Integration of Industrial and Urban Symbiosis from a Renewable Energy Perspective

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Abstract—**As the population continues to grow so do cities that are key locations responsible for pollution and resource consumption. This has led to sustainability challenges such as climate change and resource scarcity. One method of tackling these sustainability challenges is through the use of symbiosis systems, be it Industrial Symbiosis (IS), Urban Symbiosis (US), or Urban-Industrial Symbiosis (UIS), to create symbiotic relationships between groups/ organisations to reuse as many resources as possible. These symbiosis systems are also utilized because it can also bring many economic, environmental, and social benefits to the involved organisations. This is why so many governments, private organisations, etc. are encouraging the development and adoption of the symbiosis systems. This situation has led many academics to study it and there is currently a large body of literature that is rapidly growing. However, it mostly focuses on IS and material symbiosis and lacks knowledge on UIS because the latter has only recently become popular and the possibilities of energy symbiosis. This research aims to enrich the understanding of UIS systems and further explore the possibilities of energy symbiosis. This will be done via a conceptual model that will help to consolidate the information both from the industry and literature.**

Keywords—**Energy Symbiosis, Industrial Symbiosis, Renewable Energy, Urban Symbiosis, Urban-Industrial Symbiosis**

I. Introduction

The world is currently struggling with sustainability challenges such as climate change and resource consumption, amongst many others. Both mentioned issues are caused by the development of society, for resource collection & ensuring convenience and satisfying the demand for goods for a growing population respectively [1]. A few practices have emerged to tackle these issues, of which includes the especially promising symbiosis systems such as Industrial Symbiosis (IS), Urban Symbiosis (US), and Urban-Industrial Symbiosis (UIS) [2]. This is because symbiosis systems require and involves many different organisations collaborating to synthesis resource symbiosis while giving numerous benefits. It can tackle many sustainability challenges by reducing material consumption and pollution via waste and by-product processing and increased renewable energy generation/ symbiosis [3].

Many organisations and governments have adopted symbiosis systems because of these advantages; it has led to many successful & unsuccessful cases and the discovery of underperformances [4]. When these are considered in tandem with academic literature it can be seen as a lack of information or gaps in topics such as energy symbiosis and UIS systems. The energy symbiosis gaps include new sustainable energy technologies integration and using energy as a primary exchange within symbiosis systems. On the other hand, the UIS gaps are more basic, as it has only recently been popularized, such as the development and understanding of the system and technologies that support the integration of IS & US, such as control systems.

As such this paper will attempt to integrate IS and US while tackling the underperformances and gaps. This will be done through reviewing the different symbiosis systems, including IS, US, and the very limited number of UIS within industry and the literatures that contain information about symbiosis systems as well. The consolidation of that information will evidence the underperformances and gaps to not only provide transparency for this paper but also as a means to give more attention to it so that other researchers and colleagues may tackle them. The consolidation of the information will also help to develop a basic conceptual framework regarding what an UIS system is and its interactions with the different organisations within it; this is currently something that is lacking in literature.

The remainder of this paper will be structured in the following manner. Section II. and III. will review symbiosis systems from an academic and industrial point of view respectively. Section IV. will consolidate that information and provide a basic conceptual framework. Lastly Section

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V. will provide details of the further research that will be undertaken.

II. Literature Review

The way that the literature review was carried out will firstly be presented to ensure the validity and inspire confidence in the presented information. The initial literature search was conducted by using keywords such as "industrial symbiosis", "urban symbiosis", "urban industrial symbiosis", "energy", and "energy symbiosis" by itself and the combinations between them through the several databases such as Science Direct, Wiley Online Library, Scopus, etc. The papers that came up from these searches were filtered by title, abstract, and conclusion. The papers that were still relevant after that were fully read and helped to provide fundamental information about symbiosis systems.

A second literature search was done to search for the problems & barriers about symbiosis systems mentioned in literature. This process was done via using the keywords "industrial symbiosis", "urban symbiosis", and "urban industrial symbiosis" in tandem with "problems", "issues", "barriers", "challenges", and "hinderances"; the keywords were mixed around in as many combinations as possible and entered into the same databases. The papers were treated in a same manner as the first time with the ones remaining relevant giving useful information.

A final literature search was then conducted with the keyword "review" in tandem with the keywords mentioned in the first search in the same databases. This process acted as a final check to ensure the information gathered was not misinterpreted and any ideas stemming from it was not misconstrued. The total number of papers that were reviewed was 115 but was narrowed down via the process mentioned above.

A. *Industrial Symbiosis*

IS is a cross-disciplinary topic that has been studied in great detail for a long time [5]. Despite the large number of researchers studying IS, there have been very little arguments about its core concept: helping organisations benefit through resource exchanges and ensuring minimal waste output from overall operations [6] [7] [8] [9]. There are, however, subtle differences in interpretation between different researchers such as how Chertow views geographical proximity as a major influence on IS while Lombardi & Laybourn views not just materials but also knowledge as beneficial transactions, etc. Despite these minute differences all IS researchers will agree that the most popular definition is as follows:

"*Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products*." [6].

Resource exchanges are a necessity and an opportunity within IS systems and thus is an exceedingly important matter. A main method of resource management is the effective treatment of wastes [10]. This is because waste can be treated to become raw materials, commercial products, etc. [7]. These outcomes provide economic gains for the organisations that produced and received it; the former becomes exempt from the waste treatment costs or gain revenue from trading it while the latter can cut down on raw material costs [11].

The organisation that produced the waste can also positively impact the environment by keeping the waste from going to landfills [12]. This environmental benefit can be used to build more economic gains as the organisation can publicise this eco-friendly activity, through Corporate Social Responsibility reports or branding. This process can also be done by the organisation that procured the waste via promoting that it used recycled materials to make their products. This will usually happen due to economic gains being the strongest motivation [13].

In addition to waste, by-products are also treated as a precious resource because it can be substituted as raw materials or made into new commercial products [14]. The only small difference between waste and by-products is that the former has a higher chance of being turned into raw materials while the latter commercial products, however, there are always exceptions.

The core concept of IS of benefiting via resource exchanges and ensuring minimal waste can be met by material symbiosis but can also be met via energy symbiosis. Where energy symbiosis means to process wastes and by-products into energy to be exchanged between organisations. This can reduce the overall energy usage to reduce carbon emission, tackling climate change, while cutting on energy costs [15]. This process can potentially be easier due to the universal need for energy in comparison to material symbiosis that is susceptible to change, nonetheless, there are still difficulties for this process.

The most common and extensively researched method in energy symbiosis is thermal energy symbiosis because there are a lot of heavy industries within IS systems that require high temperatures, such as the steel industry [16] [17]. This method involves the exchange of excess or waste heat generated from industrial processes. The former can be captured and directly reused by the same organisation or transported to another organisation [18]. The latter, however, must first be recovered through processes such as heat exchangers, heat pipes, etc. [19] or cooling fluids, exhaust stream, etc. [20] [21]. Where the former group of technologies can let the organisation reuse the waste heat for its own production while the latter can convert the waste heat into thermal energy, electric power, or mechanical power for different processes. Both cases allow the organisation to reap the economic benefit via the exchange of heat energy or reducing the cost of producing high temperatures [17]. This helps to increase its competitive advantage as it lowers production costs and gives the environmental benefit of reduced carbon output [22].

Another method for energy symbiosis that is equal in popularity is biomass energy symbiosis. This is a very popular method because it can turn waste and by-products that normally cannot be recycled or reused into energy to generate more benefits and minimise waste [3]. Due to the multitude of waste and by-products that are generated, there are many biomass energy symbiosis methods such as anaerobic digestion, pyrolysis, incineration, and gasification. In all cases of biomass energy symbiosis, it is possible to gain economic & environmental advantages through its production of fuel/energy which reduces the organisation's expenditure for fuel while reducing carbon output and decreasing waste going to landfills.

B. Urban Symbiosis

US is a concept conceived from IS but applied to an urban setting [23]. The main resources that are exchanged within US systems is waste from urban areas and is normally formed through opportunities between urban resources and potential beneficiaries within commercial, industrial, or governmental areas, etc. [24]. The key difference between IS and US is that the latter is usually more driven by environmental benefits rather than economic benefits; US is not focused and research on in comparison to IS due to this. Most studies that do research US still focuses on economic benefits and neglects the topics of environmental & social benefits [22].

As mentioned, some of the most successful US systems are the Eco-Towns in Japan because of their detailed and well-established municipal waste and recycling programs that were created with the help of the waste source separation systems, detailed planning of a myriad of different factors, and economic incentives from the government [25] [26]. In addition to these programs, US systems also encompasses energy exchanges usually in the form of heat recycling & exchanges and Distributed Energy Resources (DERs) as a result of technological advancements [26]. However, there are very little to no examples of DERs being used within US despite it being a possibility [27].

The US system can bring about economic, social, and environmental benefits in a similar manner to IS. The urban waste materials can either be exchanged or recycled to create economic and environmental benefits for the involved organisations through sales & savings on energy costs and reduction of carbon/pollutant emissions respectively [2]. There is also the possibility of saving virgin materials via recycling, thus tackling the resource consumption issue and resource scarcity issue [28]. These waste exchanges and recycling systems can create social benefits via increased employment because new facilities are needed for new processes [25]. The other major social benefit is the increase in quality of life as a result of the economic and environmental benefits.

C. Urban-Industrial Symbiosis

UIS is the synergy & symbiotic relationships between industrial and urban areas that aim to scale up the efficiency of the previously mentioned benefits while also increasing its scope in mitigating problems like sustainability, greenhouse gas emissions, resource consumption, and waste treatment [29]. This idea has been around since the 1980s [30], but the concept was only further developed and reinforced from 1997 to 2006 through Eco-Towns via its proximity with industrial zones [23]. However, only in recent years have the number of publications regarding UIS started to grow [5]. This was brought about by how saturated the IS topic is and its growing popularity, due to the benefits it brings, despite the complexity of the system.

The main type of synergy within an UIS system is through the exchange of materials rather than energy due to its difficult physical properties and costly transport facilities [27]. However, UIS systems that focus on material exchanges have issues due to the uncertainty of sufficient quantity and quality of industrial/urban wastes [31]. Currently, material symbiosis is still the mainstream and industrial zones are required to have treatment facilities that can deal with urban waste. The typical ways industrial zones process urban waste include solid waste for incineration & recycling, wastewater for treatment, and organic waste & sewage sludge for energy production [4]. It is sometimes possible to create a commercial product from the waste and additional processing, but it is most commonly turned into raw materials or converted into energy [16].

Even though forming an UIS system primarily through energy symbiosis is difficult there are still successful examples, including one of the earliest mentions of the UIS concept in 1980 in the municipality of Köping, Sweden. Its energy symbiosis that started with thermal energy expanded to include the power grid of three municipalities in the Västra Mälardalen region [30]. There have also been a few new studies that are more inclined towards energy symbiosis UIS such as in Ulsan, Korea [32]. Ultimately, this idea has never been fully explored and can be considered as a knowledge gap.

There are many types of energy symbiosis that can take place in an UIS system, including both Industrial and US methods, with the most common being thermal energy symbiosis. Excess/ waste heat can be exchanged within an UIS system in the form of district heating. The industrial zones provide its excess/waste heat for the urban district heating network; it will require a central heating system and technology systems to function, where the latter converts the excess/waste heat's temperature to a suitable degree for urban use [32]. Meanwhile, urban areas can provide urban waste to industrial zones that can be used to generate energy, including heat. When these two processes occur in tandem it forms an energy symbiosis between urban and industrial zones. This process has been seen in many cases around the world [27].

The above system is the standard process for thermal energy symbiosis within UIS, but district heating is a flexible technology that can work with many other systems [33]. One example is the Combined Heat & Power (CHP) system that can simultaneously generate heat and electricity that can be used by both urban and industrial areas when connected to the district heating system and the grid respectively [34]. The CHP system can be fuelled by many different energy sources including biogas & biomass produced from waste and Renewable Energy Sources (RES) such as solar, wind, etc. [35]. The former energy sources help to further encourage material exchanges & recycling systems, while the latter has largely been unexplored; both will ultimately improve the sustainability of the UIS system [36].

Although RES can be used in tandem with CHPs it is also possible to be utilized by itself via infrastructures such as solar panels & solar thermal units, wind turbines, geothermal heat pumps, etc.; this method is not utilized due to financial & technical issues [37]. Despite not being widely implemented, RES energy symbiosis has a lot of promise & advantages. This is because it can generate energy without pollution or cost after initial investment, thus providing increased energy-savings & reduces pollutant emission [38]. RES can be separated into centralized plants or DERs, associated with industrial and urban areas respectively. The former refers to an entirely RES based power plant while the latter consists of small RES units that can be connected to households, etc. This can provide new energy generation possibilities and further increase energy symbiosis possibilities. However, this topic has not been largely ignored.

Further possibilities that build upon the existing energy symbiosis situation includes energy storage systems and/or central energy distribution systems. The storage system can work in tandem with RES and/or DER based generators to deal with the renewable generation's innate nature of variability and intermittency. It can increase RES energy symbiosis' flexibility and efficiency, increasing its viability within UIS systems [39]. Energy storage can include heat/thermal storage to help cope with the traditional energy symbiosis systems and increase its efficiency. It can also help deal with the energy boundaries between industrial & urban areas that have different requirements and thresholds.

Central energy distribution systems such as a Smart Multi-Energy System (SMES) or Virtual Power Plants (VPPs) can be used to enhance the efficiency of the existing energy symbiosis system and/or the energy storage system. This setup can help support energy symbiosis by identifying & choosing the most suitable generation and/or exchange options to provide the most benefits [40]. Additionally, it can help to integrate the different energy mixes being generated throughout the area and manage the different energy requirements & thresholds. The system can also enable two-way flows of power between decentralized grids, urban areas, main distribution girds, and industrial zones to allow energy exchanges to happen directly [41]. Despite the potential benefits and synergy that these technologies can bring, there are only mentions of these concepts/ideas with symbiosis systems and few studies done on it.

III. INDUSTRY REVIEW

As an overview, the industry has long used IS systems due to the organisations' inherent desire for additional financial benefits. In recent times, more of these symbiosis systems are being formed around the world not only because of its ability to increase the profitability of the involved organisations but also because it can tackle environmental problems, allowing the organisation to have a better image. Meanwhile, US systems are not as popular in the industry but there are still several examples throughout the world, with the prime examples being the Eco Towns, that have brought many benefits. There are even fewer UIS systems, but they have been able to show massive benefits that encourage the popularity and adoption of the system.

A. *Industrial Symbiosis*

IS can be split into two types: intra-firm and inter-firm. The latter is much more popular and is usually what is thought of when mentioning IS; this paper will also follow that convention thus unless otherwise stated IS will refer to inter-firm Industrial Symbiosis.

Intra-firm IS is different to the other types of symbiosis systems as it does not require the cooperation of other organisations. The intra-firm IS system is usually adopted when the organisation has a multitude of waste and/or by-products as it can use those resources to increase their competitive advantages while strengthening their foundations. This can be seen via the ability to increase the group's productivity & profitability by recycling by-products and wastes into new products. The organisation can also grow internally by expanding into new industries and mitigating the risks of operating in only one industry. It is also easier to coordinate in comparison to other symbiosis systems because it only involves one organisation, allowing them to avoid co-operation complications. The most notable and successful cases of this system are the Guitang group and the British Sugar group, the former's symbiosis system is shown in Figure 1. It was so successful that it even allowed both groups to expand their systems to encompass other organisations, showing just how effective the system can be [42] [43]. The only limitation is that organisations that want to implement it must have a large range of by-products and/or waste [44].

Inter-firm IS involves the cooperation of many different organisations. There are many places worldwide that are pushing for more IS such as in Asian and Europe, especially in China and Scandinavian countries such as Finland, Norway, Denmark, etc. [45] [46]. The reason that

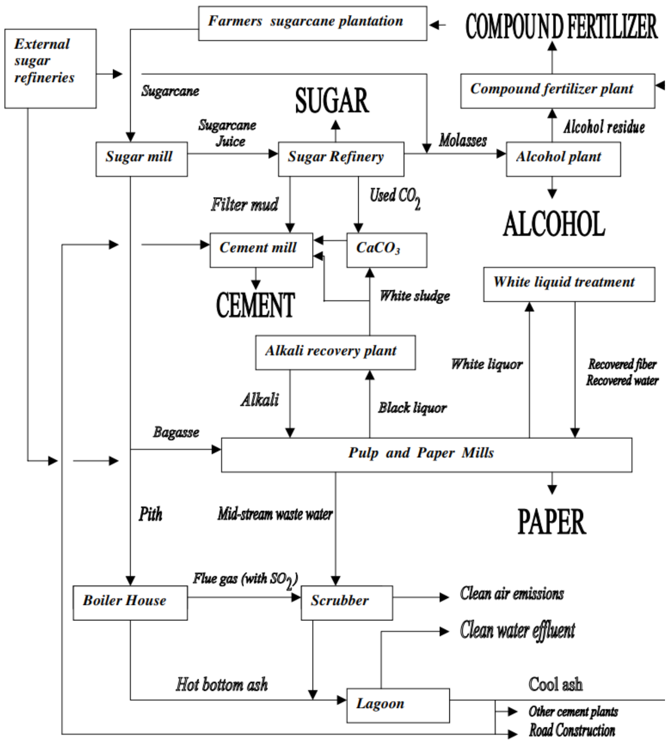

Fig. 1. Diagram of resource exchanges in Guitang group using only the organisation's wastes and by-products [43].

China has been pushing for IS systems is due to its massive industrial sector that must deal with the constraints regarding carbon emissions and resource scarcity [47]. IS can help tackle those issues while also introducing economic benefits making China pursue more than 50 IS systems [45]; one of the more prominent IS system within the 50 is in Tianjin and is shown by Figure 2. On the other hand, the main motivation for European countries pursuing IS and EIPs is the desire to increase their competitiveness and profitability through more business opportunities via material exchanges; the idea of reducing environmental damages is also a motivation for establishing IS systems and EIPs [48].

The reason that IS systems are so widespread is because it benefits all the participating organisations. The recycling of wastes and/or by-products can be turned into new revenue streams and even allow for cost savings on raw material. Both intra- and inter-firm IS will bolster the organisations profitability while also minimising pollution. The benefits for all and that that there is no need of a large range of by-products is why inter-firm IS is more popular in comparison to intra-firm IS. However, the downside is that the successful implementation of inter-firm IS systems is more complex due to the involvement of many organisations.

B. Urban Symbiosis

US was inspired by IS and requires the cooperation of local communities rather than industrial organisations to develop economic, environmental, and social benefits. The most famous cases of US is the Eco Town program, focusing on the Reduce, Reuse, and Recycle concept, developed in Japan from 1997 to 2006 for 26 areas [25]. Of

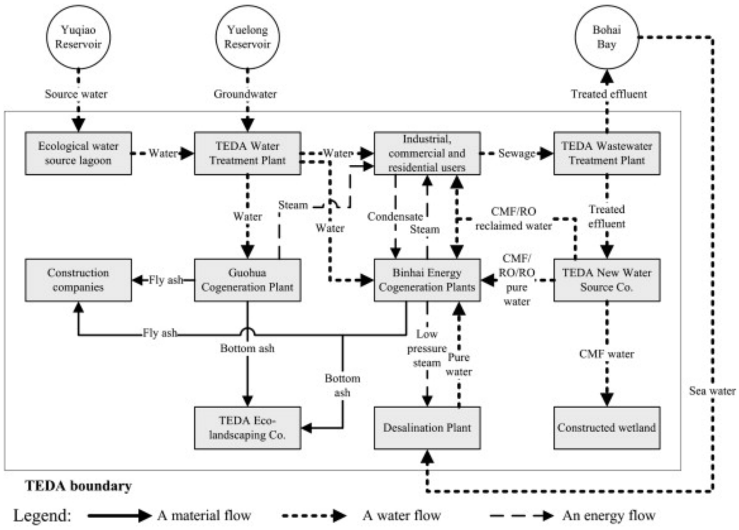

Fig. 2. Diagram of an inter-firm Industrial Symbiosis system in Tianjin China, showing the different organisations participating in the system and their exchanges [56].

these 26 zones, Kitakyushu and Kawasaki were the earliest and most famous & successful areas. This program was created to stimulate the local economy and the unique industries of the area through resource and waste recycling [49]. Additionally, the people also strongly desired for a change to improve the environment of their local communities and their quality of life [50].

The history regarding creating US systems is usually due to the local populaces' desire for change, this was the situation for Japan's Eco Town program. Kawasaki, taken as an example, is an area of industrialization and thus produced a lot of pollution. Kawasaki's industries include heavy chemical and petrochemical, steelworks, cement, etc. [51]. The industrialization of the area massively increased the air and water pollution and started to cause harm to the local community. In response, the local populace protested and pushed for change while the national government hesitated. The local government, municipalities, and community started working together to develop innovative technologies, new recycling industries, and introduced stricter environmental targets in an attempt to fight against the heavy pollution [50]. Kitakyushu went through a very similar situation and these actions are what jump started the Eco Town program all over Japan.

The US system currently revolves around waste recycling & treatment and heat recycling & recovery programs. The former helps to save virgin materials & reduce waste going to landfills while the latter can help to reduce the energy consumption of the area. Both programs will reduce the overall pollution within the area, thereby increasing the living quality and give economic benefits through the exchange of waste and reducing energy costs. Despite these benefits, US is not as common as IS because of two main reasons. The first being that authorities do not focus on it as much due to it concentrating more on environmental benefits rather than economic benefits. Secondly, it is more complex than IS in the sense that the exchanges will require adjusting how the area/community is run and involves of a multitude of organisations as well as the municipality.

C. *Urban-Industrial Symbiosis*

The UIS system combines IS and US together and affects a much larger area including both the industrial and urban area; there are currently very few UIS systems in the world. It should be mentioned that the Eco Town of Kitakyushu and Kawasaki can be considered as a prototype of an UIS system, despite its lack of IS links, due to both Eco Towns being closely associated with heavy industries there are also a few IS links but it is overshadowed due to the environmental focus of the Eco Town program.

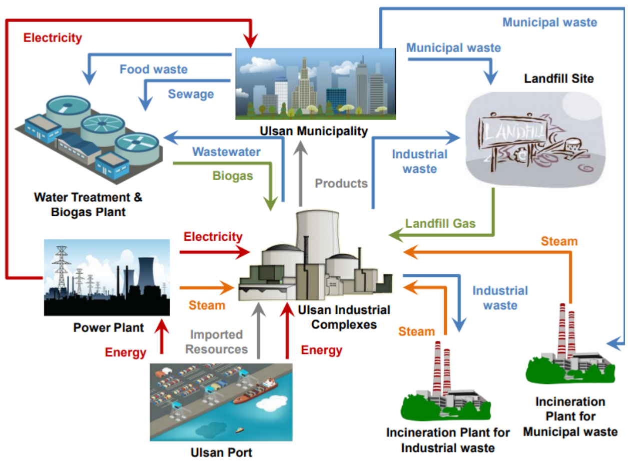

Fig. 3. Simple diagram of the resource exchanges within the city of Ulsan and its municipality [52].

One of the most recent and relevant UIS systems for this paper is the system in Ulsan, South Korea as it focuses on energy symbiosis. The Ulsan project is one of the 6 projects that was started in 2003 by The Korean National Cleaner Production Centre and the Ministry of Trade, Industry, and Economy to promote sustainable industrial development for increased economic, environmental, and social benefits [52] [53]. The cooperation across the city were based on material and energy exchanges to facilitate energy symbiosis, where the former revolves around organic waste materials & sludge and the latter dealt with waste heat, gas, and steam. New technologies and industries were developed to accommodate these exchanges, with more focus on energy [1]. It helped promote urban development and economic growth in the surrounding local areas, through the exchange of waste heat via district heating technology that covered the entire city. This project is shown in Figure 3 and had massive economic benefits of roughly 1,848 billion KRW, social benefits of creating 848 new jobs, and environmental benefits of reducing 6.48 million tons of CO2 emissions, reducing 1.09 million tons of toxic gases, saving 74.13 million tons of water, and reusing 5.21 million tons of by-products and wastes [54].

The benefits generated by the UIS system increases the economic situation of the involved areas while still tackling the environmental issues of pollution, resource consumption, and waste treatment and providing social benefits such as more employment/education opportunities and better quality of life. However, the system is very complicated to create and implement due to the involvement of so many different organisations in different areas. This has caused there to be very few UIS systems despite the numerous benefits.

IV. CONCEPTUAL FRAMEWORK

A basic conceptual framework will now be introduced in an attempt to consolidate and combine all the information from Section II. and III. This conceptual framework will also present a review of what an Urban-Industrial System and its relationships would look like.

This conceptual framework consists of three core concepts/systems of Generation, Auxiliary, and Recycling as shown by Figure 4 whereas the detailed subsystems are shown by Figure 5.

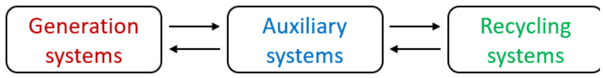

Fig. 4. The core concepts/systems within an Urban-Industrial Symbiosis system and their interactions with each other.

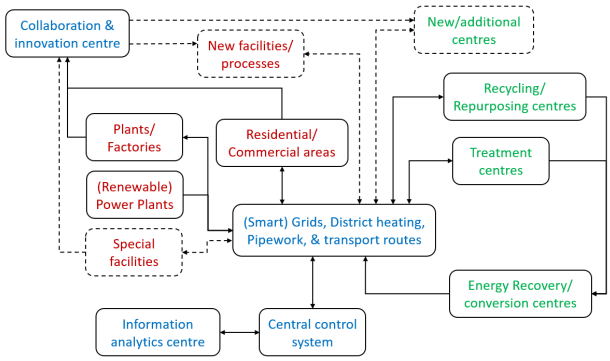

Fig. 5. The detailed subsystems of the conceptual framework and the relationships between them. The solid lines denote established subsystems and relationships whereas the dotted lined denote the potential for that subsystem, or relationship.

The Generation system is defined as the generation of all resources including energy, finished goods, by-products, waste, etc. This core concept is what drives the overall system while also benefiting the involved parties through increased profit/revenue. The theoretical basis for Generation systems is from IS literature, as it states that resource generation to provide increased economic benefit is a key component and driver for most if not all organisations in IS systems.

The Generation system highlights the importance of the Recycling system because it helps transform waste into useful resources. It aims to eliminate as much waste as possible by reusing & repurposing it to extract as much benefit from it as possible. The theoretical basis for Recycling systems is present in both IS and US, more predominantly in the latter, as both states that minimising waste from overall operations is extremely important for the economic, environmental, and social aspects of the system. This concept is also shown to be of paramount importance, along with the increase in quality of life due to environmental benefits, by the Kawasaki and Kitakyushu Eco-town cases.

The final Auxiliary system can be seen as the link between the other two systems because it is the support that ensures the overall system runs smoothly. This core concept of support will ensure continuous improvements and stability of the system via the building of symbiotic relationships & infrastructures and deals with the problems that arise from the system. This system, along with the other two, can create employment opportunities due to new processes & facilities that is needed to ensure the system functions properly.

Even more so than the others, the theoretical basis for Auxiliary systems is extremely emphasized because all symbiosis systems require the involvement and collaboration of a multitude of diverse stakeholders, actors, and organisations to properly function. This core concept is also driven by a lot of the underperformances and aims to support the system while eliminating those underperformances. This can include the inherent difficulties: complexity of the system & resources scarcity, technological competence: communication/cooperation, internal problems: awareness, and support structure underperformances: knowledge.

V. Further Research

The further research that will need to be achieved is the testing and refining of the basic conceptual framework as presented in section IV. to ensure that the framework is grounded in reality and can be appliable to real life cases. Further research will also include the additional formation of a process framework so that in tandem with the conceptual framework will allow for the creation of a tool or workbook to provide guidance on helping others successfully develop Urban-Industrial Systems to help tackle the sustainability problems that are plaguing the world.

Further research should also be undertaken for the other underperformances within the symbiosis systems currently existing in the industry such as problems involving trust, dispersing knowledge, co-operation with municipalities & governments, and the formation of symbiosis systems (either top-down, bottom-up, etc.).

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