or in the case of a demand for organic fertiliser, systems with high nutrient recovery potentials could be preselected (see also Spuhler et al., 2020c). Obviously, the resource recovery and loss potentials are not the only performance indicator for sustainable sanitation but should be evaluated simultaneously with other important indicators such as hygiene, economic and financial viability, and technical, institutional and socio-cultural appropriateness (e.g. Bracken et al., 2005; Spuhler et al., 2020a; SuSanA, 2008). In Spuhler et al., (2018) we provide a method to evaluate the technical, institutional and socio-cultural appropriateness.
2. The key factors for resource recovery and the four recommendations for their optimisation could be used for the fine-tuning of systems during the detailed planning and implementation phase. For example, the length of the system could be optimised with the combination of different recovery sinks.
3. The key factors and recommendations could also guide researchers or technology developers working on future innovations. For instance, the recommendations for resource recovery could be used to guide the development of containment and treatment technologies that minimise losses.

Above these direct practical applications, we also see a potential of the presented approach to be used by researchers or technology developer. The potential recovery potentials of a novel technology could be pre-evaluated by first generating valid system configurations and then quantifying potential recovery ratio. This aspect is discussed on in Spuhler et al., (2020c).

5.4.3 Outlook

The most obvious next step would be to make the results available to practice, an interactive user interface could be developed with different use cases. For instance, one could submit a technology and its transfer coefficients and would get back possible system configurations and phosphorus recovery potentials. Translating the influencing factors into guidelines for future technology development is another way of dissemination as described in the relevance chapter. Attempts to summarize the results with easy to interpret decision guidance for option selection were not very successful, as shown in the example decision tree shown in SI Figure 15 in the supplementary information. This hints to highly interlinked influence factors.

Another exciting future activity includes the expansion of the technology library with additional products (e.g. greywater, stormwater, or organic solid waste) and technologies (e.g. black solder flies, vertical gardens, etc.). This would allow to analyse the resulting systems and their recovery and loss potentials and to complete the set of recommendations provided here.

5.4.4 Limitations

It is important to note that the models used to produce the presented data are based on a number of simplifications that include the very generic definitions of technologies and products. Consequently, the substance transfer coefficients which are defined for each technology and product are also impacted by these simplifications. Therefore, systems must be checked by an expert for plausibility when they are being seriously considered as planning options. An example is the treatment of faeces alone in a biogas reactor; it would not make much sense from an engineering perspective, while it would make sense if sludge and e.g. organics are also digested in the same reactor. Another example concerns transfer coefficients: soil loss in a single pit could be defined much more accurately if one would know whether the input product is moist (excreta with pour flush water) or dry (pure faeces). Consequently, the approach is suitable for strategic planning but not for detailed design and implementation of a specific sanitation system.

Modelling substance flows based only on TCs is clearly a simplification, as it excludes possible substance generation, (e.g. through biological fixation, see also Spuhler et al., (2020c)). For most technologies, this limitation is not relevant. A more detailed approach would substantially increase computational demand and the collection of comparable parameters from literature would also be difficult. Another simplification is the assumption of fault free implementation, operation, and maintenance of the technologies.

Importantly, these simplifications allow the automation and generalization of the model application. Consequences of the simplifications are captured in the uncertainty calculations. The user is free to be more specific in the technology and product definition (e.g. make different types of single pits for different products), or to use more complicated TC models if more accuracy is needed.

— 5.5 CONCLUSIONS AND OUTLOOK

- Nutrient, water, and total solids recovery potentials and losses to the environment are relevant indicators in evaluation of the sustainability of different sanitation options. By analysing a large set of system options representative for almost the entire option space we could: (1) quantify resource recovery and loss potentials that are generic and can be used to influence technology design or strategic planning; and (2) identify characteristics of sanitation systems that provide information on potential resource recovery and losses and can be used to orient future technology and system development.
- The consideration of a large body of international literature data and expert knowledge to generate is the results is enabled through a novel approach to consider uncertainty.
- Factors influencing recovery are related to the interaction of different technologies in a system. For instance, even if a sink technology could potentially recover 99% of inflowing substances, the recovery of the entire system will depend on the fraction of substances that actually arrives at this specific sink. This means that resource recovery potentials have to be looked at on a system level and not at an individual technology level. It also justifies such a modelling approach that allows to look at all possible configurations.

- Factors influencing resource recovery are: source and sink technologies, the length of the systems, and the storage and treatment technologies and their level of containment. Moreover, five key recommendations for the optimization of resource recovery from sanitation systems are developed: (i) prioritize short systems that close the loop at the lowest possible level (fewer treatment steps, less losses); (ii) separate waste streams as much as possible, because this does not lead necessarily to fewer treatment steps, but it allows for higher recovery potentials, (e.g. through urine diversion); (iii) use storage and treatment technologies that contain the products as much as possible, avoid leaching technologies (e.g. single pits) and technologies with high risk of volatilization (e.g. drying beds); (iv) design sinks to optimise recovery and avoid disposal sinks; and (v) combine various reuse options for different side streams (e.g. urine diversion systems that combine reuse of urine and production of biofuel from faeces).
- The comparative analysis also showed that system templates are very efficient in describing technological diversity but not in providing indicators on resource recovery. This leads to the question of whether the concept of system templates should be adapted in order to become more performance based and thereby more useful for the strategic planning process in line with SDG 6. The factors for resource recovery which we present here could be used to implement such a performance-based characterisation, for instance, based on different types of recovery (e.g. nutrients versus energy).
- In order to make the generic resource recovery potentials available for practice, an interactive interface could be developed that would allow browsing and extracting results for a specific system. For instance, one could submit a given system configuration and the number of inhabitants of its area to receive the specific resource recovery potentials. Or one could provide a number of technologies and explore which systems could be used and find their respective resource recovery potentials. The same could be done to explore loss potentials as indicators for environmental pollution.
- Another straightforward extension of the approach would be to include additional substances (e.g. potassium), technologies (e.g. future innovations), or product streams (e.g. solid waste or storm water).
- Future research activities could look at the potential quantification of performance indicators other than resource and loss potentials. For instance, the mass flows within a system could feed into technology-specific costing functions as discussed in Spuhler and Germann, (2019). This would allow the exploration of economies of scale.

— 5.6 ACKNOWLEDGEMENTS

This work was funded by the Sawiris Foundation for Social Development through the Engineering for Development (E4D) programme of the Swiss Federal Institute for Technology (ETH) Zurich. The authors are very grateful to the inhabitants of Katarniya (Nepal), Mingma and Anjali Sherpa from 500B solutions, and Agnès Montangero from the Swiss Water and Sanitation Consortium for enabling field testing of our methods. They also gratefully acknowledge the contributions of Leandra Roller for the collection of raw data, the estimation

06 Developing sanitation planning options: a tool for systematic consideration of novel technologies and systems

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Pubilshed in

Preprint (submitted 18.06.2020)
Spuhler, D., Germann, V., Kassa, K., Ketema, A.A., Sherpa, A.M., Sherpa, M.G., Maurer, M., Lüthi, C. and Langergraber, G. 2020. Developing sanitation planning options: a tool for systematic consideration of novel technologies and systems. Journal of Environmental Management 271. DOI: 10.1016/j.jenvman.2020.111004.

Supplementary material

Data package including supplementary material:
https://doi.org/10.25678/0001QJ

Author contributions: D.S., M.M., C.L., and G.L. conceptualized this publication together. D.S. and V.G. were responsible for data curation, formal analysis, and visualisations. D.S., M.M., and V.G. were responsible for funding acquisition. The methodology was developed by D.S. with contributions from A.K., M.S., and Andreas Scheidegger (AS). D.S. administered the project and developed the underlying software with the support of A.S.. The original draft was written by D.S. with contributions from G.L., C.L., V.G., K.K., and M.S. G.L., CL., and M.M. supervised the process.

HIGHLIGHTS

→ Santiago software provides locally appropriate sanitation system planning options

→ The procedure for integrating Santiago into structured decision making is presented

→ Decision objectives and screening criteria are defined in participatory workshops

→ International data is matched with local conditions to evaluate appropriateness

→ Appropriate options for all areas are provided by considering novel technologies

ABSTRACT

To provide access to sustainable sanitation for the entire world population, novel technologies and systems have been developed. These options are often independent of sewers, water, and energy and therefore promise to be more appropriate for fast-growing urban areas. They also allow for resource recovery and and are adaptable to changing environmental and demographic conditions what makes them more sustainable. More options, however, also enhance planning complexity. Structured decision making (SDM) can help balance opposing interests. Yet, most of the current research focuses on the selection of a preferred option, assuming that a set of appropriate options is available. There is a lack of reproducible methods for the identification of sanitation system planning options that can consider the growing number of available technology and the many possible system configurations. Additionally, there is a lack of data, particularly for novel options, to evaluate the various sustainability criteria for sanitation. To

overcome this limitation, we present a novel software supported approach: the SANitation sysTem Alternative GeneratOr (*Santiago*). To be optimally effective, Santiago is required to be integrated into an SDM approach. In this paper, we present all the elements that such an integration requires and illustrate these methods at the case of Arba Minch, a fast growing town in Ethiopia. Based on this example and experiences from other cases, we discuss the lessons learnt and present the advantages potentially brought by Santiago for sanitation planning The integration requires four elements: a set of technologies to be looked at, decision objectives for sustainable sanitation, screening criteria to evaluate technology appropriateness, and about the technologies and the case. The main output is a set of sanitation system options that is locally appropriate, diverse in order to reveal trade-offs, and of a manageable size. To support the definition of decision objectives, we developed a generic objective hierarchy for sustainable sanitation. Because one of the main challenges lies in the quantification of screening criteria, we established the data for 27 criteria and 41 technologies in a library. The case studies showed, that if the integration is successful, then Santiago can provide substantial benefits: (i) it is systematic and reproducible; (ii) it opens up the decision space with novel and potentially more appropriate solutions; (iii) it makes international data accessible for more empirical decision making; (iv) it enables decisions based on strategic objectives in line with the sustainable development goals; (v) it allows to prioritise appropriate and resource efficient systems right from the beginning (vi) and it contributes to a more citywide inclusive approach by bridging strategic objectives with an area-based appropriateness assessment. The here presented approach enables the prioritisation of appropriate and resource efficient sanitation technologies and systems in strategic planning. Thereby this approach contributes to SDG 6.2, 6.3, and 11, sustainable sanitation for all.

— 6.1 INTRODUCTION

Lack of sanitation is linked to reduced health and environmental degradation, and undermines social and economic development (Hutton and Varughese, 2016). The Sustainable Development Goals (SDGs) confirm the critical importance of water and sanitation for sustainable development, with explicit reference to management downstream, resource efficiency and participation of local communities (UN, 2014). Despite these efforts, 55% of the global population did not use safely managed sanitation services in 2017 (UN, 2019), half of which was in cities (WHO and UNICEF, 2019).

One of the reasons for this is that the unprecedented growth, in informal settlements and small towns of the developing world, far exceeds the capacities of administrations (Lüthi et al., 2010; UN-HABITAT, 2003). 70% of the world population is projected to live in urban areas by 2050 (Birch et al., 2012), and over 90% of urban growth will take place in developing countries, mainly in informal settlements and slums (UNFPA, 2007).

6.1.1 A strategic sanitation planning approach

In fast growing urban areas of developing countries, challenges of sanitation provisions are exasperated by the high population and building density, a high degree of informality, and a lack of administrative and financial capacities for planning, implementing, and operating safe sanitation (Dodman et al., 2017; Isunju et al., 2011; Tremolet et al., 2010; UN-HABITAT, 2012). Conventional sanitation systems, which consist of a flush toilet, a sewer system, and hopefully a treatment plant at the end, are often not viable because sewer networks are very costly and require large quantities of water, stable institutions, and long-term planning horizons (Larsen et al., 2016). If facilities exist, they are limited to simple onsite infrastructure, such as basic latrines or septic tanks, without collection and treatment of generated waste products downstream (WSP, 2014). 80% of sludge and wastewater are currently being discharged globally without appropriate treatment (WWAP, 2017).

Already in the 1970ies in the World Bank's low-cost sanitation research project (1976-78) it was recognized that a top-down sewerage master plan approach will not help to solve the sanitation crisis in the global South. The project advocated for a more strategic sanitation approach (SSA), which plans for incremental improvement and engages with multiple actors in order to identifying technologies that are locally appropriate (Kalbermatten, 1982; Kalbermatten and Middleton, 1999; Middleton and Kalbermatten, 1990; Tayler et al., 2003; Wright, 1997). An appropriate technology is one that provides a socially and environmentally acceptable level of service, at affordable cost (Iwugo, 1979). This can be translated into technical, physical and demographic, socio-cultural, capacity and managerial, legal, as well as financial criteria (Spuhler et al., 2018).

Several strategic planning were in the following developed and tested but were never scaled up due to the technical and financial support required (Wright, 1997). As an answer to the Household-Centred Environmental Sanitation (HCES) approach (Eawag, 2005; Schertenleib, 2005) was formulated and piloted (Lüthi et al., 2009b) but this approach did not achieve the scope of citywide sanitation.

6.1.2 Sustainable sanitation

At the same time in 2008, the Sustainable Sanitation Alliance put forward its vision, defining sustainable sanitation systems as those that not only provide appropriate technologies that protect human health and the environment but are also economically viable, socially acceptable, and institutionally applicable (SuSanA, 2008). This definition and the five criteria for sustainable sanitation (health, protection of the environment and natural resources, economic viability, technological and institutional appropriateness, socio-culturally acceptance) opened the door for the integration of multi-criteria decision making into the planning approach (Kvarnström et al., 2004; Spuhler et al., 2018). Moreover, it challenged the sector to shift the focus from end-of-pipe treatment towards closing cycles in order to protect people downstream and for the recovery and reuse of resources. SuSanA also pushed a systems approach to enforce the management of sanitation products downstream and to highlight the need for a combination of compatible technologies from the point of generation to a final point of reuse or disposal (Maurer et al., 2012; Spuhler et al., 2018; Tilley et al., 2014b). The sanitation system is often also referred to as the "sanitation service chain" or "sanitation value chain" that is a systemized representation including "containment - emptying - conveyance/transport - treatment - re-use/disposal" and allows visualization not only of the technological aspects but also of the services and business model required for safe operation.

6.1.3 Citywide inclusive sanitation

With the SDGs, in particular SDG 11, the demand for sustainable sanitation was extended with a call for a more 'inclusive' approach (UN, 2014). This new urban sanitation agenda is laid out in the Manila Principles of Citywide Inclusive Sanitation (CWIS, BMGF, 2017; Gambrill et al., 2019). The CWIS principles advocate an approach to urban sanitation where all members of the city have equitable access to adequate and affordable improved sanitation services through appropriate systems of all scales, without any contamination to the environment along the entire sanitation service chain (Narayan and Lüthi, 2019a). The term 'inclusive' encompasses informal and peri-urban, sewer and non-sewer technologies, the entire value chain, all stakeholders, larger urban goals, and all groups of society, without marginalisation based on gender, disability, or low-income (Narayan and Lüthi, 2019a).

6.1.4 Technology and system innovation

The increasing recognition of a need for more strategic, appropriate, sustainable, and inclusive solutions has triggered massive investments in the development of novel technologies (e.g. urine diversion dry toilets) and innovative system configurations (e.g. container-based sanitation). Being independent from energy, water and sewer networks, these novel technologies and system innovations are more appropriate for developing urban areas. They also have the potential to enhance sustainability and resilience by reducing water requirements, being more adaptable for socio-demographic and environmental changes, and allowing recovery of nutrient, energy, and water resources (Diener et al., 2014; Larsen et al., 2016; Tilmans et al., 2015; Tobias et al., 2017). They also expand opportunities for private sector involvement in the collection and safe reuse of resources (Evans et al., 2013; Murray and Ray, 2010; Schertenleib, 2005). This "Reinvent The Toilet Challenge"[1] has significantly influenced the sanitation sector and the potential of novel sanitation has also been recognized in high-income countries, where the focus is on optimising aging infrastructure. Today, there is global consensus that sanitation technology and system innovations need to find their way into practice.

6.1.5 Structured decision making (SDM)

While sanitation innovations potentially enhance sustainability and inclusiveness, they also enhance planning complexity. From a decision-making viewpoint, selecting a locally appropriate and sustainable sanitation system and its corresponding technologies is a complex multi-criteria decision-making problem (Bracken et al., 2005; Kvarnström and Petersens, 2004; Zurbrügg et al., 2009). Structured decision making (SDM) helps tackle such problems by systematically comparing several decision options regarding the defined decision objectives in order to reveal trade-offs and balance for opposing interests using Multi-Criteria Decision Analysis (MCDA). This leads to more strategic but also more informed and thus more accepted decisions. The facilitated participatory framework covers at least six steps generic to any decision making process (Gregory et al., 2012): (1) understanding the decision context; (2) defining decision objectives and criteria; (3) identifying decision options/alternatives; (4) evaluating consequences of the options for decision objectives; (5) discussing the trade-offs and selecting for the preferred options; and (6) implementing and monitoring.

Different SDM approaches for strategic sanitation planning have been developed including Community-Led Urban Environmental Sanitation (CLUES, Lüthi et al., 2011a), Sanitation 21 (Parkinson et al., 2014), or City Sanitation Planning (CSP, GoI, 2008; MOUD, 2008). Despite the continuous development of these theoretical foundations, there is a lack of putting them into practice (Kennedy-Walker et al., 2014; Ramôa et al., 2018; Starkl et al., 2013). Missing leadership and lack of knowledge of new approaches leads to the propagation of outdated solutions which are locally inappropriate (Kennedy-Walker et al., 2014; Lüthi and Kraemer, 2012; McConville, 2010). To facilitate the adoption of SDM frameworks, recent research has focused on the development of tools to operationalize the different planning steps (Spuhler and Lüthi, 2020). Yet, most of the research focuses on the understanding of the problem (step 1 and 2 of SDM), (Peal et al., 2014a; Robb et al., 2017; Strande et al., 2018) or the selection of a preferred option (step 5 of SDM), (Schütze et al., 2019), assuming that a set of options is already available. Yet, every decision support approach is only as good as the alternatives presented. Typically, the creation of sanitation decision options (step 3 of SDM) is left over to engineers who lack data and systematic reproducible evaluation methods for considering the entire spectrum of currently available technologies and sustainability criteria (Spuhler and Lüthi, 2020). This introduces a whole range of shortcomings, such as insufficient knowledge and data leading to bias, opaque pre-selection processes based on experts' personal preferences and little local ownership.

6.1.6 Aim of this publication

The lack of suitable methods for the systematic generation of locally appropriate sanitation systems is one of the biggest weaknesses in strategic urban sanitation planning (Gregory et al., 2012; Hajkowicz and Collins, 2007) . Another shortcoming is the lack of quantification methods for important decision objectives such as resource recovery potential. In Spuhler et al., (2018) and Spuhler et al., (2020c) we present four algorithms that in combination can overcome these shortcomings. *Santiago* (SANitation sysTem Alternative GeneratOr) is a software that combines these algorithms and corresponding technology data to generate a diverse but manageable set of appropriate sanitation system configurations for a given case and that quantifies resource recovery potentials as an input into the detailed evaluation of the options. The main novelty of Santiago is that it is systematic and thus reproducible, it is generic and automated to deal with a large and diverse range of technologies and systems including novel options, and it accounts for uncertainty in order to be applicable at an early planning also for novel options.

To utilise the full strength of Santiago, it should be integrated into a facilitated and participatory process such as SDM. The aim of this publication is to present a full method description of how Santiago can be applied integrated into an SDM planning process and to discuss potential advantages brought along with this application. Santiago and the integration procedure including the needed interaction with stakeholders are presented in the methods sections. In the results section we illustrate in detail the application of these methods at the example of Arba Minch, a rapidly growing town of roughly 100’000 inhabitants in the South of Ethiopia. We also briefly summarise the experiences from other application cases in order to discuss the lessons learnt that are generalisable for any future application of Santiago and to present the advantages potentially brought by Santiago for sanitation planning in the future.

— 6.2 METHODS AND APPLICATION CASE

6.2.1 Santiago

Santiago (SANitation sysTem Alternative GeneratOr) is a software that combines algorithms and corresponding technology data that are described in detail in Spuhler et al., (2018), Spuhler et al., (2020c) and in supplementary information SI-A. Here we present a very condensed summary of the essential characteristics of Santiago. Santiago integrates four algorithms (also depicted in Figure 6.1 on the left side):

1. For the identification of all appropriate sanitation technologies from a set of potential ones based on list of criteria which are independent from stakeholder preferences and thus non-negotiable and therefore can be used for screening of appropriate technologies.
2. For the generation of all possible and valid sanitation system configurations (typically more than 100'000) using the appropriate technologies. A valid sanitation system is defined as a set of compatible technologies which, in combination, ensure that all sanitation products (e.g. excreta, sludge, blackwater) are either transferred, transformed, or end up in a sink.
3. For the selection of the desired number of appropriate system configurations from all generated options. The selection covers the full diversity of the sanitation system options space defined by 19 system templates grouped into simple onsite, urine diversion, biofuel, or blackwater systems.
4. For the modelling of substance mass flows along entire systems in order to quantify resource recovery potentials and environmental emissions for nutrients, organics, energy, and water.

The diverse set of locally appropriate sanitation system options is the main output of Santiago, which is passed over to the SDM process for further evaluation, discussion of trade-offs, and selection of the preferred options using any kind of facilitated MCDA method (steps 5 and 6 of SDM). Resource recovery and loss potentials provide some of the relevant performance indicators for this further evaluation. The options cover the technological aspect of the system only; aspects related to management and service delivery are to some extend considered in the appropriateness assessment.

The appropriateness assessment explicitly accounts for uncertainties related to the technologies or the local context and quantifies the appropriateness in a score between 0 and 100% expressing the confidence in how appropriate a technology is given the available data and information. The uncertainties of transfer coefficients (e.g. due to technology implementation or different qualities and quantities of inflow products) are also considered and represented in the standard deviations of the results from the substance flow modelling.

The algorithm for the technology appropriateness assessment (is implemented in R (R Development Core Team, 2018) and is accessible at https://github.com/Eawag-SWW/TechAppA (v1.0). The algorithms for system generation, system selection, and substance flow modelling are implemented in Julia (Bezanson et al., 2017) and are accessible at https://github.com/Eawag-SWW/SanitationSystemMassFlow.jl (v1.0). A copy of all four algorithm, along with the input and output data from the application case are available in the associated data package at ERIC: https://doi.org/10.25678/0001QJ ([dataset] Spuhler, 2020b).

Santiago also comes with a technology library which covers 41 technologies which can be combined to more than 100'000 valid system configurations. The 41 technologies are based on Spuhler et al. (2018) and Tilley et al. (2014) and are complemented with a few promising novel options: e.g. 'vermi-composting' as used by the Biofil toilet (Amoah et al., 2016a; Lalander et al., 2015), 'struvite precipitation', and 'struvite application' (Dalecha, 2012), liquid urine fertilizer ('Aurin') production and application (Etter et al., 2015a), 'briquetting' (based on the process implemented by Sanivation in Naivasha (Jones, 2017), and 'Latrine Dehydration and Pasteurization', LaDePa, (Septien et al., 2018b). For each of the technologies, the library also provides international literature and expert data for 27 screening criteria to be used for the appropriateness assessment and transfer coefficients for four substances (total phosphorus, total nitrogen, water, and total solids) to be used for substance flow quantification. Internationally valid inflow masses for the four substances (per person and year) are also made available. But these inflow values could be adapted if local data is available. The technology library is available as a descriptive document that also contains all literature references as well as in an editable table that can be directly read by the algorithms. Any new technology can be added to the table following the instructions provided in the descriptive document. The resources are available in the data package associated with Spuhler et al., (2020c): ([dataset] Spuhler and Roller, 2020) at ERIC: https://doi.org/10.25678/0000ss.

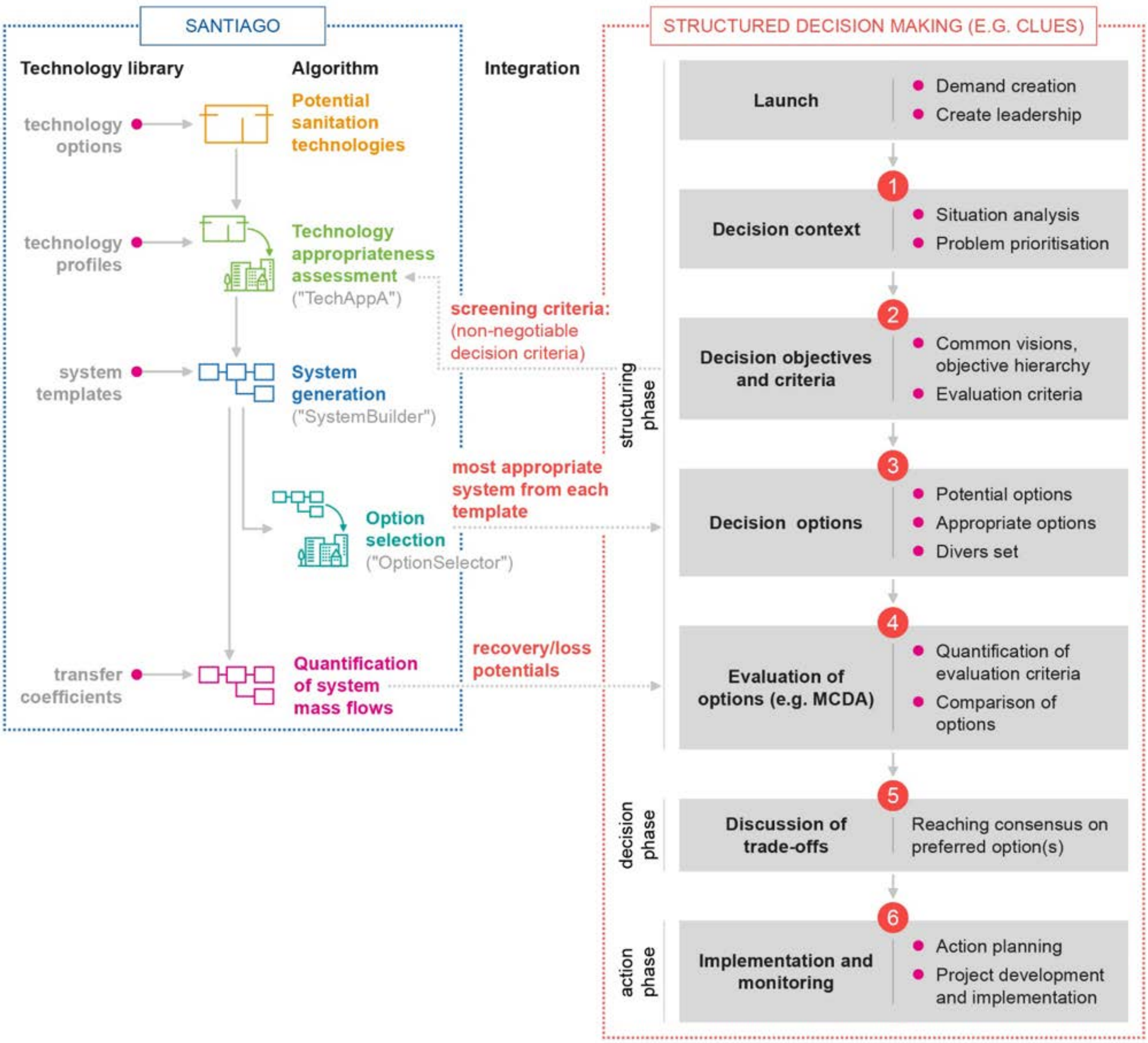


Figure 6.1: Integration of the SANitation sysTem Alternative GeneratOr (Santiago) and the Structured Decision Making (SDM) approach which happens at two stages. First, the decision objectives are used to derive screening criteria which allows assessment of the appropriateness of potential sanitation technologies for the given application case. The potential technologies are characterized in the technology library. Then, Santiago generates all possible system configurations, calculates their appropriateness scores, and identifies the most appropriate system from each template to be handed over to the decision-making process. Optionally, it can also quantify resource recovery potentials and environmental emissions as inputs into further evaluations.

6.2.2 Integration of Santiago into a Structured Decision Making Process

The integration of Santiago into a regular SDM planning process happens at steps 2, 3 and 4 (see Figure 6.1). In SI-B, we provide an overview of all SDM steps. Here we describe the three elements that are needed to apply Santiago:

1. A list of screening criteria that can be used to identify technologies appropriate for the given context. Screening criteria are derived from the overall decision objectives and cover criteria that are non-negotiable, meaning they are objective, fixed, and typically exogenously defined. Non-negotiable criteria are often environmental factors (e.g. groundwater table, water availability), socio-demographic factors (e.g. population density), as well as capacity-related factors (e.g. availability of spare parts).
2. Evaluation data to characterize the application case and technology profile for the screening attributes.
3. The number of sanitation system decision options that can be managed. This number lies somewhere between three to 50 options and depends on the model complexity of methods used in steps 4 and 5 of the SDM process to deal with more or fewer options.

6.2.2.1 Screening criteria and decision objectives

The screening criteria as a subset of the overall decision objectives for sustainable sanitation planning are obtained in two steps:

1. **Decision objectives:** the objective hierarchy and the corresponding evaluation criteria for the given context are established by combining locally-defined objectives with a generic objective hierarchy for sustainable sanitation as shown in Figure 6.2 and further detailed in SI-C.
2. **Screening criteria:** the evaluation criteria are sorted into negotiable and non-negotiable criteria. The criteria useful for screening are the ones which are non-negotiable criteria (exogenously defined, independent from stakeholder preferences) and for which enough information and data are available at the structuring phase (see SI-D, Figure 11 and Figure 12). Negotiable evaluation criteria serve as a basis for the MCDA in a later step of SDM. A master list of screening criteria is provided to make sure that no relevant criteria are omitted.

The generic objective hierarchy and master list of screening criteria are available in Figure 6.2, SI-C, and SI-D. These are based on a broad literature review (e.g. Balkema et al., 2002; Bracken et al., 2005; Dunmade, 2002; Kvarnström et al., 2004; Kvarnström et al., 2011; Montgomery et al., 2009; Muga and Mihelcic, 2008; Palme et al., 2005; Sahely et al., 2005; SuSanA, 2008; van Buuren, 2010; Willetts et al., 2013) and completed with expert interviews. The aim of these resources is to use international expertise in order to produce a more empirical outcome (Bond et al., 2008). These lists are not intended to be taken without discussion and should be adopted from local stakeholders and adapted to their specific needs. In the case studies we organised one or two multi-stakeholder workshops to obtain the locally contextualise decision objectives and screening criteria. Stakeholders included interested citizens from the community, experts (consultants, academia), government representatives, and local and international non-governmental organisations. The composition of the group of stakeholders determines how much the decision objectives are supported by actors from different levels (e.g. community, municipality, region). We suggest a workshop procedure of six steps to obtain suitable inputs for Santiago (based on Gregory et al., (2012) and Bond et al., (2008):

1. Brainstorming decision objectives for sustainable sanitation (facilitated using e.g. coloured cards and a flip chart).
2. Structuring objectives and comparing with the generic objective hierarchy. This can be done by e.g. clustering similar objectives and providing them with cluster names similar to the generic objective hierarchy. The moderator might also suggest adding objectives from the generic hierarchy which were previously omitted.
3. Brainstorming non-negotiable and negotiable criteria and attributes (in smaller groups, ideally with a moderator). Groups might be split according to the highest-level objectives (e.g. health, environment, technology, governance, finance).
4. Testing non-negotiable criteria for the fulfilment of the basic requirements for screening: data is available at the structuring phase, exogenously defined, independent from stakeholder preferences (also done in groups).
5. Comparing the resulting list of screening criteria with the master list (all together).
6. Establishing a merged list of screening criteria (can be done with a smaller task force after the workshop).

The workshop outcomes strongly depend on good orientation of the participants at the beginning and skilled moderation. One way to start off the brainstorming is to look at the main problems identified in an earlier SDM step and to test different objectives that describe these problems as deficits in regards to the current state and the state to which people would aspire (Reichert et al., 2015). Means-ends analysis and cognitive mapping can support this process.

After the workshops we went through the list once again with a few key stakeholders in order to check whether the criteria were really non-negotiable and independent from preferences, and if data was available. At the end, the list of screening criteria was reduced to the 20 most important criteria. More criteria would have reduced the robustness of the screening outcome, as we use the geometric mean for aggregation (Grabisch et al., 2011; Spuhler et al., 2018). We checked overlap between objectives in order to develop composite criteria or to decide which to delete (e.g. operation and maintenance skills and operation and maintenance frequency). To structure the screening criteria, we used five categories which are legal, technical, physical, demographic, social and and capacity and management-related (Goldhoff, 1976; Iwugo, 1979; Kalbermatten et al., 1980), see also SI-D Figure 11 and Figure 12 (based on Spuhler et al., 2018).

It is also worth mentioning that some screening criteria include both, non-negotiable as well as negotiable aspects. For example, to be appropriate, a potential technology should not have water needs that exceed water availability. Additionally, among the appropriate technologies, those having lower water use, in a context where water is scarce, are potentially more sustainable, information that would be relevant for the detailed evaluation of the options in step 4 of SDM.

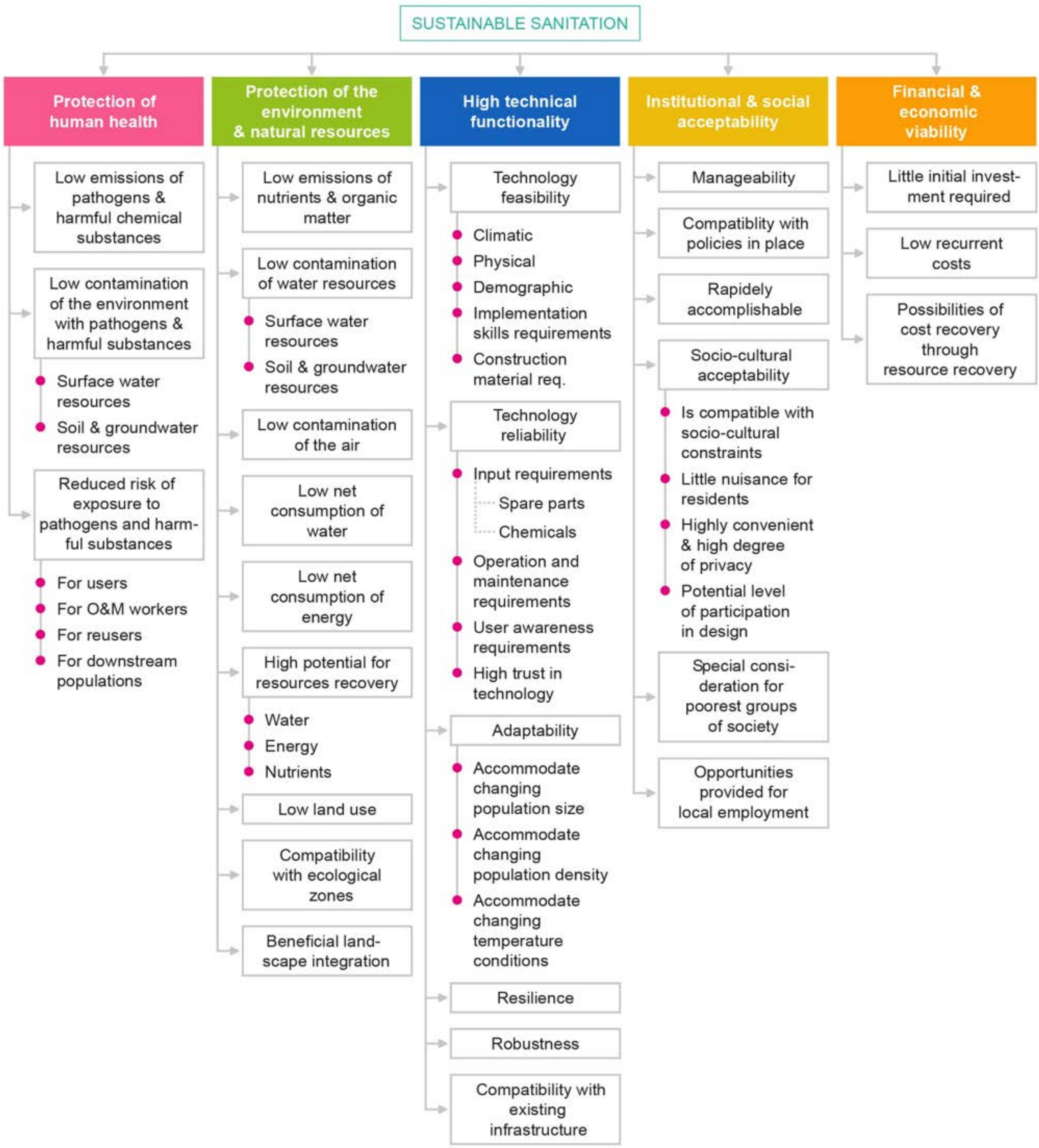


Figure 6.2: Objective hierarchy for sustainable sanitation based on the five sustainability criteria of the Sustainable Sanitation Alliance (SuSanA, 2008) and a broad literature review (Spuhler et al., 2018). The list of corresponding evaluation criteria is available in SI-C. For the application of Santiago, the objectives and corresponding criteria are classified into non-negotiable and negotiable criteria. The non-negotiable criteria can be used for the screening of appropriate sanitation technology and systems. Negotiable criteria are the basis for the detailed evaluation in a later step of the decision-making process.

6.2.2.2 Evaluation data: technology profiles and application case profiles

Each screening criterion consists of a pair of “technology attribute” and “application case attribute”. The appropriateness of a technology for a given screening criterion is evaluated by matching the two attributes (e.g. the performance of a technology given a certain water availability is compared to local water availability). To account for the different areas within a city (e.g. centre, informal dense, peri-urban), different case profiles are established. To account for uncertainties related to the context or the technology, probability functions are used to quantify the attributes. By aggregating all criteria scores for a given technology and application case, the technology appropriateness score (TAS) is obtained. In principle, any uncertainty model could be used but it should fit the data (Spuhler et al., 2018). We recommend using rather simple models including triangular, trapezoid, uniform, and categorical distributions (Spuhler et al., 2018). For instance, if we know that a technology has a performance of 100% from 5 °C to 35 °C and 0% below and above we use an uniform distribution with a minimum at 5°C and a maximum at 35°C. The triangular function and the trapezoidal function works similarly but use additional data points. The categorical function is best applied when the data is not continuous and can be aggregated into different categories: e.g. 30% of the population has ‘low’ access to water, 50% has ‘moderate’ access, and 20% has ‘high’ access.

The technology library ([dataset] Spuhler and Roller, 2020) provides the profiles of 41 technologies and 27 screening criteria. The 27 screening criteria broadly cover the master list provided in SI-D. The library also provides sufficient information to add any additional screening criteria. It also includes guiding questions to establish the application case profiles based on the data available from step 1 of the SDM process (baseline assessment). This data can be completed with reports from previous projects, statistics, field visits, and key informant interviews. More sophisticated data collection methods, such as household surveys, should not be required for the application of Santiago.

6.2.2.3 Number of decision options and system templates

From 41 potential sanitation technologies, more than 100’000 valid can be generated. Many of them might be appropriate. At the other hand the number of systems that can be managed by the SDM process strongly depends on the evaluation methods used in steps 4 and 5 of SDM. In the case of a more sophisticated MCDA (e.g. using multiple−attribute value theory, MAVT), this number might be as high as 50. Whereas in a simple context, as described in CLUES, using a simple scoring method (Lüthi et al., 2011b), three to eight options are the most that can be dealt with (Gregory et al., 2012). Thus, the question remains, which of the appropriate systems should be pre-selected. Because the performance of the systems regarding the main decision objectives is expected to be highly variable (e.g. resource recovery, costs) the selected set of options needs to be diverse in order not to impact the final decision and to reveal mayor trade-offs between the main decision objectives. To characterise the diversity of the sanitation system option space, we use the 19 system templates shown in Figure 6.3. The system templates use 9 binary conditions to assign each system to one of the templates (Spuhler et al., 2020c). By selecting the most appropriate option from each template a set of locally appropriate sanitation systems which is of manageable size and diverse can be obtained.

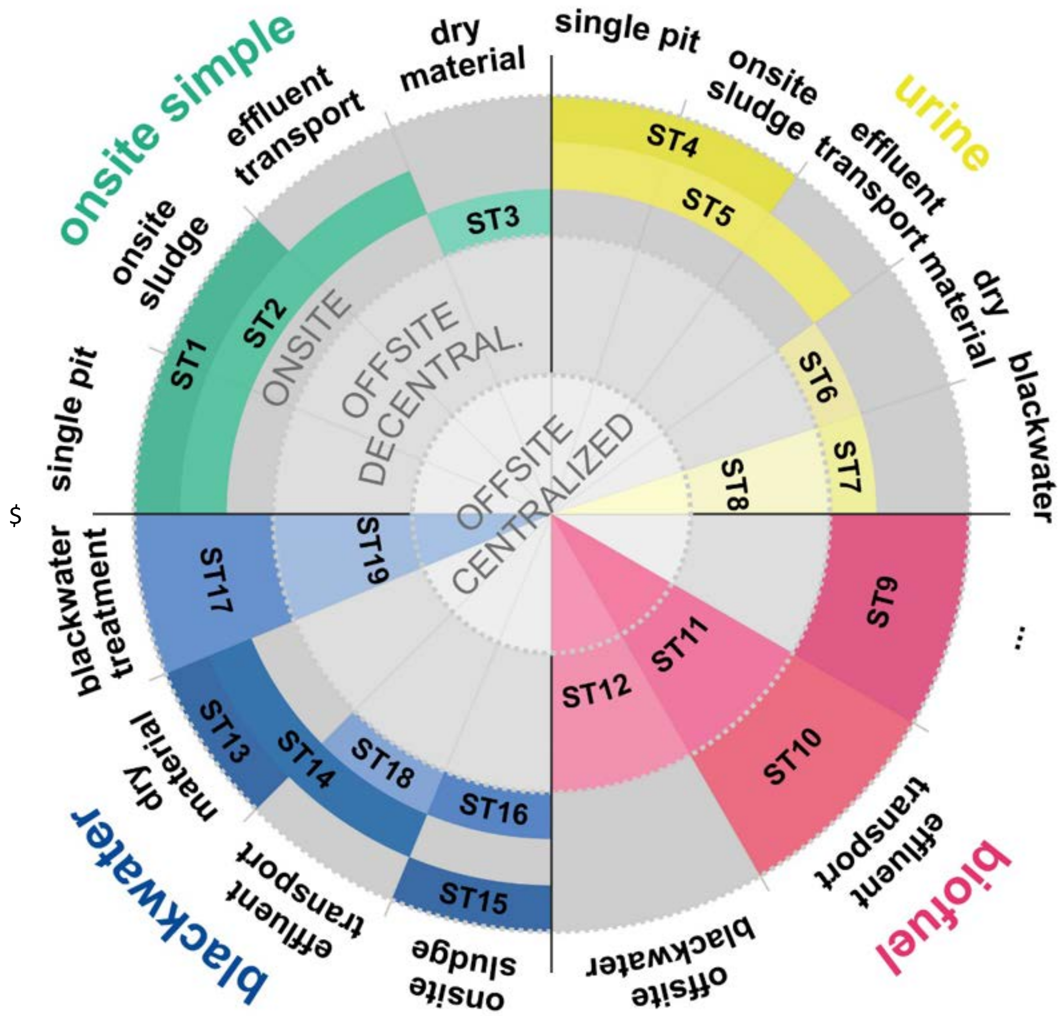


Figure 6.3: To characterise the diversity of the sanitation system option space we used nine binary conditions in order to define 19 different system templates that characterise systems according to different paradigms (onsite simple, urine diversion, biofuel, blackwater) and their degree of centralization. Note that modular systems integrating semi-centralized management of some products are considered as centralized.

6.2.3 Application case Arba Minch Town (Ethiopia)

To illustrate in detail the methods of Santiago and its integration we present the results and experiences of the application case Arba Minch, which are representative for many of the experiences made in total six case studies.

6.2.3.1 Background

The example is based on the application of Santiago that was implemented by the Swiss Federal Institute of Aquatic Science and Technology (Eawag) in collaboration with BOKU University Vienna, Arba Minch University (AMU) and Arba Minch Town Municipality (AMTM). Arba Minch, Ethiopia was selected because of the success of previous joint projects (Langergraber et al., 2010; 2014) which introduced novel technologies for resource recovery. These project payed little attention to the evaluation of the scalability for citywide services and ownership at AMTM. Therefore, in 2015, AMU involved key persons from AMTM in the preparation of a Strategic Sanitation and Waste Plan (SSWP). With this, AMU laid the basis for the for a more strategic approach to sanitation planning, with the full commitment of the AMTM administration. The aim of applying Santiago in this context was to test how Santiago performs in terms of option generation and how it can contribute to the planning process.

6.2.3.2 Geography

Arba Minch is located in the southern part of Ethiopia and, in 2017, had a population of 114,570 inhabitants. With an annual growth rate of 4.5%, it is one of the fastest growing cities of Ethiopia (CSA, 2007). The area is large (56 km^2), with a low average density (approx. 2000 inhabitants per km^2). But most of the population is concentrated in the residential areas around the university. AMTM is part of the Great Rift Valley, and is bordered by the Abaya and Chamo lakes in the East, and by a mountain escarpment in the West. The topography is very diverse and combines both steep and undulating terrain of the upper town area and flat areas in the valley. It is divided into four sub-cities, which have been restructured into eleven administrative “kebeles” (smallest administrative zone).

6.2.3.3 Sanitation situation

The majority of households in Arba Minch have simple pit latrines with wooden floors. In the peripheral areas, open defecation is still practised; however it has decreased in recent years (Kassa et al., 2015; Teklemariam et al., 2007). Additionally, sanitation technologies like Fossa alterna, UDDTs, Arborloo, and co-composting were introduced in the previous research projects. The central part of Arba Minch is not serviced by a sewer network. Hotels, hospitals, university campuses often build and manage their own decentralized sewer-based treatment facilities. For instance, the main campus of AMU has its own sewer system combined with a set of waste stabilization ponds for treatment. In condominium houses (housing with three or four storey buildings), flushing toilets with septic tanks are common; however, most of them are not connected to any leach field or soak pit and are not emptied regularly and are therefore overflowing onto other housing areas. Currently private hotel owners selectively provide desludging services for the public because they have the equipment and see a business opportunity. Currently, a sludge drying bed is near completion at the southern part of the city, but insufficient budget allocation delays its completion. Manual emptying is very common and an important informal business, especially for poorly constructed pit latrines. Water is generally available from springs and three wells and distribution is mostly via yard or in-house connections.

The main challenges for improving the sanitation situation are rapid population growth due to migration from nearby rural villages, unfavourable soil conditions (primarily either loose black cotton or rocky soils), frequent flooding, lack of awareness of the importance of sanitation, and lack of operational and maintenance resources, including insufficient availability of desludging services (SMEC, 2018).

6.2.3.4 Key sanitation stakeholders

AMTM department of Sanitation, Beautification and Greenery and the health office are responsible for the regulation of onsite and non-sewer sanitation. Arba Minch Water Supply and Sewerage Enterprises (AWSSE) is responsible for the operation and management of the water supply, the sewer network, and centralized treatment plants (once they exist). Households without sewer connections (the majority of the town) are themselves responsible for constructing and operating pit latrines or septic tanks, and their emptying. The kebeles, together with the health offices, are responsible for health promotion campaigns, that are implemented by health extension workers and a number of community-based organizations. Other important stakeholders include the service providers (pit emptier, solid waste collectors, masons) and farmers (users of compost). The agricultural offices provide composting and biogas training. Federal and regional ministries for water resources and the ministry of health are responsible for legal and financial issues. AMU is involved in various international sanitation research projects, is responsible for the education of future water and sanitation engineers, and played a key role in the development of the SSWP.

6.2.3.5 Strategic sanitation planning

Traditionally, strategic sanitation planning did not exist in Arba Minch, mainly due to the lack of clearly allocated responsibilities and resources. Sewerage, which would fall under the responsibility of AWSSE, is not feasible. The AMTM sanitation department which is responsible for onsite sanitation is understaffed and underfunded and limits itself to regulation. Households have to take care of construction and emptying. Recently, AWSSE organized itself to take over the sludge drying bed and sludge truck management which promises an improvement of the emptying services in the future. The first citywide strategic planning attempt was the SSWP which addresses all of the SDM steps (see Table 7 in SI-E). Despite the contributions brought about by the SSWP, challenges related to the high technical personnel turn-over at the municipality, ownership, and lack of political will and financial resources persist. To implement the SSWP, strategic sanitation planning needs to be institutionalised through the allocation of responsibilities and resources.

— 6.3 RESULTS FROM THE PRACTICAL APPLICATION

6.3.1 Santiago inputs

6.3.1.1 Decision objectives

A first workshop to identify decision objectives was conducted with 32 participants representing the major stakeholders in Arba Minch town. Participants were grouped to work on different topics in a World café format (30 minutes each): decision objectives, stakeholder analysis, steps of SDM, and enabling environment. The decision objectives were then organised in a hierarchy with six upper level objectives with different weights defined using pocket voting: protection of health & the environment (21.5%), ensuring ownership (19%), ensuring sustainability (19%), capacity development (17%), monitoring and evaluation (14%), cross-sectional approach and responsibility (9.5%) (see also Table 8 in SI-E).

6.3.1.2 Screening criteria

Screening criteria were defined in a separate workshop using the workshop methodology described in the methods. During the workshop, 59 criteria were defined and organised in five groups: (1) financial, (2) technical and physical, (3) socio-cultural and demographic, (4) environmental, legal and institutional and (5) capacity and management, see details in SI-E. There were no major differences with the master list provided by Santiago, but some aspects were mentioned in much more detail. In the following weeks, we met with a number of key stakeholders individually to merge the workshop list with the master list and to reduce the number of criteria to become more practical and meaningful. The list of the resulting 19 criteria and an example of how they can be quantified is provided in Table 6.1.

Table 6.1: Example of input data required by Santiago. The screening criteria are translated in to questions in order to define for each criteria a technology and a case attribute and a corresponding uncertainty function making up the technology and case profiles. Only the examples of the case of Chamo (a kebele of Arba Minch) and vermi-composting (a technology from the functional group S) are shown. The use of 'd-' at the beginning of the function name refers to the density function, 'p-' refers to the conditional probability, 'cat' stands for a categorical function, 'triangle' refers to a triangular distribution, 'range' refers to a uniform distribution, and 'trapez' refers to a trapezoidal distribution. The technology is additionally characterised by it input and output products used to build entire systems and the transfer coefficients used for the substance flow modelling.

	Application case question	Case profile (Chamo)	Technology question	Technology profile (e.g. vermi-composting, functional group storage, S)
Screening criteria and attribute functions				
Water supply	Which water supply options are available? (house, yard, public, none on site)	dcat, c(house=0.1, yard=0.9, public=0, none=0)	What is the performance under the given water supply options? (house, yard, public, none)	pcat, c(house=1, yard=1, public=1, none=1)
Energy supply	Is energy supply available in the application case?	dcat, c(energy=0.8, no energy=0.2)	What is the performance of the technology under the specific energy supply conditions?	NA
Frequency of operation and maintenance (O&M)	Which level of O&M can be expected (also consider previous projects)? (regular, irregular)	dcat, c(regular=0.4, irregular=0.6)	What is the performance of the technology in case of regular and irregular O&M? (regular, irregular)	pcat, c(regular=1, irregular=0.4)
Temperature range	What is the min., mean, max. average monthly temperatures?	dtriangle, a=12, b=35, c=24	In which temperature range is the technology able to perform well to what extent?	ptriangle, (a=0, b=30, c=20)
Flooding	What is the flooding risk for the area?	dcat, c(flooding=0.75, no flooding=0.25)	What is the performance of the technology under these conditions?	pcat, c(flooding=0.8, no flooding=1)
Vehicular access	How accessible are the plots? (no access, narrow, full)	dcat, c(no access=0, narrow=0.3, full=0.7)	What is the performance under the various categories of accessibility (no access, narrow, full)?	pcat, c(no access=0.2, narrow=1, full=1)
Slope	What is the slope range of the area?	drange, c(lower=0, upper=10)	What is the performance at a certain slope range?	ptrapez, (a=0, b=0, c=5, d=25)
Soil type/ hydraulic conductivity	What is the soil type in the area?	dcat, c(clay=0.1, silt=0.2, sand=0.7, gravel=0)	What is the performance of a technology under each category of soil type (concerning permeability)?	pcat, c(clay=1, silt=1, sand=1, gravel=1)

Groundwater depth	What is the depth of the groundwater table in the area?	drange, c(lower=20, upper=200)	What depth of the groundwater table is tolerated?	prange, lower=0, upper=+Inf
Excavation	Is excavation easy or hard in the area? (easy, hard)	dcat, c(easy=1, hard=0)	What is the performance under the given category? (easy, hard)	
Population density	What is the population density?	drange, c(lower=4200, upper=6500)	What is the performance at a certain population density?	prange, lower=0,upper=30000
Construction skills	To what extent are the skill levels locally available?	pcat, c(low=1, moderate=1, high=1)	Which level of skills are required for construction?	dcat, c(low=0, moderate=1, high=0)
Design skills	To what extent are the skill levels locally available?	pcat, c(low=1, moderate=1, high=0.9)	Which level of skills are required for design?	dcat, c(low=0, moderate=1, high=0)
O&M skills	To what extent are the skill levels locally available?	pcat, c(low=1, moderate=1, high=0.7)	Which level of skills are required for O&M?	dcat, c(low=0.5, moderate=0.5, high=0)
Religious constraints	Which anal cleansing methods are used by the population?	dcat, c(water=0.7, soft=0.1, hard=0.2)	What is the performance of a technology with the use of different anal cleansing methods?	pcat, c(water=1, soft=1, hard=1)
Cultural constraints	Is it culturally okay to have contact with faeces? (contact, no contact)	pcat, c(contact=0.5, no contact=1)	What is the probability of having contact with faeces? (contact, no contact)	dcat, c(contact=0.5, no contact=0.5)
Drinking water exposure (drinkexp)	Are there drinking water sources (e.g. groundwater well) closer than 30 m from point of infiltration? (percentage of houses)	dcat, c(closer=0, not closer=1)	Is the technology appropriate if drinking water sources are closer than 30 m?	pcat, c(closer=1, not closer=1)
Chemical	Are chemicals locally available? (chemicals, no chemicals)	dcat, c(chemicals=0.2, no chemicals=0.8)	What is the performance of a technology for any category of chemical availability?	pcat, c(chemicals=1, no chemicals=1)
Odour	What is the sensitivity to the levels of odour emissions?	pcat, c(low=0.95, moderate=0.67, high=0.33)	What is the level of odour emissions?	dcat, c(low=1, moderate=0, high=0)

Input and output sanitation products	faeces, excreta, blackwater, organics -> compost, effluent
Transfer coefficients	
Total phosphorus (TP)	compost=1, effluent=0, airloss=0, soilloss=0, waterloss=0
Total nitrogen (TN)	compost=0.68, effluent=0, airloss=0.32, soilloss=0, waterloss=0
total solids (TS)	compost=0.52, effluent=0, airloss=0.48, soilloss=0, waterloss=0
Water (H2O)	compost=0.53, effluent=0, airloss=0.47, soilloss=0, waterloss=0

6.3.1.3 Potential technologies

38 technologies were selected from the technology library to test Santiago in Arba Minch (see Figure 6.4).The selection was made based on the results from previous research projects in Arba Minch while ensuring that onsite and offsite, natural and intensive, and conventional and novel options are covered.

Figure 6.4: Potential technologies tested with Santiago in Arba Minch. Each box represented a technologies and the arrow indicate the input and output products used to check their compatibility. A detailed description for each technology is provided in the technology library at ERIC: https://doi.org/10.25678/0000ss.

6.3.1.4 Application case profiles for three kebeles

Santiago was applied to three different kebeles: Woze, located in the north of the town, a low-income residential area with ample space availability and medium population (15,250 inhabitants, 5000 m^3 monthly water consumption); Chamo, situated in the higher parts of Arba Minch, a medium- to high-income area with many hotels and governmental institutions (10,374 inhabitants, 14,000 $m^3 month^{-1}$ water consumption); and Mehal Ketema, in the centre of the town, with commercial centres, residential buildings, hotels, a hospital and other institutions (6,634 inhabitants, 18,000 $m^3 month^{-1}$ water consumption). For these three kebeles, baseline reports of previous projects, academic reports, as well as semi-structured interviews with various stakeholders were used to establish the application case profiles (see example in Table 6.1). The inflow masses were estimated based on the international values provided in the technology library and adapted to the local context for nitrogen and water. Details are provided in SI-F. For phosphorus, nitrogen and total solids, the inflows were the same for all toilet sources (0.454, 2.866, and 31.317 $kg^{-1} year^{-1} person^{-1}$ respectively). The water inflows were estimated to be 14 162.0, 3029.5, and 474.5 $kg^{-1} year^{-1} person^{-1}$ for the cistern flush, pour flush, and dry toilet sources respectively.

6.3.1.5 Number of decision options

The number of options was set to 36. This relatively high number allowed a high diversity of the options, illustrating also that within one template, very different systems with similar appropriateness can be found.

6.3.2 Santiago outputs

6.3.2.1 Technology appropriateness

The technology appropriateness assessment provided for or each of the three application cases Woze, Chamo, and Mehal Ketema and each technology a technology appropriateness scores (TAS), (SI-G, Figure 13 and Figure 14). Although for many technologies the scores were similar in all three cases, the source and storage technologies showed quite high variation with some technologies being only appropriate in some cases. For instance, the 'cistern flush toilet' and the 'conventional sewers' were fully inappropriate in the case of Woze because continuous in-house water supply is not available in this kebele. But these were the only technologies with a TAS=0. High appropriateness scores were achieved e.g. by the technologies pour flush toilet, composting chamber, urine bank and co-composting. One important observation was, that for all technologies and cases, some criteria showed to be more relevant for the appropriateness. These are water and energy supply, operation and maintenance frequency, vehicular access, flooding, slope, and social and cultural constraints.

6.3.2.2 System generation and system appropriateness

From the 38 potential technologies we could build 67 470 valid sanitation system configurations. The highest number of systems by far, were generated with the source urine diversion dry toilet (UDDT, 65 482) because this source has two output streams (versus one) leading to more possible permutations (see SI-G, Figure 15). The two wet sources, cistern flush and pour flush toilets, lead to the same number of options (660) because they have the same output product (even though in different quantities) and the dry toilet led to 308 mostly onsite options.

The system appropriateness scores (SAS) generated for Chamo and Mehal Ketema were very similar and relatively high (see SI-G, Figure 16). For Woze, there are many systems with a low SAS because of the lower appropriateness of all the four toilet sources.

To describe the diversity of the options, we used the 19 system templates as described in Figure 6.3 and shown for the case of Chamo in Figure 6.5. The figure shows, that for all templates, both systems with low and high appropriateness can be found. This shows, that templates are not a good indicator for system appropriateness and that therefore, an automated approach that quantifies the SAS for all systems is required. Nevertheless, some system templates (e.g. ST1, ST2, ST17, and ST19) show clearly lower median system appropriateness scores (SAS), while others show generally higher scores (ST3, ST6 and ST13).

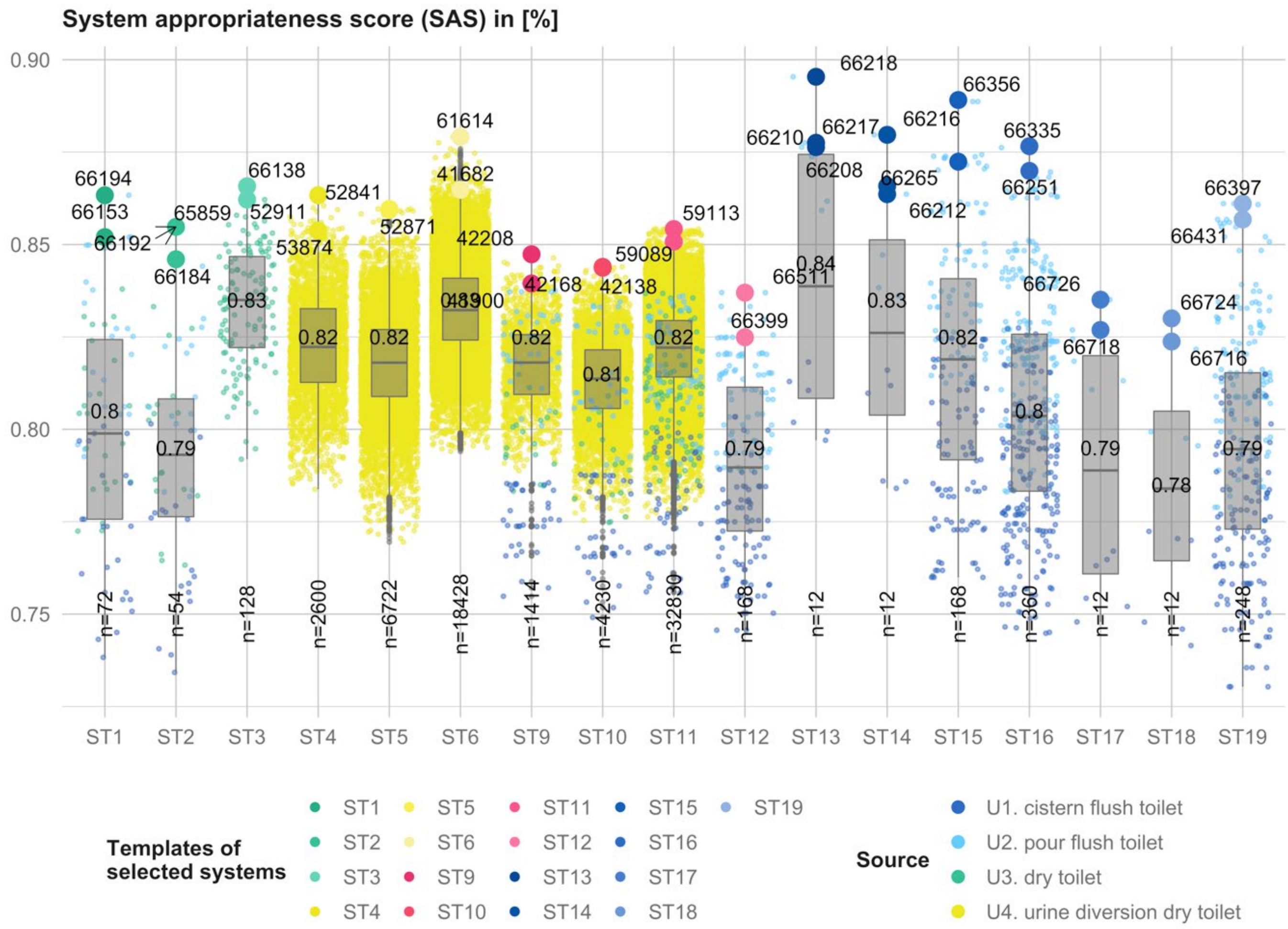


Figure 6.5: System appropriateness scores (SAS) in % (1.00 = 100%) for the case Chamo. Each dot represents one of the 67 470 systems. The colours blue, green and yellow indicate the toilet sources. The systems are organised according to the 19 system templates shown in Figure 6.3. The larger numbered dots indicate the selected systems (two or three per template). The middle line of the boxplot represents the median of all scores. The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). Outliers are shown as grey dots. Some systems show clearly higher medians, but within each templates, there are systems with low and with high appropriateness showing that the templates are not a good indicator for appropriateness.

6.3.2.3 Option selection

The selected systems were similar, but not the same for the three cases. In Figure 6.6 we show some of the 36 selected systems for Chamo. From these examples we can learn four things:

- The set of options is diverse in terms of sources (all except cistern flush), system lengths (e.g. ID-66218 and ID-53874), and system templates (including onsite, decentralized, centralized, systems as well as systems including onsite and off-site elements such as ID-59113 and ID-66716).
- Moreover, the set of options contains also novel options such as vermi-composting (ID-66218), Fossa alterna (ID-65859), and solids-free sewers (ID-66216). The vermi-composting system is particularly promising as it is not only the shortest system but also among the most appropriate in all kebeles and also shows very high recovery potentials (see next section).
- Long systems (systems with more technologies) show lower recovery because of more losses (e.g. ID-59113, see SI-G, Figure 17).
- Furthermore, the set of options highlights the importance of a system level evaluation as it reveals that technology-level analysis alone is insufficient for finding the best options. For instance, System ID-53874 contains technologies with low TAS (struvite production and single pit) but still achieves a SAS in the mean range. Similarly, ID-67140 integrates a number of technologies with relatively high TAS (e.g. waste stabilization pond, application of stabilized sludge), but due to two technologies with low TAS (cistern flush toilet, conventional sewer) it has the lowest system appropriateness (SAS) of all systems for Chamo kebele.

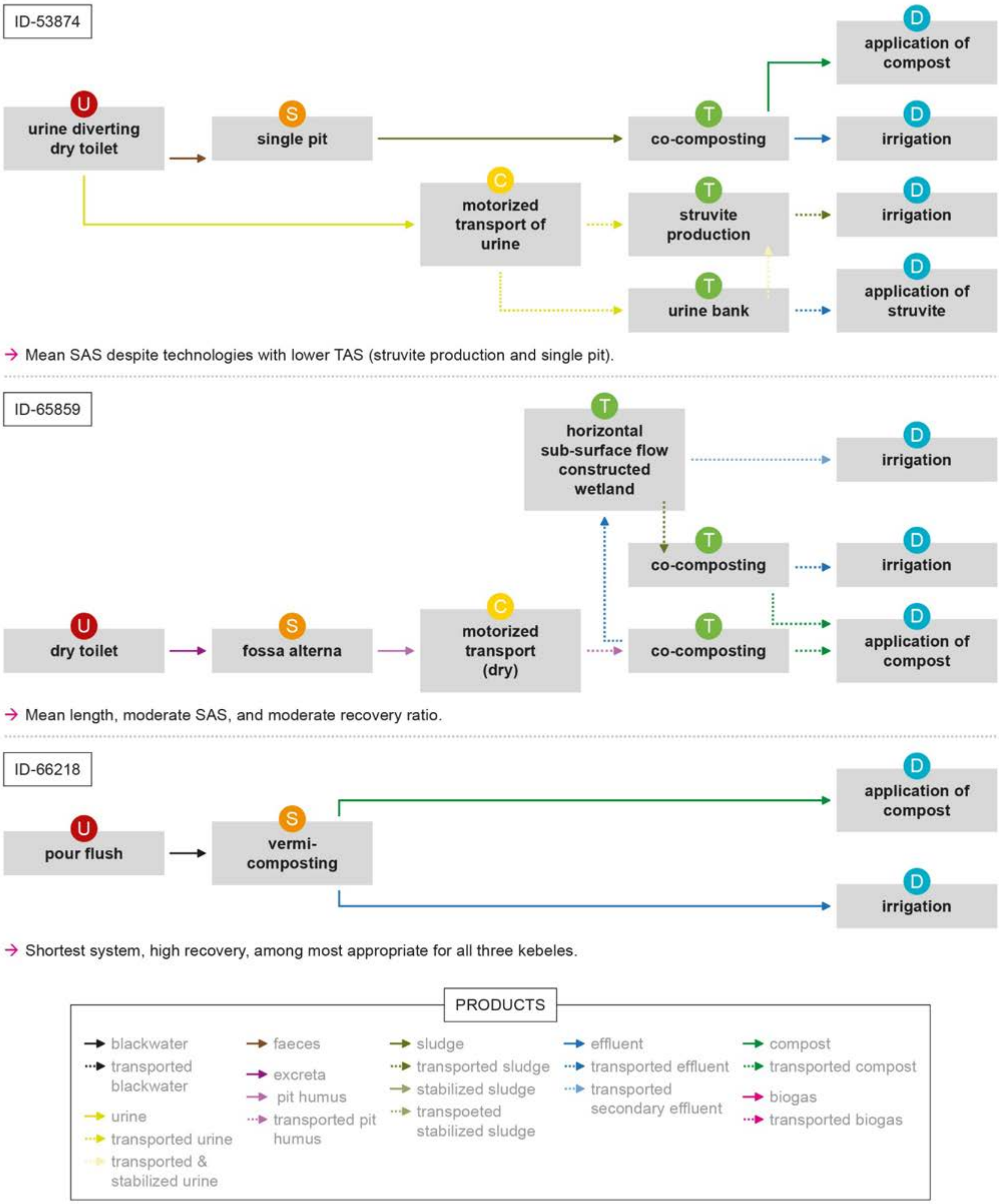
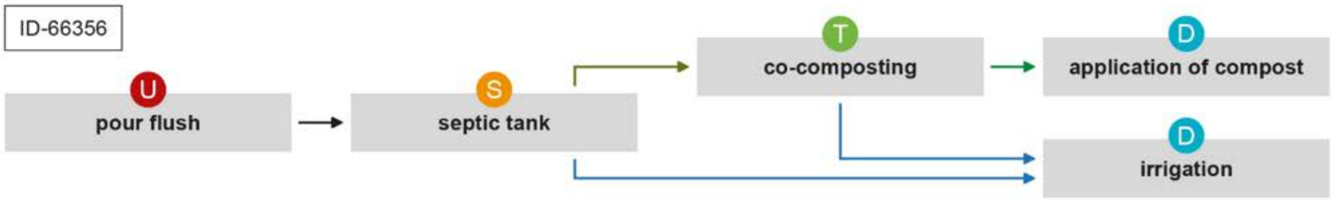
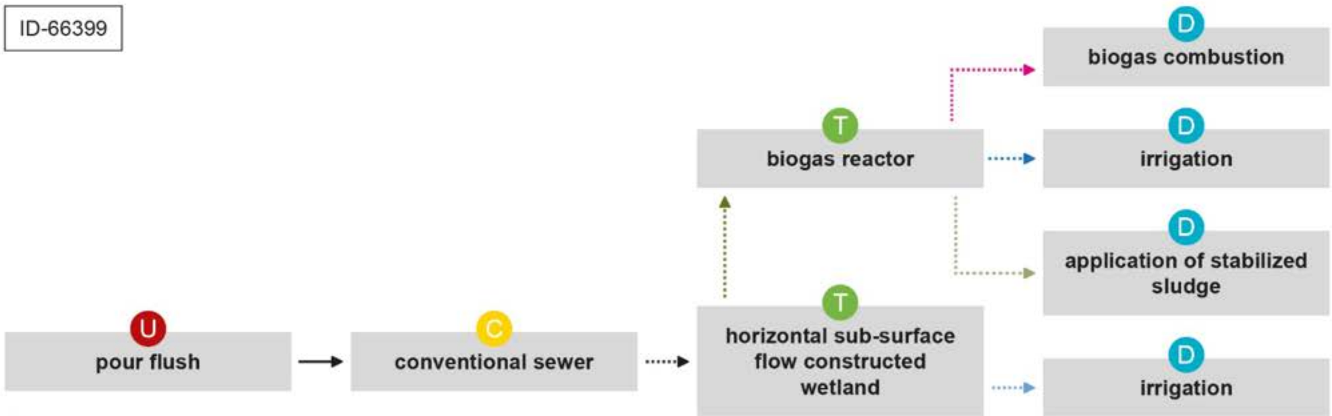


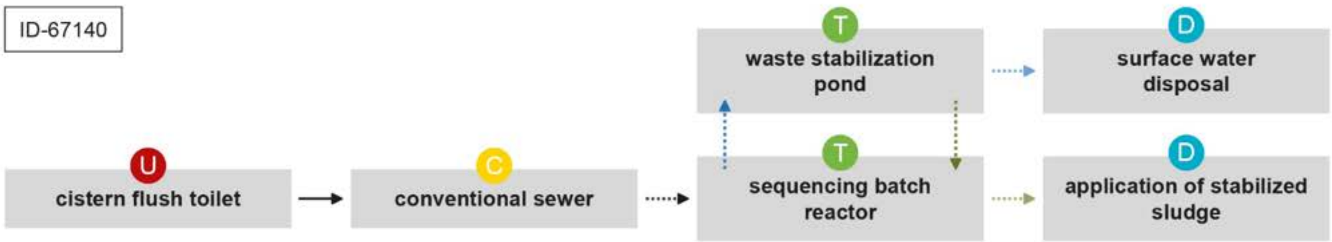
Figure 6.6: Flowcharts of some selected systems for the case of Chamo in Arba Minch town. Each box represents a technology and the arrows represent the product flows. This selection shows that the set of selected sanitation systems is diverse (including different system technological characteristic), and contains also novel options which one might not have thought of and which are very promising. Furthermore, the set of options also highlights the importance of a system level evaluation and reveals that technology-level analysis alone is insufficient for finding the best options.



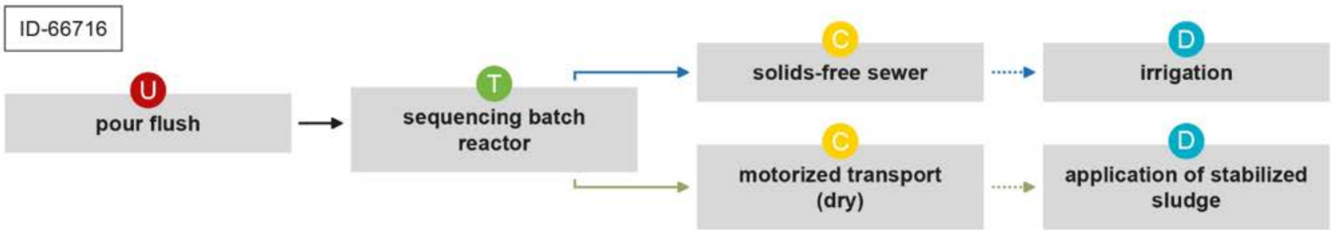
→ System with highest recovery ratio and also very high SAS (only Chamo).



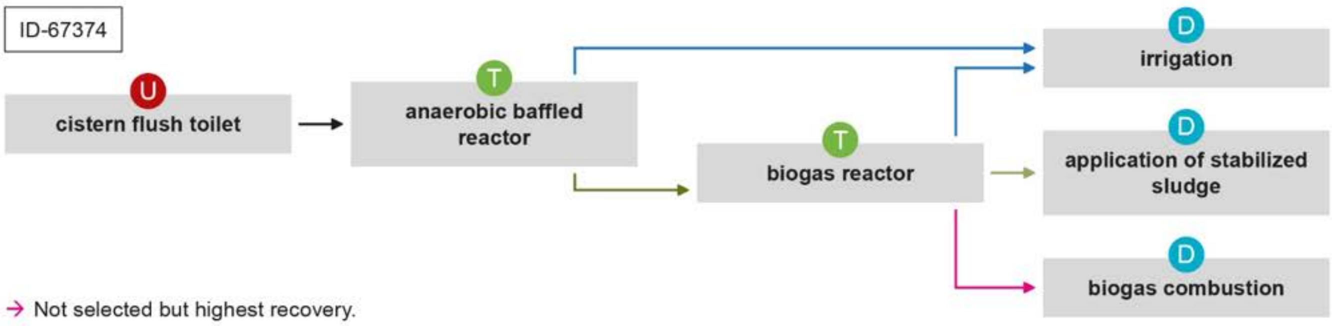
→ Low SAS, high recovery.



→ Lowest SAS even though some Tech with high TAS.



→ Lowest SAS, high recovery, moderate length.



→ Not selected but highest recovery.

Figure 6.6b: Continued: flowcharts of some selected systems for the case of Chamo in Arba Minch town.

6.3.2.4 Resource recovery and losses

Similarly, as for the appropriateness, we found recovery potentials that range from almost nothing to almost 100% within a same template (see SI-G, Figure 18). Thus again, templates are not sufficient indicators for recovery. In Figure 6.7 we show the resource recovery of all 67 470 systems (y-axis) compared to the system appropriateness scores (x-axis).

The selected systems are highlighted by colours according to their template. As expected, some selected systems have high appropriateness and high recovery rates (e.g. ID-66218, see also Figure 6.6), others have low appropriateness and high recovery (e.g. ID- 66716) or high appropriateness and low recovery potentials (e.g. ID-69113, a long system based on motorized collection, or ID-6639, a centralized sewer system). The system with very high recovery potential and also highest appropriateness (for Chamo) is an onsite composting system (ID-66356). The absolutely highest recovery in Chamo, which could be achieved with a cistern flush system linked to biogas, was not selected due to low appropriateness (ID- 67374 in Figure 6.6). This shows that there is no single best solution, but that different indicators such as resource recovery and appropriateness involve trade-offs and that therefore a model that can quantify these indicators at an early planning phase and for all options is required.

Knowing the resource recovery potentials of all systems already at the planning phase, would also allow to use this additional information for the preselection in case that all decision makers agree on the importance of resource recovery and there is no a need to discuss related trade-offs (as for the non-negotiable screening criteria used for the appropriateness assessment).

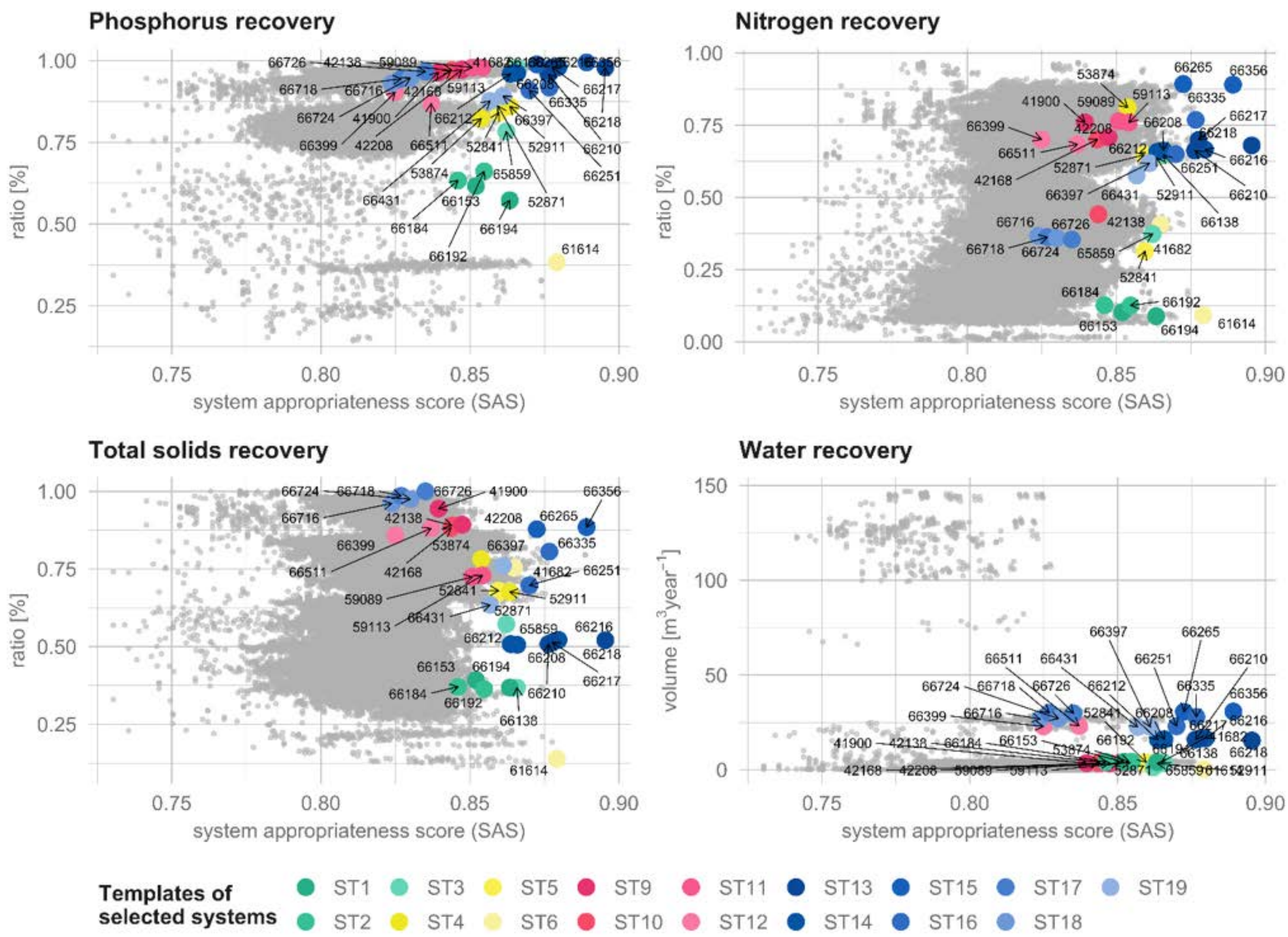


Figure 6.7: System recovery potentials for the four substances phosphorus, nitrogen, total solids, and water versus appropriateness scores (SAS) for Chamo kebele (1.00 = 100%). Each grey dot represents one of the 67 470 systems. The larger numbered dots indicate the selected systems coloured by template. This figure shows that the selected systems are as expected very diverse in terms of appropriateness and recovery potentials and that there is no single best solution but that appropriateness and different recoveries involve trade-offs.

6.3.2.5 Next step: evaluation of trade-offs

In our application case, we were not involved in the next steps of the SDM process. However, to illustrate how the Santiago outputs could be used and how one could deal with trade-offs, for instance among different types of reuse (e.g. nutrients against energy), we produced a hypothetical example based on CLUES Tool D17.1 (Lüthi et al., 2011b) for four systems in Table 6.2. According to this simplified example where all types of recoveries are weighted the same (and not considering other important indicators such as costs), system ID-66356 is the preferred system for Chamo which includes a septic tank and co-composting of sludge.

Table 6.2: Hypothetical example of how the selected systems can be further evaluated using scoring and ranking in order to deal with trade-offs among different performance indicators (here different recovery potentials) The numbers indicate the rank and the numbers in bracket show the result obtained by Santiago for the recovery potential ratio in percentages (0.82 = 82%). ID: system identification number, TP: total phosphorus recovery potential, TN: total nitrogen recovery potential, TS: total solids recovery potential, H2O: water recovery potential.

Option		Ranking according to the recovery potential (ratio)				Summarised score	Ranking
System template	ID	P	N	TS	H2O		
ST4	53874	1 (0.82)	3 (0.81)	3 (0.89)	2 (0.78)	9	2
ST14	66216	3 (0.98)	2 (0.67)	1 (0.52)	1 (0.52)	7	4
ST15	66356	4 (0.99)	4 (0.89)	4 (0.98)	3 (0.88)	15	1 (preferred)
ST18	66716	2 (0.93)	1 (0.37)	2 (0.85)	4 (0.96)	9	2

6.3.3 Other application cases

The integration of Santiago into SDM has been field tested so far in six cases and four countries (two in Nepal, two in Ethiopia, one in Peru, and one in South Africa). In 2016/2017 for instance, we tested Santiago in an emerging small town in South-Western Nepal (approx. 4000 inhabitants). From 40 technologies, we generated more than 100’000 possible systems. 17 sanitation systems were then selected for further investigation. This set included well-established systems (e.g. double pit latrines and pour flush toilets with biogas production) and novel options that could be more appropriate, such as urine diversion latrines with vermi-composting of faeces. In 2019/2020 we applied Santiago for the case of a small Komani San settlement in South Africa (approx. 500 people) and identified two different sets of options, for two scenarios (community-based implementation versus government-driven implementation). Even though the scale as well as the partners were different for all application cases, the lessons learnt regarding both the applicability of Santiago and its integration into the SDM process were very similar.

— 6.4 DISCUSSION

In this publication we presented Santiago and how to apply this tool integrated in into any SDM planning process. We demonstrated the entire process to obtain inputs and its outputs for Arba Minch Town Municipality in Ethiopia and shortly summarized the results from in total six application cases. In the following we briefly summarise the experiences from other application cases in order to discuss the lessons learnt that are generalisable for any future application of Santiago, and to present the contributions and advantages potentially brought by Santiago for sanitation planning in the future.

6.4.1 Lessons learned

Decision objectives: We observed that the workshop provided a useful platform for stakeholders to meet and to clarify expectations and responsibilities. This is particularly helpful in the situation were a lack of ownership and political will persist as illustrated in the case of Arba Minch. In this case, it was particularly encouraging to see how the definition of a local objective hierarchy allowed also to agree on a joint vision, creating momentum and triggering ownership and leadership.

Screening criteria: We observed that to identify screening criteria was not such a challenge and the list of screening criteria obtained in the workshops were always very similar to the masterlist. However, it was important to rework the list after the workshop in order not to be overly comprehensive (max 20 criteria). With more criteria, the appropriateness scores become almost indistinguishable as we use the geometric mean for aggregation. The master list that we provided for adaption by stakeholders, turned out to be a strong method for developing a robust set of criteria as suggested also by Haag et al., (2019).

Providing international data: While naming the criteria was not such a challenge for the local partners, they were overwhelmed by the task of quantifying those especially for novel technologies and in the absence of data. The technology library provided by Santiago fills in this gap. But the experts require guidance on how to choose a suitable uncertainty model for the characterisation of the application case profile. This is relevant as the choice of uncertainty model can significantly impact ranking of the technologies, although the effect is smaller when looking at entire systems. The most important recommendation here is to use the simplest compatible model, such as uniform or triangular functions (Spuhler et al., 2018) and to use simple best guesses in the absence of any data.

Key factors for technology appropriateness: The analysis of the different results from the technology appropriateness assessment also allowed us to identify the most relevant screening criteria: water and energy requirements, operation and maintenance frequency and skills, vehicular access, flooding, design skills, and religious or cultural requirements. These were more or less the same in all cases and therefore need special attention in future technology development and during the creation of the local enabling environment.

Need to look at entire systems: We observed that both the appropriateness of sanitation systems as well as their resource recovery and emission potentials are significantly influenced by technology interactions within the system. Therefore, these aspect have to be evaluated at system level. This is illustrated in the case of Arba Minch for SanSys 67140 (Figure 6.6) which integrates a number of technologies with relatively high appropriateness in the case of Chamo. But because the system also contains two technologies with particularly low appropriateness, the appropriateness of the entire system is the lowest of all systems.

No optimal solutions: To organize the large number of systems generated, we used 19 system templates as previously introduced (Spuhler et al., 2018; 2020c; Tilley et al., 2014b; Tilley et al., 2010). The results from Arba Minch and other cases showed that these templates are efficient to describe technical diversity but are neither indicators for appropriateness nor for recovery (Spuhler et al., 2018; 2020c). This shows that there is no single best solution and further highlights the need for an automated approach that allows to quantify different indicators such as appropriateness and resource recovery potentials already at a pre-planning phase and for the entire systems options space.

Prioritisation of more appropriate and resource efficient systems: The quantification of appropriateness and resource recovery potentials enabled stakeholder to prioritise more appropriate and also more resource efficient systems already at an early planning phase.

Follow-up steps in the SDM: The example application show that there is most often a trade-off between different types of recoveries (e.g. nutrients versus energy) and appropriateness. It is important to be aware that once Santiago has been applied, the planning process is not finished yet. According to SDM, the next steps consist of the detailed evaluation (step 4 of SDM) so that stakeholders are can be made aware of the relevant trade-offs, can discuss them and can then make an informed selection of the preferred option (step 5 of SDM). Thereby it is important to consider different stakeholder preferences (e.g. nutrient recovery versus energy recovery) but also additional performance indicators, such as costs, health and hygiene aspects, and operation and maintenance requirements. For the costs, we are currently developing an extension of Santiago (Spuhler and Germann, 2019). In the absence of quantitative information on additional performance indicators, the evaluation can be based on “best guesses”. We provide a method to deal with trade-offs using a simple method such as manual scoring (see section 6.3.2.5) based on CLUES tool D17.1, (Lüthi et al., 2011b; Sherpa et al., 2012). Such simple methods have the advantage that they are easily understood and directly applicable by decision makers in a workshop setting. But the disadvantage is that the scales are not well defined: e.g. is it a relative or an absolute scale? (Belton and Stewart, 2002). If more accuracy is needed, more rigorous MCDA models could be used (e.g. Mustajoki and Marttunen, 2017; Schütze et al., 2019) which also implies that more information and data are required.

Iteration: Analysis of the deficits of the selected options regarding the main decision options (e.g. resource recovery, costs) can help generate additional (and for the decision, optimized) options (Reichert et al. 2015). As Santiago allows to quantify resource recovery potentials for all systems this information could be used already at the pre-selection phase. For instance, a minimal phosphorus recovery potential threshold could be introduced in the appropriateness assessment.

Interaction with stakeholders: We estimate that two workshops are sufficient for integrating Santiago into an SDM process. Such workshops provide an opportunity for learning about SDM in general, different technology options, and concepts such as sustainable sanitation, technology appropriateness, and citywide inclusive approaches. However, to implement the overall SDM process, more facilitation and interaction is obviously required where knowledge and understanding are sequentially built upon, in order to create local momentum, develop capacities, and encourage ownership by all relevant actors.

6.4.2 Novelty of the method

Based on the above lessons learnt, we identified the two main scientific contributions of Santiago:

1. Any (future) technology option can systematically be considered when generating sanitation system options; and
2. Resource recovery potentials can automatically and ex-ante be quantified for a large and diverse set of systems enabling the consideration of this performance indicators when making strategic planning decisions.

Existing methods for sanitation option generation cannot deal with the growing diversity of currently available technologies and the huge number of possible system configurations. They are either (Spuhler and Lüthi, 2020):

a) comprehensive (entire systems), but not systematic (do not provide transparent criteria for pre-selection): e.g. Compendium (Tilley et al., 2014b), WSP guide (WSP, 2007), CMS (LeJallé et al., 2012).
b) systematic, but not comprehensive: e.g. decision trees (Kalbermatten, 1982), SANEX (Loetscher and Keller, 2002), TAF (Olschewski, 2013), SANCHIS (van Buuren, 2010); or
c) systematic and comprehensive, but not flexible for novel technologies and automated for comprehensive system generation: e.g. CLARA (Ketema and Langergraber, 2014).

Santiago is comprehensive, systematic, and flexible:

- Santiago enforces the consideration of **entire systems** by ensuring that all products are either transferred, treated, or safely disposed. This is relevant because both the appropriateness of sanitation systems as well as their resource recovery and emission potentials are significantly influenced by technology interactions within the system and therefore have to be evaluated at system level.
- Cause-effect analysis, creativity-based techniques, decision matrices and strategy tables are useful methods for option generation resulting in a manageable number of options (Eisenführ et al., 2010; Keeney, 1996; Larsen et al., 2010; McConville et al., 2014; Tilley et al., 2014b). But they strongly rely upon available expertise and are therefore somewhat arbitrary. Santiago is **more systematic**, as it enables the consideration of the entire option space while using a reproducible method to focus on the locally most appropriate options.
- Santiago includes a technology library with 41 potential technology options that may or may not be included in the assessment and which is **flexible** to add any (future) technology.

A mayor strength of Santiago is also that it is **generic and automated** and therefore can be applied to any almost thinkable (future) technology or application case and for a very large and diverse set of sanitation options simultaneously. Moreover, **uncertainties** related to the technologies, their implementation, and the local context are explicitly considered. For the technology appropriateness score this uncertainty is expressed as the confidence between 0 and 100%. For the substance flow model, the uncertainty is expressed as the standard deviation of the resource recovery or loss potentials that can be used to evaluate the robustness of the results. The consideration of uncertainties makes the methods **applicable ex-ante** also for novel technologies which have never been tested at scale.

6.4.3 Relevance for planning practice

The two main advantages that Santiago bring over simple expert evaluation are:

1. The set of decision options contains novel options, which an expert might does not know or would not have thought of based on experience and knowledge alone; and
2. Santiago streamlines the process allowing to prioritise more appropriate and resource efficient systems right from the beginning.

These advantages are supported by the **integration of international knowledge and data** that can be matched and contextualized for the given case a hand. The provided knowledge includes: (1) a generic objective hierarchy for sustainable sanitation; (2) a master list of screening criteria; (3) and the technology library which also allow more strategic and empirical decision making. The definition of decision objectives is critical for **strategic decisions based on fundamental values** rather than short term personal and often biased preferences (Keeney, 1996). For instance, a flush toilet might be comfortable, but would not provide the required services if no water is available. The generic decision objective hierarchy for sustainable sanitation support the definition of strategic objectives and help to align those with internationally recognized definition of sustainable sanitation and the SDG 6.2 (UN, 2014)SuSanA, 2008 #190}. The master list of screening criteria provides the suitable evaluation metrics for strategic objectivise that allows to evaluate those contextualized for each application case. The technology library provides the data for 27 screening criteria and 41 technologies based on international literature and expert knowledge for **more empirical** decision making. The field experiences showed, that this technology library is an important value proposition for the local experts, because lack of data and knowledge is one of their mayor challenge.

One mayor challenge given by the framework of SDM was to provide a method for preselection, while **avoiding impacting the final decision** (Siebert and Keeney, 2015) by eliminating options too early or by prioritising the wrong options. A diverse set of options increases the chance that all important trade-offs among decision objectives are highlighted and can be discussed during the follow-up steps of SDM and that a balanced decision can be made, eventually by reinterring the pre-selection based on learnings from the discussions. Santiago combines system templates to describe technological diversity with a systematic appropriateness assessment to provide **a set of sanitation systems that is appropriate, of manageable size, but still** diverse in order not to impact the final decision.

6.4.4 Contributions to local planning culture

The field experiences also indicated potential contributions to the local planning culture and towards a more strategic approach:

- **Balancing decisions:** SDM and Santiago allow to combine engineering science with methods from MCDA. This also to comparably scale very different criteria, as required for evaluating sustainability (Guest et al., 2009). This would be impossible with alternative methods such as Cost-Benefit Analysis or Life-cycle Analysis.
- **Structuring participation:** Santiago clearly defines inputs of stakeholders and how those are to be used. Thereby, it efficiently combines technical know-how with stakeholder preferences and avoids some of the adverse effects of participation (e.g. endless discussions without any action).
- **Developing capacities:** The workshops, as well as collaboration between internal and external actors, contribute to the exchange of knowledge and skills and capacity development for both technical and planning aspects at the individual and organisational levels.
- **Bridging citywide objectives with area-based appropriateness assessment for more inclusivity:** A major strength of SDM is that the discussion of the problems and possible solutions, and the definition of decision objectives can (if adequately moderated and attended) lead to the creation of a joint vision for sanitation planning shared by all stakeholders. A joint vision is the basis for more ownership. Santiago supports this process through the integration workshops but then also allows to bridge these citywide decision objectives with an area-based appropriateness assessment (see SI-G Figure 19). This help to account for the different socio-demographic conditions but also stakeholder preferences as suggested by (Mara, 2018; Reymond et al., 2016). Santiago then provides a set of appropriate, and thus feasible options, for each and every zone within a given city, thereby contributing to more Citywide Inclusive Sanitation (CWIS, BMGF, 2017).

6.4.5 Delicate aspects and remaining challenges

There are several aspects related to the Santiago application that can have a significant impact on the output and which we therefore briefly summarize here (see also Spuhler et al., 2018 and Spuhler et al., 2020c).

- **Potential technologies:** The technology library provides a large and diverse range of potential technologies but is not comprehensive and therefore should continuously be extended following instructions in the introduction ([dataset] Spuhler and Roller, 2020)
- **Decision objectives:** Problems are often quite easily formulated. However, SDM requires that objectives are defined and based on fundamental values which might be not represented by the most pressing problems. Translating problems into decision objectives and values requires careful facilitation. While objectives which are rather superficial might be agreed upon, it might not be feasible to fully clarify values in a multi-stakeholder workshop. At the other hand, it is crucial for a robust outcome that the decision objectives remain concise (Haag et al., 2019; Marttunen et al., 2019). The workshop procedure and the generic decision objective hierarchy provided by Santiago can help focus the discussion and structure the process. But this support also bears the risk of becoming a vehicle for imposing foreign values, negatively impacting ownership.
- **Screening criteria:** The set of screening criteria must accurately represent the case requirements, in order to reflect appropriateness. Moreover, the chosen uncertainty models have to be looked at carefully especially for killer criteria (e.g. the energy supply may improve in the near future..
- **Plausibility:** In some circumstances compatible sanitation system configurations might not be very efficient from an engineering perspective (e.g. treating dried faeces in a biogas digester). Therefore, the set of sanitation system options needs to be checked for plausibility before it is handed over to the SDM process.
- **Completeness of the generated options:** The sanitation system options need to be complemented with non-technical aspects related to the business model (e.g. service models, financing mechanisms, or institutional arrangements). The quantified resource recovery and emission potentials also need to be complemented with other indicators relevant for the decision-making process (e.g. costs).
- **Real impact:** In reality, planning is often not as structured or as rational as suggested in the literature, but is rather a political process and therefore always depends on local leadership. The integration of Santiago is flexible for different layouts of the SDM process as long as the interfaces can be managed. However, the uptake of Santiago results is difficult to control. Our field experiences show, that lack of political will and public support and lack of clearly allocated responsibilities and resources are the most important bottlenecks for structured sanitation planning, see also (Evans, 2005; Kennedy-Walker et al., 2014; Tayler and Parkinson, 2005). The hope is that Santiago will at least contribute to establishing a joint vision, but also a local ‘planning culture’ (Tayler and Parkinson, 2005) in order to move away from occasional donor-driven interventions. Consequently, the experts applying Santiago and moderating the interaction with the SDM process have to avoid helping things along by taking over planning responsibilities. The planning process needs to remain a learning experience without predetermining what the outcome will be, and the roles and responsibilities need to be defined from the start and independent of external actors (Byrns and Madryga, 2018). Roles and responsibilities then need to be institutionalized. A formal document summarizing the results of the Santiago application can enhance uptake.

6.4.6 Future developments

Online user interface: To make this tool available for practice, an accessible user interface and a centralized data management system are required. We imagine a Santiago web-based tool that is complemented with a hardcopy guidance document summarizing the procedure for the integration of Santiago and SDM. The web-based tool would be interactive, and guide users through the collection of data and analysis of the results both analytically and visually in real time (e.g. during a workshop).

Integration in an adaptive strategic planning frameworks for CWIS: Santiago complements other currently developed tools (e.g. Shit Flow Diagrams. SFDs, Prognosis for Change, etc., Scott et al., 2019). Together with them, Santiago provides a starting point for the development of an adaptive strategic planning frameworks for CWIS. Within this more holistic framework, Santiago would provide a set of appropriate and thus feasible options for all different urban zones (e.g. city-centre, dense informal, peri-urban), offering a basis for consideration of the entire city, along with the required performance indicators for selecting the most resource efficient system for each zone. Santiago could also be applied for testing hybrid systems, e.g. combining systems for different zones, such as treatment of faecal sludge (from on-site sanitation) with centralized blackwater treatment.

Expansion: A required and exciting future activity also consists of the expansion of the technology library with upcoming innovations. Additional products (e.g. organic waste, stormwater) can be added in order to integrate other sectors into the assessment. Moreover, both the technology library and the algorithms could be integrated as building blocks into other tools, such as the emergency sanitation compendium (Gensch et al., 2018), SamPSon (Schütze et al., 2019), or UrbanBEATS (Bach et al., 2014).

Adaptation to industrialized countries: Many of the methods presented here are equally applicable to industrialized countries such as Switzerland. With the progressive deterioration of urban infrastructure and high costs of replacement, there is an increasing potential for many of the technology innovations to enhance sustainability (e.g. augmented capacity, enhanced control of micropollutants, enhanced resource efficiency and recovery, and more flexibility and resilience). Moreover, the calls for circular cities, and closed water and material cycles with urban metabolism, have gained increasing attention (Kisser et al., 2020; Oral et al., 2020). A first step would consist of testing and adjusting the objective hierarchy, screening criteria, and data contained in the technology library for such a context.

Other possible applications of Santiago:

- Santiago could be used to develop context-specific catalogues of appropriate technologies and systems for different settings (e.g. small town, metropolitan, emerging) and cases (e.g. centre, low-income dense, peri-urban) as low-level planning support.
- It could be used to identify setting-specific factors for technology appropriateness, which could then be used to guide technology development.
- The procedure for the integration of Santiago could be standardized for regional or national planning procedures.
- The resource recovery and loss potentials could be used to promote the value of sanitation products and their potential contribution to sustainable and circular cities (Oral et al., 2020).

— 6.5 CONCLUSIONS

- The Santiago tool (software together with the integration procedure) supports strategic sanitation planning by generating a set of sanitation systems that are appropriate for different urban zones. Compared to past methods, Santiago enables the consideration of a diverse and large range of conventional and novel technology and system options. Furthermore, it makes a large body of international literature, data and expert knowledge available for the local planning process and systematically compares this to local preferences and conditions. It re-evaluates technologies again, in each case providing solutions appropriate to the specific situation at hand. The technology library is versatile, and therefore able to accommodate any future innovations. Uncertainties are explicitly considered, making it applicable at the structuring phase. Santiago also ensures the consideration of entire systems. This is relevant because both the appropriateness, as well as the resource recovery and emission potentials of sanitation systems, are greatly dependent on technology interactions.
- Experiences from six case studies in Nepal, Ethiopia, Peru, and South Africa showed that Santiago can be applied with minimal available data and stakeholder interaction. However, to utilise the full strength of Santiago, it should be integrated into a facilitated and participatory process such as SDM.
- Elements required for integration include a set of potential technologies (given by the technology library), decision objectives and screening criteria (obtained in a participatory workshop supported by a generic objective hierarchy and a master list of screening criteria for sustainable sanitation), evaluation data for the application case profiles (collected by the expert), and the number of options manageable in the follow-up steps of the SDM process (number varies with each case). The technology library covers 41 well-established and novel technologies and data for 27 screening criteria from the master list and for four substances (phosphorus, nitrogen, total solids, water).
- The main challenges for integration lie in appropriate moderation and the facilitation skills of the expert in charge. If these hurdles are well managed, Santiago can provide substantial benefits. It provides a set of options that integrate novel and potentially more appropriate options. Because the set is diverse, relevant trade-offs can be revealed and discussed (e.g. appropriateness versus resource recovery). International literature and expert knowledge are made accessible for the local planning process so that knowledge biases are avoided and more empirical decisions are made. Inappropriate options are eliminated at the beginning, streamlining the process. Options are based on systematic evaluation of strategic objectives and not on expert judgement, thus enhancing reproducibility and transparency.
- The application case in Arba Minch indicated that the activities that come with the integration of Santiago can positively influence the local planning culture by (i) supporting the definition of a joint vision shared by all stakeholders; (ii) bridging citywide objectives with area-based appropriateness assessment; (iii) structuring stakeholder participation, and enhancing ownership while avoiding confusion and endless discussion; and (iv) contributing to organizational and individual capacity development. However, as also shown in the example of Arba Minch, the adoption of the Santiago results and the follow-up of the SDM process rely heavily on local leadership. This can be enhanced by defining responsibilities as early as possible and independently of external consultants.
- Santiago was designed as a support for step 3 of SDM and targeted to engineering consultants, local and regional governments, policy makers, development agencies and NGOs. But the tool is generic enough to be used for the development of standardized catalogues and procedures for different urban contexts and typologies (e.g. small town, metropolitan, emerging) and areas (e.g. centre, low-income dense, peri-urban). Other possible applications include the identification of area-specific factors for technology appropriateness or resource recovery to guide future technology development.
- A logical next step would be to develop an interactive web-interface for Santiago. As Santiago becomes more widely used, the technology library could be extended for novel technologies or additional products (e.g. organic

waste). Ideally, Santiago could also be adapted for other sectors such as solid waste or integrated as a building block in other tools such as the emergency compendium or SFDs (excreta flow diagrams).

- To reach the SDG 6, water and sanitation for all, huge numbers of city sanitation plans are required. The tool presented here can be applied for the development for a large share of these plans. Thereby it would enable the consider novel technology options in order to provide more appropriate and feasible solutions for a variety of urban contexts (e.g. city-centre, dense informal, peri-urban). It would also allow to prioritise options with high resource recovery for more circular cities. Thereby, this tool may become essential in planning for more appropriate and sustainable sanitation system options and for achieving citywide inclusive and sustainable sanitation worldwide.

— 6.6 ACKNOWLEDGEMENTS

This work is funded by the Sawiris Foundation for Social Development through the Engineering for Development (E4D) programme of the Swiss Federal Institute for Technology (ETH) Zurich. The authors are very grateful to the inhabitants of Arba Minch, and Teshale Dalecha and Zemed Menberu from Arba Minch University, for enabling field testing in Ethiopia. The authors are also very grateful to the inhabitants of Thimi Municipality and Katarniya, Nepal, as well as Agnes Montangero from the Swiss Water and Sanitation Consortium, for field validation in Nepal. In addition, they also gratefully acknowledge the contributions of Mosisa Teferi for the facilitation of local interactions in Arba Minch and for the invaluable comments on the manuscript.

— 6.7 FOOTNOTES

[1] https://www.gatesfoundation.org/Media-Center/Press-Releases/2018/11/Bill-Gates-Launches-Reinvented-Toilet-Expo-Showcasing-New-Pathogen-Killing-Sanitation-Products. Access: 29.05.2019.

07 General discussion

— 7.1 OUTLINE OF THIS CHAPTER

This thesis presents a theoretical development and practical application of methods for the generation and assessment of sanitation system options, with the aim to serve as an input for strategic planning. The methods include four algorithms as well as a technology library that are tied together in a software which can support strategic sanitation planning. The four algorithms are designed for (1) the assessment of technology appropriateness in a given case; (2) the generation of all valid sanitation system configurations from a set of technologies; (3) the selection of a subset of options (sanitation systems) that is diverse, appropriate for the given case, and of manageable size; and (4) for the quantification of substance flows (nutrients, total solids, and water) for all valid sanitation systems in order to estimate resource recovery and loss potentials. The technology library provides data for 41 technologies, 27 screening criteria, and transfer coefficient for four substances, all based on a broad range of international literature and expert knowledge.

This software complements existing practice because it is generic (applicable to almost any case, any technology, any product, and different substances), automated (to be able to deal with large number of options), systematic (and thus reproducible), and can deal with uncertainties related to technologies or the local context. The last point makes it already applicable at the structuring phase of the planning process. These results, if implemented in practice, will enable for the consideration of novel sanitation technology and system configurations in strategic planning and structured decision making (SDM), thereby contributing to sustainable sanitation for all, SDG 6.2, and sustainable cities, SDG 11.

The three main contributions of the thesis are discussed subsequently:

1. Generation of locally appropriate sanitation system options for planning
2. Quantification of substance flows
3. Integration with SDM and strategic planning

The chapter then ends with a discussion of data collection aspects and of shortcomings.

— 7.2 GENERATION OF LOCALLY APPROPRIATE SANITATION SYSTEM OPTIONS FOR PLANNING

Overview: For planning purposes, options of locally appropriate sanitation systems are obtained in three steps:

1. Comparing the technology profiles (characterized by screening criteria) to the application case profile resulting in a technology appropriateness score between 0 and 100%.
2. Generating all valid sanitation system configurations from the appropriate technologies (typically more than 100,000 possible configurations). A valid sanitation system is defined as a combination of compatible technologies which ensure that all sanitation products (e.g. excreta, sludge, blackwater) are either transferred, transformed, or end up in sink for disposal or reuse.

3. Selecting the desired number of appropriate system configurations from all generated options. The desired number depends on what is manageable in the follow-up planning process. The selection covers the full diversity of the sanitation system options space. The diversity is defined by 19 system templates, categories of system based on technological conditions (e.g onsite simple, urine diversion, biofuel, blackwater, etc.). The 19 templates include 3 simple onsite templates, five urine diversion templates, 4 biofuel templates, and 7 blackwater templates. If a system integrates urine and biofuel, blackwater, compost, etc. it is still classified as urine diversion system.

The diverse set of locally appropriate sanitation system options is the main output of the method and serves as an input into the planning process for further evaluation (SDM step 4), the discussion of trade-offs, and the facilitated selection of the preferred option using MCDA in order to account for differing stakeholder preferences (SDM steps 5).

Efficiency of screening and impact on the final decision: System templates as previously introduced by Tilley et al. (Tilley et al., 2014b; Tilley et al., 2010) showed to be an effective mean of describing technological diversity of the sanitation system option space. However, the number of valid systems within one template remain very high and the template do not allow to compare options based on performance in terms of appropriateness. Nevertheless, the suggested approach allows to reduce the set of decision options to a manageable size while maintaining diversity. Because the set of options is diverse, it allows to cover very different characteristics and therefore can potentially be effective to reveal all major trade-offs, also when the follow-up steps of SDM (i.e. evaluation of trade-offs and selection of preferred options, step 5) uses a simple MCDA approach that can deal with few options only (e.g. 3 to 5 as outlined in the CLUES tool D17.1 (Lüthi et al., 2011b). This explicit consideration of diversity in the screening methods allows more balanced decisions and reduces the impact of the pre-selection on the final decision outcome in comparison with simple expert judgement.

Definition of screening criteria: An additional element that allows to minimise the impact of the screening step on the final decision is the definition of conditions that screening criteria need to fulfil. Screening criteria are different from the performance criteria used in MCDA as they are used to quantify the suitability of an option and not to identify a single best option (Eisenführ et al., 2010). Criteria useful for screening are those that are non-negotiable (exogenously defined and/or independent from stakeholder preferences), and for which data is available at the structuring phase (see also (Spuhler et al., 2020a; Spuhler et al., 2018)). Typical screening criteria cover technical aspects (e.g. energy requirements, spare parts), physical aspects (e.g. climate, vehicle access), demographic (e.g. population density), socio-cultural (e.g. religious constraints), or managerial aspects (e.g. operation and maintenance frequency, construction skills). The negotiable criteria, which depend on the often-differing preferences of stakeholders are to be considered in the later MCDA in step 5. It is however important to note, that some screening criteria might also be relevant later in the SDM process. For example, a common screening criterion is water use; a potential technology should not require an amount of water that exceed the amount available in the application case. Among the ones matching this criteria, the decision-maker still might want to prefer those with lower water use.

Quantification of screening criteria and uncertainty: Screening criteria are evaluated by comparing for each criterion a technology attribute (e.g. water requirement) to the application attribute (e.g. water availability). To account for uncertainties related to the technology implementation or the local context, probability distributions are applied to characterise each attribute. By matching the case and the technology function, a criterion appropriateness score is obtained. By aggregating all criterion scores, the technology appropriateness score is obtained. This approach allows to work in the case of scarce or uncertain input data. But the practical applications showed, that the choice of the distributions has a sensitive impact on technology ranking. Therefore, it should be chosen carefully according to the data that is available (Spuhler et al., 2018). Fortunately, an effect on the system option selection was not observed.

Aggregation and sensitive criteria: To obtain the technology appropriateness scores, the scores for each screening criteria are aggregated using the geometric mean. This aggregation function fulfils several useful conditions: it can be applied for different number of criteria, is normalized, doesn't imply weighting, and turns into zero if one score is zero (Grabisch et al., 2011). However, using the geometric means also implies that data for all relevant screening criteria is always required, or at least an educated estimation for each type of data. Moreover, killer criteria (criteria with score zero) need to be carefully used as they lead to the full elimination of an option. The geometric mean also requires a limited number of criteria (i.e. no higher than 20) in order to obtain a robust comparison of different technologies. Most sensitive and therefore relevant criteria are: water and energy requirements, operation and maintenance frequency and skills, vehicular access, flooding, soil type, space requirements, design skills, and religious or cultural requirements. Financial criteria were excluded from the screening criteria because they involve trade-offs that need to be discussed with stakeholders and data is often not available at the structuring phase. Knowing the sensitive criteria helps to reduce the list of screening criteria and could also guide future research on technology development or local capacity development activities.

System definition: The technology compatibility within a system is defined by the input and output products. To be generic and in order to automate the system generation, very generic definition of technologies and products are defined. A typical generalisation which creates a lot of discussions among practitioners is 'sludge': a sludge from a septic tank has very different qualities than a "sludge" from a biogas digester. Moreover, a biogas digester not only has sludge as an input, but also as an output. Another typical example is a septic tank. The quantity and quality of sludge and effluent from these kind of technologies which see very different implementations is also highly variable. Therefore, system generation maybe leads to combinations of technologies which are valid according to the algorithm definition, but do not make sense from an engineering perspective (e.g. treating dried faeces alone in a biogas digester). Therefore, all selected systems should be checked for plausibility before passing them over to the SDM process.

Most appropriate systems: The practical applications of the model in case studies showed that most appropriate systems for the context of expanding urban areas in developing countries are: onsite storage and treatment combined with centralized treatment of some of the product streams (e.g. sludge, compost, urine, effluent), or very short systems involving few treatment steps. This confirms what is generally reported in literature (e.g. Darteh and Appiah, 2008; Kalbermatten et al., 1982; Loetscher, 1999; Mara, 2018; Monvois et al., 2012; Murphy et al., 2009; Reymond et al., 2016). Moreover, the applications showed that the appropriateness depends strongly on technology interaction within a system. For instance, a cistern-flush toilet might be highly appropriate in a given context but if there is no appropriate blackwater treatment technology to combine it to, corresponding systems will be fully inappropriate (see the example of the kebele Chamo in Arba Minch). Therefore, local appropriateness has to be considered at the scale of an entire system and cannot be evaluated for single technology elements only.

— 7.3 QUANTIFICATION OF SUBSTANCE FLOWS

Overview: The substance flow model uses transfer coefficients and inflow volumes to propagate substances through the system. The flow paths are defined by the products linking different technologies. The main result is the fraction of substance entering the system that is either lost to soil, air, or surface water or can be recovered.

Relevance of substances: The model is implemented for four substances that are most relevant to the discourse on sustainable sanitation: total phosphorus, total nitrogen, total solids, and water. Both phosphorus and nitrogen have value and crucial significance: as important macronutrients, there are resources to be recovered; and as environmental pollutants, there are emissions to be minimised. Total solids can be used as a proxy for energy that could be recovered, for example, in the form of briquettes or biochar (e.g. Andriessen et al. 2019, Motte et al. 2013), as well as for organic matter that could be recovered as soil amendment (e.g. Diener et al. 2014, Septien et al. 2018a). If discharged into the environment, total solids also has significant pollution potential. Water is under increasing pressure in many urban areas and has become a scarce commodity which should either be saved or reused. A more detailed description of the four substances and their relevance can be found in (Spuhler and Roller, 2020). Implementing the model for additional substances should be straightforward.

Inflows: For these four substances, we also defined inflow masses for toilet sources based on international literature (e.g. (Lohri et al., 2010; Rose et al., 2015)). These data can be complemented for additional sources (e.g. greywater) and should be adapted to the local context for the number of inhabitant numbers as well as the time period (i.e.. per year or per month, etc.). For more accuracy, the inflow masses might also be adapted using local flushing volumes, greywater production, details on the local diet and substance concentrations in human excreta and other sanitation products, etc.

Transfer coefficients and uncertainty: The transfer coefficients provided by technology library are based on literature and expert knowledge. The uncertainty expressed by the variability of the reported data points in literature or the confidence in the substance and the knowledge about the technology (i.e. the technology readiness level) is quantified and provided. To model this uncertainty, the Dirichlet distribution is used. The required assumption behind is that the sum of all transfer coefficients for a substance is always equal to one (assuming no biological fixation). The practical application of the model and the library data showed, that the resulting accuracy is comparable to other studies using classical ex-post material flow analysis (Keil et al. 2018, Meinzinger et al. 2009, Montangero et al. 2007).

Factors influencing resource recovery: The practical applications showed that system templates are not an indicator for resource recovery (as they are not for appropriateness). Factors influencing resource recovery are the type of source (e.g. source separation, dry, wet), the length of a system (number of technologies), the type of storage and treatment technology (level of containment), and obviously the sink (recovery or loss sink). However, there was no unequivocal set of factors determining resource recovery or losses and the resource recovery depends again on technology interaction. This highlights the need for a generic and automated model that allows substance mass flows to be quantified even for large numbers of sanitation systems in reasonable time.

Recommendations for resource recovery: The practical applications allowed to develop a number of key recommendations for the optimisation of resource recovery: (i) prioritize short systems that close the loop at the lowest possible level (fewer treatment steps, less losses); (ii) separate waste streams as much as possible: It does not lead necessarily to fewer treatment steps, but it allows for higher recovery potentials (e.g. through urine diversion); (iii) use storage and treatment technologies that contain the products as much as possible, avoid technologies with leaching (e.g. single pits) and technologies with high risk of volatilization (e.g. drying beds); (iv) design sinks for recovery; and (v) combine various reuse options for different product streams (e.g. urine diversion systems that combine reuse of urine and production of biofuel from faeces). These recommendations, and in particular point (i) imply to rethink the way how we currently design systems and move away from minimising effluent concentration towards a design that optimises the level of treatment to the desired reuse in a given case. It is also important to note, that the recommendations above are based on the analysis of masses and not on the actual value of a reuse product. For instance, depending on the local markets or the stakeholder preferences, biofuel recovery would be given higher priority over nutrient recovery. The follow up step of SDM (step 5, discussion of trade-offs) can account for these preferences by defining stakeholder-specific value functions.

— 7.4 PRACTICAL APPLICATIONS AND INTEGRATION WITH SDM AND STRATEGIC PLANNING

Practical applications: To address objective three and to integrate the developed methods with practice I adopted in this thesis a design thinking approach. To do so, I collaborated with various partners in Nepal, Ethiopia, Peru, and South Africa that was the basis for sic different practical applications. The first application happened in Nepal in 2015 and consisted in testing the applicability of the technology appropriateness assessment for the case of Thimi Municipality in the Kathmandu valley with approximatively 80'000 inhabitants at that time. This first test was carried out in collaboration with the Environmental and Public Health Organisation (ENPHO) and WaterAid Nepal. Unfortunately, the mayor earthquake in 2015 interrupted the project. But the experience provided the basis for further developing the methods and the strategies for data collection and interaction with local stakeholders. Intercooperation and the Swiss Water and Sanitation Consortium in Katarniya an emerging small town of a few thousand inhabitants in South-Western Nepal. In parallel, the methods for data collection was also applied to Arba Minch, a town in Southern Ethiopia with about 100'000 inhabitant in collaboration with the Municipality and the local University. This allowed to further develop the methods and add the substance flow model extension which was then tested in a second application in 2019 in Arba Minch. The same version was also tested in collaboration with the University of Stuttgart in an informal settlement of Quebrada Verde in Lima, located in the lower part of the Lurin River Basin with approximatively 800 inhabitants.

> *These practical applications were crucial to understand how the developed methods perform, how they are accepted and applicable by practitioners, and how to further improve them in a way that they respond to concrete and real needs. The practical applications was only made possible through the continued support of the partners in the different countries and their crucial feedback.*

Overview of the integration procedure: The software (algorithms + library) described above is designed to support step 3 of SDM (identification of decision options) and provide input data (substance balances) for MCDA in step 4 and 5 (evaluation of options and discussion of trade-offs). The integration with SDM requires a number of elements including: the screening criteria, evaluation data to characterize the application case, the number of options that can be managed in step 4 and 5 (i.e. something between 3 and 50), and optionally local inflow data (see also 'data collection'). The main results are a set of sanitation system planning options and the corresponding resource recovery potentials (for phosphorus, nitrogen, total solids, and water) that can be used to compare the options. The integration is facilitated by an engineering consultant with technical expertise but also requires additional skills for e.g. stakeholder management, facilitation of participatory workshops, or capacity development.

Stakeholder engagement and capacity development: To apply the models, one or two workshops are sufficient (see 'data collection'). However, to implement the entire SDM process and to optimally benefitting from the strengths of the software here presented, several workshops are required to build up knowledge and understanding, in order to create local momentum, develop capacities, and encourage ownership by all relevant actors (see also Spuhler et al., 2020a).

Providing the required expert support: The practical applications showed that local stakeholders are able to provide the required inputs, in particularly the relevant screening criteria, but have difficulties to quantify those for a growing number of technologies and to formulate decision objectives. The objective hierarchy for sustainable sanitation and the master list of screening criteria helps to cover all relevant local aspects (see the SI in the data package associated with (Spuhler et al., 2020a): ([dataset] Spuhler, 2020b) or directly at ERIC: doi.org/10.25678/0001QJ). The library provides the knowledge and data for the technologies ([dataset] Spuhler and Roller, 2020). The results are suitable to support the SDM process but are not complete.

Missing Elements: Sanitation system decision options and resource recovery performance indicators need to be complemented with non-hardware aspects (e.g. related to service and business model) and performance indicators for all relevant decision objectives. The main additional performance indicators are costs and health risk. For costs, data are often not available at the structuring phase. Moreover, costs involve trade-offs. Therefore, costs have to be dealt with in step 5 of SDM (discussion of trade-offs). For the health risk, it is assumed during the appropriateness assessment that technologies are perfectly implemented. However, once the sanitation system options are combined with different operation and maintenance schemes, there might be different in terms of exposure frequency, etc.. Other sustainability criteria (e.g. institutional appropriateness, compliance to laws, regulations, and standards) can be dealt with in the appropriateness assessment.

Flexible adaption to local planning process: In reality, sanitation planning is not as structured as designed in SDM. As shown in our practical application in Arba Minch, the application of the suggested software and integration procedure is flexible and fits well to a more organic definition of the different planning steps.

— 7.5 TECHNOLOGY LIBRARY AND DATA COLLECTION

The practical applications showed, that a major challenge is the quantification of suitable input data. Therefore, an important part of this thesis is the collection and compilation of required input data based on literature in the technology library (Spuhler and Roller, 2020). The library provides the data for 41 conventional and novel technologies and 27 screening criteria for the appropriateness assessment, and transfer coefficients for the four selected substances. It also provides guidance on how to define and characterise additional technologies or screening criteria. This data was collected based on an extensive literature review involving many different students at different times, complemented with interviews with selected experts. The main challenge is to compile very different data: for some technologies, literature is very abundant, while for others, especially novel technologies, it is difficult to find performance information regarding full scale operation. Considering uncertainties is the approach used to integrate these diverse kinds of data in the same database. Not all the input data can be prepared in advance as the aim is to provide a context specific decision support. Thus, a number of elements need contextualisation in interaction with the local stakeholder and the SDM process (see also chapter 6 and (Spuhler et al., 2020a). Local input is required for (i) the selection of the most relevant screening criteria (not more than 20), (ii) the quantification of the application case profiles, (iii) as well as the number of options that is manageable. Some relevant aspects for these elements are discussed below.

Screening criteria: The selection of the relevant screening criteria can be linked with the definition of decision objectives (step 2). To support this process, a generic objective hierarchy for sustainable sanitation based on international literature and expert input is provided. The hierarchy is complemented with a master list of screening criteria (chapter 6 and (Spuhler et al., 2020a). The decision objectives and the screening criteria are contextualized based on one or two workshops. These workshops require detailed orientation of the participants at the beginning and careful moderation based on (Gregory et al., 2012) and (Bond et al., 2008). The aim of the moderation is to keep the discussion focussed, provide room for everyone express his/her opinion and to help finding a compromise or even a consensus of what criteria to consider for the screening process. In a first step, the decision objectives are brainstormed and organised in a hierarchy, then the criteria that are non-negotiable are identified. Typical non-negotiable criteria are the environmental factors (e.g. groundwater table, water availability), socio-demographic factors (e.g. population density), as well as factors related to capacity (e.g. availability of spare parts). The generic objective hierarchy and the master list mainly help the facilitation, and are shared with participants at the end of the workshop only in order to ensure, that no important element is omitted. The contextualisation of the screening criteria is essential, because both the condition, (i) if a criterion is negotiable or not, and (ii) if data is available, depends on the context and sometimes even on opinions. Thus, in reality, if something is negotiable or not becomes a negotiation in itself that requires careful moderation. For instance, legal aspects are generally recognized as fixed in Switzerland but are seen as flexible in Nepal. Another example is that of financial criteria: in some cases, they are perceived as stakeholder-independent killer criteria, even though they involve major trade-offs. But in most of the cases, costs are not quantifiable at the structuring phase.

Application case profiles: The characterisation of the application case profile can be based on step 1 of SDM (understanding of the decision context), secondary literature (e.g. baseline report), or previous projects that involved data collection relevant for sanitation. Data gaps can be filled with field visits. Because the models use probability distributions in order to deal with the unavoidable uncertainties encountered at the structuring phase of SDM, it can also work with a best guess only if needed. Again, the quality and quantity of available data is dependent on the case, as well as the criteria. For some criteria, such as water availability, statistical data might be available. For other criteria, such as space or vehicular access, assumptions and approximations are required. The identification of suitable probability distributions and input data often itself involves discussions with and information from some key stakeholders. Especially the space issue is difficult to quantify, because not all technologies need space at the same level: sometimes the space is required onsite, and other times offsite, and there, the distance become a relevant factor. Vehicular access shows the same problems: it can be quantified e.g. by classing streets according to their width and by quantifying road density using e.g. geographic information systems. But again, for some technologies, access is required within the settlement, while others (e.g. drying bed) are situated far away from the toilet sources.

Number of options: The number of options that can be managed depends on the type of SDM process and the model complexity of methods used in steps 4 and 5. In the case of a more sophisticated MCDA (e.g. using multiple−attribute value theory, MAVT), this number might be as high as 50. Whereas in a simple context, as described in CLUES, using a simple scoring method (Lüthi et al., 2011b), three to eight options are the most that can be dealt with (Gregory et al., 2012). The advantage of the simple methods is that they can be implemented interactively in a workshop setting (see e.g. Sherpa et al., 2012). The advantage of more options is the increased diversity contributing to more balanced decision. Using the system templates as indicator for diversity in the practical applications, the optimal number of option is equal or higher to the number of system templates. Thus, the recommendation is to select the system with the highest appropriateness score from each template. If the SDM process can manage only fewer options, than, the 90% quantile of the system appropriateness within a system template can be used to prioritise certain templates. If more options can be managed, than, the length (number of technologies) and the complexity (number of connections per technology within a system) can be used to form diversity clusters of systems within one template allowing to select several most appropriate options from a same template.

— 7.6 LIMITATIONS AND SHORTCOMINGS

The presented approach (software + integration procedure) is by no means intended to replace the technical know-how required for detailed planning and implementation. It is a tool to integrate the growing number of decision criteria and technological options into the planning process. Similarly, the generated results are not intended to replace in-situ post-ante performance measurements, but provide the *expected* appropriateness and resource recovery potentials at the structuring phase.

Moreover, the appropriateness assessment and system generation are sensitive to several aspects: the selection of screening criteria, evaluation attributes and uncertainty descriptions as well as the definition of technologies (which can be more or less generic). These aspect require expert skills and local knowledge to provide suitable inputs. Moreover, the resulting sanitation systems require a plausibility check and also needs to be complemented with additional aspects related to the service or business model (relevant for operation and maintenance and costs) .

The sensitive aspects for the substance flow model are related to a number of simplifying assumptions: (i) the generic definition of technology implementation and products not fully accounting for the variations in terms of implementation and product quality in reality; (ii) a purely linear model for the transfer coefficients (e.g. again the quality of the entering product is not considered as well as other factors such as scale are ignored); and (iii) the exclusion of the substance assimilation in the substance flow model (e.g. through biological fixation). Importantly, these simplifications allow the automated substance flow quantification and the consequences are captured in the uncertainty. For instance, the transfer coefficients found in literature for a septic tank vary greatly. This variability is expressed by the uncertainty coefficient associated with transfer coefficient (see also Spuhler et al., 2020c). As for the sanitation system options, also the resource recovery and loss potential are not enough but need to be complemented with additional performance indicators (mainly for the decision objectives costs and health) as well as value functions to capture the stakeholder preferences.

The methods presented here become only effective, if they are taken up by practice. Historically, development support in the sanitation sector has gone through three paradigm: (1) support through infrastructure provision; (2) provision of methods to develop locally appropriate technologies; and (3) a systematic approach including decision support and capacity development and where not only the end result but also the process is important. The methods presented here are intended to be integrated in SDM which in turn is intended to support the third paradigm. The methods here are no guarantee for the needed local leadership and human and financial resources for follow-up and implementation. Developing cities commonly lack the capacities for planning and implementation and often short-term thinking provides a major obstacle for the application of the presented methods (e.g. Reymond, 2014). Moreover, compared to other services, the provision of sanitation is often not very high on the political agenda, or when it is on the agenda, high-income areas of a city are on focus. It is the SDM approach, that is assumed to deal with this complexity.

Last but not least, the presented methods are efficient in providing appropriate, and thus feasible options for the different areas within a city (e.g. centre, informal dense, peri-urban). But several challenges have not yet been addressed: (i) how the options in different areas of the city interact with each other or with existing infrastructure (i.e. hybrid systems); (ii) how the options performance interacts with options for other sectors (e.g. solid waste); and (iii) how different options are best complemented with aspects related to business and service models as this has an effect on the operation and maintenance, costs, and health, which are all important criteria for the evaluation of trade-offs (step 5). These challenges could be addressed when integrating the methods within a broader adaptive strategic planning frameworks for Citywide Inclusive Sanitation (CWIS).

08 General conclusions and contributions

— 8.1 OUTLINE OF THIS CHAPTER

This chapter contains five sections that present the content in different formats, each relevant for a different audience. Therefore, some arguments, assertions, or thread of thoughts might be repeated but presented from another angle. The five sections are:

- Answers to the research questions, recommended for supervisors and scientists. In this section I draw conclusions from my work in order to answer to the research questions initially outlined in my research plan submitted and accepted in 2016 (chapter 8.2).
- Contribution to science and planning theory, recommended for all readers. In this section I present the main innovation that my work brings along and how they might contribute to the current state-of-the art (chapter 8.3).
- Implications for practice, recommended for practitioners. In this section I compile a list or results, lessons learned, and conclusions that have potentially implications for practice and therefore should be taken into consideration in any practical application of the outcomes of this thesis (chapter 8.4).
- Generalisations recommended for both scientists and practitioners; provides information what of this work is directly transferable (chapter 8.5).
- Outlook and open questions, recommended for both scientists and practitioners. In this last section, I provide an overview on the most interesting future applications of the results from a scientific as well as practical point of view (chapter 8.5).

— 8.2 ANSWERS TO RESEARCH QUESTIONS

In the following three paragraphs we present the original research questions related to the three research objectives respectively followed by the answers.

Objective I: To develop a systematic method for the generation of locally appropriate sanitation system decision options at the structuring phase of the decision-making process.

1. Can we objectively identify locally appropriate sanitation system decision options at the structuring phase of decision-making considering a growing number of conventional and novel technologies and systems?
    1.1 What is a comprehensive and consistent set of criteria to evaluate the appropriateness of sanitation technologies?
    1.2 How can the number of options be reduced to a manageable number without impacting the decision-making process?
    1.3 What are the uncertainties related to the appropriateness of the options and how does it influence the ranking of the decision options?

- A generic algorithm to identify locally appropriate sanitation system decision options at the structuring phase was developed. The method is based on a set of locally defined objective screening criteria and their systematic evaluation.
- The screening criteria to evaluate appropriateness can be derived from the higher-level objective of sustainable sanitation as defined in literature and should not only cover technical aspects. Criteria useful for screening are those that are non-negotiable: exogenously defined, independent from stakeholder preferences, and for which data is available at the structuring phase. Typical screening criteria cover technical aspects (e.g. energy requirements, spare parts), physical aspects (e.g. climate, vehicle access), demographic (e.g. population density), socio-cultural (e.g. religious constraints), or managerial aspects (e.g. operation and maintenance frequency, construction skills).
- International literature is used to characterise the screening criteria and to provide 41 technology profiles that then can be compared to each case individually. This data is made available in a technology library. Only case specific data has to be collected. This enables the consideration of a diverse and large set of technology options and enhances transparency and reproducibility.
- From the appropriate technologies entire systems are generated. Because the appropriateness of systems depends on the interaction of technologies, the appropriateness has to be looked at on system level. For instance, a sink technology that is highly appropriate can only lead to a highly appropriate sanitation system if all technologies before it are also appropriate. A weighted geometric mean is used to aggregate the individual technology scores to a system score. The weight allows to balance for the length of systems (longer systems are only slightly penalized). Systems with technologies that are totally inappropriate are eliminated further streamlining the process.
- In order to reduce the overwhelming set of options (typically more than 100’000) to a smaller set which is manageable but still diverse and therefore able to reveal major trade-offs, system template can be used. Based on nine characteristics inspired from the Compendium of Sanitation Systems and Technologies (Tilley et al., 2014b), 19 unique systems templates were defined to structure the entire sanitation system option space. The resulting characterization is technical, and not performance-based.
- To consider uncertainties related to the technologies or the local context, probability distributions are used to quantify the screening criteria. However, the uncertainty is not propagated but integrated in the scores. Moreover, the technology scores remain sensitive to the probability distributions used as well as to the evaluation data. The method is thus not robust enough to provide information on the single best option, but provides a comparative ranking.

Objective II: To develop a generic method for the quantification of resource recovery potentials suitable for the comparison of a diverse and large range of sanitation systems.

2. Can we develop a generic model to quantify key performance indicators for a broad range of sanitation technologies and systems at the scale of an urban settlement?
    1.1. With what system elements can we quantify the performance indicators in order to compare a broad range of options?
    1.2. Which is the optimal spatial and time reference in order to quantitatively compare a broad range of systems?
    1.3. What is the uncertainty of the model outcome and how can we minimize it in the application of the developed approach?

- Resource recovery and loss potential were selected to answer the questions above because it is one key performance indicator for sustainable sanitation that contributes also to the discussion of sustainable cities and circular economy.
- To quantify the resource recovery and loss potentials, a generic substance flow model was developed that is enough generic to compare a diverse and large range of sanitation systems at the scale of an urban catchment at the structuring phase of decision making (thus ex-ante).
- The model uses technologies as building blocks and products as connectors to describe the systems. Each technology contains the transfer coefficients and the flow path of substances is defined by the product connections.
- As the definition of technologies and systems are generic, the model can be automatized for a large and diverse set options. To support the automatization, the corresponding transfer coefficients for 41 technologies and for four substance were estimated based on international literature and expert knowledge and included in the technology library.
- Using this data over 100'000 systems were generated and for each of it, substance flows were quantified to calculate the recovery and loss potentials for each system.
- The spatial and time reference is defined by the mass of inflowing substances (e.g. per person and year, e.g. per family week, per area per month, etc.).
- Uncertainties related to the transfer coefficients and given by the variability of literature data, are modelled using the Dirichlet distribution and propagated using Monte Carlo. The resulting uncertainties of resource recovery and loss potentials are similar to the uncertainties obtained by models using material flow analysis in combination with in situ measurements.

Objective III: To develop a standardized procedure for the integration of the methods with structured decision-making in expanding urban areas and to evaluate their contribution.

3. How can these methods be integrated in sustainable sanitation planning in urban areas of developing countries?
   - 3.1 How do the developed methods integrate in the practical application of structured decision-making?
   - 3.2 What are the locally most appropriate and most sustainable sanitation options and how is this outcome related to specific option properties such as degree of centralization and resource efficiency and how is this influence by the uncertainties?
   - 3.3 What is the potential contribution of the application to the local strategic planning process?

- A procedure for the integration of the software (algorithm + technology library) in SDM was developed. The integration happens at steps 2, 3 and 4 of SDM and requires three elements: (i) a list of screening criteria useful for the local context, (ii) evaluation data to establish the application case profile, (iii) a decision how many sanitation system options can be managed by the SDM process.
- To support the interaction with the stakeholders, a master list of screening criteria was developed based on literature. The evaluation data is based on secondary literature for the application case and the technology library for the technology options. The desired and manageable number of decision options depends on the complexity of the methods used for the final selection and lies somewhere between 3 to over 50.
- The practical application showed that for the case studies, systems combining onsite storage and treatment and centralized treatment of some side-streams are most appropriate (e.g. onsite toilets with effluent infiltration and centralized treatment and reuse of sludge). Also, some very simple short systems turn out to be appropriate as

well (e.g. pour flush toilet with septic tanks and local infiltration) but those need to be checked carefully for effluent quality because fewer treatment steps are involved.

- The appropriateness and the resource recovery potentials are clearly not related. Nevertheless, there are many highly appropriate sanitation systems that show high potential for resource recovery. Thus, resource recovery, or appropriateness alone are never enough to make a final decision. These indicators, have together with other indicators for all sustainability criteria be looked at in detail in step 5 of SDM in order to evaluate and discuss trade-offs using a facilitated MCDA methodology.
- The length of the systems has a negative effect on the resource recovery potentials as more losses can occur. The highest resource recovery is obtained with systems that involve only three or four technologies. However, also some long s (and more appropriate) systems achieve very high resource recovery especially when they combine the recovery and reuse of different product streams: e.g. combining urine diversion and treatment and biofuel valorisation as it is done for instance by Sanivation in Naivasha, Kenya (Russel et al., 2019).
- For the appropriateness assessment uncertainties related to technology implementation (e.g. operation and maintenance frequency) and the local context (e.g. population density) are considered but not quantified in the final result. It is therefore important that the user understands that the appropriateness scores are useful for ranking, but not to identify a single best option.
- For substance flow modelling, uncertainties are explicitly considered in the final results and can be used to evaluate the robustness when comparing different systems using e.g. MCDA.
- The practical application of the methods provided several benefits for the local SDM process (see below).

— 8.3 CONTRIBUTION TO SCIENCE AND PLANNING THEORY AND PRACTICE

This thesis contributes with a theoretical description, implementation, and practical applications of methods for: (1) the generation of locally appropriate sanitation system options considering novel technologies; and (2) the quantification of corresponding resource recovery potentials for their comparison at the scale of entire city.

> *The methods enable a systematic consideration of technology innovations and sustainability criteria at the structuring phase of strategic sanitation planning. They are not intended to replace any existing planning framework that addresses the entire SDM process (e.g. CLUES) but provide the tools to operationalize step 3 (identification of decision options) and step 4 (evaluation of options).*

The detailed description of the research needs and gaps are presented in a peer-reviewed article (chapter 2, Spuhler and Lüthi, 2020). The theoretical description is provided in additional three peer-reviewed academic publications each complemented with an example application (chapters 3, 4 and 5, Spuhler et al., 2018; 2020b; c). The experiences of the practical application in six cases (two in Nepal, two in Ethiopia, one in South Africa, and one in Peru) are summarized in a fifth peer-reviewed publications (chapter 6, Spuhler et al., 2020a). This is completed with several articles in non-academic journals (Spuhler and Germann, 2019; Spuhler and Rath, 2017; Spuhler and Scheidegger, 2019) and two conference presentations (Spuhler, 2019; Spuhler and Lüthi, 2018), and various smaller internal and external presentations (e.g. Aguasan workshop 2017 and 2019 in Spiez; “30 ans de la Fedevaco” 2019, Lausanne, Switzerland). The practical applications were implemented with local partners from development agencies (e.g. Helvetas), NGOs (e.g. ENPHO), local consultants (e.g. 500B Solutions), local research institutes (e.g. Arba Minch University), and local governments (e.g. Arba Minch Town Municipality). The example application and the practical applications showed that the methods have several advantages over existing methods and have the potential to contribute to more structured and strategic decision making and beyond.

The main innovation can be summarized as follows:

i. The methods are generic and therefore versatile to be applied to a diverse set of sanitation technology and system options.
ii. The methods are flexible for the integration of almost any thinkable novel technology or decision criteria.
iii. The methods are systematic and thus reproducible and comprehensive: (i) the technology appropriateness assessment uses a set of clearly defined criteria and a standardized procedure for their quantification; (ii) an algorithm generates all valid sanitation system options; and (iii) it makes technical suggestions for each and every product and therefore enforces the consideration of entire sanitation systems.
iv. Thanks to a number of simplifications, the methods are automated and can therefore deal with a very large number of technologies and systems.
v. Uncertainties related to the technologies, their implementation, and the local context are explicitly considered. This makes the methods applicable at the structuring phase r5of decision making and enables an evaluation of the robustness of the results.
vi. The technology library compiles suitable input data for 41 technologies, 27 screening criteria, and transfer coefficients for four substances based on international literature and expert knowledge. The library can also be seen as a "machine-readable" review as it summarizes a lot of knowledge and makes it available to the local context.

> *The two main scientific contributions of this thesis are*
>
> 1. *Any (future) technology option can systematically be considered when generating sanitation systems*
>
> 2. *Resource recovery potentials can automatically and ex-ante be quantified for a large and diverse set of systems by compiling international data and using uncertainty quantification.*

Beyond these scientific contributions this thesis potentially contributes to structured decision making for strategic sanitation planning practice:

i. The set of decision options is designed to be diverse and thereby (i) opens up the option space with potentially more appropriate and sustainably options which one might not have thought of manually, and (ii) has the potential to reveal the majority of relevant trade-offs regarding the main decisions' objective, and thereby the risk of impacting the final decision by this structured screening is lowered.
ii. Because international performance data is matched with local information, more empirical decision making is enabled. This potentially enhances ownership and reproducibility.
iii. The decision-making process is streamlined as the options are reduced to a manageable number of appropriate options only.

iv. The option generation is based on decision objectives and is not limited to the knowledge and experiences of the involved experts.

> *The two main potential added values that practitioners can get from this thesis are:*
>
> 1. *To find appropriate sanitation systems which they may not have thought about without the software (algorithms + library). This helps to think out of the box, and to leapfrog to up-to-date knowledge.*
>
> 2. *To increase resource recovery and circular economy.*

The practical applications also indicated that the integration of the methods has the potential to improve local planning culture by:

i. supporting the definition of a joint vision shared by all stakeholders;
ii. bridging top-down objectives with local preferences through the formulation of screening criteria specific for each area;
iii. structuring stakeholder participation, enhancing ownership while avoiding confusion and endless discussion;
iv. contributing to organizational and individual capacity development.
v. Moreover, it provides appropriate options and corresponding sustainability criteria for each and every area within a city thereby contributing to a more *Citywide Inclusive Sanitation (CWIS)* planning approach.

The methods could be used to develop value propositions for practice:

- **Engineering consultants and urban planners** (users) could be enabled to systematically consider the growing number of technology options and provide a manageable but diverse set of locally appropriate sanitation system options to the local planning process
- **Local and regional governments and policy makers** (clients) could be interested in the enhanced reproducibility and the support provided to structure the participation of various stakeholders enhancing also ownership and streamlining the planning process.
- **Development agencies and NGOs** (funders) could be interested in improving the planning culture by integrating elements from SDM. They could also be interested in the explicit consideration of all the different areas within a city and the consideration of multiple criteria from all sustainability dimensions.
- **Academia** could be interested in testing the appropriateness of newly developed technologies or in defining design criteria for appropriateness or resource recovery. They could also be interested in expanding the library with their own technology innovations or to explore what system configurations could be generated from those.
- **Private sector and industry** could be interested in the suggested approach to explore what kind of future technology or system would have the biggest benefit. Also, industry could identify scenarios for which their technology or system solutions are most suitable.

— 8.4 IMPLICATIONS FOR PRACTICE

- There is no unequivocal set of screening criteria that serves as a proxy for technology appropriateness, but some criteria are generally sensitive (see chapter 3 or Spuhler et al., 2018). **The criteria with the most sensitive impact** on the appropriateness scores are: water and energy requirements, operation and maintenance frequency and skills, vehicular access, flooding, soil type, space requirements, design skills, and religious or cultural requirements. Financial criteria were excluded from the screening criteria because they involve trade-offs that need to be discussed with stakeholders and data is often not available at the structuring phase. Whether legal aspects are negotiable or not, depends on the context.
- What are the most appropriate systems is context specific but in the practical application in expanding urban areas of developing countries the appropriate systems tend to be similar (see chapter 6 or Spuhler et al., 2020a). **Most appropriate systems** are system that combine onsite storage and treatment and centralized treatment of different products (e.g. sludge) or that are fully onsite. But (1) the appropriate systems are not the same for all zone within a city (e.g. city centre versus peri-urban areas) as shown nicely in the case of Arba Ming; and (2) all system templates integrate highly appropriate systems.
- **A diverse set of options** can be obtained by using system templates. However, system template structure the option space along technologies and their characteristics and not along performance in terms of appropriateness or resource recovery (see chapter 3 and 5 and Spuhler et al., 2018; 2020b).
- The appropriate sanitation system options need to be checked for plausibility and **completed with aspects related to the business and service models** as those have an effect on the operation and maintenance, costs, and health risks which are important criteria for the final decision.
- The substance flow model allows to quantify recovery and loss potential **for four exemplary substances** which are most relevant to the discourse on sustainable sanitation and circular economy: total phosphorus and total nitrogen as nutrients, total solids (as indicator for energy and organics), and water which is a resource under increasing pressure (see chapter 4 and Spuhler et al., 2020c). However, adding another substance to the algorithm and library should be straightforward.
- By applying the substance flow model to a representative real-life case, we could extract some **key factors that influence resource recovery** (see chapter 5 and Spuhler et al., 2020b): the length of a system (the more the technologies, the more the potential losses), the type of source (source separation can support resource recovery), type of storage and of treatment technology (the level of containment defines the level of losses), along with the types of sink technologies (either designed for disposal or recovery and reuse).
- The generic application case also allowed to develop **recommendations for the optimisation of resource recovery** (chapter 5 and Spuhler et al., 2020b): (i) prioritize short systems that close the loop at the lowest possible level (fewer treatment steps, less losses); (ii) separate waste streams as much as possible, because this does not lead necessarily to fewer treatment steps, but it allows for higher recovery potentials, (e.g. through urine diversion); (iii) use storage and treatment technologies that contain the products as much as possible, avoid technologies with leaching (e.g. single pits) and technologies with high risk of volatilization (e.g. drying beds); (iv) design sinks for recovery; and (v) combine various reuse options for different side streams (e.g. urine diversion systems that combine reuse of urine and production of biofuel from faeces). These recommendation for resource **recovery implies to rethink the way how we currently design systems and move away from minimising effluent concentration towards a design that matches the level of treatment to the desired reuse** in a given case.
- The recommendations for resource recovery however require to be put into context as the resource recovery and appropriateness are not related. **In some cases, resource recovery and appropriateness might even be contradicting**. For instance, in many developing countries, drying beds are the only appropriate sludge treatment option although they can lead to high air losses.

- The substance flow model quantifies the potential masses of resource that could be recovered. It does not consider the value of these resources (e.g. the value of biofuel might be more important than the value of nutrients). The follow up step of SDM (step 5, discussion of trade-offs) can account for these preferences by defining stakeholder specific **value functions**.
- Both, the local appropriateness and resource recovery depend on technology interactions and system configurations (see chapter 3, 4, and 5 or (Spuhler et al., 2018; 2020b; c). This shows that performance in terms of appropriateness or resource recovery **must be based on the analysis of the entire system**. Moreover, the work was not able to identify an unequivocal set of factors determining appropriateness or resource recovery. This highlights **the need for automated approach** that allow to compare a large and diverse range of technologies and system in reasonable time and ex-ante.
- The methods presented here are flexible to be integrated in different layouts of the SDM process (see chapter 6 or Spuhler et al., 2020a). SDM should not be taken as a blueprint approach suitable to every application but rather as a guiding framework to ensure, that no essential steps are omitted. The key challenge lies in the **facilitation of the stakeholder interaction** that is required to optimally utilise the strength of the approach (definition of decision objectives and screening criteria, acquisition of evaluation data).
- Moreover, the uptake of the application results **depends strongly on local leadership** and human and financial resource to support the planning process and the follow-up activities (see also chapter 6 or Spuhler et al., 2020a).
- The practical applications in urban areas of developing countries showed that the suggested methods **support the identification of not only more appropriate but also more sustainable sanitation system options** in terms of resource recovery (chapter 6 or Spuhler et al., 2020a). This opportunity should also be utilized by industrialised countries such as Switzerland.

— 8.5 GENERALISATION

The methods developed here are fully generalisable and can be applied to almost any thinkable technology, sanitation product, or application case. For most of the inputs generic data is provided, which can be adapted with little effort for other applications. The generic input data include: the decision objectives for sustainable sanitation, a master list of screening criteria, 41 potential technologies, system templates, inflows, transfer coefficients, and the number of options (equal to number of templates). Moreover, systems for a given set of technologies will not change from a case to another, only their appropriateness score. Thus, the methods could be used to develop catalogues of sanitation systems from potential technologies, which could also be contextualized with appropriateness scores for typical settings as low-level planning support (e.g. for small town, metropolitan, emerging) and cases (e.g. centre, low-income dense, peri-urban).

The list of sensitive criteria and the factors for resource recovery that were developed based on the practical applications can be used to guide future technology development or local capacity development activities.

The application of the substance flow model to a representative real-life case of 1000 people resulted in recovery and loss potentials (including uncertainties) that are also generic and can be reused as input for any other decision-making process.

— 8.6 FUTURE RESEARCH AND OUTLOOK

8.6.1 Future research

From a scientific point the results presented here call for a number of future research activities:

Validation: If the presented results here are to be validated, the first and question to ask would be whether and how the expected contributions for practice actually become true. A possible approach to answer this question would be to conduct a field study where local experts are first asked to determine options just the usual way they do it, and then do it with the software from this thesis in order to compare the two outcomes. To measure the actual impact, an experimental approach might not be feasible, but a quasi-experimental method such as “qualitative comparative analysis” or “most-significant-change” could be envisaged.

Simplification of appropriateness assessment: Another question would be whether the suggested methods can be further simplified to make them accessible to broader audience. This is particularly relevant for the appropriateness assessment which requires the most of the local input. In the practical applications local experts required substantial support to define suitable probability distribution. A web-based user interface might help (see below). But from a scientific point of view, the question is whether a comparable outcome can be obtained by using a discretised approach with scorecards that are filled in manually. By overlying technology and case scorecard, the appropriateness core could then be quantified visually and manually e.g. by counting the overlapping fields for each criteria). First tests in South Africa in a rural setting were promising and showed that such an approach could also enhance local ownership of the entire process.

Standardized set of criteria and options for different types of settings: The analysis of the results from the practical application allowed to identify a set of sensitive criteria for appropriateness and the types of appropriate systems for the case of expanding urban areas in developing countries. The question is, whether similar results can be obtained for other more specific settings, e.g. growing small town in Nepal, metropole in emerging economies, medium-sized city in Switzerland, etc. or for different cases within a setting e.g. urban neighbourhood in (e.g. high-income centre, low-income dense, peri-urban area of a small town in Nepal, neighbourhood in Zürich, etc.). With the progressive deterioration of urban infrastructure and high costs of replacement, there is an increasing potential for many of the technology innovations to enhance sustainability also in industrialized countries (e.g. augmented capacity, enhanced control of micropollutants, enhanced resource efficiency and recovery, and more flexibility and resilience). Moreover, the call for closing material cycles in sustainable cities, have gained increasing attention at a global scale through the definition of SDG 11 (Kisser et al., 2020; Oral et al., 2020). It is therefore relevant to explore, what broader contribution the presented methods could provide.

Guide future technology and system development: The information on site-specific most sensitive criteria and the system characteristics for resource recovery could then be used to guide future research on technology and system development, both in academia, as well as in practice. Questions that could be asked are: how would the most appropriate technology look like for a peri-urban area of a small town in a developing country. Or what is the optimal system for recovery of biofuel at the scale of an urban catchment, etc. The answers to these questions would not only be relevant for industry, but also for policy makers, development agencies, etc.

Stretching the system boundaries: The expansion of the scope of the practical application would imply to add to the technology library additional (novel) technology options, screening criteria, and substances. As the algorithm itself is generic and can deal with any product or technologies, this would allow to stretch the system boundaries to include also other sectors. The opportunities here are many, but the most obvious and interesting ideas are:

- If organic solid waste is added to the list of products together with corresponding technologies, then can synergies in terms of appropriateness and resource recovery be observed/identified?
- What is the added value if technologies for the entire water and nutrient cycle are added to the library? Can the agricultural, industrial, and municipal flows be modelled simultaneously and what is the added value in terms of modelling results?

In order to simplify the application of such an extended approach, different technology libraries for different purposes could be developed: a technology library for municipal wastewater, for stormwater, for drinking water supply, for emergency sanitation, etc. Another promising, but more challenging model extensions lies in the definition of microbiological indicators (i.e. pathogens) in analogy to the chemical substances.

Complement for missing elements. To be fully operational in the support of SDM the here presented approach should also be complemented for missing elements. These elements are (1) non-technology related aspects such as the business and service models (e.g. operation and maintenance); and (2) performance indicators for other important decision objectives such as costs or hygiene. For the non-technical aspects, strategy tables could be used. The most challenging missing performance indicator are the costs. There is a lack of generic models that allow to compare the costs of different sanitation system options at the scale of an urban catchment at the structuring phase. Most of the available methods require detailed knowledge on the implementation and are therefore only applicable for a few options post-ante. A more automated approach would fill in an important gap in strategic urban sanitation planning. Such an approach could be developed by defining technology-specific cost functions in the existing library and make them functions of the substance masses and number of facilities. For a few technologies this was already successfully demonstrated (Spuhler and Germann, 2019). As number of facilities would be linked to the total volumes, this model would also allow to investigate economies of scale (another missing element). Moreover, it would provide a first step towards analysing not only options individually, but also how hybrid systems (combinations of different systems) would influence the overall performance (e.g. difference of costs in a scenario 1 with 50% of option A and B, or in a scenario 2 with 30% of option A and 70% of option B).

Hybrid systems: The algorithm presented, is equipped with the required functionalities to deal with systems that combine different systems (hybrid systems). Because, depending on the size of the set of the potential technologies, computational limitations are quickly reached this additional feature was never tested in a real case. An optimisation of the algorithm might allow to explore the hybrid solutions also in practical applications. This could then also be used to investigate the compatibility of the approach with scenario planning. Moreover, it would allow to investigate how the consideration of hybrid systems can provide an improved planning support by offering information on how different (new and existing) systems in different city zone perform as a whole in terms of e.g. costs, affordability, coverage, resource recovery, etc.

Improving the algorithm: There exists several ways how the current algorithm could be improved e.g. by training it for the avoidance of the plausibility check or in order to develop easy to interpret decision trees for option selection.

Complementarity with other tools: Another question is whether the generic resource recovery and loss potentials and uncertainty estimations could be used (i) as an input into other complementary tools such as life-cycle analysis (LCA), Cost-Benefit Analysis (CBA), or MCDA; or (ii) to promote the value of sanitation products and their potential contribution to sustainable and circular cities. Moreover, there is also a potential that each of the algorithms presented in this work could be applied individually and integrated as building blocks into other tools, such as the emergency sanitation compendium (Gensch et al., 2018), SamPSon (Schütze et al., 2019), or UrbanBEATS (Bach et al., 2014).

Performance-based system templates: The system templates effectively describing the technological diversity of the sanitation systems option space. However, this work highlighted that they fail to predict resource recovery or appropriateness and are therefore not useful to compare different options. This leads to the questions whether a more performance-based characterisation of systems would contribute to streamlining the decision-making process. The most sensitive criteria and the key factors for resource recovery could be used to define system templates that operationalise SDG 6.2 and SDG 11 using characteristics such as freshwater abstraction, energy recovery, etc.

Value functions: This work quantified resource recovery potentials in terms of masses. These masses have to be complemented with stakeholder specific value functions (e.g. biofuel might have more value than nutrients in a given context). Moreover, they need to be complemented with aspects related to how these amounts of resources are effectively used. E.g. how is it conveyed to potentials reuses and what are the market prizes, associated health risk, etc.

8.6.2 Outlook

This thesis also provides a number of opportunities for implementation:

Interaction design and user interface: From the practitioners stand point, a next step could be to bring these results to production status, allowing to make it available to a more general audience. This could be achieved by developing a user-friendly online interface for the software and a centralized data management system that facilitate the provision of suitable input and allows to browse results interactively (for instance in a workshop setting). This should be complemented with a user manual, a hardcopy guidance document summarizing the integration procedure, and a training package for dissemination.

Dissemination: A business model based on this online tool would allow for a greater dissemination. As a starting point, the value propositions for the different clients (e.g. for engineering consultants, local and regional governments, development agencies and NGOs, academia, and/or industry) could be further developed in business products around software, consulting, and training.

Integration in an adaptive strategic planning frameworks for CWIS: The complementarity of this tool with other currently developed supporting tools for strategic sanitation planning could be investigated. Such complementary tools exist for SDM steps 1 and 2, assessment of the current situation (Peal et al., 2014a; Robb et al., 2017; Scott et al., 2019; Strande et al., 2018) or step 5, selection of a preferred option (Schütze et al., 2019). From this, an adaptive strategic planning frameworks for citywide inclusive sanitation (CWIS) could be developed. Within this more holistic framework, the tool could provide a set of appropriate and thus feasible options for each and every city zones (e.g. city centre, dense informal, peri-urban) offering a basis for consideration of the entire city.

Providing contextualized planning support. To reach the SDG 6.2 and SDG 11, sustainable sanitation and sustainable, inclusive cities for all, large number of city sanitation plans are required. Each of these plans will need to provide the options that are appropriate and most sustainable specifically to a given zone within a given area considering technology and system innovations. The software and integration procedure presented here could become an essential tool to move away from a top-down master planning approach towards a more empirical and contextualized approach. This approach would then provide appropriate options for different context along with the required performance indicators to select the most resource efficient system in each case, thereby contributing to more inclusive and sustainable sanitation worldwide.

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List of supplementary material and data packages

Name	Accessible at ERIC [3]	Relevance	Description
Supplementary information for: Review of strategic sanitation planning from a structured decision-making perspective	Temporary link: https://doi.org/10.2166/washdev.2020.062	Supplementary material for chapter 2.	Detailed overview on results from the literature research on approaches and tools for structured decision making in urban sanitation planning.
Data for: Generation of sanitation system options for urban planning considering novel technologies	https://doi.org/10.25678/0001PH	Data package and supplementary material for chapter 3.	This package contains the software and data used (1) to quantify the appropriateness of a set of sanitation technologies for a Katarniya, a small town in Nepal; (2) to generate all valid sanitation system options from the appropriate technologies; and (3) to select a diverse set of options as an input into the planning process. Full modelling results are also provided.
Data for: Ex-ante quantification of nutrient, total solids, and water flows in sanitation systems	https://doi.org/10.25678/0000HH	Data package and supplementary material for chapter 3.	This data package contains the software for the substance flow model and data of a didactic case with 9 technologies out of 41 and four substances: phosphorus, nitrogen, total solids, and water flows.
Sanitation technology library: details and data sources for appropriateness profiles and transfer coefficients	https://doi.org/10.25678/0000SS	The technology library compiles the required data and methods for chapter 4, 5, and 6.	This package contains a PDF report and raw data in a machine-readable csv forma that can be used to identify locally appropriate sanitation system options and quantify corresponding resource recovery and loss potentials. It covers 41 technologies, 27 screening criteria, and fours substances: total phosphorus, total nitrogen, total solids, and water.
Data for: Comparative analysis of sanitation systems for resource recovery: influence of configurations and single technology components	https://doi.org/10.25678/0001TN	Data package and supplementary material for chapter 5.	This package contains the software and data to quantify substance flows of over 100’000 generic sanitation system options from 41 technologies and four substances: total phosphorus, total nitrogen, total solids, and water. It also contains the entire dataset resulting from the simulation and used for the comparative analysis of resource recovery and loss potential.
Data for: Developing sanitation planning options: a tool for systematic consideration of novel technologies and systems	https://doi.org/10.25678/0001QJ	Data package and supplementary material for chapter 6.	This package contains software, input data, and modelling results from a case study in Arba Minch. The data was used to generate sanitation system options for three Kebeles of Arba Minch Town (Ethiopia) and to quantify corresponding appropriateness scores as well resource recovery potentials. The data covers 38 technologies, 67’470 valid sanitation systems, and 36 selected options to be considered in the decision-making process.

[3] ERIC/open: The Eawag Research Data Institutional Repository, https://opendata.eawag.ch

Acknowledgements

Although on the cover of this thesis is only one name (Dorothee Spuhler), clearly this is a work of many. Throughout the journey from the initial motivation to the final product, I was inspired, guided, and supported in very different ways and by a large and diverse range of persons. Each of these persons provided a relevant contribution to this work and without each and every of it, this thesis would not be the same. In the following, an alphabetical list is provided. Because of the alphabetical order, titles are not listed. In case someone has been forgotten, please feel free to amend the list accordingly:

Abishek Sankara Narayan,
Agnès Montangero,
Ainul Firdatun Nisaa
Alice, Xavier, Magda, Maury Lapillonne,
All Sandec, especially POs,
All SWW, especially PhDs,
Andreas Scheidegger*,
Anjali Sherpa,
Anne-Marie, Hans, Christine, Markus Spuhler,
Ariane Eberhardt,
Atekelt Abebe Ketema,
Barbara Jeanne Ward,
Bastian Etter,
Bipin Dangol,
Caterina Della Torre,
Christoph Lüthi,
Christoph Ort,
Dandiel Ddieba,
Endrias Olto,
Günter Langergraber,
Harald von Waldhoff,
Jagam Shrestha,
Joan Moy de Vitry,
Joel Gundlach,
Johannes Heeb,
Juliette Ndounla,
Kinfe Kasse,
Leandra Roller,
Lena Mutzner,
Linda Strande,
Magalie Bassan,
Mariane Schneider,
Matthew Moy de Vitry,
Max Maurer,
Mingma Sherpa,
Mosisa Teferi,
Philippe Reymond,
Rajendra Shresta,
Reetu Rajbhandari,
Roland Schertenleib,
Roshan Shresta,
Samuel Renggli,
Teshale Dalecha,
Verena Germann

*) gets an extra star.

This work was funded by the Sawiris Foundation for Social Development through the Engineering for Development (E4D) programme, as well as by the chairs of Urban Water Management (Prof. Max Maurer) of the Swiss Federal Institute for Technology (ETH) Zurich.

Om mani padme hum. One love, one heart, one world is enough for all of us, Dorothee

Curriculum Vitae

Experience

PhD candidate

2014-2020 • Eawag • Dübendorf, Switzerland

- → Swiss Federal Institute of Aquatic Science and Technology (Eawag), Department for Urban Water Management (SWW) and Department Sanitation, Water and Solid Waste for Development (Sandec)
- → Design and implementation of research activities
- → Stakeholder management and facilitation of case studies in Nepal, Ethiopia, South Africa, and Peru

Project manager

2009 – 2017 • seecon • Bern, Swizerland

- → International project design, management, and coordination (e.g. Switzerland, India, the Philippines, Nepal, Zambia, Senegal)
- → Capacity development and training
- → Innovations for sustainable development

Project officer and trainer

2011 – 2015 • cewas • Willisau, Swizerland

- → Training design and facilitation

Workin group lead for capacity development

2010 – 2020 • Sustainable Sanitation Alliance

- → Strategy development and facilitation of knowledge exchange e.g. through international meetings, conference events, and the moderation of the open online discussion forum

Scientific assistant

2009 • EPFL • Lausanne, Burkina Faso

- → Experimental and theoretical foundations for enhanced solar water disinfection

Project engineer

2007 • CREPA • Ouagadougou, Burkina Faso

- → Design of citywide ecological sanitation

Education

Doctoral thesis (PhD)

2020 • ETH • Zürich, Switzerland

- → Development of methods for the generation and evaluation of sanitation system planning options considering innovation

Certificated of advance studies (CAS)

2017 – 2020 • ETH • Zurich, Switzerland

- → NADEL: Centre for Development and Cooperation
- → Project management and evaluation, impact evaluation, influencing policy dialogues, urbanisation, food security, etc.

Master of Science (MSc)

2009 • EPFL• Lausanne, Switzerland

- → Environmental Sciences and Engineering
- → Master thesis: The Influence of the photo-Fenton reagent on Solar Water Disinfection (SODIS)

Expertise

Languages

German, English, French, Spanish, Danish

Expertise and topics

Environmental engineering, sustainable sanitation and water management, water and wastewater technologies, structured decision making and multicriteria decision analysis, strategic sanitation planning, innovation for sustainable development, transdisciplinary

Skills

Project management, leadership, knowledge management, capacity development, networking

About

This thesis addresses the difficulty of making an optimal infrastructure choice in strategic sanitation planning under uncertainty: how can the growing portfolio of potentially more appropriate and sustainable sanitation technologies be considered for a specific context? And how can relevant sustainability indicators such as resource recovery and losses be quantified?

The thesis contributes with a theoretical description, implementation, and practical applications of methods for: (1) the generation of locally appropriate sanitation system options considering novel technologies; and (2) the quantification of corresponding resource recovery potentials for their comparison at the scale of an urban catchment. The methods are generic and automated to deal with a large and diverse range of conventional and novel sanitation technologies and system configurations. The methods are not intended to replace any existing planning framework or detailed technical planning, but to enable a systematic consideration of technology innovations and sustainability criteria at the structuring phase of decision-making.

The methods are freely accessible online and are complemented with a technology library providing the required data for 41 technology options. The experiences of the practical application in Nepal, Ethiopia, South Africa, and Peru were enabled through the collaboration with local research institutes and local governments. These applications showed that the presented methods have the potential to improve planning practice by providing more appropriate and sustainable sanitation options and by enhance reproducibility and transparency.

As more technology and sanitation system options are added to the already large portfolio, the methods presented in this thesis may become an essential tool for the operationalisation of SDG 6 and SDG 11, sustainable, inclusive, and circular sanitation and cities for all.

Dorothee Spuhler is environmental engineer specialised in sanitation and water management and innovation for sustainable development. She has experiences in the academic world, the private sector, and the civil society and expertise related to technology, capacity development, and transdisciplinary.From 2014 to 2020 she implemented her doctoral research at Eawag, the Swiss Federal Institute of Aquatic Science, and at ETH Zurich.

Suggestion for citation:

Spuhler, D., 2020. Generation and evaluation of sanitation options for urban planning: systematic consideration of technology innovations and sustainability criteria. Doctoral Thesis, ETH Zurich, Zurich, Switzerland.