Challenges and Opportunities for Complexity Analysis in Food-Energy-Water Interdependent Systems

Industrial Symbiosis, Life Cycle Assessment, and Urban Metabolism in Arizona

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Abstract

The Food-Energy-Water (FEW) nexus is the interaction and the interdependence of the food, energy and water systems. These interdependencies exist in all parts of the world yet little knowledge exists of the complexity within these interdependent systems. Using Arizona as a case study, systems-oriented frameworks are examined for their value in revealing the complexity of FEW nexus. Industrial Symbiosis, Life Cycle Assessment (LCA) and Urban Metabolism are examined. The Industrial Symbiosis presents the system as purely a technical one and looks only at technology and hard infrastructure. The LCA framework takes a reductionist approach and tries to make the system manageable by setting boundary conditions. This allows the frameworks to analyze the soft infrastructure as well as the hard infrastructure. The LCA framework also helps determine potential impact. Urban Metabolism analyzes the interactions between the different infrastructures within the confines of the region and retains the complexity of the system. It is concluded that a combination of the frameworks may provide the most insight in revealing the complexity of nexus and guiding decision makers towards improving sustainability and resilience.

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The Food-Energy-Water Nexus (FEW)

The food system, the water system and the energy system are closely linked with each other. The interactions between food, water and energy are complex and inseparable on a global scale, agriculture uses about 70% of the world's freshwater withdrawals while also accounting for 30% of the energy consumed (Food and Agriculture Organization of the United Nations, 2014). This trend is also evident in Arizona, about 69% of the water is used by agriculture (Arizona Department of Water Resources) but the direct energy use for agriculture in Arizona is not well established. The USDA has just started the On-Farm Energy Initiative that would audit farms to estimate their energy consumption (United States Department of Agriculture, n.d.). Large volumes of water is required for agriculture but water is also required for electricity production, the mining of resources and for the growing of feedstock for biofuels among other process in the residential, commercial and industrial sectors. Food and energy have become basic necessities for the sustenance and hence puts the freshwater system under severe stress. A water - energy nexus already exists as it is evident from various studies (Gleick, 1994, Cousins & Newell, 2015, Bartos & Chester, 2014). The food system includes all processes including seeding, land preparation, labor, transport and storage. It is evident that the food system require energy, but additional human demands for energy and the use of carbon fuels would influence the availability of energy to the food system (Finley and Seiber, 2014). This results in the Food Energy Water (FEW) Nexus. When we are speaking about the food system in Arizona specifically, this cycle becomes Arizona's FEW nexus.

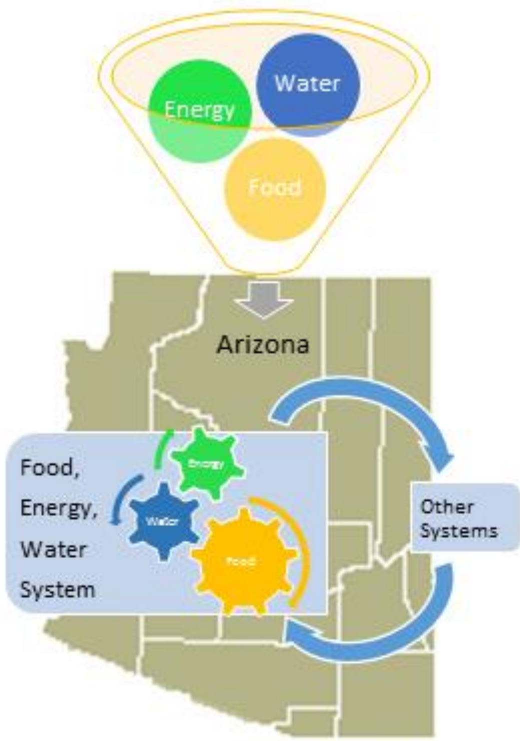

Figure 1 Diagrammatic representation of the FOOD-ENERGY-WATER Nexus in Arizona

Urban System Analysis Frameworks

There are many urban systems analysis frameworks that are present. The frameworks selected for this paper are the Industrial Symbiosis, Life Cycle Analysis and Urban Metabolism frameworks.

Industrial Symbiosis

The ecosystem metaphor that 'in nature nothing is wasted' is borrowed to increase resource productivity as well as reduce environmental impacts of products and their associated system. The waste from one entity is supplied as a resource to another. This collaboration and transfer of by-products forms the basis for Industrial Symbiosis (IS) (Berkel, Fujita, Hashimoto, & Geng, 2009). Chertow (2000) portrays IS as the interaction between 'traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and/ or by-products.' She also recognizes the importance of collaboration and the synergistic possibilities of geographic proximity.' The goal of the FEW system within Arizona would be to produce the required amount of food while managing the energy and water needs, but the goal of the IS framework would be to reduce waste and potentially reduce transport distances. In essence the framework would transform the FEW system into a regionally based closed loop infrastructural system. If this system was to be represented mathematically using the IS framework (FEW_{IS}) then

$$FEW_{IS} = F_L(E,W) + F_R(E,W)$$

$$F_R(E,W) = LVRF(E,W) + I(E,W)$$

where $F_L(E,W)$ is the energy and water in food grown within Arizona (local) while $F_R(E,W)$ is the energy and water in food grown outside Arizona (remote). $F_L(E,W)$ can be estimated by looking at all the energy and water inputs to the various resources and infrastructure required for food production. IS would aim to replace the remote food with local equivalents (LVRF(E,W)) through the integration of existing infrastructure or the creation of new ones (I(E,W)). But for the sake of the analysis let us consider only the food that is grown within Arizona.

Crop cultivation requires water, seeds, fertilizer and sunlight. Arizona has about 300 days of sunlight, on average. Sufficient amount of water is supplied through infrastructures like the SRP dams and reservoirs, and the CAP canals from Lake Havasu. The transport of these two sources of water consumes a large amount of energy in itself (Bartos & Chester, 2014). Arizona being a net exporter of energy (U.S. Energy Information Administration, 2015) indicates that the energy needed to transport the water is produced locally. The seeds can also be obtained from the previous harvest thus limiting these components to the geographical boundaries of Arizona while the infrastructure for farm activities are readily available as well.

The only component that might require new infrastructures or changes to the existing infrastructure would be the fertilizer component. This is where there will be a need for synergy and collaboration between infrastructure, within FEW and outside, in Arizona. The fertilizer requirement can be met organically (USDA Natural Resource Conservation Service, 1995) or chemically. Arizona has a billion dollar beef industry (Arizona Beef Council), not only does it contribute to Arizona's GDP but it also has the potential to contribute towards the fertilizer need of the Agriculture industry (Lander & Moffitt, 1996). A smaller contributor to the fertilizer need would be bio solids from sludge treatment and the anaerobic digestion industry. There are already 124 bio solid land applications in Arizona (Artiola, 2011) and there are studies now that look at the potential for anaerobic digesters around the Phoenix MSA (Martin, 2007). These are potential sources of natural fertilizer as well and would need to be developed. Wastewater treatment to obtain usable bio solids is pretty established in Arizona but imports a lot of its sludge from other states (Artiola, 2011), which may not fit well with the Industrial Symbiosis framework.

There are three main ingredients for chemical fertilizers - Nitrogen, Phosphorous and Potassium (The University of Arizona Cooperative Extension, 1998). Natural fertilizers may not provide the required amounts of nutrients to meet the needs of the crops. Extensive infrastructure need to be set up for the production of fertilizer so as to meet the need when natural fertilizers fall short. Ammonia is commonly produced via the Haber Bosch process after steam reforming natural gas. It is a very energy intense process. One way to reduce the energy intensity is to use the anaerobic digestion infrastructure or even from the methane gas available from landfills (New Zealand Institute of Chemistry). Potassium is another nutrient that is necessary for healthy crops (International Plant Nutrition Institute). It is supplied, as fertilizer, in the form of potassium chloride which is commonly found in Potash ores. Arizona is said to have a Potash deposit at the Boldbrook Basin, but at depths greater than 1000 meters (U.S. Geological Survey, 2015). The third component, phosphorus can be extracted from sludge as well (Zhang, et al., 2013). The extraction of both these essential compounds from these sources would require extensive and expensive mining and processing setup as well as water treatment facilities respectively.

Fertilizer of required combination can be produced but there are by-products as well. Phosphogypsum is one of them (U.S. Environmental Protection Agency, 2015) that has appreciable amounts of uranium in it which can be fed into the nuclear power plants present across Arizona. This could even compensate for the increased energy demand for the production of ammonia. As we can see the different by-products of a variety of processes can feed into each other in manner such that there is sufficient input for the production of crops. With regards to the transport of the various by - products, the road network is Arizona already connects the three major urban regions here as well as regions outside of Arizona so that the produce can be transported and consumed. This scenario is just one of the closed loop pathways that are possible, there can exist many other using a variety of technologies and infrastructures.

As we can see, this framework views the problem entirely as an engineering one and hence focuses on technology and the hard infrastructure, such as industry and transportation networks. Another major problem is this framework would look only at the food production to estimate the energy and water demand, the major concerns the FEW system. In this sense, it is easy to design the system as it does not consider the complex socioeconomic interactions with the hard infrastructure but it is very difficult to implement it successfully due to the same reason. The IS framework tends to look purely at the infrastructure and the goods that go into the system and come out of it. The benefit is that the framework proposes a cradle to cradle set up where the utility of by-products are maintained. It is also obvious that this framework does not look into the institutional infrastructure. Political and social acceptances are important aspect for the success of any hard infrastructure. While the framework does look at the potential impact of the entire system and not at the individual industries that make up the system, it misleads us by making the assumption that local is better, environmentally and socially. It does not look at the environmental and economic impacts of the changes that would be needed in the infrastructure.

One such example would be the current tradition of combining materials with little consideration to separation as separation is expensive and sometimes technologically infeasible. Another hurdle for the implementation of this approach would be the long term collaboration of the various industries. On a conceptual level IS looks at the reduction of waste but does not address the consumption levels (i.e.) IS does not propose a framework where consumption of resources may is reduced; it simply proposes a framework to reduce the waste to the environment (Nehm & Ulhøi, 2002).

Life Cycle Assessment

Life Cycle Assessment (LCA) was first developed to consider the entire lifecycle of products and their associated flows and impacts. It typically includes 1) acquisition and processing of necessary resources 2) manufacture 3) use and 4) reuse/recycle/disposal. The intermediate step between the phases mentioned above, that is also commonly included, is the transportation phase. LCA's help quantify or characterize all the material flows, specify their environmental impacts and develop alternate approaches that reduce the impacts (Graedel & Allenby, 2010). Hence LCA can be used to assess cradle to grave impacts of products, services, activities and even complex systems that stretch beyond the systems boundary (Ramaswami, Hillman, Janson, Reiner, & Thomas, 2008). The LCA framework has two parts to it - Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA). Using these two phases the LCA framework tries to evaluate the inputs and outputs of the system as well as the impact created by the outputs. To evaluate the FEW nexus it is sufficient to use the LCI part alone and LCIA can be used to determine potential impacts based on the inventory. Mathematically the LCA framework would represent the FEW system as follows

$$FEW_{LCA} = FP(E,W) + TR(E,W)\ [+ M(E,W) + U(E,W) + D(E,W)]$$

where the energy and water consumption is calculated for each life stage (food production <FP>, transport <TR>, manufacturing <M>, use <U> and disposal <D>) and then added up. Let us consider the life stages from the equation above for the FEW system. This framework depends heavily on the data available for the products, the process and the infrastructure. This in itself creates problems for this approach. The LCA will analyze the interaction between the technosphere and the environment within the confines of the FEW system. The LCA depends on how the boundary (ISO 14044, 2006) (ISO 14040, 2006) is set up. In IS the framework enforces a geographical boundary limitation but LCA enforces a conceptual boundary to the system. Retaining the identity of the crop, both physical and nutritional would be one such boundary condition. This would limit the analysis to crop production and transport if the data on the different transformations that a crop can incur is unavailable. An example of this would be corn. Corn is used as feed for livestock, source of food at residences, fuel use as well as industrial uses (U.S. Department of Agriculture, 2015). Unless this distribution is known along with the different manufacturing process it would be impossible to determine the impacts of this phase and the corresponding life phases downstream.

The LCA framework revolves around the infrastructure currently in place. The LCA of the FEW system with the above mentioned constraint would include and evaluate the impacts of infrastructures associated with the production of food and the transport of food. This can be measured per unit weight of food which would be the functional unit for the analysis. The energy and water intensity of the food system can be estimated through the attributional LCA

(A-LCA) the impact of the intensity of the food system on the other systems in Arizona can be evaluated through a consequential LCA (C-LCA). The LCA framework has a defined set of sustainability indicators to measure impact. The most common one is GHG emissions. But it is possible to measure energy used as well as water used. Given that our system is FEW, using energy consumption and water consumption indicators makes the most sense. A two tiered approach can be followed to measure the impact the FEW system has on the environment when using the LCA frameworks. The first tier would include all the direct energy and water used by the available infrastructures for the production and transportation phase. The second tier would estimate the indirect energy and water used by the different infrastructures in each phase.

For the food production phase the different crops that are being produced must be obtained. There are different data sets like USDA and Cropscape (USDA National Agricultural Statistics Service). Then the framework helps analyze how the production process would be carried out. At the most basic level, the crop production phase has four steps - land preparation, seeding, growing and harvesting. Land preparation is the process in which the land is ploughed and made ready to seed. The seeding process during which the seed is planted. The growing phase needs water supply through various irrigation techniques and fertilizer to make sure the crop gets its essential nutrients to grow. Harvesting is the phase where the crop is harvested once it reaches its optimum. In this phase, the first tier direct impacts that can be measured using our indicators would be the amount of water used, the amount of energy used via fuel for the machinery and electricity for the irrigation pumps. The second tier indirect impacts would thus be represented by the embedded energy in the water that is transported (CAP canal pumping, SRP canals and groundwater pumping), the embedded water in the energy that is consumed (electricity generated from water transport), and the embedded energy and water in fuel (fuel manufacturing and transport) and the infrastructures (farming equipment, pumping equipment) involved.

The transportation phase revolves around the transportation network. The data for transportation can be obtained from the Freight Analysis Framework (FAF) (U.S. Department of Transportation, 2015). If we were to measure the transportation impacts similar to the food production impacts then the direct impact would be just energy used since only fuel is directly used for transportation. The indirect impacts would be the embedded water and energy in the fuel, the vehicle and the transportation infrastructure represent the indirect impacts. If we notice in both phases the hard infrastructure pops up in the indirect impacts section. In reality it is difficult to accurately estimate its contribution to the impacts of the FEW system. Even though it is possible to do a LCA of an infrastructure like a road, canal or a tractor, it is difficult to allocate parts of energy and water used, from the operation and maintenance of the infrastructure, during the period of use to the FEW system. This simply represents the impact of service provided by the infrastructure. The difficulty is primarily due to the scale of use of the infrastructure as well as the temporal aspect associated with these large scale infrastructures when compared to the time period of the crop in each phase. These two factors tend to make the contribution of the infrastructure small and difficult to incorporate. If good data is available for the other life phases then they can be incorporated using a similar mechanism. Once this is done then the energy and water demand for the system in its current state can be determined. Since the energy and water intensity are already divided up into different phases, it is easier to determine the phases and the infrastructures that consume the highest energy and water. This would allow researchers to propose changes that could potentially reduce the energy and water intensity of food within this FEW system, which can be evaluated using the LCA framework as well.

The infrastructure that is inherently accounted for are the institutional ones such as crop rotation, farming practices to ensure quality and safety of the crop, among others. These are assumed to be standard practices in the production phase and hence are incorporated. A similar institutional infrastructure that is incorporated into fuel consumption estimation would be the speed limit on transport vehicles. In this way the LCI part of LCA framework evaluates the energy and water density of the interaction between nature and the infrastructure. To determine the potential impacts of this inventory, the LCIA needs to be conducted but this has its limitations as well since it helps determine only the potential impacts (Owens, 2008). Unlike the IS framework where the focus shifts to waste reduction, this keeps the focus on the FEW nexus. While the IS framework looks at the product and aims to reduce waste, the LCA framework looks at the processes involved in the FEW system and the products. LCA has its limitations too and cannot always be applied. One example of a product where LCA cannot be applied is information. There is no way to identify the different stages of information thus making estimation of the different inputs that go into each phase an impossible task. Though rules and regulations are incorporated into the LCA framework, one major infrastructure that is completely left out is the human infrastructure. There is a human component with every infrastructure and service within the FEW system – eg: the farming infrastructure needs to be operated and overseen by humans, the transport equipment must be handled by humans. The energy invested by the human and the impact that the outputs have on the human are completely excluded by the LCA framework. And so is the socioeconomic value that the system has. The LCA inherently tries to simplify the complexity of the system by dividing it into different life stages. While this does make the analysis a bit easier, it does lead to the loss of information.

Urban Metabolism

Urban metabolism (UM) is a concept that was developed to analyze cities through the quantification of inputs - water, food and fuel, outputs - sewage, emissions and waste and tracking the respective transformations and flows (Wolman, 1965). The two major conceptual models used in UM are Emergy and Mass Flows (Holmes & Pincetl, 2012). Emergy is defined as the available energy used directly or indirectly to make a product or deliver a service (Odum, 1998) and this approach looks at the flow of energy through an urban region. The Mass flows approach looks at the flow of materials since human societies use energy to transform resources and virgin material to meet demand through the economy (Huang et al., 2006). UM can, hence, be defined as the sum total of technical and socioeconomic processes that occur in cities that results in growth, energy production and waste elimination (Kennedy et al., 2007).

As we saw before the LCA establishes the material flow into each life stage of a product and estimates the impact. Thus LCA in itself is a tool that represents the material flow through the system under consideration and hence would fall under the urban metabolism framework (Holmes & Pincetl, 2012). As defined before Urban Metabolism is the flow of resources through urban regions. It can be divided into anabolic process, where resources is consumed to produce a product, and catabolic process, where the decomposition or recycling occurs. This categorization would help define the role for the various components and exchanges among them (Zhang, Yang, & Yu, 2015).

Plants are primarily made up for hydrogen, carbon, oxygen, nitrogen and potassium (Smith, 2007). A study of flow of food is essentially a study of flow of these elements through the city. While material and energy is required to sustain the metabolism of the hard infrastructure in cities, water and these nutrients from food are essential to sustain the metabolism of the human infrastructure which drives the metabolism of cities. Human activities lie at the root of these consumption patterns (Zhang, 2013). But for the sake of our discussion let us maintain food as a flow. Fig 1 shows a hypothetical conceptual model of food, water and energy flows within the FEW system in Arizona using network analysis under UM framework (Zhang, Yanga, & Fath, 2010). This is a high level model of how the FEW system looks like in Arizona. As we can see there are different flows from one infrastructure to another. Hence the various infrastructures are nothing but nodes in the system. It is in this infrastructure that the material that flows gets converted into another or gets consumed. The important thing to notice is that, unlike IS and LCA the transportation infrastructure is not a node. It is important to understand that the transportation network like roads and bridges, conveyance infrastructures like canals and transmission infrastructures like transmission lines are all embedded in the flow. These infrastructures are the ones that enable this flow of material and energy within this system. All the infrastructures in the FEW nexus (outside of the transportation network) are both anabolic as well catabolic. The agricultural sector uses energy and water, among other resource, to produce crops which are used by the residential, industrial and energy sector. Water treatment takes in impure water or sewage or sludge and produces cleaner water or recycled water respectively while the energy sector consumes resources to produce energy and emissions along with it. These different functions determines the material that the flow represents when each infrastructure interacts with the other. The transportation infrastructure that enables the flow is the only component that went through catabolic a catabolic process during the creation of the infrastructure. The sum of the energy and water flows within this system as from outside that enable the food flow would determine the energy and water intensity of food.

In UM it is hard to determine boundaries since they don't physically exist in reality. Invariably UM uses geopolitical boundaries and urban boundaries to determine the flows within its boundary and flows from outside its boundary. This geo-political boundary helps determine the various flows outside and the urban boundary would help determine the flow to the city even when it is an entry point to the hinterland. This spatial representation of flows and recognizing the transboundary nature of infrastructures is unique to UM. This model still represents only part of what urban metabolism is meant to do. The above diagram presents all the physical infrastructure of the system, the resources required to construct, operate and maintain the different systems, and the interactions (represented by food, energy and water) between these infrastructures. Some flow would also represent the interaction between people or groups of people. It is also essential to understand that the human infrastructure is involved with section of the system that is represented. This involvement of human infrastructure is not considered in the LCA thus making that framework a more static one while UM is more dynamic The dynamic characteristics stems from the uncertainty induced by human nature.

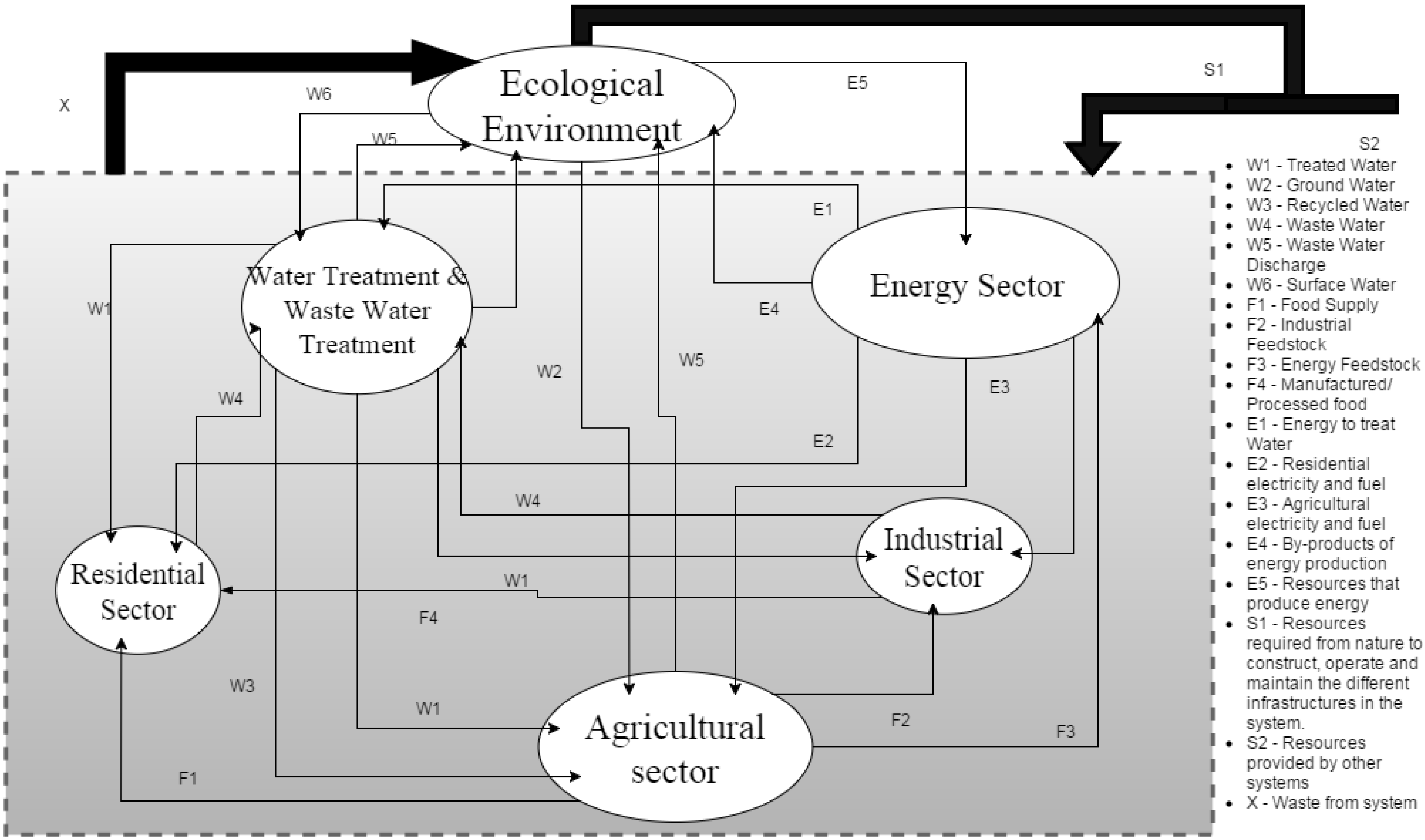

Figure 2 Hypothetical conceptual model of resource flows within the FEW system

There are many filters that UM requires this model to go through to come as close to reality as possible. UM recognizes that urban systems are complex systems that have social, ecological and technical components. Jane Jacobs in her book 'The Death and Life of Great American Cities' pioneered the idea of the urban region being a complex system. The infrastructures would represent the technical and to some extent ecological components and these filters are required to enforce the institutional and social components of the complex system. One of the most influential filters that this system would need to go through would be the market (supply-demand) filter which is partially based on the preferences of people. This would create a need for a variety of food products which would push the system to enable the different flows that make the production of these food products possible so that the demand can be met. Similar institutional filters would be policy restrictions on food manufacturing industry and HOA regulations. Another socio-economic filter would be gentrification of a city, which could potentially create a change in the food consumption pattern. These examples are simple one of the many that are directly related to the food system. Give that the food system is part of a much larger complex system, there could be many other influences that could act as restrictions of driving factors for the system.

As mentioned above, the UM framework intends to represent the complex system as it is and does not simplify the system like an LCA. Hence it is essential that all the interaction and causal relationships between the hard infrastructure, the soft (human + institutional) infrastructure and the environment are established and understood. If these are clearly established then it would allow us to predict emergent properties within the system, but this is not the case as we do not understand the system completely. Prediction can be done only when the system is completely understood and UM research is currently in the phase that tries to establish these interconnections. The benefits of the UM framework is that it considers the FEW system in Arizona as a biophysical entity where infrastructures are the means through which the needs and wants of society are met. Social actors are the agents of change and institutions are the instruments through which these actors shape the infrastructure so that their demands can be met through the extraction and transformation of energy and material obtained from nature (Ramaswami, et al., 2012). Hence the specific energy and water flows as well as the energy and water embedded in the different infrastructure that are associated with food can be determined using material flow analysis (MFA), a tool of UM (Holmes & Pincetl, 2012). The sum of all these would give us the energy and water intensity estimate of food within Arizona. The MFA is a more suitable approach to the problem of FEW nexus rather than the emergy approach since it requires us to quantify both energy as well as water.

The UM framework is the most difficult to use among the three but it helps quantify the consumption and also the waste which would allow us to control for both. There are many limitation to this framework and one major drawback of the UM framework is that it does not provide information on the impacts of the infrastructure as well as the flows. Another major hurdle, just like in LCA is data. It is hard to determine exact flows without tracking each unit of food, water and energy. A common proxy that is used in UM is monetary value which satisfactorily represents the quantity of material within our current economic setting. This proxy allows us to determine inter-city flows as well as intra-city flows, but bear in mind that the monetary flows should be specified with the material as well as the monetary value. FAF is also another proxy data set that helps determine material flow through freight movement. Another major limitation in the UM framework is that the framework, while establishing the flows to and between the infrastructures within the system, it does not evaluate the impact of these flows and infrastructures. It does not look at how these flows and infrastructure affect the human infrastructure or nature even though it quantifies the flow of waste. The UM framework views socioeconomic activities and the human infrastructure purely as a driver to the different flows but in reality the flows, that are constrained by the capacities of the physical infrastructure as well as the institutional infrastructure, influence the drivers as well.

UM-LCA Coupled Framework

All three frameworks have their limitations but also their uses. The IS framework in essence is the easiest approach. It provides a solution where the FEW system can be completely local (i.e. within Arizona). Rather than analyzing the FEW system in its current state, the IS framework tries to create a closed loop system by consider just the physical infrastructure and the technology available. While making the FEW system local, it does not guarantee a solution to the nexus. Arizona is a state which already is conditioned to work under water constraints, and by using the IS approach the strain on the water infrastructure can get out of hand and could potentially increase the energy consumed as well. While the solution may not be the desired outcome for the FEW nexus, it is a solution that addresses the feasibility of a completely local food system. The LCA framework on the other hand, handles the FEW nexus within the current infrastructural setting pretty well and provides the energy and a water density of food as it is. If the goal is to establish some control over the emissions of the FEW nexus and possibly reduce the strain of the nexus then the LCA framework would work. It tries to understand the FEW nexus as a system where the physical infrastructure interacts with the environment given some institutional constraints. Along with the intensities, the LCA framework would also estimate the impact of the nexus. But if the goal is represent the nexus in a manner that is close to reality with socioeconomic as well as infrastructural interactions, then the UM framework provides the best platform due to its ability to analyze the FEW nexus as a socio-ecological-technical systems. The UM framework also portrays the spatial distribution of energy and water within the food system. As we can see both LCA and UM are much more difficult approaches to use to analyze the various infrastructures within the FEW system, but have the best potential to represent and analyze the system. Both LCA and UM try to incorporate the complexity that is found in reality into their respective frameworks, but UM does it to a greater extent that LCA. In order to gain complete understanding of the FEW nexus system the goal must be to look at the infrastructure in the system, the distribution of the material as well as the impact of the infrastructure and distribution. If the drivers as well as the impact on the environment and society is understood then new mitigation measures or policies to control consumption/emissions can be put in place that would be reflected in the metabolism of the system. Hence the coupling of the LCA approach and the UM frameworks would provide most knowledge about the system as well as the opportunities to make it more sustainable.

Another advantage that the UM-LCA framework would have is that UM provides a spatially distributed system over which the LCA framework can evaluate the impacts. The LCI phase of the LCA framework would provide the emissions as well inputs requires for the various infrastructures but the impact would change based on the geographical region. Let us imagine a hypothetical situation where the UM framework establishes an electricity flow from Phoenix to Los Angeles. It is common knowledge that Arizona produced most of its energy from coal plants (U.S. Energy Information Administration, 2015). Emissions from coal power plants are extremely detrimental to both the environment and to humans. The LCA would be able to adjust the impact assessment of this flow in its LCIA phase. In this manner, the coupled UM-LCA framework would enable us to determine region specific flows as well as region specific impacts. This would enable us to estimate the flows as well as the impact of these flows, which represent the interaction between infrastructures as well as social elements. .Based on these region specific impacts, local policies can be framed and local infrastructure modified in order to mitigate these impacts based on the preferences of the people in that region as they are the actors that would drive this change. Thus the proposed framework completes the loop of interactions and influences that UM and LCA left open when they functioned individually. LCA did not consider the influence of humans on the system while UM did not consider the impact of the system on humans. The proposed coupled framework looks at the system where the human is not only a driver but is also influenced by the metabolism within the system.

Conclusion

The coupling of the LCA-UM frameworks seems to be the best option available for analysis. The IS framework limits waste and creates a closed loop system, the LCA frameworks analyzes the existing system and evaluates its impacts through its life cycle, and the UM framework establishes the physical and socioeconomic interconnections in the system through energy and material flows. The UM and LCA try to build the analysis around the existing conditions on the local, regional, national and international scale while the Industrial symbiosis framework aims to convert the regional, national and international dependencies into local one's. These different outputs can be used to attain various goals within the urban system. The coupled UM - LCA framework would provide the best platform that represents the urban system entirely and has the flexibility to adjust based on the knowledge of emergent properties of the system. Once these interactions have been established and the system is understood, it would be possible to tweak the system slowly to achieve the desired state.

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