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Influence Profile of Wastewater Chain in Amsterdam: towards resilient system for Phosphorus Recovery & Valorisation

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Abstract: The wastewater system of Amsterdam offers an opportunity to recover phosphorus, and contribute to circular economy. However, it remains unclear where to intervene in system to maximize recovery and valorisation in a resilient and feasible way. The Design Structure Matrix method was tested to define the system architecture from Food-Water-Energy nexus perspective. Physical, phosphorus, and ownership dependencies between Infrastructure, Stakeholder, Resource and Cleantech domains (elements) of the wastewater system in Amsterdam are analyzed in a Multi-Domain Matrix model. Change Propagation Indicator quantified critical elements, and emergent changes. An Influence Profile unveiled four levels of system leverage: household, neighborhood, city-block, region. The stakeholders can engage into optimizations at each level, to generate individual and shared benefits. Hybrid infrastructure, plug&play solutions and modular approach to cleantech will harness up to 100% of phosphorus available. The method proved to be an effective tool for analysing complexity and engineering resilient solutions for the circular economy.

Keywords: wastewater, phosphorus, nexus, DSM, design, resilience, Amsterdam.

1. Introduction

The role of cities in the Circular Economy is humongous. On one hand, cities account for more than 67% of the global greenhouse gas emissions, (IEA, 2008) and consume up to 80% of global resources (Metabolic, 2017). On the other hand, they offer opportunities for climate-neutral, self-sufficient and sustainable living from waste (AMS, 2016). However, most opportunities remain hidden behind the complex interactions of various types of systems (e.g. stakeholders, infrastructure, policies). Unveiling this complexity is a necessary task in optimizing cities towards resilient and healthy living. Water cycle plays a key role in the transition to the Circular Economy (Henriquez et.al., 2017); specifically, wastewater (WW) – as it carries various materials (e.g. cellulose, phosphorus (P), nitrogen) and energy, which could be reused in local and regional economy (Agudelo et.al, 2012). The WW system could cover up to 100% of energy (E), 80% of water (W) and 60% of nutrients (N) demand nationally (van der Hoek et. al., 2017), if changes to existing structure of WW cycle would be applied and managed across domains of the Amsterdam Metropolitan Area (AMA) almost simultaneously, from utility to user (Roefs et. al., 2017). However, the WW system adopts complexity of a city in terms of distribution of infrastructural, governmental, cleantech and resource interdependencies and assets in space, time, quality.

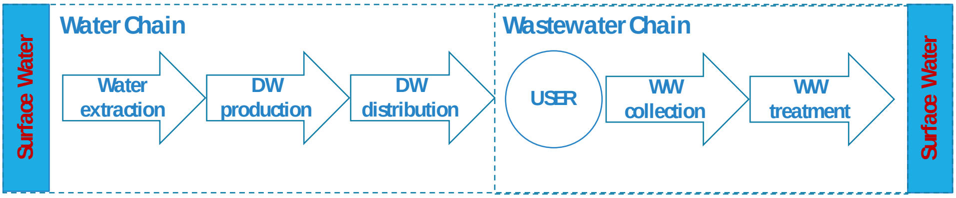

Figure 1. Simple perspective on WW system at AMA (adopted from van der Hoek et.al., 2017)

P is a raw material critical to the European Union (EU), and has strategic value with respect to its recovery (EC, 2017): about 60% of P is located in Morocco, with estimated depletion in 50-300 years (Schoumans et.al., 2015). Annually EU imports 220 tton of P in various products and raw materials; and exports 220 tton as waste. In Amsterdam, up to 60% of P is in WW chain (van der Hoek et.al., 2017), which is mainly withdrawn from the local reuse cycle. P enters WW in a form of detergents, urine, feces, cooking waste, and is delivered by sewers and trucks to WW treatment plants (WWTP); where sludge is incinerated, and the effluent is discharged to the surface water. At present, part of the P (<15%) is recovered through struvite precipitation. P recovery is not just a 'global challenge', but a solution to a local problem: P causes clogging of the infrastructure (pipes and equipment). Recovery of P prevents uncontrolled loss of P and reduces operation and maintenance costs for WWTPs up to EUR 15mln/year. The challenge for Waternet, the water utility of Amsterdam and surroundings, is to increase P recovery. 100% P Recovery & Valorisation (R&V) is of high priority for local stakeholders and a national security. However, it remains unclear to Waternet and linked stakeholders: where to intervene first to recover P or scale-up the pilots in most feasible and resilient way; who is responsible and how benefits are distributed; what should be optimized in a city to 'unlock' the potential; which changes have the most influence etc.

In order to advance decision-making process on the topic of P R&V, and to aid the needs of stakeholders, the study will answer the main research question:

Where to intervene in the architecture around WW chain to recover up to 100% of P in a way that supports the transition of Amsterdam towards resilience?

The main research question can be split up into four sub-questions:

1. What is the definition of the WW chain architecture in Amsterdam?
2. What are physical, P, ownership dependencies of WW elements?
3. Where in the WW chain are the elements critical for change management?
4. How it is possible to recover and valorise 100% of P at AMA?

2. Materials and Methods

2.1 Introduction

The Design Structure Matrix (DSM) is selected as a tool to structure knowledge about complex system into a simple overview of a *system architecture*. It is selected as an effective measure to study changes in the system, such as inflicted by risks (e.g. climate change, population), cleantech (e.g. P recovery) or policies (e.g. EU list of critical raw materials). A case of P R&V from WW system in the AMA is selected to test DSM for studies on potentials for R&V of other resources systematically and in participatory way.

2.2 Case

The AMA is selected as the main System Boundary that included sub-systems physically and organizationally linked to the WW chain – to represent the P propagation from sources to sinks. The final case is a physically connected infrastructure bounded by ownership to the stakeholders that together operate the life-cycle of P through WW and AMA. Where various infrastructural *products* shape the specific WW *process* which is *organized* by a number of stakeholders. P is a *product* that flows through this *organization*.

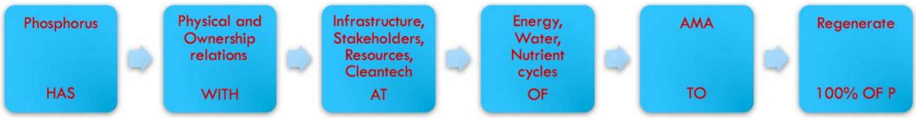

Figure 2. Desired P propagation via established system boundaries

From source to sink P is linked by physical coupling of infrastructure elements (e.g. pipes), including W, Food, and E sectors, that are owned by various actors in the chain, who together influence quality and quantity of P in WW chain, and the cycle of P at AMA. In Amsterdam, there are 1.2 million customers producing 125 million m^3/year of WW and 591.7 tons of P (vd Hoek et.al., 2017). 4000 km of sewers are managed by 20 municipalities. 12 WWTPs are managed by Waternet. WWTP West treats 80% of sludge produced in the AMA and imports additional 179.4 tons. 4200 ha of nature resources are managed by Waternet and regulated by EU. 58.9 tons of P are discharged to the surface water from WWTP, and 598.6 tons are incinerated. Currently, there are four cleantech projects for P recovery in Amsterdam. A micro-scale (house) system at De Ceuvel which generates (theoretically) 50 liters of P a year. A large-scale (street) system at 'Heineken Experience', which generates around 100 tons. A large-scale (neighborhood) system at Buiksloterham that generates (theoretically) 30 tons a year. A large-scale (city) system at WWTP West that generates 500 tons, with estimated potential of 1000 tons. These cleantech produce P for N sectors.

2.3 Design Structure Matrix method

DSM is an *nxn*, square matrix containing nodes and relations within a single domain. Current study adapted an approach of Eppinger et.al. (2012) to create Multi-Domain Matrix (MDM) model (process, product, and organization DSMs). MDM is an *mxn* rectangular matrix containing nodes and relations across 4 domains, where the rows represent one domain and the columns represent another domain. Steps to make DSM are:

1. Decompose: break system's categories down into its constituent elements/nodes.
2. Identify: document the relationships among the system's elements.
3. Analyze: rearrange elements / relationships to understand structural patterns.

4. Display: create a DSM/DMM model, and highlight important features.
5. Improve: through iterations enhance the accuracy and the richness of model.
6. Model: select Variables, establish rules and plot the variables.
7. Evaluate: define Change Propagation Indicators; Critical elements.
8. Design: group elements by score into Influence profile, engineer strategies.
9. Validate: set-up expert meetings to align on terminology, model, and gaps.

Steps 1-9 were repeated 7 times to reach desired level of details in DSMs, and final MDM.

For example, internal components of a house system (site, skin, structure, services, space and stuff (adopted from Brand, 1994)) were decomposed, recorded and characterized in a *House Product DSM* (adapted from Eppinger et.al., 2012), that is arranged by hierarchies of WW, E and N sub-systems (and processes). Physical coupling of all components in a house resembled the system boundary of P flow, owned by the user. High-grade *Product DSMs* were created for WWTP West, household, cleantech pilots, low-grade – for other systems. Multi-Domain Matrix integrated all DSMs, as in Fig.3.

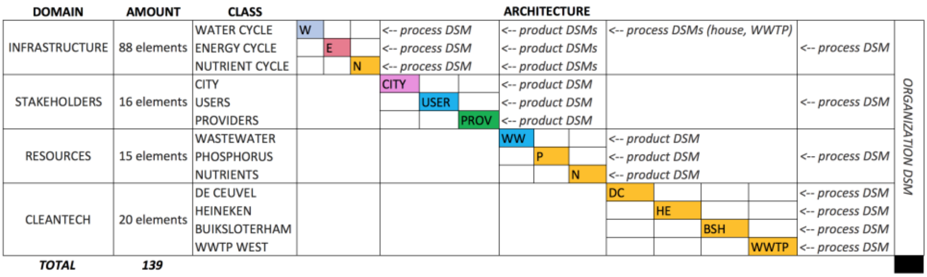

Figure 3. Conceptual design of the final MDM model

Fig. 3 shows simplified view of the final MDM model, and how different products and services are linked and looped to each other. The model is further used to plot physical (spatial), P (material) and ownership (information) dependencies. In order to perform evaluation of the variables between the elements, the basic rule is introduced:

Table 1. The basic Rule

Parameter	Variable	Specification
Spatial	Physical coupling	Is connected = 1; not = 0
Material	Phosphorus coupling	Is present = 1; not = 0
Information	Ownership coupling	Is owning = 1; not = 0

Each variable is plotted into MDM model, and assigned and value ‘1’ or ‘0’. In step 7, the change propagation indicators (CPI) are calculated using these values. Change propagation indicates how a change to one element of a process results in additional changes either within or different parts of the design, whether or not the change initiator is aware of propagation consequences. CPI is calculated for each element by summing all incoming variables ($\Sigma CPI_{2,\ IN}$); and outgoing variables ($\Sigma CPI_{1,\ OUT}$), and then calculated by deducting incoming variables from outgoing (see in Fig. 4):

$$\Delta CPI = \Sigma CPI_{1,\,OUT} - \Sigma CPI_{2,\,IN} \qquad (1)$$

Fig. 4.a shows a conceptual design of the change network diagram type created for the case-study to navigate the population of model with data. Fig. 4.b shows the resulting DSM model and analysis of the CPI with critical elements indicated as Multipliers (M), Carriers (C), and Absorbers (A) of change. ΔX is the external change driver that is leading to a risk or change in component A. It can be seen that element A is changed as a result of an external change, signified by ΔX. This change driver can be related to policy, markets, customer demands or similar changes that take place in the context in which the technology / element has to function. The change to a system component A can be considered the initial change or an innovation as a response to the change driver. This innovation is however not isolated; it rather requires more changes to the system. In the generic example of Fig. 4.a the initial change to component A, propagates the change to the component B, C and E, which themselves propagate change from B – N D, F; E – N F and C – N B, E. This type of change is called emerging change (Eckert et al., 2004).

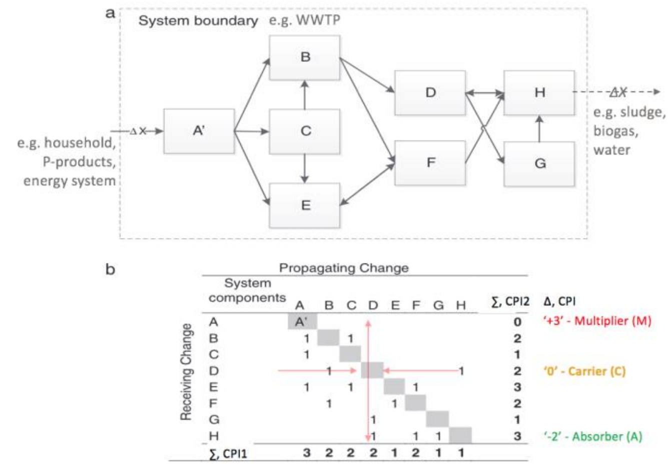

Figure 4. Analytical framework for CPI (graphics adopted from Spiller 2017)

The $\Sigma CPI_{2,\ IN}$ informs on the vulnerability of elements to a change driver. The highest values are considered as points for optimization. E.g. to increase flexibility or/and reduce incoming dependencies of an element. ΔCPI represents an influence of an element on the system when a sequence of changes occurs simultaneously. '+' value means that the element is M, 0-value means that the element is C, the negative value - A. This classification is of value as it draws attention to the key systems elements. "Multipliers are prime candidates for incorporating flexibility. These are elements that, as more changes are added, make the system harder to change". M - propagate more changes than receive. Carriers – propagate as many, absorbers – receive more. One must investigate elements connected to M elements to understand the nature of change. These elements as well might require flexibility to reduce or even eliminate change propagation altogether.

In step 8, by applying a *clustering algorithm*, the elements with the highest scores (physical, P and ownership) and closest locations were grouped into an *Influence Profile* (IP). IP informs on closely related networks of elements that can be integrated or optimized, so to tackle the problems emerging from a complex system. IP is used in further steps to design and evaluate strategies for systemic interventions. Validation step was performed by comparing the data from various sources; including meetings with experts from academia, government and business, and workshops with mixed groups of students and stakeholders in Amsterdam and Singapore. Over 100 publications, technical documents, presentations, brochures were used as the main sources of data.

3. Results and Discussions

139 elements across 4 domains related to P R&V from WW were integrated into the MDM model, and analyzed. MDM provided an insight into distribution and concentration of P flow, structures of technologies and sub-systems, owners, and relations in and outside WW chain – providing an answer to the sub-questions 1 and 2. As a result, the architecture of the WW chain is defined as a tightly coupled physical hierarchical system that cascades the flows of P-products from Sources (e.g. house) to Sinks (e.g. nature) through different levels of ownership; dependent on drinking W, E, food, and solid waste products and services (domains), which together affect quality and quantity of P in the WW and the AMA. Physical, P and ownership dependencies revealed patterns in the design of AMA.

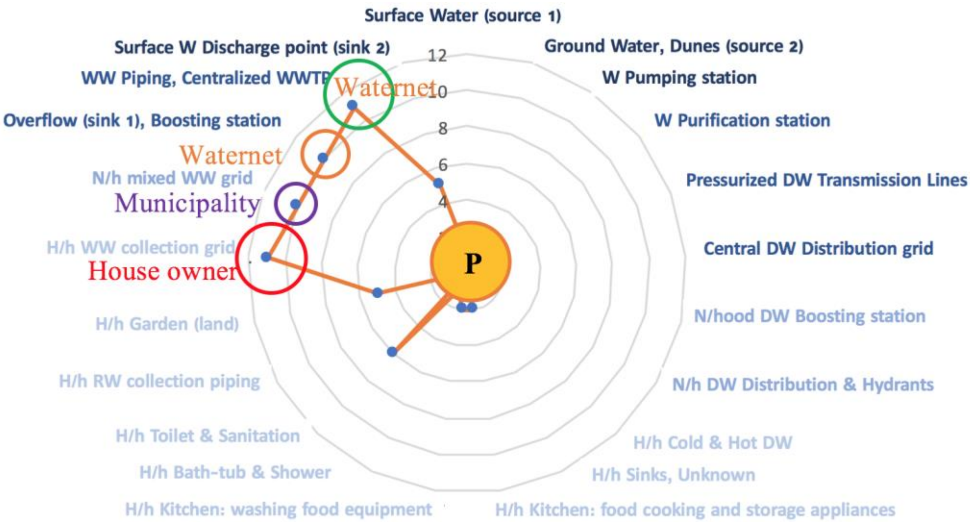

Figure 5. Points for P R&V at Water Cycle of Amsterdam

Fig.5 presents WC of AMA system: where to recover P, and whom to engage. It shows 4 points where P can be recovered: at house, street, neighborhood and city levels by house owners, municipalities, Waternet. Change propagation analysis showed Critical Elements.

Table 2. Change Propagation table: selection of top Critical Elements

Category	**Top Critical Elements**	**ΔCPI**
Infrastructure	E Distribution Infrastructure	M
	Hot & Cold Drinking W Interfaces	M
	Toilet & Sanitation	A
	Gravity-based WW Sewer Lines	A
	WW Boosting Station	C
	Pressurized Centralized WW Sewer Line	A
	WWTP	C
	Nature-based WW discharge point (sink2)	A
Stakeholders	Citizens (house owner)	M
	Municipality	M
	Solid Waste Management Utility	M
	Waternet	A
	Cleantech providers	A
Resources	Drinking W	M
	Rain W	M
	Electricity	M
	WW	C
	Kitchen waste	C
	Sludge	A
Cleantech	De Ceuvel, ‘Struvitje’ (house)	C
	Buiksloterham, ‘Resource Station’ (hood)	C
	WWTP West, ‘Fosvaatje’ (city)	C

The Table 2 rates the candidates for the change management in the current design. It predicts the roles of elements, and how they will act as a change driver or receiver in established physical constraints (the design). Given certain changes (e.g. P-recovery), one can predict how change will propagate across the design, through direct and indirect dependencies. For example, *Toilet & Sanitation* is *absorber* of change, owned by *citizen*, with highest concentration of *P*. P-recovery will require less changes to the *sanitation*, however, it will impact e.g. *drinking W interfaces* that are *multipliers*, which will propagate to other *infrastructures* at household and outside (e.g. to *WWTP West,* which is *C, etc.*). In practice, e.g. application of a *vacuum sanitation* would result with higher efficiency of WW transportation system, and reduce leakage, but cost more energy. In this way, an overview of systemic transformations at each domain is derived, answering the research sub-question 3; and allowing further interpretations.

Selected critical elements are grouped into an Influence Profile (IP) of the WW chain based on values of ΔCPI, direct and indirect dependencies (Fig. 6). IP shows points of intervention distributed across four levels of the WW chain: 1 - household, 2- street and neighborhood (combined), 3 - city and 4 - region. Fig. 6 shows 4 leverage points across a selection of infrastructure and stakeholders where interventions and change management strategies can be applied most effectively in individual and/or integrated manner so to reduce the emerging changes at each level (separately) and/or to tune them across all levels. For example, at a *household level* *sanitation*, *drinking & hot W* infrastructure, *E system*, *kitchen (waste) services* can be integrated into a (semi) self-sufficient system for P-recovery, beneficial for other systems inside and outside the house. However, the WW system (e.g. *sewers*) itself acts as a centralized platform, which if made flexible, can adopt (absorb) P-recovery techniques (and emerging changes) from each level of intervention. In practice, a combination of plug&play solution at house, modular solution at neighborhood and a platform solution at city levels could unlock a *hybrid* approach that would provide required flexibility and resilience to the established system design. E.g. low-density area can adopt plug&play solution at house level; as the area grows – modular street-level systems could replace the latter, and if necessary – connect to the sewers or advanced natural environments for post-treatment. The current WW chain can act as a platform to carry and absorb changes around recovery and valorisation of P, if the critical elements (simultaneously) tuned-in towards each other across entire design Such approach to infrastructure and its interfaces would allow flexibility in transition towards 100% P-regeneration via range of feasible solutions that are designed for change. These physical interventions will require changes among relevant owners, and coordination. The IP is a roadmap that answers the main research question, and provides strategic insight for further interpretations, in-depth analysis, and engineering scenarios for resilient P R&V at AMA. The method tested in this study provides guidelines for further research and development.

- The DSM method application adapted from Eppinger et.al. (2012), allowed design of a model about the case from *0-knowledge* to a high definition MDM. DSM and MDM are also applied in cases, such as: *NASA Mars Mission*, *Intel*.
- The MDM model aggregated knowledge and data about WW at AMA to a high level of details, and showed similarities with DSM model of Spiller (2017). However, both WW system and AMA were not explored to an extent as in MDM, which, in fact, can adopt DSM analytics of Spiller (2017) to make better insights.
- The IP of the WW chain, showed similar results as studies of Roefs et. al. (2017) and van der Hoek et.al. (2017). The IP provided additional perspective: how a *hybrid approach* to WW infrastructure domain within context of current AMA architecture can be integrated and leveraged for feasible transition to a resilience.
- The study utilized 1 DSM application out of 100s available (www.dsmweb.org).

4. Recommendations and Further Research

The DSM method is worth further exploration in the field of resilient city systems engineering. It provides a concise overview of a complex system, and a plan for engineering resilient solutions. It also serves as guidelines for participatory research and decision-making. Fundamental nature of DSM – mathematics and graph theory – provide vast opportunities for scale-up of this line of research, especially combined with digital solutions and automation. This method is recommended for structuring circular projects.

However, current MDM data-model is difficult to manage manually. Digital solution would allow automation of data visualization and analysis. As a result, research coverage could be enhanced and shared with other researchers and decision-makers in a user-friendly way. Digital environment would allow application of DSM methods and algorithms, such as *sequencing*, *clustering*, *banding*, *tearing*, *coupling*, *sensitivity* and *network-based* analysis in order to create more innovative insight and a digital framework (e.g. engineering system matrix) for integration of R&D on circular economy around P R&V and other topics. By plotting intended interventions, such as P-recovery or policy, at each level of leverage, we can further design and test the vision for maximum P R&V. More specific strategies and areas of research can be shaped (see Fig. 6). To make such design work, it is necessary to look deeper into content of this roadmap at each level. New products and services can be engineered across Food-Energy-Water nexus of AMA. Moreover, there are many applications of DSM method (models and algorithms) that can create innovative insights. Adding new variables, such as energy coupling, financial coupling etc.; or elements, such as cleantech, business models, governance can unveil their impact on current Influence Profile, and can be compared.

5. Conclusions

The study allowed to unveil the complexity of the WW chain of AMA from an integrated perspective, and answered the research sub-questions with help of an MDM-framework.

The results show that physical connectivity, P concentration and ownership distribution play an important role in definition and organization of the system design and performance. A 100% P R&V target can be achieved by integrating and optimizing critical elements and dependencies in WW, E, drinking W, food and waste infrastructures, business models, products and services at household, neighborhood, city and regional levels. Finally, this study shows where to intervene first, which stakeholders to engage and how to leverage and optimize the current design for resilience and circular economy.

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8. Appendix

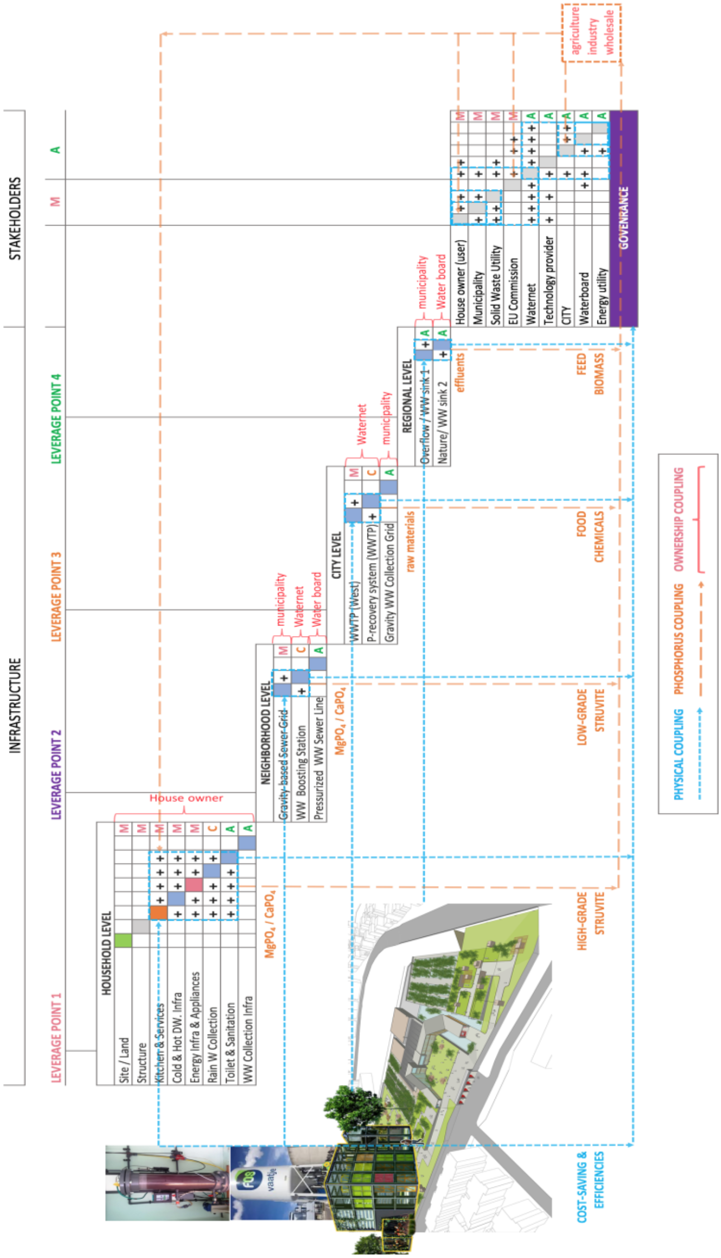

Figure 6. IP & a Roadmap towards 100% P regeneration at AMA (sample)