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Influence of Cleantech Interventions on Wastewater Chain and city of Amsterdam: towards a resilient system for Phosphorus Recovery & Valorisation.

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Abstract: The wastewater chain of Amsterdam offers an opportunity to recover up to 100% of phosphorus per year, versus 47% currently recovered. However, for the stakeholders of Amsterdam (e.g. citizens, business) it remains difficult to scale-up existing solutions for resource recovery. Mainly, due to the limitations of the widely-used methods (e.g. mass flow, life-cycle analysis) to provide holistic assessment of the solutions and the changes they will propagate outside the wastewater chain (e.g. solid waste). In the current study, three existing phosphorus recovery Solutions applied at three scales of Amsterdam (city, neighborhood, house) were analyzed. The study showed that the house scale closed-loop solution has higher positive influence on resilience of the city. Moreover, the DSM indicators could be used to measure resilience of the city and constituent parts, given an influence of a specific Solution. The developed toolkit is applicable for analysis of other resources in the wastewater of Amsterdam.

Keywords: Design Structure Matrix, city, wastewater, phosphorus recovery, circular economy.

1 Introduction

Implementation of the circular economy in cities is of high importance for local and global communities aiming to address the issues related to climate change, biodiversity loss and resource depletion (Henriquez et.al., 2017). Alignment among business, academia, industry, citizens, technology providers, investors and government is required to achieve a systemic change effectively (van Buuren et.al., 2016). Exemplary is the case of Waternet - the drinking and the wastewater (WW) utility in the Amsterdam Metropolitan Area (AMA), which serves 1.2 million customers, 32 municipalities, and cooperates with other utilities e.g. with the waste-to-energy plant of Amsterdam. Sludge and biogas are incinerated, generating heat and electricity which are used in the treatment works (Van der Hoek et al., 2017). In its policy to become circular, Waternet already implemented a number of full-scale projects: recovery of struvite from WW (Van der Hoek et al. 2017), reuse of calcite from drinking water (Schetters et al., 2015) and thermal energy recovery from drinking water (Van der Hoek et al., 2019). Many pilot projects are planned and carried out, but it is difficult to scale these projects up due to the lack of agreements among the stakeholders (e.g. WW utility Waternet, incineration utility AEB, citizens, municipality

of Amsterdam, solid waste utility) along the wastewater chain, and connection to new markets (e.g. fertilizer, pharma industry) for valorisation. For Waternet it is risky and costly to manage such complex projects alone.

Because of phosphorous (P) depletion (Fixen, 2009), many wastewater utilities focus on the recovery of P from the WW. For many utilities the questions are similar: where to intervene to recover resources, which markets are available for valorisation; which technological interventions add to the resilience of cities; how to engage and benefit various stakeholders in transition; and what are their roles in the new (circular) economy. It remains difficult to apply a single Solution that would integrate the systems of resources, stakeholders and infrastructure in cities (Spiller et.al., 2015). The challenge is two-fold. On the one hand, Solutions are developed internally, in a 'knowledge silo' that delivers one-sided insights disconnected from other systems. On the other hand, the methods applied by the stakeholders, like mass flow analysis, life cycle or cost-benefit analysis are limited in their scope: reflecting in a high detail and often within the very particular system boundaries, but lacking a holistic overview of the system from a larger scale.

The Design Structure Matrix (DSM) methodology (Eppinger et.al., 2012) is proposed to unveil the complexity of the AMA and WW system in it, and can be used to suggest a **strategic direction to Waternet** for 100% P recovery from the wastewater system in Amsterdam. Compared to the limitations of the widely-used methods, the DSM method provides a holistic framework for integration of multiple disciplines, metrics and domains of knowledge. It allows to map, visualize and analyze complex systems, elements in them, and relations in-between; and derive change management strategies that represent the interests and needs of multiple stakeholders. Amosov et. al. (2018) utilized the DSM method to determine the risks and the most effective intervention points for P recovery from the WW system in Amsterdam. An integrated data-model was built to cover the regional-scale system (including household, neighbourhood, and city), and used to analyze a city-scale P-recovery Solution and its influence on stakeholders. However, the previous study only covered the application of the city-scale P-recovery. An extension with a comparative analysis of the household, neighbourhood and city scales is required, to fully understand the difference between the applied Solutions at different scales, and to enhance interpretation of the values generated by DSM in the first study. Therefore, the main aim of this study is to assess the differences between the P-recovery Solutions at the household, neighbourhood and city scales. In doing so, the DSM method will be further advanced in the field of engineering circular economy and resilient cities, with respect to phosphorus recovery from the wastewater system within the Amsterdam Metropolitan Area (AMA).

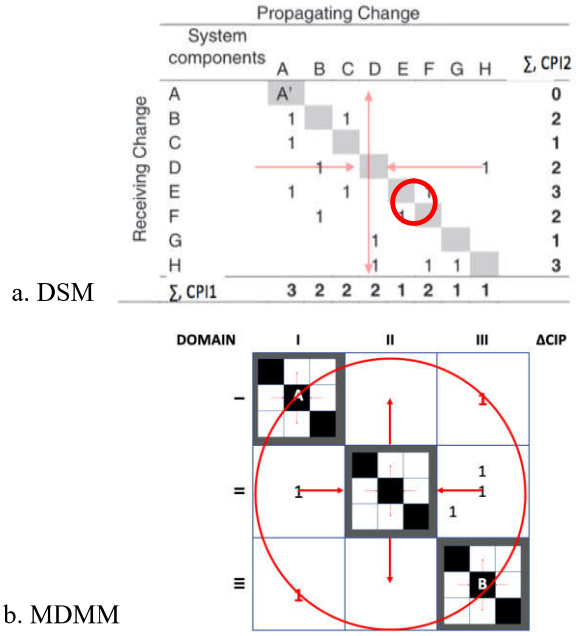
2 Materials and Methods

Following the method described in Amosov et.al. (2018), this study compares influence profiles of the Solutions for P recovery applied at three scales of the WW management (household, neighborhood, and city) in the AMA, using the DSM methodology. Structuring, analysis, and comparison of the data is performed in the 'Soley Studio' (complexity management software). Individual expert meetings at Waternet provided validation of the assumptions and the data used for the modelling. Last but not least, the hybrid Solution (a combination of the three scales) was developed, in order to understand

the influence of an integrated design for phosphorus recovery in Amsterdam, that currently co-exists in reality.

2.1 Design Structure Matrix (DSM)

DSM is an *nxn* square matrix with elements and relations within a single domain. In Fig. 1 (a) the principles of DSM are explained. DSM is designed to describe a domain of knowledge around a subject at hand. Several domains are combined into a Multi-Domain Mapping Matrix (MDMM), which adopts similar principles, as the constituting DSMs (Fig.1,b).



a. DSM

b. MDMM

Figure 1. Example of a DSM, with elements (A-H) and associated indicators (a); and MDMM, with three domains (I, II, III); CPI – change propagation indicator (described further in the text)

The Fig.1 shows that a component/element propagates-receives change to-from another, via an existing dependency (marked with '1'). Four types of dependencies can be investigated: physical (e.g. space), energy (e.g. power), material (e.g. water) and information (e.g. policy), also referred to as flows. The *red arrow* depicts the direction of inputs-outputs (dependencies) within a system. The ΣCPI evaluates all in-/outgoing dependencies. It shows how a change to one element results in extra changes either within or different parts of a system, whether or not the change initiator is aware of the consequences. Hence, one can predict how e.g. element E depends on A. In reality, physical dependency determines how energy, materials and information will propagate via an established system. The dependencies (and elements) are the key metric in the DSMs. The overarching rule, is that anything that exists in a physical world (e.g. cities, products, people) is considered as an element with four types of dependencies (incoming and outgoing) that can be mapped within single and multiple domains. Together, these elements

and dependencies create hierarchies and direct/indirect feedback loops that govern the system. In the Fig.1 *red circles* indicate such (closed) loops: for elements E and F (Fig.1,a); and domains I and III, elements A and B (Fig.1,b)). In the current study, only physical dependency is analyzed, as the main conductor of other dependencies (e.g. phosphorus, ownership).

Three system domains are mapped into the MDMM (Fig.2), which include separate DSM matrices of: 1) resources domain; 2) stakeholders domain and 3) infrastructure domain. Each Solution for P-recovery is evaluated in a separate MDMM, and compared. The final MDMM matrix, structured in the previously described manner, contained a total of 72 elements. In this study, the physical dependency is investigated, assuming that all elements within the AMA are linked and locked in space and time, creating highly coupled hierarchies that define how material, energy and information flows and changes are distributed across. To map the dependencies within and across the three domains, in total 9 DSMs were created (Fig.2). In order to map the dependencies, each DSM was given a relationship question. A 'positive' answer (it exists) is marked with '1'. By answering questions in the 'direction' of the dependency the MDMM is filled in, see the Fig.2 below.

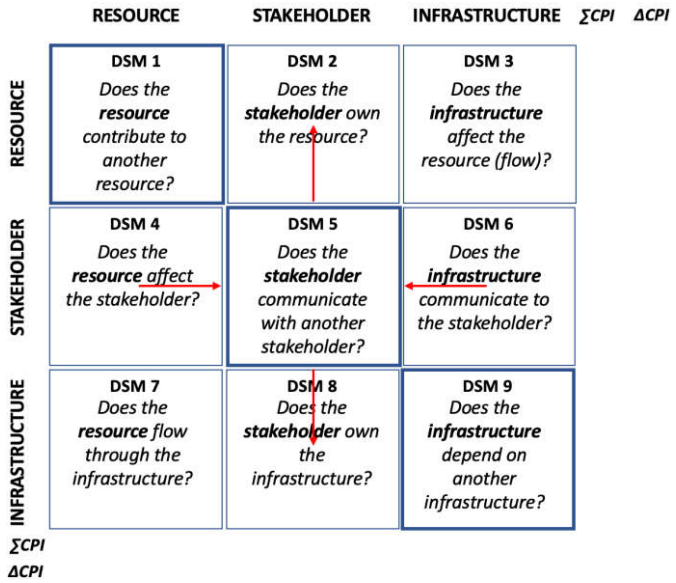


Figure 2. The rationale for definition of the physical dependencies between elements in the domains of stakeholders, infrastructure and resources in the MDMM, which contains 9 DSMs

In the Fig.2 the questions are answered following the rationale: the DSM_5 'gives' inputs to the DSM_1 via the DSM_2; and 'receives' outputs from the DSM_1 via the DSM_4. The DSM_5 provides to the DSM_9 via the DSM_8, and receives via the DSM_6. For example, Waternet in the DSM_5 (stakeholder) is responsible for the WW sludge in the DSM_1 (resource), and wastewater treatment plant (WWTP) in the DSM_9 (infrastructure); and WWTP communicates to Waternet in the DSM_5 about e.g. the WW flow. '1's placed accordingly for each physical relation into the MDMM, and the ΣCPIs are evaluated.

To understand the influence of an element and its role in a sequence of physical change propagations of a system, the ΔCPI is calculated. A sum of all incoming ($\Sigma CPI_{x1}{}^{n}{}_{IN}$) changes is deducted from the outgoing changes ($\Sigma CPI_{x1}{}^{n}{}_{OUT}$), as shown in the Fig. 1:

$\Delta CPI_{x1\text{-}72}{}^{n} = \Sigma CPI_{x1\text{-}72}{}^{n}{}_{OUT} - \Sigma CPI_{x1\text{-}72}{}^{n}{}_{IN}$ (*n – is the number of $X_{1\text{-}72}$-elements in MDMM).*

ΔCPI represents the influence of an element when a sequence of changes occurs simultaneously across a system of elements - $X_{1\text{-}72}$. $\Delta X_{1\text{-}72}{}^{n}$ is the external change driver that is leading to a risk or change in other elements (Fig. 3). This change driver can be related to different policies, markets, customer demands or technology changes that take place. From this perspective, any innovation is not isolated; it rather requires more changes to a system. For example, the P-recovery at the household level (Tab.1) will require changes to the centralized sewers, the WWTPs, but also energy, water, etc.

Each of the P-recovery Solutions has its own MDMM for analysis, which is run as a separate model within the AMA.

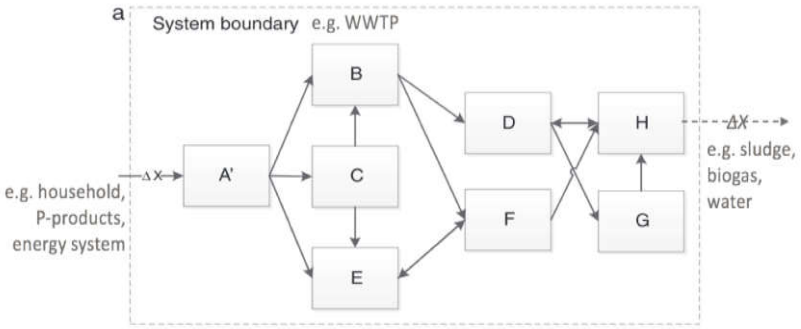


Figure 3. Conceptual diagram of system and external drivers (Spiller et.al., 2015)

The Fig.3 shows the system of the Fig.1, where every element in MDMM is ΔX in the context of systems owned by various stakeholders: e.g. food is a driver for the WW and P content. In its essence, ΔCPI shows if an element (X or ΔX) is a Multiplier (*M*), a Carrier (*CA*) or an Absorber (*A*) of change. The *M* indicates the prevalence of outgoing changes over incoming (positive value, '+'). It indicates high risks, and high influence on an element onto system, in terms of propagating a change and impact on other elements in the system. The *CA* indicates the equality of incoming-outgoing changes (neutral, '0'). The *CAs* link the changes propagated between the other elements. It also indicates that an element should be further decomposed and studied (Eppinger et.al. 2012). The *A* indicates the prevalence of incoming changes ('-' value). These are the elements that will absorb the changes upstream the chain. The *Ms* are the prime candidates for incorporating flexibility and change management strategies (Browning et.al. 2001). The *Ms* are critical elements that, as more changes added - make the system harder to change, while *As*, on the other hand, receive all the changes, and therefore are prone to the risks (for example, costs). The *CAs* are critical due to the ability to create grid-locks between the elements. The ΔCPI allows to define priorities for intervention in a system, and design optimizations. The elements with high ΔCPI are visually investigated in the MDMMs, to better understand the context and potential response to risk-management. By grouping the elements, based on location and the CPI values, the system leverage points are obtained for each MDMM.

Further analysis included a comparison between ΣCPI and ΔCPI for $\Delta X_{1\text{-}72}$ across 3 MDMMs, in order to identify the effects of each P-recovery Solution on the system of WW and AMA. Moreover, a shift of influence and/or risk propagation pathway for each scale of the Solution is derived on a systemic level. For example, under different scales of the same type of Solution (e.g. P recovery), a stakeholder (e.g. Waternet) can shift influence from *M* to *A*, which requires different strategies for managing the risks incoming or outgoing from the stakeholder. To understand potentials for the change management, the MDMMs were visually investigated, by comparing strategies and context of each Solution. Strategies are defined from the position and influence of an element in a sequence of predicted changes. Both ΣCPI and ΔCPI indicate resilience of a system. A hierarchic position in a chain, CPI value and role (*Ms, CAs, As*) of an element in a complex system defines how flexible is the system (e.g. WW), and which elements provide inflexibility and multiplication of risks. In addition, complexity is evaluated, as part of resilience. *Number of elements* in the MDMM indicates the sum across 3 domains. The *number of dependencies* ('1's), indicates the sum of physical interfaces that run the system. The *connectivity* indicates number of dependencies per element. The *absolute CPI* is the sum of the ΔCPIs (*Ms, CAs, As*) that indicates how critical or risky the system is, whereas lower value of the *absolute* $\Sigma_{\Delta}CPI$ means more flexibility. The latter indicators inform on overall complexity of the system; the less the value – the less complex system, while complexity implies how large are the boundaries of the system, and how many elements and dependencies to optimize in order to unlock new Solutions.

2.2 Soley Studio

The Soley Studio (SS) is a complexity management software originating from TU Munich. It was used to plot models, do DSM-analytics and visualize insights. The data set which was collected by Amosov et.al. (2018) was used. The data structure in the MS Excel was optimized and uploaded into the Soley Studio. Nodes and edges are the basic components of data-model. A node represents a point (element) in a network at which lines or pathways intersect or branch. An edge is the outside limit of an element (object, area, or surface), which connects nodes into dependencies across 3 domains (Fig.2). The case-study was developed in the SS following online guidelines (www.soley.io), and expert calls. For upload of the Excel files (with 3 scales of P-recovery) into SS, a meta-model was created, that included data on AMA and WW. Nodes and edges were compared with elements and dependencies in the MDMMs for inconsistencies. ΣCPI, ΔCPI and $\Sigma_{\Delta}CPI$ were programmed into the SS.

2.3 Case

The AMA is the system boundary with food-water-energy-governance nexus perspective (Hake et.al., 2017; Schlör et.al., 2017; Chinese et.al., 2017) linked to the WW chain (from User to Surface Water (Fig.4)).

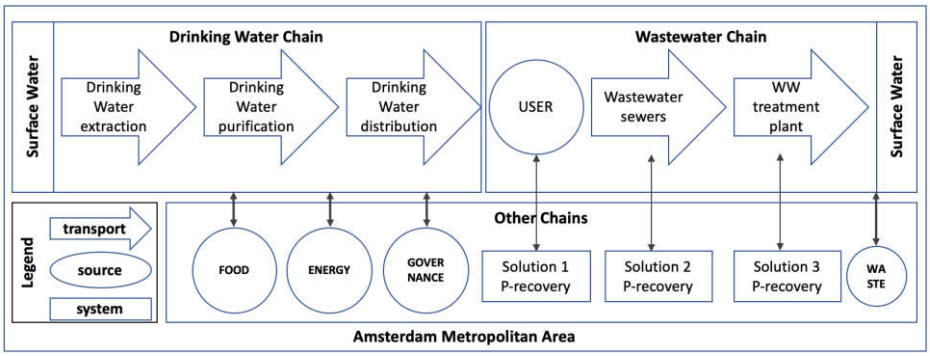


Figure 4. Interventions into the WW system of the AMA (source: van der Hoek et.al., 2017)

The P enters WW in the form of detergents, urine, feces, cooking waste from household, and is delivered by a network of sewers and trucks to WWTPs. WWTP Amsterdam-West treats sludge produced by 12 WWTPs operated by Waternet, and imports additional 179.4 tons of sludge. 113.6 tons of P are recovered and valorized, 58.9 tons of P are discharged to surface water and 598.6 tons of P are incinerated as sludge.

Solution 1 is a *household scale* semi-autarkic system applied in the North (De Ceuvel) that closes the P cycle, without connection to the sewer. Solution 2 is a *neighborhood* scale system applied in the city-center (Heineken Experience) that discharges effluent to the sewer. Solution 3 is a *city scale* centralized system applied at the end of the pipe at the WWTP West (Fosfaatje), see the Tab.1. The Solutions are currently piloted in the AMA, with considerable success and limitations.

Table 1. The P-recovery Solutions implemented at AMA

	Elements	Description
1	urine-diverting dry toilet, separate WW piping, P reactor, biofilter, human-powered container, composter, greenhouse, soil.	Low-grade P, compost and food produced from urine, human, kitchen waste. P-recovery- ±0,050kg/yr/house.
2	P recovery / pre-treatment system, urinals, motorized collection transport, sewer.	High-grade-P from urine collected at festivals. P-recovery = ±2 t/yr.
3	sewer, WWTP, P recovery, anaerobic digester, post treatment, surface water.	Low-grade-P produced from WW sludge. P recovery = ±500 tons/yr.

2.3 Estimation of P-recovery potential

Simple mass flow and P-recovery-potential calculators were integrated for demo-testing in the Soley Studio. Properties were assigned to the nodes, e.g. mass (liters), concentration, recovery rate. Mass flow analysis from various publications, and performance descriptions from technical documentation, were integrated into the data-model in the SS next to the qualitative DSM analysis. On the one hand, it is used to compare the studies (results) and

added value of DSM; on the other hand, to evaluate possibilities of combining qualitative and quantitative analysis, using the generic meta-model and specific data.

3 Results and Discussion

The summary of the comparison between the three Solutions is presented in the Tab.2.

Table 2. Performance of 3 Solutions for P recovery at the system of AMA

Solution	1	2	3
Scale	household	neighborhood	WWTP
Elements	42	45	41
Dependencies	214	206	185
Connectivity	2.97	2.86	2.57
Σ_{Δ}CPI (absolute)	108	78	56
P-recovery	92%	66%	47%

The Tab.2 shows that within a complex system 92% of P recovery could be achieved at a household scale, given that P is recovered by technologies onsite. The Solution 1 has 42 active elements out of 72, due to disconnection with sewer and elimination of other steps in the WW chain. The dependencies and the connectivity indicate an increase in the complexity as there are many highly interconnected elements at one scale. The Σ_{Δ}CPI value indicates an increase in the criticality of a household and risks/commitments required from the Users to maintain the Solution. The city-scale Solution 3 has the least P-recovery rate due to the recovery of only one type of the P products (namely struvite), when compared to the Solution 1, where other P products are recovered (mineral and chemical fertilizers from solid waste and waste water streams). However, from a systems perspective, the Solution 3 at WWTP is easier to manage: Σ_{Δ}CPI is 2 times less than of the Solution 1, also due to distribution of the elements across scales. At a household scale, more technologies may be incorporated – due to higher flexibility for infrastructure to adopt, but it brings a whole new level of complexity. At a household scale, the Solution 1, extra 29 new dependencies are required to close the cycle of P. The complexity level increases with the increase in decentralization (Tab.2). For example, if citizens receive more responsibilities to manage and benefit from their own waste and resource products, such a model of P recovery would allow for flexibilities: e.g. in terms of financial models for the WW utility Waternet, who could possibly outsource an investment into Solution 1 via joint ventures with citizens and startups, reducing the threshold for changing the WW system and the WWTPs. This would, in turn, lead to a higher level of complexity in business, policies and communication; compared to the Solution 3, where the WW utility Waternet invests alone in the “end of the pipe” approach. Given diverse urban landscapes of the AMA, Solution 1 appears to be the best choice for areas, which are disconnected from the centralized sewers or low-density; while the Solution 2 may have the best performance – for upcoming developments: e.g. brownfields in Amsterdam North (160 ha). The Solution 3 can play as a back-up mechanism in transition towards decentralization, using the Solutions 1 and 2. For example, De Ceuvel has an on-site WW treatment, but has a connection to the centralized sewer system, as failure backup.

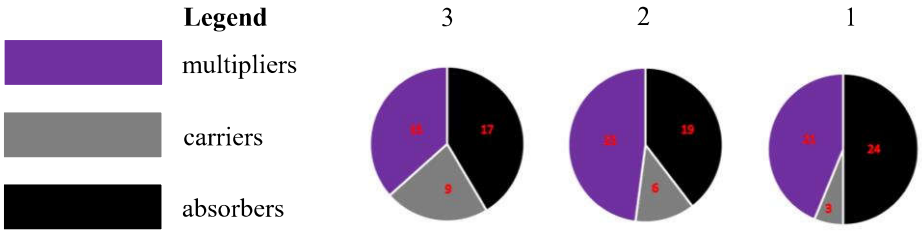


Figure 5. Total number of Multipliers (*M*), Carriers (*CA*) and Absorbers (*A*) at the three scales of the Solutions at the AMA

The Fig.5 shows the distribution of *Ms*, *CAs* and *As* at the AMA, given one of the Solutions. The highest amount of *Ms* is achieved in the Solution 2. The highest amount of *As* is in the Solution 1, while the highest score of *CAs* is in the Solution 3. Solution 1 has 21 *Ms,* 24 *As,* and 3 *CAs*. The *Ms* and the *As* constitute highly dependent system, where the main risks are spread across the moving parts of the Solution 1: if 1 of the *Ms* fails – the entire system may be corrupt, unless the *As* have a flexibility to adopt change (e.g. generate or redirect the flow of urine if the P-reactor or toilet is broke, to the biofilter). There are three *As* more than the *Ms*, which provides extra-capacity for the optimization towards better absorption of change. The 3 *CAs* indicate that the Solution 1 has three elements which create grid-locks (or inflexibilities). The *CAs* need further investigation and decentralization of functions (by integrating new technologies), or replacement with plug&play modules, because in case of failure –capacity of the *As* to receive change from the *Ms* via the *CAs* will be disrupted. For example, if the separate piping fails (*CAs*, see Tab.3), urine cannot be directed neither to a P-reactor, nor to a biofilter; leading to the accumulation, overflow and sanitation hazards. Using the DSM for further optimization, may result in a new infrastructure that either integrates the piping into a modular WW management Solution, or abandons it.

The Fig.5 indicates a triple increase in the *CAs* between the Solutions 1-3, showing that the Solution 3 has more risks of disruption and overflow; and higher inflexibility to adopt for the changes. The opportunity for the Solution 3, however, lies in the optimization of the 9 *CAs* into decentralized interventions for P recovery, like the Solutions 1 and 2, that could close the P cycle. For example, Boosting Stations (Tab.3) of the WW utility Waternet could be redeveloped into resource refineries, that could use the Solution 3 as a back-up. The hybrid Solution proves that point by indicating reduction of *CAs* in the AMA to 4 elements. The Solution 2 is the least resilient, since it has more *Ms* than *As*, and 6 *CAs* (grid-locks).

Review of the ΔCPIs for the 3 Solutions, indicated: individual level of influence of an element; and a shift of influences between the elements. In the Tab.3, a selection of top-1 critical *Ms, CAs, As* for each scale of the Solution (1-3) demonstrates it. The selection is based on the highest values of the CPIs for each element in the MDMM. The *CAs* were selected based on the highest difference of in/outgoing changes for each scale of the Solution. For simplicity, only 2 domains are presented in the Tab.3, below. The *Ms* are selected based on the logics, where an *M* with 99 incoming and 100 outgoing changes is prevalent over an *M* with 4 incoming and 5 outgoing changes; where factor of multiplication is '+1'.

Table 3. Overview of ΔCPIs and shift of Influence between Solutions 1 and 3, sample of analysis

Solution	**Types of ΔCPI**		
ΔCPI	*Ms*	*CAs*	*As*
1	**Influence of Solution at De Ceuvel on AMA**		
Stakeholder	Citizens (house), +2	Wastewater utility Waternet (city), +10/-10	Solid waste utility (city), -3
Infrastructure	P-reactor, house, +2	Separate piping (house), +3/-3	receptacles (house), -9
3	**Influence of Solution at WWTP West on AMA**		
Stakeholder	Citizens (H), +2	Municipality of Amsterdam, +9/-9	Waternet (C), -5
Infrastructure	Digestion tank (city), +2	Boost Station (hood), +4/-4;	Mixed sewer (hood), -2

The Tab.3 shows that in the case of the Solution 1 applied within the AMA, the citizens will multiply extra two changes towards Waternet, who carries ten in/outgoing changes, and Waste utility that absorbs extra three changes (e.g. produced P, reduced sludge for the incineration). In the infrastructural domain, all changes are managed at the household scale. In case of the Solution 3, in the stakeholder domain, citizens multiply two extra changes towards Waternet. The municipality of Amsterdam (municipalities) is the main *CA*. In the infrastructural domain, the most critical elements are managed by Waternet. An important observation is that, compared to the Solution 3, in the Solution 1 - the main absorber role shifts from Waternet to the solid waste utility. These parties would need to discuss and co-create win-win-win business models, Solutions and rules; or define individual strategies for investing into risk-management at own expense.

The influence of each element (*Ms, CAs, As*) and their location in the structure informs on potential strategies to negate the risks or turn them to advantage. These strategies revolve around algorithmic optimizations, which can be applied depending on the context. For example, the Solution 1 reduces direct dependencies with the *Ms*; 2 - buffers indirect change propagation effects around the *CAs* or the *As*; 3 - increase level of connectivity around the *Ms* (integrate functions: food, water, energy); (4) increase flexibility of the elements to carry and direct the change towards the desired outcome. Visual investigation of the MDMMs unveiled further insights into the strategies. For example, in the Solution 1 Waternet is a *CA*. In the Solution 3 it is an *A* of change, which, in turn, means less risks to Waternet: e.g. develop a win-win-win energy-saving business model with citizens that would encourage private investment and civil entrepreneurship. Instead of solely investing into a central Solution the responsibilities and investment can be distributed. The Solution 1 shows a massive shift of responsibility (criticality) to the citizens and multiplication of their role in the production of sustainable feedstock (P in a form of food, compost and struvite) and resilience of the utilities (WW, Waste). In this Solution, the utilities become the *CA* of change – a safe position to diversify business models and revenue, while allocating the risks to citizens, city of Amsterdam and other utilities (e.g. energy, water, waste). From the infrastructural perspective, the household shifts risk of clogging with P up the WW chain, allowing for flexibility in managing the sewers and extra-capacities for the WW treatment, due to reduced concentration of P in the WW (via onsite treatment of

feces, as at De Ceuvel). The next level of decentralization (Solution 2) shifts the risks back to Waternet (as in the Solution 3), which will have to *absorb* the change. The Solution 2 also puts under risk technologies at the WWTP due to extra dependency with the Heineken Solution. Semi-autarkic (closed-loop) approach to the Solution 2 (such as the Sustainable Implant described by van Timmeren, 2004) expected to be as beneficial as the Solution 1. The WW chain (sewers, boosting stations), if optimized, can function as the *CAs* of change, providing a plug-and-play platform to integrate the *Ms-CAs-As* elements with various interdependencies and value-chain generated for individuals and entire organization of the AMA. In current Solution implemented by Waternet at the WWTP - revealed that the *citizens*, the *municipalities* and the *WW utility* are the most critical elements responsible for the risks via use of e.g. the *hot & cold* water and the *sanitation* at a house, the *WW Boosting Station* and the Centralized *Mixed Sewer* at a neighbourhood, and *digestion tank* at a city scale. Where Waternet, is the most critical *A* of change that is highly dependent on behaviour of customers up the chain. Analysis of the *WW flow* and the *P concentration* in the system revealed that the *sewer* at a house, the *Sewer* and the *Boosting Station* at a neighbourhood, and the *WWTP West* at the city level are the most effective places for P-recovery, as shown in the Tab.2, the Tab.3 and the Fig.5. Simultaneous optimization of these top-critical *Ms*, *CAs* and *As* would allow to fine-tune a shift to a circular economy in cost-effective and risk-aversive manner (Meadows, 2008). Important to note: none of these Solutions is the best fit. Mostly, it will depend on the context of intervention (e.g. geographical location of the elements, business models). In reality, the P-recovery Solutions, most likely, will co-exist at different scales, as it already happens at the AMA.

Last but not least, in this research the individual Solutions (1, 2, 3) were integrated into a so-called hybrid Solution (Roefs et.al., 2016). As expected, it is possible to recover up to 100% P due to (anticipated) application of the P-cascading techniques demonstrated in the closed-loop Solution 1 (Tab.2), which could be replicated at the other scales, depending on the context (e.g. remote or low-density urban development). A fully integrated hybrid Solution shows an increase in the complexity: up to 2 times in elements, 3 times in dependencies and connectivity, and 2 times in criticality (Σ_{Δ}CPI); for a total of 72 elements, when compared to the Solution 1. The hybrid Solution, could be an ultimate scale for managing the transition to the circular economy, shared among citizens, utilities, etc. In reality, 100% is not yet achieved since each individual Solution would require a number of simultaneous changes among the stakeholders of the WW chain and AMA.

The results were compared with the studies of van der Hoek et.al., 2017, van Leeuwen et.al., 2016 and Spiller, 2017 to investigate similarities and differences in the insights and methods applied. The DSM study showed similar results with regard to the selection of most effective scales for P-recovery within the AMA – critical elements (points of interventions) are suggested (Tab.3): among others, the sanitation system at household scale, and the boosting station at a neighbourhood. The difference is that the other (quantitative, e.g. mass flow) studies use indicators like concentration of P and performance of P-recovery technologies (e.g. life-cycle). The DSM measures resilience of the entire system and individual influence of elements that propagate a specific flow or impact, based on the values of ΣCPI, ΔCPI and Σ_{Δ}CPI.

5 Conclusions

The DSM is proven to be an effective method to develop Solutions for circular economy and resilience. It allows evaluation of influence of Solutions for P recovery at four scales, from an integrated (nexus) perspective. The DSM method provided approach to create insights into the leverage points in the current multi-domain (resources, infrastructure, stakeholders) system within the AMA. It shows in a complex model of elements and dependencies - where to intervene, and how to manage changes towards desired performance on an individual and a hybrid scales. It also unveils which mechanisms and structures in the multi-domain system of the AMA and the WW chain lead to a particular mass flow, environmental impact or risk, regarding the P recovery. The DSM also informs on the structural changes and the set of requirements to the stakeholders (e.g. municipality, utilities, industries, citizens); and provides a framework to continuously improve the design of the Solution and enhance/extend the data-model with new parameters.

The study showed that a closed-loop Solution 1 at a household and the Solution 2 at neighborhood scales have the highest potential for unlocking resilience and 100% P-recovery rate. Integration of these Solutions allows for effective resource management; and distribution of risks and costs among the stakeholders within the AMA. The 100% P target can be achieved by integrating and optimizing the elements in wastewater, energy, water, food and solid waste systems of AMA. The developed data-model in the Soley Studio and methodology can be applied to further study and design the Solutions.

This study successfully applies the DSM methodology to the field of engineering resilient city systems and Solutions for resource recovery. The developed approach can be applied outside of the scope of the current project by the DSM community (e.g. www.dsm.org), and integrated into the developed circular economy study. For example, DSM community focuses on the improvements of efficiencies in manufacturing lines for the industries. Manufacturing is a large part of the circular economy. Combination of the work between DSM and WW engineers, using the developed methodology, would allow creation of pathways for valorisation of resources recovered from the WW, like cellulose, into components for manufacturing the final products (e.g. the sewer pipes), resulting with improved impact of the industries relying on DSM.

4 Recommendations and further research

The DSM methodology provides holistic insights, based on qualitative indicators. However, the use of quantitative indicators should not be undermined. Once, the leverage points and strategies are defined, there is a need for quantitative assessment of the Solutions. The quantitative indicators are useful when pitching to investors, as an examine for potential economic and environmental costs-benefits of a Solution. In this regard, it is recommended to further merge qualitative and quantitative data to improve strategic insights and business cases around P recovery and valorisation. The demo within the Soley Studio confirmed such possibility of further integrated research and design of resilient AMA, that is beneficial.

The current study looked only at the three existing Solutions applied within the AMA, consisting of already applied technologies to recover and valorise P. However, there are many more combinations of technologies that can be studied (e.g. application of a gasifier for production of energy from sludge, food forests). Application of a compatibility analysis framework provided by Maurer et.al. (2012), and Spuhler et.al. (2018) could further enhance an understanding on technological possibilities for integrated resource recovery and valorisation at the AMA in a resilient way. The Solution 2 was not described in the study, in a high detail due to low performance. However, application of a closed-loop approach at a neighborhood scale would potentially result with performance similar to the Solution 1. A follow-up study should be conducted, which can be done for their new design of a Resource Station in Amsterdam North, that is planned as a multi-functional and closed-loop system that has to adopt to a growth of population 5-fold until 2040. The new study would help to create a pathway for feasible and flexible transformation for Waternet, reducing risks and costs.

Overall, the study shows a possibility of deriving patterns and algorithms that govern a complex system (like AMA). The DSM shows a possibility of integrating qualitative and quantitative metrics across multiple domains of knowledge about the AMA systems and P-recovery Solutions. Further study of the AMA system, with new domains, systems and Solutions from a nexus perspective would allow to derive more algorithms and patterns that can be applied to the Solutions to fit different contexts. Potentially, new ways of measuring resilience are discovered via the DSM (e.g. ΣCPI, ΔCPI, Σ_{Δ}CPI, value of Ms, CAs, As). Further investigation of the system boundaries, properties and types of dependencies can be performed to define how to understand the qualitative indicators and associated knowledge on system patterns and algorithms for unlocking Solutions that lead to resilience. It would also be benficial to compare WW chains and metropolitan areas in the Netherlands and across the globe. This would confirm initially obtained problem-solving algorithms.

Study of Hajko (2017) indicates a need to create a replicable data-management framework that could link different data into a meta-model, that could be repetitively used for purposes of automation in the field of complexity engineering. The developed DSM methodology allows to add this data in a structured way, which would lead to a generic engineering metric and a standard for addressing similar (algorithmic) problems across other 18.000 WWTPs globally and 21 Water Board in the Netherlands. Study on the data and ontologies from Water Boards might be a first good step to link data and metrics.

When developing the study, only Individal meetings with experts from Waternet, among others, were held to validate the data-model. However, a workshop with Waternet experts is planned for 2019 to fully validate the data-model and insights.

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