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The Role of Design Considerations in Life Cycle Sustainability Performance of Water and Carbon: A Case Study of Shamsabad Industrial Park

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The Role of Design Considerations in Life Cycle Sustainability Performance of Water and Carbon: A Case Study of Shamsabad Industrial Park

by

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Abstract

Transforming Industrial Park (IP) into Eco-industrial Park (EIP) has been recognized as an effective way to address environmental, social, and economic problems arising from industrial development. Iran requires considerable efforts to develop EIPs to address environmental challenges, such as water scarcity, carbon emission, and waste production. In this regard, special-case frameworks which present a set of design considerations and straightforward steps for the transition of IPs into EIPs are essential to address the environmental problems and achieve maximal benefits economically, environmentally, and socially. This research aims to develop a framework based on the Life Cycle Assessment (LCA) and local legal and regulatory factors analysis, to serve as a guideline for stakeholders and decision-makers during the first stages of developing new EIPs. It adopts a mixed-method approach to form industrial symbiosis for reducing the environmental impacts of the Shamsabad IP which is set to be transformed into an EIP. Also, it proposes strategic solutions for improving the effectiveness of the policies, regulations and plans promoting the development of the EIP and its sustainable performance. The strategic solutions include increasing penalties and taxes, designing programs for strategic investment technologies and committees, and developing programs to raise awareness of EIPs. The outputs of various stages of this study comprise: (1) enterprises forming the new EIP and exchange flow types among them, (2) impact analyses of the materials and processes of Behnoush food packaging systems on the water and carbon life cycle using LCA, and (3) laws, policies, regulations, plans and programs which guarantee the establishment and future sustainable performance of the EIP.

Keywords: eco-industrial park; industrial symbiosis; circular economy; industrial ecology; life cycle assessment; water and carbon footprint; design consideration; Iran

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List of Abbreviations and Acronyms

Industrial Park (IP)

Eco-industrial Park (EIP)

Circular Economy (CE)

Life Cycle Assessment (LCA)

Life cycle inventory (LCI)

Life cycle impact assessment (LCIA)

Islamic Revolutionary Guard Corps (IRGC)

United Nations (UN)

United Nations Industrial Development Oragnization (UNIDO)

German society for International Cooperation (GIZ)

Rey County Environment Department (RCED)

Waste Management (WM)

Environment Impact Assessment (EIA)

Department of Environment (DOE)

Department of Environment, Climate Change and Water (DECCW)

The International Organization for Standardization (ISO)

Air Quality Company of Tehran Municipality (AQCC)

Carbon dioxide (CO_2)

Nitrous oxide (N_2O)

Chapter 1: Introduction and Methodology

1.1 Introduction

Sustainability entails consideration of ecological integrity, social dimensions, and economic effectiveness. Eco-industrial parks (EIPs) take advantage of interaction and interdependency, accentuated by industrial ecology, to meet sustainability requirements and address various environmental, social, and economic problems arising from industrial growth. Developing new EIPs via transforming Industrial Parks (IPs) into Eco-Industrial Parks (EIPs) optimizes the consumption of materials, energy, and waste through a shift from the traditional linear models to the circular models and build of industrial symbiosis at the scale of IPs.

According to the World Bank Group (2018), "IPs can be defined as designated, serviced industrial areas where firms are conglomerated. They facilitate commercial activities and provide resident firms with collective infrastructure and services, including roads and utilities. IPs are considered an economic development strategy for increasing industrial output and boosting economic growth. However, they can potentially generate significant negative environmental effects, including air emissions, water pollution, land contamination and over-exploitation of resources. Therefore, governments, regulators, and nongovernmental organizations encouraged IP developers and management to transform IPs into EIPs for environmental and social improvements of communities (p. 3-4)". By contrast, EIPs are distinguished by collaboration of various enterprises, shared infrastructure, products, by-products, waste, and energy in the context where circular economy (CE) and industrial symbiosis are introduced. Practical case specific EIP frameworks are essential for establishing EIPs that ensure utilizing the local and regional resources and energy flows appropriately and achieve high efficiency of EIP performance. These frameworks focused on various areas such as industrial ecology, logistics, supply-chain technology, and needs identification.

Circular economy (CE) is defined as a design pursuing durability, reuse, remanufacturing, and recycling to keep the circulation of the primary and by-products, components, materials, and wastes in the economy (Samson-Bręk et al., 2019; Ormazabal et al., 2018)). Industrial symbiosis is defined as the collective collaboration of diverse industries to share services, utilities, energy and by-product resources for adding value, reducing costs, and improving the environment. The industrial symbiosis's circular model is important in encouraging waste reduction and efficiently using resources (World Bank Group, 2018). From an industrial competitiveness viewpoint, the key drivers for forming industrial symbiosis include:

- Providing an improved and active business environment,
- Minimizing risks of exposure to natural resource scarcity,
- Minimizing production costs, and
- Providing access to high-quality infrastructure offered in the top international EIP practices, such as Kalundborg EIP, which are highly supported by governmental policies and regulations.

Life Cycle Assessment (LCA), one of the valuable tools to implement the principles of sustainable development in CE, assists EIP developers in closing the life cycle of products by considerably increasing the level of recycling and use of all raw materials. Therefore, it contributes to resolving environmental problems associated with industrial development, e.g., greenhouse gas emission, water resources use, and waste production (Bojarska et al., 2021). The Cradle to Grave LCA, which explores the impacts of products from raw material extraction and processing through manufacturing, distribution, retail, consumption, and product disposal, is one of the appropriate ways to address the EIP environmental challenges and promote sustainable development.

Iran faces several environmental problems due to extreme energy and freshwater consumption, high carbon emissions, and major waste production. Therefore, the transformation of IPs into EIPs is on the agenda of relevant organizations and institutions to reduce water and carbon footprints by improving the life cycle sustainability performance of water and carbon in IPs. According to the DOE (2022), Shaeri and Rahmati (2012) and Piadeh et al. (2014), up to now, 689 industrial areas have been constructed in Iran. Most of the 153 operational industrial parks, including the Shamsabad IP, are confronting a lack of water resources and showing considerable carbon emissions and waste production. According to the above studies, the energy industry (21.4%), iron and steel (16.6%), and chemical and petrochemical industries (14.7%) were the highest sources of CO_2 emissions in the Shamsabad IP. Also, chemical and petrochemical (28.2%), iron, steel, and non-ferrous metals (26%), energy industry (20.4%) and food industries (10%) were the most significant water consumer industries. Moreover, machinery and metal (35%) and chemical and petrochemical (22%) showed the highest waste consumption among industries.

Although the Iranian Government proposed the establishment of new EIPs to resolve the environmental problems of the IPs effectively, more effort has yet to be made to develop Iranian EIPs (Iran's small industries and industrial parks organization, 2013f, 2012a, 2011). Morcheh Khort EIP is the only existing EIP planned and developed in Iran (Shaeri & Rahmati, 2012). One of the most significant reasons for the failure to transform IPs into EIPs in Iran is the lack of frameworks to help EIPs designers in the first stages of the transformation. The framework should be established based on several factors contributing to the establishment and sustainable performance of EIPs and, therefore, a significant reduction of environmental impacts. These factors include:

- Enterprises forming the EIP,
- Exchange-flow types of material, energy, and waste,
- LCA results for evaluating and improving the efficiency of industrial symbiosis in reducing environmental impacts,
- Regulations, policies, plans and strategies for promoting EIP development are the results of this research.

Establishing the EIP framework for the transition of Shamsabad IP into EIP is the aim of this research study, examined over the following thesis chapters. This framework will guide the development of other case specific EIP frameworks to promote the establishment of EIPs at the national and global levels to address environmental challenges such as water scarcity and global warming.

1.2. Research Questions

This research answers the following questions:

1. What are the economic, environmental, and social motivations for designing the Shamsabad EIP?
2. What are the entities forming the EIP?

3. Where is the most carbon and water footprint coming from?
4. Where are the most waste materials coming from?
5. What are the possible exchange flows between entities?
6. How much potential for reduction/saving of water, carbon and waste can be achieved by transforming to EIP?
7. What policies and regulations support transforming the IP into an EIP?

1.3. Research Objectives

This research aims to propose an EIP framework, which serves as a guideline for stakeholders and decision-makers during the first stages of developing new EIPs. In contrast to several EIP frameworks, including the international framework for EIPs, which are general frameworks for EIPs that provide only strategic details for EIP requirements, this framework will be a specific EIP framework for resolving issues associated with a particular case. It can be used as an effective means to develop new EIPs for sustainable growth. According to Al-Quradaghi et al. (2020), researchers necessitate more specific frameworks that contribute to resolving local problems via developing new EIPs to achieve economic, environmental, and social benefits.

1.4. Research Methodology

Establishment of the targeted EIP framework relies on a mixed-method approach used to collect and analyze the data. The Shamsabad IP was considered as the case study, and the necessary data was acquired via the literature review, face-to-face interviews, field visits, and LCA. The data was analyzed, and the research questions were answered.

- Literature Review

A systematic academic literature review was conducted as part of the study for several purposes. While this thesis aimed to formulate a framework to be used in the initial steps of developing EIPs, life cycle assessment (LCA), eco-industrial park (EIP) and circular economy (CE) were explored as essential concepts. The current state of research for the concepts helped to build the theoretical foundation for this project. The literature was reviewed for the theoretical evaluation of the existing frameworks for developing an EIP based on important concepts. The evaluation assisted in understanding the concepts, identifying the essential characteristics of EIPs, and identifying the specifications of the efficient frameworks for developing EIPs. In this regard, several research studies, guides, and handbooks were used, which included Beers et al. (2020), Belaud al. (2019), World Bank Group (2018), Kwak and Kim (2015), Paideh et al. (2014), Palmer (2013), Côté and Cohen-Rosenthal (1998), and Coˆte' et al. (1995). Reviewing the literature helped to recognize the best practice examples of developing EIPs and material/waste/energy exchange opportunities reported in the literature.

- Face-to-face Interview

Together, 25 face-to-face interviews with 10 participants were conducted. The participants included the representatives and stakeholders of the Shamsabad IP, including government bodies, high-impact industry sectors, park operators and park developers. A well-structured and detailed stakeholder mapping was conducted in January and February 2022 to ensure the data collection required for selecting the EIP's existing and new enterprises (World Bank Group, 2018). The interviewer performed semi-structured interviews. The interviews were conducted from July to September 2022, each taking around 60 minutes. The interviews occurred either at the participants' office, the IP or by phone or videoconference. If the interview took place at the IP, participants were asked to move through the selected sites with the researcher.

Interviews were audio-recorded to allow for greater reliability of the data. After the interview, the researcher or a transcriber who signed a confidentiality agreement created a transcript. The transcript of the interviews was provided to the participants by electronic mail. The participants were asked to provide feedback on interpretations at a later date. These interpretations were provided by electronic mail. Another in-person, phone or video-conference conversation was involved for participants who were unable or did not wish to correspond through e-mail. Participation in providing this feedback was optional. If the participants did not respond within two weeks, it was assumed that they approved the analysis. Participation was completely voluntary, and participants might refuse to participate at any time completely or in any part of this study without penalty. Participants had the right to choose whether to answer any question during the interview. The researcher also reserved the right to end their participation at any time. The participants were able to withdraw from this study up to four weeks after data collection (i.e., after the interview), and any data related to their participation was destroyed.

To manage the time and data within the project, the interviews focused on the industrial facilities capable of having the most exchange flows to share. Several questions were provided to the selected participants to gain information about the used materials and ongoing processes in the chosen industries of the IP, the economic, environmental, and social benefits and concerns associated with the existing industries, and the policies and regulations regarding the industrial city (Appendix-8.1).

The interviews facilitated identifying stakeholders' interests for secure participation and commitment in developing the Shamsabad EIP and identifying the existing regulatory and institutional framework for developing the EIP and reducing environmental impacts of the IP (World Bank Group, 2021, 2018, 2016, 2014; Sertyesilisik & Sertyesilisik, 2016).

The researcher obtained the following information by analyzing the interview results:

1. The environmental, social, and economic motivations for forming the industrial symbiosis and developing the Shamsabad EIP
2. Participating enterprises of EIP
3. Existing enterprises and synergies
4. Potential new enterprises
5. Existing government bodies, agencies, and organizations related to EIP development
6. Existing regulations, policies, plans and strategies and their implementation mechanism.

- Field Visit

Field visits were conducted to collect information from the management and executive team of the Shamsabad IP, government bodies, and the management team of Behnoush Co., which was selected for Life Cycle Assessment (LCA) in this research. Several guides and research studies, such as World Bank Group (2018) and Piadeh et al. (2014), were used to conduct the data collection. Various information was obtained, including information on inputs and outputs of firms, processes and operational attributes of firms, row/used materials, and wastes exchanges between firms, and needs and capacities of firms in terms of production.

Furthermore, LCA was conducted on one of Iran's main beverage and beverage packaging industrial facilities, Behnoush Co., with a focus on cradle-to-grave scope which allowed for an analysis of both the direct and indirect environmental impact of packaging in the food industry. The purpose of the LCA study was to evaluate the effectiveness of the exchange flow types designed in this research. Several studies, including Bojarska et al. (2021), Bręk et al. (2019), Czaplicka-Kolarz et al. (2017), Saleh (2016), Amienyo et al. (2013), Curran (2013, 2012), and Büsser and Jungbluth (2009) were used to conduct the LCA.

Chapter 2: Literature Review

2.1. Introduction

This research study aims to establish a framework for planners and developers to be used in the first steps of developing EIPs. Therefore, reviewing the literature devotes special attention to the main terms and concepts related to the framework's broader goal, formation, and performance, which accelerates its establishment process. It specifies an efficient framework for promoting EIPs' environmental, social, and economic performance.

A systematic literature review in this research study helped identify, select, and critically appraise research to answer the formulated research questions (Dewey et al., A. 2016). Identification and selection of the literature were conducted comprehensively and transparently. For this, the most recent literature related to the main concepts and specific terms of the research were selected by searching keywords over multiple databases and replicated literature produced by several researchers. Then, the researcher applied a well-thought-out search strategy which focused on selecting the literature, helping the researcher answer the defined research questions. The selected literature was reviewed. In this way, the type of information was identified, categorized, and criticized within four months, starting September 2021, to establish the theoretical foundation of the research.

Eco-industrial Park (EIP), Circular Economy (CE), and Life-Cycle Assessment (LCA) are the fundamental concepts and specific terms relevant to the research topic and valuable for answering research questions. Several definitions of Eco-industrial parks provided by scholars were discussed, and significant differences between Industrial Parks (IPs) and Eco-industrial Parks (EIPs) were detailed. The environmental, social and economic performance of IPs and EIPs were differentiated using the literature highlighting the benefits of the circular model and industrial symbiosis evident in Eco-industrial Park. In the next stage, significant drivers and barriers to developing EIPs were explored by emphasizing government guidelines, case studies and other relevant literature presenting successful EIPs around the globe. In this regard, the specifications associated with the successful EIPs were analyzed by focusing on their planning and design aims, components and benefits for communities.

Then, the researcher drew attention to the articles related to the development of EIPs in Iran. By pointing out the minimal effort in the field of EIPs development in Iran compared to Europe and North America, the importance of Iranian EIP establishment on the national and international scales was elaborated using statements from relevant pieces of literature. Also, drivers and barriers to developing Iranian EIPs were explored for the next steps, where the research framework was established.

In the next step, the interrelation between EIP and circular economy (CE) was explained using several studies which provided definitions of CE and industrial symbiosis. The application of Life Cycle Assessment for assessing environmental risk and its potential for establishing industrial symbiosis in EIPs were discussed by criticizing its application in the design process and performance evaluation of EIPs using scholars' statements.

The research study aims to develop a framework for the first stages of transforming IPs into EIPs. The researcher selected and analyzed the most relevant literature, which examined developing EIP frameworks considering several criteria to identify the need for studies. The government reports and guidelines were explicitly investigated to understand the EIP establishment's legal and regulatory frameworks and strategies.

2.2. Eco-industrial Parks

2.2.1. Definition of Eco-industrial Parks

An Eco-Industrial Park (EIP) is defined as "a large tract of land, sub-divided and developed for the use of several firms simultaneously, distinguished by its shareable infrastructure and close proximity of firms" (Peddle, 1993, p. 108). Several definitions for EIP have been provided by various research studies. Tessitore et al. (2014, p. 9) pointed to the following definitions provided by some papers:

"An EIP is:

1. An industrial system which conserves natural and economic resources; reduces production, material, energy, insurance and treatments costs and liabilities; improves operating efficiency, quality, worker health and public image; and provides opportunities for income generation from use and sale of wasted materials (Coˆte and Hall, 1995)

2. A community of companies seeking enhanced environmental and economic performance through collaboration in managing environmental and resources issues including energy,

water, and materials. By working together, the community achieve a collective benefit that is greater than the sum of the individual benefits each company derives (Lowe et al., 1995)

3. A community of businesses that cooperate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat), leading to economic and environmental quality gains, and equitable enhancement of human resources for the business and local community (Lambert & Boons, 2002).

4. An industrial system of planned materials and energy exchanges that seeks to minimize energy and raw materials use, minimize waste, and build sustainable economic, ecological, and social relationships (Lambert & Boons, 2002).

5. A dedicated area for industrial use at a suitable site that seeks sustainability through the integration of social, economic, and environmental quality aspects into its siting, management, and operations (World Bank Group, 2014)."

There are significant differences between Eco-industrial Park (EIP) and Industrial Park (IP). According to the World Bank Group (2018), "IPs can be defined as designated, serviced industrial areas where firms are conglomerated. They help facilitate commercial activities and provide collective infrastructure and services, including roads and utilities to resident firms. As such, they provide fertile ground for collaboration across sectors and businesses, resulting in efficiency gains. As a result, governments often consider them as policy tools that can help fulfill a country's national economic development strategy for increasing industrial output and boosting economic growth. Although IPs can contribute to the economic growth and social development of a country or a region, they also have the potential to generate significant negative environmental externalities in the form of air emissions, water pollution, land contamination and over-exploitation of resources. Furthermore, IPs that are not properly managed can negatively impact the workforce and communities in which they operate. Global buyers increasingly demand sustainably sourced and processed products; governments, regulators, and nongovernmental organizations also pressure IPs to operate in a more environmentally and socially responsible manner. Many industries and firms are also willing to take voluntary actions to fulfill their perceived economic, social and environmental responsibilities in competitive markets. Yet, IP developers and operators aim to provide differentiated services to tenants in ways that are unlike other types of IPs. One way to meet this growing demand is to develop an EIP or to transform existing IPs into EIPs (p. 3-4)".

2.2.2. Performance of Eco-industrial Parks

According to World Bank Group (2018) "EIPs have been acknowledged in the literature for some time as an effective way to achieve sustainable design, management, and operation of IPs. They have been recognized as a means to address the challenges made by IPs and reduce resource intensity, improve productivity, minimize environmental impact, and improve the well-being of workers" (p. 172). Compared to IPs, EIPs are capable of bringing sustainable direct and indirect and holistic benefits to the industrial sectors and resident enterprises. EIPs significantly improve capital efficiency, obtain utility cost savings, attract foreign direct investments, increase exports, and generate additional revenues in firms and industrial sectors (MOTIE, 2017).

According to Quradaghi et al. (2020), EIPs promote a shift from the traditional linear model to the circular model, where industrial symbiosis plays an important role in encouraging the exchange of materials, energy, and waste. This allows for creating a synergy in the network that leverages waste reduction and efficiently uses resources.

Industrial symbiosis, a specific common term used in EIP studies, has been defined in several studies. "Industrial Symbiosis is a term used in industrial ecology to describe traditionally separate industries that engage in a collective approach to competitive advantage involving the physical exchange of materials, energy, water, and by-products, as well as knowledge sharing and long-term cultural change" (Chertow, 2000, p. 314). As the World Bank Group (2018) stated, "industrial symbiosis refers to the collective collaboration of industry, for example, the sharing of services, utilities, energy and by-product resources among diverse industrial actors to add value, reduce costs, and improve the environment" (p. 145). Also, as Liu et al. (2015) highlighted, industrial symbiosis is an innovative approach that aims to bring together industrial firms from various categories in order to improve resource efficiency and sustainability and reduce environmental impacts by sharing and reusing resources.

As Ayres (1995) and Felicio et al. (2016) stated, in an EIP, at least one major firm exporting raw or processed materials is connected to other firms utilizing considerable portions of waste materials. These firms are linked to several enterprises which convert the waste materials into usable goods, for which the coordination mechanism and information sharing play a significant role. The interactions among businesses and the businesses and the natural environment are the essential feature of an EIP (Al-Quradaghi et al., 2020; Felicio et al., 2016; Eilering & Vermeulen, 2004; Lowe et al., 1995). The following sections elaborate on the interaction between enterprises is formed by key drivers and reduced by barriers.

2.2.3. Key Drivers of Eco-industrial Parks

Several research studies, handbooks, and governmental reports highlighted the drivers of EIPs (Aggeri, 2021; Sakr et al., 2011; Majumdar, 2001). According to these papers, the main drivers for EIPs from an industrial competitiveness viewpoint include providing an improved and active business environment, minimizing risks of exposure to natural resource scarcity, minimizing production costs, and providing access to high-quality infrastructure. The top international EIP practices, such as Kalundborg EIP, present desires to attract local and foreign investors and provision of environmentally, socially, and economic services highly supported by governmental policies and regulations. Also, the overall park concept is attractive for industrial enterprises and uses access to cheaper resources; therefore, cost savings are a strong motivation for investors and industries.

Key environmental drivers of EIPs include mitigating climate change at the national and global level through significant contributions to reducing carbon emissions, alleviating resource constraints through the use of by-products and waste of energy and material and increasing demand to improve efficiency and growth. Also, key social drivers of EIPs involve improved working and labor conditions, creation of local job opportunities, provision of social infrastructure to local community and workers for the long-term, improved occupational health and safety, and transition to more sustainable land use. Moreover, key economic drivers of EIPs include direct and indirect employment creation and business expansion, linkages between IP firms and the network of communities and industries outside the IP, and technology and knowledge transfer through the linkage between industrial firms.

2.2.4. Barriers to the implementation of Eco-Industrial Parks

EIPs are subject to a range of barriers faced by park owners, operators, and resident businesses. These barriers, which cover a range of aspects from technology to managerial deficiencies, include insufficient financial returns on businesses generated for sustainability purposes, lack of proper and enforceable regulations, limited technological development and cost-efficient solutions, lack of public awareness about the benefits of EIPs, complexity in organizational structure, limited demand for sustainable products, and lack of financial supports for EIP enterprises (Sakr et al., 2011).

2.2.5. Eco-industrial Parks Around the Globe

Developing EIPs is now recognized as a popular approach because of their ability to transform the traditional model of EIPs into more sustainable forms of environmental and economic development. According to Côté and Cohen-Rosenthal (1998), there are many examples of practices for exchanging material and recovering and recycling material in the process of cascading water and energy. However, EIP practices and studies of industrial ecosystem terms are limited. In many countries, including the United States and Canada, planning and design of EIPs are underway, and some industrial sites have been transformed into EIPs with specific characteristics. Some of the EIPs projects in the United States are Port of Cape Charles, Virginia; Fairland, Maryland; Brownsville, Texas; Riverside, Vermont; Chattanooga, Tennessee. Some of the specifications of this Category of EIPs include sustainability technologies, waste re-use, environmental technology, clean industries, renovation of the existing facility, natural features, regional approaches to waste materials exchange, bioenergy, waste treatment, community-based park, resource recovery-based park, landscape development, energy efficiency, and a new development integrating commercial and residential and environmental businesses.

According to Peck and Callaghan (2018) and Peck and Associates (1997), a few industrial projects in Canada present ecological characteristics, such as Burnside Park, for which the establishment began by conducting multi-disciplinary initiative research and transformation of Burnside into an industrial ecosystem. Burnside Park is identified as the largest EIP in Boston and east of Montreal, encompassing 1,200 hectares with almost 2,000 enterprises. Various industrial ecology strategies have been used in this EIP, which include waste reduction, pollution prevention, environmental auditing, and industrial symbiosis and waste exchange. Also, Taiga Nova EIP is an example of EIPs in Canada, with 131 Acres, located in Fort McMurray, Alberta. This EIP is recognized as a highly efficient EIP that uses green infrastructure, and innovative sustainable design approaches resulting in high-quality industrial ecology and material exchange flows among businesses to function as a community.

Similar projects have been underway in Toronto, which involve enterprises in a variety of sectors in manufacturing and services and the exchange of waste and energy at different levels. These projects have the potential to be many more across Canada. According to Peck and Callaghan (2018) and Peck and Associates (1997), Canada has immense potential for EIPs with energy cascading and recycling across Canada. In this regard, nine sites have shown excellent possibilities for eco-industrial development, which are located in Vancouver, British Columbia;

Fort Saskatchewan, Saskatoon; Sault Ste. Marie, Ontario; Nanticoke, Ontario; Cornwall, Ontario; Becancour, Quebec; Montreal East, Quebec; Saint John, New Brunswick; Point Tupper, Nova Scotia. This category of industrial sites includes key industries such as steam generators, paper mills, power generation, thermal generating stations, oil refineries, and sugar refinery IPs.

The establishment of EIPs has also been considered in several other countries, including Denmark, Thailand, Switzerland, Germany, France, the Philippines, South Africa, Jordan, etc. (Al-Quradaghi et al., 2020). Kalundborg, Denmark, is the most well-known example of transforming an IP into an EIP, recognized as a model of industrial symbiosis. As Kalundborg Symbiosis (2020, 2016), Jacobsen (2006), and Ehrenfeld and Gertler (1997) highlighted, Kalundborg's EIP shows both direct and indirect economic benefits for participating companies. It relies on the exchange of waste and heat between a coal-fired power plant, an oil refinery, a pharmaceutical plant, and a plasterboard manufacturing plant (figure 1 & 2).

Figure 1- Flow of Material and Energy between EIP Enterprises (Kalundborg Symbiosis, 2020)

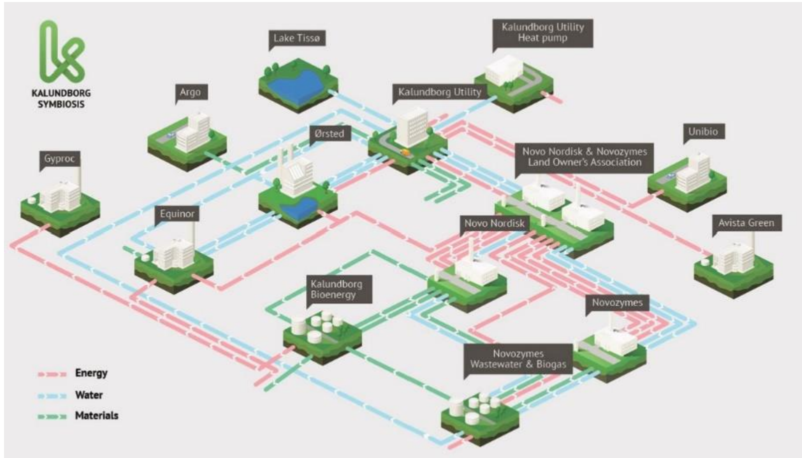


Figure 2- Flow of Material and Energy between EIP Enterprises (Kalundborg Symbiosis, 2020)

According to Kalundborg Symbiosis (2020, 2016), several conditions have been identified for the success of the Kalundborg EIP, including careful screening of new companies, a clear vision of the park's values, complete transparency between local businesses in terms of their operations, methods and information to support companies in seeking by-product trades, and flexibility in recruitment strategy. Also, the size and diversity of the companies involved in the industrial eco-park played a significant role in the success of the EIP (Massard et al., 2014; Korhonen, 2001). Despite numerous examples of EIP operating, planned or in development in various countries, few have garnered the success of Kalundborg (Massard et al., 2014).

Iran, which is located in an arid and semi-arid region, has been facing water scarcity as one of the most critical concerns of industrial estates and several related environmental problems (Piadeh et al., 2014). In Iran, the government supports the concepts of EIPs because the development of industrial settlements with water reuse and carbon reduction ensures sustainable development. This approach towards sustainable development is possible through resource sharing and material exchange between industries to reduce waste and pollution and to optimize water efficiency (Von Koerber et al., 2021: Piadeh et al., 2014). The concept of sharing resources and reusing wastewater was highlighted by the Rio+20 conference in 2012, where it highlighted the role of EIPs in the reuse of water and achieving green economy aims (UN, 2012, 2011; UN-Water, 2012; Elabras Veiga & Magrini, 2009).

According to Piadeh et al. (2014) and Iran small industries and IPs organization (2011, 2012a), up to now, 689 industrial estates have been constructed in Iran. Most of the 153 operational industrial parks, including the Shamsabad IP, are in dry areas and near megacities such as Tehran. Nearly all IPs face lack of water resources and show considerable carbon emissions (Shaeri & Rahmati, 2012). Therefore, the establishment of new EIPs and the transformation of the existing IPs into EIPs can be effective solutions to the problems of the IPs. According to Iran's small industries and industrial parks organization (2013f, 2012a, 2011), the establishment of Iranian EIPs is not too old compared with the developed countries. Iran has little experience in developing EIPs. Considerable efforts should be devoted to developing EIPs for addressing environmental and ecological challenges, such as water consumption, carbon emission, and waste production, while retaining EIPs' role as production hubs and growth centers.

Morcheh Khort EIP is the only existing EIP planned and developed in Iran (Shaeri & Rahmati, 2012) (figure 3). This EIP is located in the north of Isfahan City, comprises around 300 active firms with 17,000 employees, and presents designing the growing industrial settlements in a coordinated, resource-efficient and environmentally friendly way. The EIP was designed by a project team, including research institutes, governmental bodies, and companies, which brought years of experience in the field of water management. The basic idea for designing the EIP was the creation of networks within an industrial settlement to mutually use and reuse resources, connect firms to the local wastewater treatment plant and promote the exchange flow of materials and water between them.

Figure 3 – Morcheh Khort Eco-Industrial Park (Von Koerber et al., 2021)

As Von Koerber et al. (2021) stated, the analysis of the water demand and wastewater production of the firms, the design of network models and technical modules for wastewater treatment, and the preparation of recommendations for the future industrial settlement development were some of the activities conducted to develop Morcheh Khort EIP plan. The plan contributed to optimizing resources (saving four million m^3/y fresh water) and establishing environmental-friendly and cross-linked industrial settlements. The design and executive teams for the development of Morcheh Khort eco-industrial park have encountered significant problems that arose from inefficient and unsupportive policies and regulations established by the government bodies to develop eco-industrial parks.

According to the results of exploring various EIP practices, forming a network of enterprises based on their common social, cultural and environmental interests/requirements, supported by effective policies and regulations, results in integrated long-term benefits and success of EIPs. The EIP concepts, which follow a variety of advantages at different levels, accelerate the transformation of IPs into EIPs and guarantee their future sustainable performance.

2.3. Circular Economy

"Circular Economy (CE) is a response to the multiple challenges of the modern world, economic, environmental, and social ones. The purpose of the CE is to maintain the value of products, materials, and resources for as long as possible to ultimately minimalize waste generation" (Samson-Bręk et al., 2019, p. 4). To reduce waste production, raw materials should be repeatedly recycled and exchanged between various industries, and waste should be used as raw materials. Several studies, such as Ormazabal et al. (2018) and Czaplicka-Kolarz et al. (2017), emphasized that CE contributes to using natural resources economically and with care as they are not public good which can be used with significant restrictions. Preventing and reducing industrial waste is a critical area of the circular economy and should be a key priority for scientists, environmentalists, and managers of industrial sites (Diaz-Ruiz et al., 2018; European Commission, 2017). In this regard, the huge challenge is the lack of new policies and regulations for using new and wasted materials and packages in industrial sectors and packages to guide business entities to fully implement the raw and recycled materials policies (Samson-Bręk et al. 2019; Yedla & Park, 2016). Also, "there is a lack of proposals to improve the social acceptance of the recycled materials because the specific problem in the implementation of CE is that companies do not tend to engage in activities for environmental protection as the latter have not been identified with increasing the company's profit and competitiveness" (Samson-Bręk et al., 2019, p. 5). Therefore, research studies which provide relevant information are necessary to contribute to directing CE and reducing numerous environmental impacts of the production system to the area of the ecosystem, human health and resources used (Ormazabal et al., 2018).

EIP is considered one of the oldest forms of drivers for CE since they are industrial zones that promote collaborations between enterprises and communities, generating various environmental, social, and economic benefits. The exchange of material, water and energy between interdependent enterprises operating complementary activities, described as CE, takes into consideration available resources in and around EIPs (Aggeri, 2021).

2.4. Life Cycle Assessment

According to Bręk et al. (2019), "life cycle assessment (LCA) is a technique designed to assess the environmental risks associated with the product system or activity either directly by identifying and quantifying the energy and materials used and the waste introduced into the environment or indirectly by evaluating the environmental impact of such materials, energy, and waste. The assessment relates to the whole lifespan of the product or activity, from the mining and mineral material processing, product manufacturing process, distribution, use, reuse, maintenance, and recycling up to the final disposal and transportation. LCA directs the study of the environmental impact of the production system to the area of ecosystems, human health and the resources used" (p. 1).

Many studies, such as Rogall et al. (2010) and Slagstad and Brattebø (2013), highlighted that LCA is one of the valuable tools to implement the principles of sustainable development in the circular economy (CE). LCA helps to close the life cycle of a product by considerably increasing the level of recycling, and reuse of waste and use of all raw materials, which significantly decrease greenhouse gas emission and water resources use (Bojarska et al., 2021; Bręk et al., 2019; Czaplicka-Kolarz et al., 2017). Therefore, LCA benefits the environment and the economy and helps businesses and consumers to be involved in a stronger economy (Bojarska et al., 2021; Curran, 2012; Samson-Bręk, 2012). It ensures high ecological (environmental), economic and sociocultural standards for both the present and future generations (Rogall, 2009; Ormazabal et al., 2018; Flintsch, 2008).

As the world's industrial sites increase, so does the demand for studies with a focus on reducing the environmental impacts of the industries' activities (Høgaas Eide, 2002; Guinee et al., 2001; Abbasi & Abbassi, 2004). “In this context, LCA has been widely accepted as a decision support tool in many productions as well as waste management areas to investigate, quantify and compare the potential environmental impacts of materials and industrial processes” (Tan & Khoo, 2005, p. 204).

LCA has specifically been used for developing EIPs where small and medium enterprises are often grouped in a restricted territorial area (Ardente et al., 2017; European Commission, 2003). The main benefit of LCA in EIP development is its results contribute to determining design considerations for resolving environmental problems, including resource depletion, air emissions, and landfill waste (Ardente et al., 2010; Lowenthal & Kastenberg, 1998; Schwartz & Steininger, 1997) and therefore, improving the collective environmental performance of industries and small and medium enterprises (Lowe et al., 1995). “LCA provides a framework for estimating the environmental impact of products or processes from the cradle to the grave, that is, from raw material extraction and processing through manufacturing, distribution, retail, consumption, and product disposal. The European Commission stated that the best way to demonstrate the efficacy of the LCA approach is to apply it to various practical applications such as EIP areas" (Ardente et al., 2003, p. 53).

Reviewing the literature demonstrates that studies of LCA with the purpose of supporting EIPs are limited (Minjung & Kim, 2015). However, due to the extremely high-water demand and carbon emission by industries, LCA was recommended as a useful tool for planning and design of eco-industrial clusters to create open recycling loops in which waste materials are reused (Ardente et al., 2017; Faraz A Consulting Co., 2012; water and wastewater research consulting company, 2012).

2.5. Framework for EIP Development

As mentioned above, this research study aims to develop a practical framework for EIP establishment. EIP studies, such as Haskins (2007), Ardente et al. (2010), Chertow (2000, 2007), and Ehrenfeld and Gertler (1997), emphasized that EIP frameworks help EIPs embody the local and regional resources and energy flows properly for the maximal efficiency in their interaction. The frameworks assist EIP designers/developers in a significant reduction in water usage and carbon emission resulting from managing materials and energy flows with attention to the possibility of chemical linkage and a more extensive range of connections between sources, which lead to environmental sustainability and lower environmental damage (Sopha et al., 2010).

Reviewing literature shows a noticeable need for more EIP frameworks. As Al-Quradaghi et al. (2020) and Sopha et al. (2010) highlighted, establishing frameworks for the design of EIPs and developing guidelines for the implementation of EIPs, which contribute to improving the sustainability performance of water and carbon, have been accomplished slowly. Based on the report on the Environmental Management of the Industrial States released by the Industry and Environment Office of the United Nations Environment Program (1997), “IPs have become common features of the global landscape. There are more than 12,000 IPs around the world which can facilitate sharing of materials, energy, and waste because of the co-location of several industries” (Coˆte´ & Cohen-Rosenthal, 1998, p. 184). This report, which provided guidelines for the design of new EIPs, recommended strategies for providing integrated economic, ecological and social benefits. It proved the establishment of the EIP framework, performing as a guide for EIP developers to address various social, environmental and environmental problems arising from the established, under-construction, and planned IPs (Coˆte & Cohen-Rosenthal, 1998).

To achieve the expected long-term benefits of EIPs, frameworks present a set of design considerations which are necessary to guide stakeholders and decision-makers during the first stages of developing EIPs. The EIP developers delicately use the design considerations to form an industrial symbiosis, which enhances the life cycle sustainability performance of water and carbon in the industrial processes and achieves social, economic and environmental benefits. Optimal design considerations are critical success factors for manufacturers and take advantage of LCA (Kwak & Kim, 2015).

Several studies in literature proposed frameworks for EIPs. These frameworks were used for EIP projects in Argentina, Australia, Brazil, Canada, Chania, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Singapore, Switzerland, the UK, the USA, and others (Ardente, 2010; Chertow, 2007; Zhu et al, 2015). The international framework for EIPs was created by the United Nations Industrial Development Oragnization (UNIDO), World Bank Group, and German society for International Cooperation (GIZ). According to Al-Quradaghi et al. (2020), “this framework provided general information and strategic details for EIP requirements” (p. 16). In addition, several studies investigated general frameworks (Haskins, 2007; Chertow, 2007; Ehrenfeld & Gertler, 1997) and special-case frameworks (Liu et al., 2017; Behera et al., 2012) for establishing EIPs. These studies expressed frameworks based on a combination of specific factors, such as:

1. Engineering, industrial ecology, logistics, and supply-chain theories (Haskins, 2007)
2. Needs identification, requirements definition, performances specifications, analyzing, designing, and improving, and implementation (Sopha et al., 2010)
3. Dynamics of industrial symbiosis in societal and regional industrial systems (Boons et al., 2011)
4. Functionality, theoretical knowledge; adaptability; reliability; and lifespan (Romero & Ruiz, 2013)
5. Identifying environmental impact, sustainability indicators, and assessing the environment (Dumoulin et al., 2017)
6. EIPs’ topology and operation, uncertainties, and risks (Kuznetsova et al., 2016)
7. Defining cooperative plants in the intended EIP, identifying interactions between plants, and configuring the EIP (Andiappan et al., 2016)

2.6. Conclusion

According to the literature review, establishing an EIP framework, which is the aim of this research study, relies on the decisive understanding of industrial symbiosis, which builds the functional and sustainable structure of EIPs. Designers and developers of successful EIPs focus on expanding the industrial symbiosis, increasing the motivations and incentives for enterprises, and eliminating/reducing the inhibiting factors for the public. An efficient framework pays attention to a specific industrial town's key and special aspects in its geographical context. It obliges the designers of the industrial town to implement things that ultimately and, in the long run, benefit society and the founders of the industrial town. "LCA, as a systematic tool, could be employed to reveal the major areas of environmental concern of EIPs by focusing on the manufacturing processes in a holistic manner, calculating and quantifying the environmental impacts, classifying the environmental impacts and highlighting important areas for improvements in terms of environmental performance" (Tan & Khoo, 2005, p. 196). Thus, it is a useful tool for forming industrial symbiosis in a way that the performance of EIPs results in minimum environmental impacts. Also, legal and regulatory systems must be contemplated for the proper functionality of the framework and to guarantee the EIP's sustainable performance.

According to the literature review elaborated on general EIP frameworks, scholars have made considerable efforts in ways and methods to design EIPs. However, research studies which aim to develop a simple, clear, and strategic framework for design considerations are essential. According to Al-Quradaghi et al. (2020), researchers, stakeholders and decision-makers necessitate more specific frameworks which contribute to resolving local problems via developing new EIPs to achieve maximal benefits economically, environmentally, and socially. They could follow the framework in the initial steps of planning and developing EIPs. By reviewing the relevant concepts elaborated in this chapter of the research, including EIP, CE, industrial symbiosis, and LCA, it is concluded that the desired framework which will be used on a specific case study, the Shamsabad IP, consists of four steps: (1) identifying EIP enterprises and their motivations, (2) determining industrial symbiosis based on the motivations and shareable material, energy and waste of enterprises, (3) evaluating the effectiveness of industrial symbiosis in resolving environmental impacts by LCA, and (4) identifying regulations, policies, plans and strategies supporting the development and performance of the new EIP. This framework is qualified to improve the efficiencies of the industrial facilities in the sustainability field in given districts and thus, enables them to enhance their competitiveness on a global scale (Al-Quradaghi et al., 2020; Iran small industries and industrial parks organization (2011, 2012a, 2013f). Next chapter of this research is dedicated to identifying and analyzing the specific characteristics of the Shamsabad IP, identifying the EIP's enterprises and their motivations, and forming the EIP's industrial symbiosis.

Chapter 3: Case Study of Shamsabad Industrial Park

3.1. Introduction

Thus far, a literature review has been conducted to establish the theoretical foundation of this research study. The thesis elaborated on the main terms and concepts related to the broader goal, formation, and performance of the aimed framework. In that elaboration, developing a framework for the initial stages of EIP development proved to be a remarkably effective means for developing EIPs. Developing the framework consists of four steps, explained in the previous chapter. This chapter presents a case study where the establishment of the framework will be examined through the development of the Shamsabad EIP. Identification and analysis of the Shamsabad IP's significant features, identification of the EIP's enterprises and their motivations, identification of sharable material, energy and waste of the enterprises, and formation of the EIP's industrial symbiosis are conducted in this chapter. In this respect, the researcher recommends a series of design considerations and simple steps for EIP designers and decision-makers to develop EIPs efficiently and conveniently.

3.2. Case Study Background

The Shamsabad Industrial Park (Shamsabad IP) is the largest IP in Iran and one of the largest IPs in the Middle East. This IP is located in the south of Tehran province, adjacent to Hassanabad City, 45 km from the Tehran-Qom highway, and 5 km from Imam Khomeini International Airport. It has an area of 3,000 hectares. The executive operation of the Shamsabad IP started in 1993 and 1650 hectares were put into operation, of which 900 hectares are in the existing plans, and 750 hectares are in the development plans. At present, 1200 industrial facilities are active in the industrial park. Chemical and plastic, construction, cellulose, tobacco, textile and clothing, food and beverage, electricity generating and electronics, metal and machinery, and non-metallic minerals and services are some of the industrial facilities operating in the Shamsabad IP. Over 20,000 people are employed in this park, and with the completion of its inactive industrial facilities, the number of jobs created in this park will reach 50,000.

An industrial facility is defined as any land, and any building or other improvement thereon, which is maintained and utilized as a business enterprise for manufacturing, processing, or assembling any product, commodity, or article, characteristically using power-driven machines and materials handling equipment. The term “industrial facility” does not include non-manufacturing business establishments, such as wholesale businesses, retail stores, warehouses, storage facilities, and any land, and any building or other improvement thereon, that is primarily utilized for federal, state or local government activities (figure 4).

Figure 4- Geographical Location of the Shamsabad Industrial Park (Figure by the Researcher)

3.2.1. Green Space

The green space area of the Shamsabad IP, which is one of the characteristics of this park, is over 240 hectares, which is one of the most brilliant features of this large industrial park, considering the regional climate. According to the executive affairs of the IP, more than 240 hectares of the area of this park, including 160 hectares in the parking area and 80 hectares inside the facilities, are dedicated to green space.

3.2.2. Water and Electricity Supply

As the management and executive team of the Shamsabad IP stated, in terms of infrastructure facilities, there are ten water wells with a water supply of 100 liters per second, which could meet 20% of the needs of this park. This IP has brought water to the industrial facilities through the construction of a water transmission line. As the executives of the IP highlighted, the construction of the water transmission line from Muhammadiyah Canal to the Shamsabad IP started in 1992. However, this development project was about 28 km long, of which 20 km was implemented.

The electricity required for the Shamsabad IP is currently 900 MW. Electricity and gas costs to industrial facilities are unfortunately high and put pressure on the industrial facilities. As mentioned above, despite the problems of services such as water and sewage, telecommunications, and electricity, 1200 industrial facilities are now active in this economic zone. According to the management team of the Shamsabad industrial park, The Rey County Environment Department (RCED) cooperates with the management and executive teams of the IP to eliminate some of the existing pollutants according to the standards. In this regard, Environment Impact Assessment

(EIA) and Waste Management (WM) studies are currently being seriously pursued to transform the IP into a green and sustainable park in the near future.

Figure 5- Entrance of the Shamsabad Industrial Park, (Shamsabad Industrial Park, 2022)

Figure 6- View of Industries located in the Shamsabad Industrial Park (Shamsabad Industrial Park, 2022)

Figure 7- View of Industries located in the Shamsabad Industrial Park (Shamsabad Industrial Park, 2022)

As the management and executive team of the Shamsabad IP stated, 47 food packaging facilities are active in the park (Figure 5). This research will focus on the food packaging facilities due to their significant environmental problems in Tehran and the whole country. According to the Department of Environment (DOE), current food production and consumption practices in Iran generate a lot of packaging, and new forms of packaging are constantly being developed (DOE, 2020). Food packaging materials make up almost half of municipal solid wastes in Iran (Iran small industries and industrial parks organization, 2011). According to the DOE (2020), in 2019, out of the 48 million tons of municipal solid waste generated in Iran, more than 58 percent was of packaging materials (for food and other purposes). Only 15 percent of the packaging waste was recycled or composted. Accordingly, the Shamsabad IP possesses considerable waste resulting from food packaging industries. According to the 2022 statistics on waste production, Carbon dioxide (CO_2) emission, and water consumption, the food packaging industries of Shamsabad IP have posed enormous environmental problems, which begin with their creation (Environmental Office of the Ministry of Industry, Mine and Trade, 2022a). These problems arise from food packaging forms which use a lot of resources like energy, water, chemicals, petroleum, minerals, wood, and fibres to produce, emit greenhouse gases, heavy metals and particulates, and produce wastewater and/or sludge containing toxic contaminants. In this regard, using old factory equipment because of severe financial problems arising from economic sanctions has majorly contributed to air pollution, water contamination, waste production, and energy consumption.

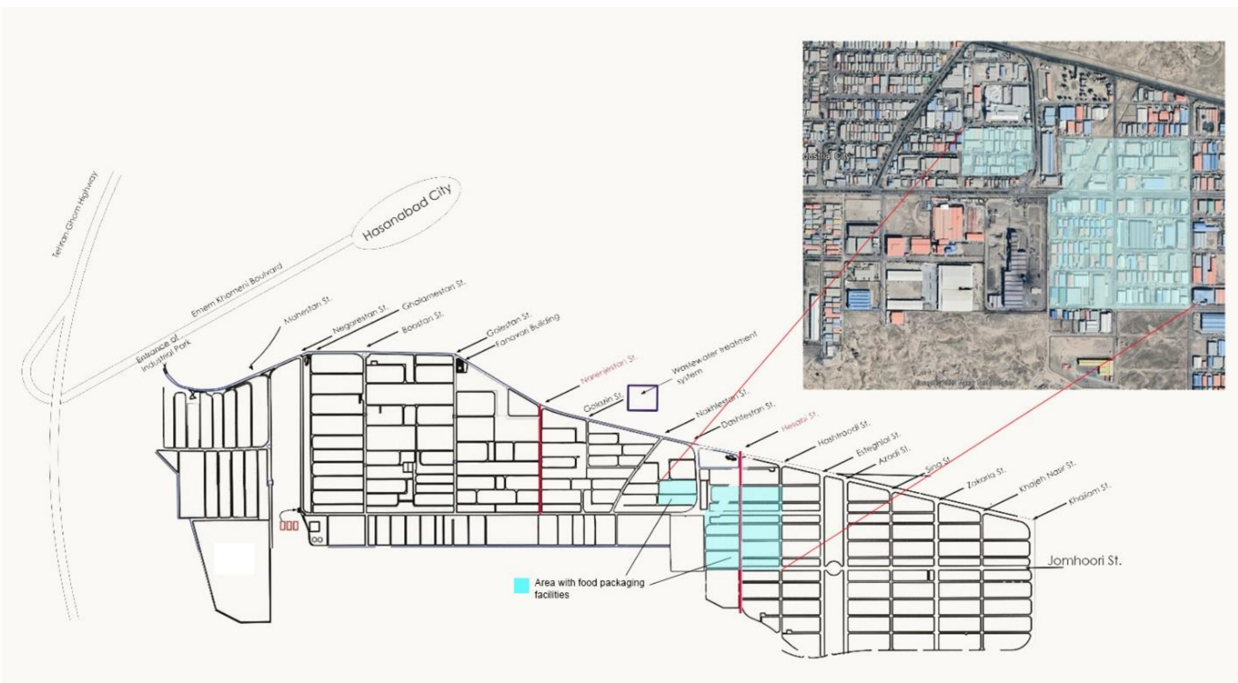


Figure 8- Map of the Shamsabad Industrial Park (900 ha) and

the Area with Food Packaging Facilities (Figure by the Researcher)

Number	Name of Food packaging Facility	Packaging Type
1	Masoud Tea	Tea Packaging
2	Zarrin Chai	
3	Golestan Tea	
4	Mahmood Tea	
5	Parsian Tea	
6	Shayan Tea	
7	Sina Co.	
8	Mahmood Tea	
9	Bahbah Tobacco	Tobacco Packaging
10	Radin Protein	Meat Packaging
11	Khagineh Co.	
12	Niloo Meat	
13	Zarifi Co.	
14	Liloo Co.	
15	Targol Co.	
16	Mah Protein	
17	Negin Darya Protein	
18	Jonoob Vegetables	Vegetable Packaging
19	Barootiha Co.	
20	Zaber Saffron	Saffron Packaging
21	Kianoosh Co.	
22	Noavaran Fruits	Fruit Packaging
23	Tavazoe Co.	Dried fruits, nuts, and saffron Packaging
24	Almadasht Co.	
25	Mehdineh Co.	
26	Khamesi Co.	
27	Karmaniah Co.	
28	Saharkhiz Co.	
29	Karamel Co.	
30	Andishe CO.	
31	Aida Co.	Egg, cereal, and sugar Packaging
32	TST Foods	
33	Rio Coffee	Coffee and cocoa Packaging
34	Safa Beans	Bean Packaging
35	Abaris Beans	
36	Vahid Co.	Beverage Packaging
37	Sahand Co.	
38	Behnoush Co.	
39	Arasbaran Co.	Egg Packaging
40	Mamatin Co.	Cereal Packaging
41	Nooshineh Khoram Co.	
42	Nil Gostar	Sugar Packaging
43	Mehregan Co.	Rice, nut, sugar, and tea packaging
44	Lili Co.	Dried mushroom and vegetable packaging
45	Zamin Mehr Co.	
46	Ladan Co.	Margarine oil Packaging
47	Nematian Co.	Margarine oil, pasteurized cream and milk, and buttermilk packaging

Table 1- List of Food Packaging Facilities of the Shamsabad Industrial Park (Table by the Researcher)

3.2.3. Environmental Problems of Shamsabad Industrial Park

- **Contribution to CO_2 Emissions**

The sources of CO_2 production in the Shamsabad IP were recognized using the 2022 statistics on CO_2 emissions (Environmental Office of the Ministry of Industry, Mine and Trade, 2022a). Table 2 and Figure 9 present the contribution of the industrial, residential, commercial and transportation facilities in CO_2 production. Identifying the contribution helped to concentrate on the significant carbon footprint sources and efficiently define the material, energy, and waste exchange flows between existing and new enterprises.

Facility Type		Contribution Percentage	CO_2 Production Source
Industrial	Energy Industry	21.4%	Processing of oil and gas
	Iron and Steel	16.6%	Manufacturing of iron and steel
	Chemical and Petrochemical	14.7%	Manufacturing of fertilizers, chemicals, pharmaceuticals, and oil and gas processing, etc.
	Food and tobacco	11%	Manufacturing of tobacco products and food processing
	Non-ferrous Metals	10.4%	Manufacturing and processing of non-ferrous metals such as aluminum, copper, lead, nickel and tin
	Paper, Pulp, Cardboard, and Carton	3.1%	Conversion of wood into paper and pulp
	Machinery	3%	Production of machinery
	Other Industries	14.8%	Construction, textiles, wood products, food packaging, etc.
Commercial and Residential Buildings		2%	Generation of electricity for lighting, appliances, etc. and heating in commercial buildings
Road Transport		3%	emissions from the burning of petrol and diesel from all forms of road transport, including cars, trucks, motorcycles, and buses.

Table 2– Contribution of Industrial Facilities of Shamsabad Industrial Park in CO_2 Emission in 2022 (Table by the Researcher)

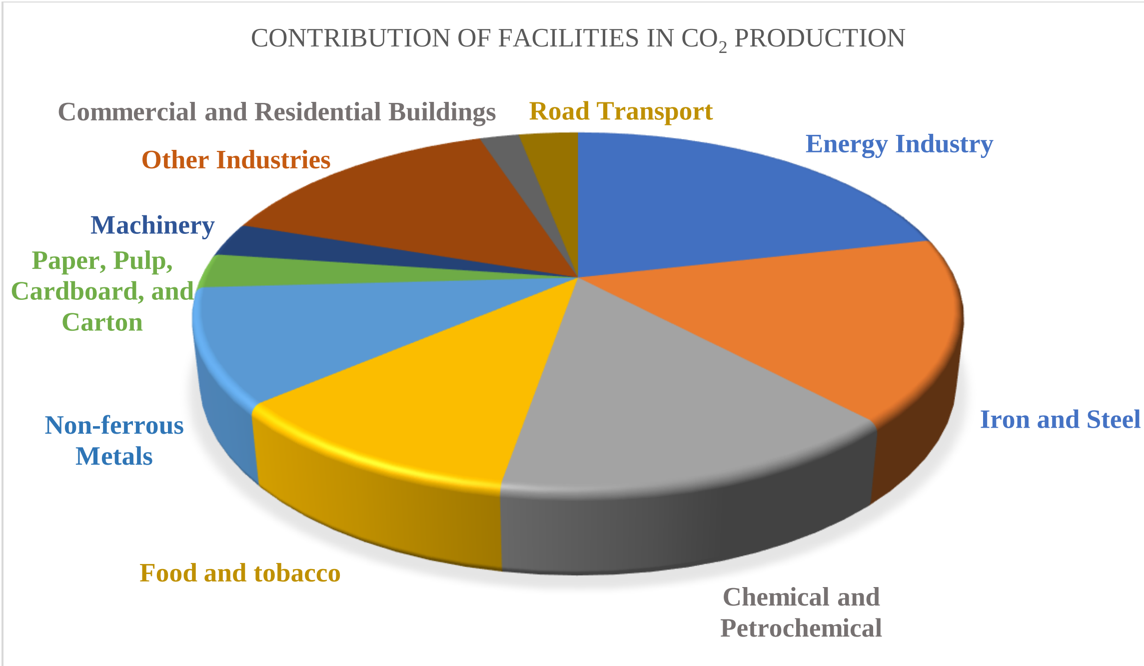


Figure 9- Contribution of Facilities of Shamsabad Industrial Park in CO_2 Emission in 2022 (Figure by the Researcher)

According to figures 9 and 10, energy industry (21.4%), iron and steel (16.6%), and chemical and petrochemical industries (14.7%) were the highest sources of CO_2 emissions in the Shamsabad IP. Other facilities groups, including construction, textile, wood products, food packaging (14.8%), and the non-ferrous metals industries (10.4%), were in the next rank in CO_2 emissions.

- **Contribution to Water Consumption**

According to the 2022 statistics on water consumption (Environmental Office of the Ministry of Industry, Mine and Trade, 2022a), the largest industrial water consumption with a share of 28.2% was chemical and petrochemical. Iron, steel, and non-ferrous metals, with 26% water consumption, are presented as the second water-intensive industry in the park. The energy industry, with 20.4% and the food industries, with 10%, ranked third and fourth in industrial water consumption. Other industries, including construction, food packaging, machinery, textile, and wood products, showed 15.4% water consumption in the industrial park (figure 10).

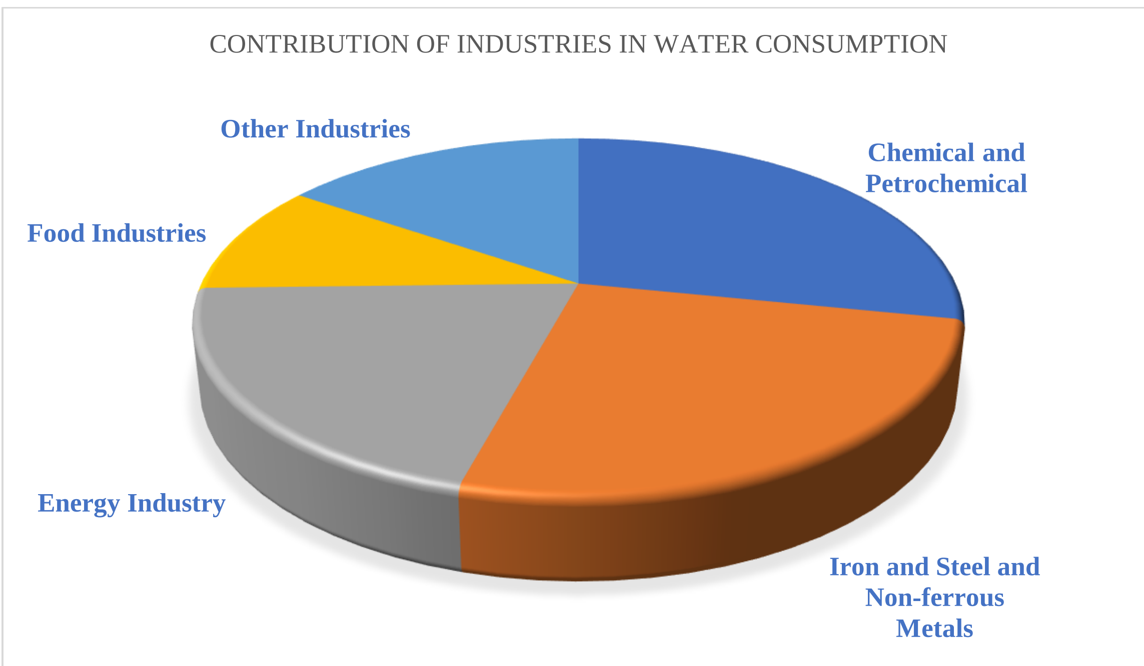


Figure 10- Contribution of Industries of Shamsabad Industrial Facilities in Water Consumption in 2022. (Figure by the Researcher)

- **Contribution to Waste Production**

According to the 2022 statistics on waste production (Environmental Office of the Ministry of Industry, Mine and Trade, 2022a), generally, 48%, 34%, and 18% of industries belong to the private sector, government, and government-cum-private organizations, respectively. Figure 11 presents the contribution of industries to waste production. According to the figure, the contribution of the industries are as follows:

1. Machinery and Metal (35%)
2. Chemical and Petrochemical (22%)
3. Food and Tobacco (12%)
4. Energy Industry (10%)
5. Other Industries (Construction, Textiles, Wood Products, Food Packaging, etc.) (21%)

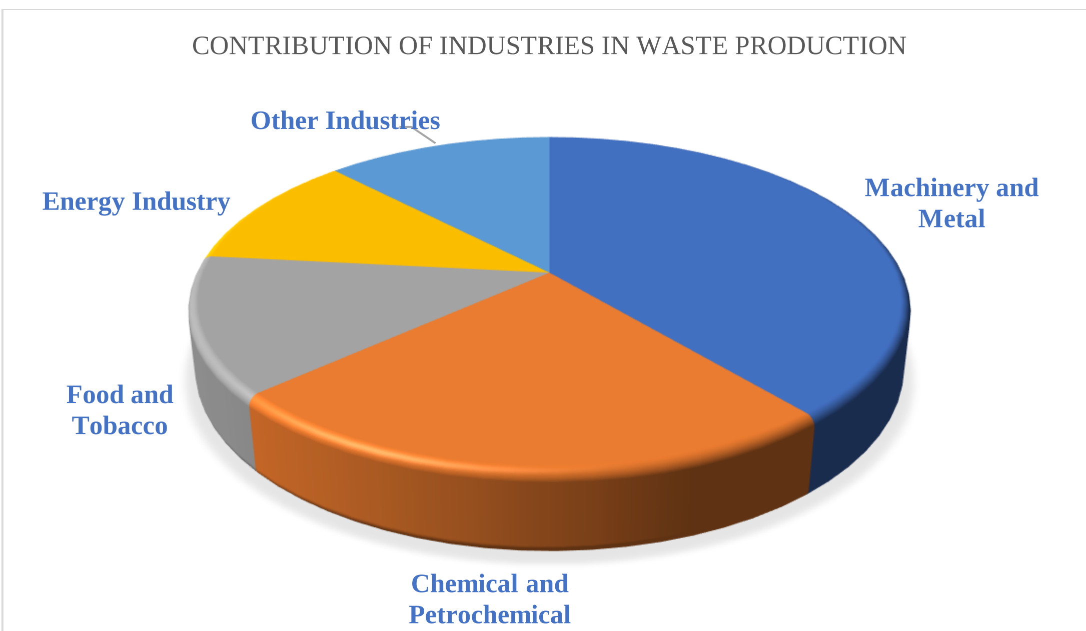


Figure 11- Contribution of Industries of Shamsabad Industrial Park in Waste Production in 2022 (Figure by the Researcher

3.2.4. Linkage to the Environmental Problems in a Broader Context

Tehran is a typical industrial city of Iran which is located in a fairly restricted basin on the southern foothills of the Alborz Mountains (35°34–35°50′N and 51°08–51°37′E). The area of Tehran is about 730 km2. The city has a population of over 11 million people, which is one of the most populated regions of the country. The annual average temperature and precipitation are between −7.4 °C and 38.7 °C and 245 mm to 316 mm, respectively (Hassanvand et al., 2015). Tehran suffers from serious air pollution and water scarcity due to the rapid growth of industrial activities, traffic density, and urbanization development. According to the World Bank (2018), "Tehran is one of the most air-polluted cities in the world. The air pollution of Tehran is related to various pollutants in the air, which the most measured include particulate matter (PM), carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and ozone (O_3). The city is ranked 12th among 26 megacities in terms of ambient PM10 levels. After Cairo, Tehran is the most polluted non-Asian megacity. In 2016, the annual ambient level of PM10 was estimated at 77 µg/m3 (micrograms per cubic meter). This is almost four times the WHO's recommended threshold of 20 µg/m3" (figure 12).

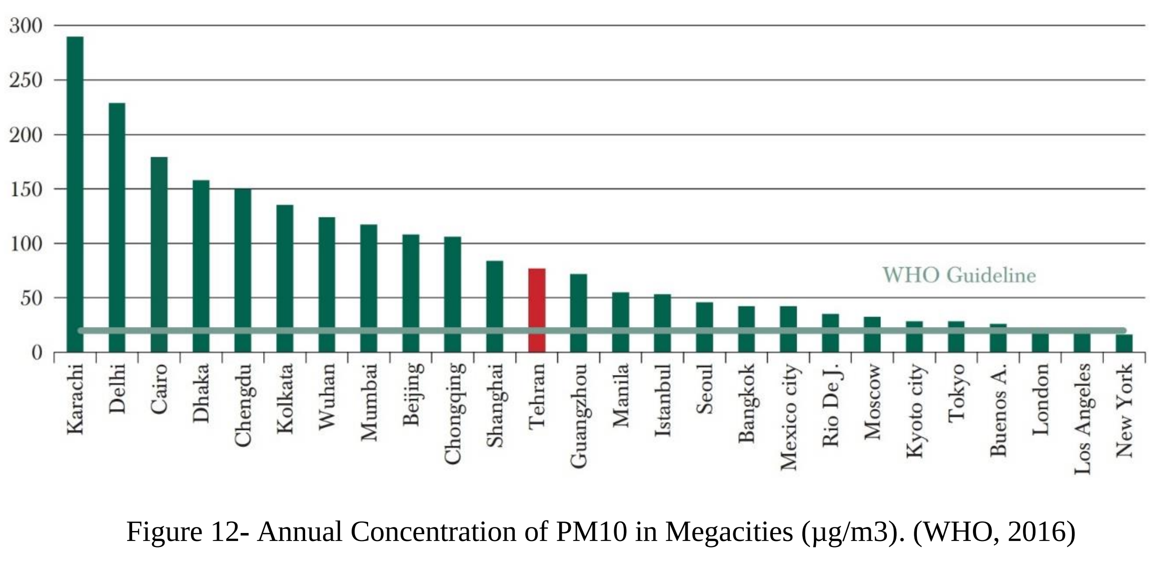


Figure 12- Annual Concentration of PM10 in Megacities (µg/m3). (WHO, 2016)

Tehran is surrounded in all four geographical directions by high mountains with an altitude of 1000 to 4000 m above sea level. Therefore, air circulation is limited, and occasional temperature inversions are common, which makes air pollution much worse (The World Bank, 2018). According to Heger and Sarraf (2018), "air pollution concentrations in Tehran vary substantially within a year. During autumn and winter, Tehran becomes more polluted, and atmospheric temperature inversion worsens air pollution during that period" (p. 4) (Figure 13).

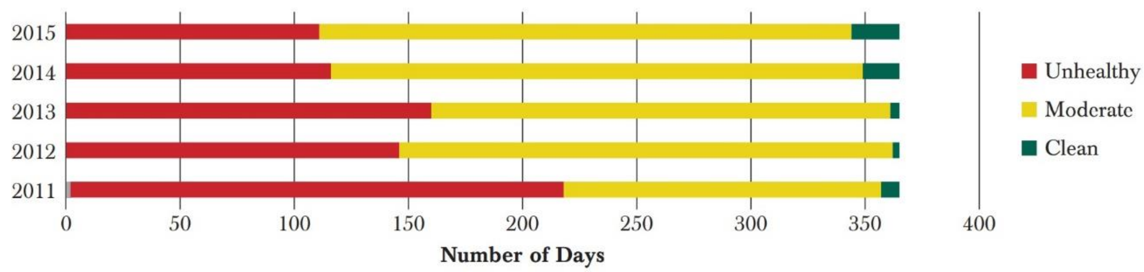


Figure 13- Air Quality Index in Tehran (2011–2015) (Air Quality Company of Tehran Municipality (AQCC), 2016)

3.2.5. Establishment of Eco-industrial Parks in Tehran

According to the Department of Environment (DOE) and the Air Quality Company of Tehran Municipality (AQCC), although until a few decades ago, industrialization was an integral part of some of Iran's metropolises, now many large cities, including Tehran, have changed their policies towards industry and industrial factories (DOE, 2020). Sustainable development, modernization, access to the latest equipment and prosperity are just one side of industrialization. But on the other hand, there is environmental pollution and water consumption. Industrial pollution, which includes industrial estates, and everything related to industry and in and around cities, is one of these environmental pollutions that cause many problems for citizens and the city.

Also, water consumption for manufacturing processes causes significant problems for people and the living environment in dry lands.

In Iran, most of the largest industries are located in the provinces of Tehran, Isfahan, Markazi, East Azerbaijan and Fars. According to the Tehran Industrial Parks Company, there are 19 parks and industrial zones around and inside the city of Tehran. The Shamsabad IP is the largest IP located in the suburbs of Tehran, which has a prominent position in the province. According to the decree of the Environmental Protection Organization of Iran and the Iranian Ministry of Industries and Mines, although Tehran's industrial parks claim to comply with environmental laws and regulations and control and reduce environmental pollution (air, water and sewage pollution), environmental experts believe that industries located in industrial parks have significant direct and indirect effects on increasing pollution and water use. Nearly ten years ago, many industries were forced to leave Tehran and settle in the suburbs to prevent and decrease environmental pollution.

Also, transforming IPs to EIPs has been on the agenda of relevant organizations and institutions since 2010 to spark economic growth while reducing environmental and social impacts (DOE, 2020). In this regard, the Tehran Development Plan, which proposes the future 15 years of growth of Tehran, brings new order to its irregular urban expansion and responds to the growing population. The plan shows that the Shamsabad IP is set to become an EIP to provide significant environmental, social and economic benefits to the people and the living environment (Iran small industries and industrial parks organization, 2012b, 2013a). As the Iranian Ministry of Industries and Mines stated, the new eco-industrial parks can be recognized as the key strategies for implementing industrial ecology and, therefore, resolving several environmental problems resulting from industrial processes. The industrial sectors need to develop a network of by-product exchange among co-located companies to enable a reduction in the use of virgin materials as resource inputs, re-use of waste materials, and reduction of water and carbon footprints (Iran small industries and industrial parks organization, 2012b, 2013a).

3.3. Establishment of Shamsabad Eco-Industrial Park

The purpose of developing the Shamsabad EIP is to improve environmental, social and economic qualities by establishing a community of businesses that efficiently share their materials, energy, and infrastructures with each other and with the local community. In the typical Iranian IPs, including the Shamsabad IP, the strongest interactions happen between the park and the surrounding areas. Industries mostly acquire raw materials and energy from the main suppliers of energy, and the energy and material cycles are dramatically lost because of the lack of industrial symbiosis. The by-products are discarded outside the parks, mostly in surrounding areas, and a majority of the waste is disposed of in landfills. The IP is characterized by low sustainability indices (DOE, 2020).

3.3.1. Environmental, Social and Economic Motivations for EIP

The following motivations/interests were identified by interviewing IP representatives and stakeholders, which were considered for forming the industrial symbiosis and developing the EIP:

1. Increasing local jobs
2. Creating new business opportunities
3. Improving working and labor conditions

4. Minimizing operating costs and improving process efficiency and productivity
5. Improving linkage between industrial park firms and communities and industries outside the industrial park
6. Minimizing risks of exposure to natural resource scarcity, specifically water scarcity
7. Alleviating resource constraints using by-products, and waste of energy and material
8. Mitigating climate change at the national level through the transition to more sustainable land use
9. Improving the environmental quality (air, water and soil quality)

According to the identified interests, potential EIP enterprises have relevant solid environmental, social, and economic motivations which ensure the secure commitment of the enterprises in forming the industrial symbiosis and guarantee promotion of industrial symbiosis in the future. A significant change could be made most concretely at the local level to attain a range of long-term benefits if the regulations, policies, and plans support the activities that promote the Shamsabad EIP development. These benefits include improved economic livelihood conditions, social health, environmental quality, and sustainability.

3.3.2. Participating Enterprises of EIP

Enterprises of IPs which could participate in EIPs development are the key beneficiaries. The interests, positions, and influence of the enterprises facilitate identifying opportunities for an industrial symbiosis network and launch and develop the business cases. According to World Bank Group (2018), "industrial symbiosis refers to the collective collaboration of industry, for example, the sharing of services, utilities, and by-product resources among diverse industrial actors to add value, reduce costs, and improve the environment" (p. 145). Through identifying and forming industrial symbiosis opportunities, an industrial ecosystem, which behaves like natural ecosystems, is developed to enable the reusing of materials, energy, and waste in IPs. The industrial circularity of by-products, waste, and energy help reduce the environmental impacts of IPs. Also, most initiatives related to spreading the awareness of EIP, exchanging knowledge of industrial ecology and environmental problems among industrial facilities, and creating industrial symbiosis are developed by the participating enterprises. Forming the industrial symbiosis is conducted based on the interest/motivation of EIP enterprises, which grantee the secure participation and commitment in developing the EIP (Majumdar, 2001; World Bank Group, 2018, 2017, 2016, 2014; Sertyesilisik & Sertyesilisik, 2016).

- **Existing Enterprises and Synergies**

The existing enterprises and synergies in the Shamsabad IP were identified, which were used to take part in the EIP industrial symbiosis. These enterprises and synergies are as follows:

- Sabzineh Farm Ltd.: Sabzineh Farm Ltd., which is a crop producer which grows wheat, canola and grain, provides Ladan Ltd. with 18 t/yr of canola grain.
- Ladan Plant: Ladan Plant is a canola plant that uses canola seed to produce crude canola oil. The plant requires approximately 420,000 t/yr of canola grain as its primary input.
- Bistoon Co.: Bistoon Ltd. provides Atlas Pood Co. with 34.5 t/yr of fibre. Atlas Pood Ltd. is one of the largest textile industrial facilities in Iran.
- Niloo Co.: Niloo Co. provides Atlas Pood Co. with 18.2 t/yr chemical and auxiliaries raw materials, which enable a processing operation in preparation, dyeing, printing or finishing of fabric to be carried out more effectively. These materials include pretreatment chemicals and yarn lubricant.

- Atlas Pood Ltd.: Atlas Pood Ltd. is active in the production of curtains, tablecloths, bedspreads, textured polyester thread and cardboard spindles.
- Vazin Plast: Vazin Plast produces 24.7 t/yr plastic bags, containers and other plastic goods using cellulose and crude oil provided by the Shams Plast.
- Sanat Sabz Co. provides Tehran Carton Co. and Avin Pack with 17.3 t/yr recycled paper and 8.5 t/yr virgin paper.
- Almahdi Aluminum Factory: Almahdi Aluminum Factory produces 80,000 t/yr aluminum and provides Sial Co. and Amir Sanat Co. with 25,000 t/yr aluminum. Sial Co. and Amir Sanat Co. use 53,000 t/yr aluminum to produce window frames and power lines.

- **Potential New Enterprises**

New enterprises, which had the potential to form an industrial symbiosis and be involved in exchanging their waste, material, and energy, were recognized. Four main categories of food packaging industries, including nine active industrial facilities, showed their interest to be Shamsabad EIP enterprises (Table 3). Also, table 4 presents 47 industrial facilities, currently active or under construction, identified as the potential enterprises to be part of the Shamsabad EIP.

Food Packaging Facilities			
Dry fruit, Nut and Saffron Packaging	Tea Packaging	Meat Packaging	Beverage Packaging
Tavazoe Co.	Golestan Tea	Negin Darya Protein	Behnoush Co.
Mahdineh Co.	Mahmood Tea	Radin Protein	Sahand Co.
	Sina Co.		

Table 3 - Potential Food Packaging Facilities for the Shamsabad EIP (Table by the Researcher)

New Enterprises		
Aburihan Pharmaceutical Co.	Feedlots	Mani Electronics Co.
Asphalt Tous Refinery Co.	Gharb Oil and Gas Exploitation	Iran Tobacco Co.
Green houses	Tehran Water and Sewage Co.	Alumtechnic Industrial Complex
Irankhodro Co.	Iran Tire Co.	Pars Silis Co.
Mahyar Construction	Tire recycling plant	Alvand Ceramics
Hasan Abad Fish Farm	Hegmatan Concrete	Abadis Ceramics
Tehran Water and Sewage Company	1&1 Products	Mahyar construction
Shamsabad cogeneration plant	Barekat Farm	SAIRAN
Alinejad Asphalt Co.	Sabz Daneh Co.	Iran Tejarat Co.
Tehran Tejarat Co.	Aria Parto Co.	Irankhodro Co.
Nooshineh Khoram Co.	Plastics Plant	Sahand Co.
Aida Co.	Landscaping and Gardening Sectors	Iran Plastic Recycling
Ethanol Plant.	Avin Pack Co.	Iran Carpet
Faradaneh Co.	Tehran Carton Co.	Zomorrod Carpet
Atlas Pood	SAIran Electronics Co.	Kashan Yalda Kavir Carpet
Shamsabad Recycling Co.	Official units	

Table 4 - New Enterprises for the Shamsabad EIP (Table by the Researcher)

3.3.3. Design Considerations and Steps for Forming Industrial Symbiosis

The following design considerations were recommended by the researcher to develop EIPs including Shamsabad EIP. These design considerations were determined based on the current IP conditions, the environmental, social, and economic demands of the beneficiaries, and the principles used in successful EIPs and presented by MOTIE (2011), Massard et al. (2014) and Hollander (2000):

1. Using heterogeneity of the industrial park's context for effective successful collaborations between diverse industrial facilities, creating a kind of ecosystem with closed loop flows of energy, water, materials, wastes and related benefits
2. Selecting the most polluting industrial facilities and facilities with the potential to have the most exchange-flow types as the cores of industrial symbiosis
3. Choosing enterprises within close proximity for effective industrial synergies
4. Using specific structural characteristics of the industrial facilities for creating multi-connections between them and enhancing the efficiency of different flow types
5. Applying sustainable design solutions (e.g., installing solar panel networks and using anti-heat options) in industrial facilities to promote sustainable environmental performance
6. Establishing strong informal ties between managers of industrial facilities
7. Choosing a park operator that can organize exchanges of flows of materials, water, energy and waste between enterprises
8. Providing access to competitively priced water, energy, and raw materials
9. Setting up digital platforms to identify reserves of materials and waste and their sources
10. Providing financial incentives for industrial facilities to engage with industrial symbiosis, such as tax exemption.

According to the above-mentioned design considerations, the four straightforward steps to transition from IP into EIP, recommended by the researcher to be used by EIP developers and decision-makers, include:

1. Establishing a platform for EIP enterprises to register EIP enterprises and collect information concerning their available material, waste, and energy to share
2. Categorizing enterprises into consumers and producers based on material, energy, and wastewater
3. Forming initial cores of the industrial symbiosis by high polluting enterprises and enterprises with potential to have most exchange flow types
4. Connecting producers and consumers to the initial cores and other enterprises based on proximity and flow-type needs

The following thesis sections will present how the design considerations and straightforward steps will be contemplated to form Shamsabad industrial symbiosis.

3.3.4. Potential New Synergies

The design considerations and four steps for forming industrial symbiosis were taken into account to create new synergies between the existing and new enterprises and form an industrial symbiosis (Table 5 and Figure 14).

	Type of Synergies between the Existing and New Enterprises						
	Steam	**wastewater**	**Electricity**	**Natural Gas**	**Material**		
Producers	Asphalt Tous Refinery Co.	Gharb Oil and Gas Exploitation Co.	Shams Gostar power plant	Gharb Oil and Gas Exploitation Co.	Radin Protein	Golestan Tea	Irankhodro Co.
	Shamsabad cogeneration plant	Tehran Water and Sewage Co.	Shamsabad cogeneration plant	Asphalt Tous Refinery Co.	Negin Daria Co.	Feedlots	Iran Tire Co.
	Gharb Oil and Gas Exploitation Co.	Shamsabad cogeneration plant			Tavazoe Co.	Gharb Oil and Gas Exploitation Co.	Almahdi Aluminum Factory
	Shamgostar powerplant				Sahand Co.	Ethanol Plant	Ladan Plant
	Asphalt Tous Refinery Co.				Niloo Co.	Shams Plast Co.	Faradaneh Co.
	Tavazoe Co.				Behnoush Co.	Mahmood Tea	Amir Sanat Co.
	Sahand Co.				Pars Silis Co.	Sina Co.	Shamsabad construction sector
	Behnoush Co.				Bistoon Co.	Sanat Sabz Co.	Asphalt Tous Refinery Co.
					Shamsabad glass recycling Co.	Sabzineh Farm Co.	Hasan Abad Fish Farm
	Steam	**wastewater**	**Electricity**	**Natural Gas**	**Material**		
Consumers	Aburihan Pharmaceutical Co.	Green houses	Tavazoe Co.	Alinejad Asphalt Co.	Iran Carpet	Atlas Pood Co.	Tehran Carton Co.
	Hasan Abad Fish Farm	Landscaping sectors	Mahdineh Co.	Tehran Tejarat Co	Abadis Ceramics.	Iran Tobacco Co.	Faradaneh Co.
	Official units	Gardening Sectors	Negin Darya Protein		Zomorrod Carpet	Ethanol Plant	Alvand Ceramics
	Ladan Canola Plant	Tehran Water and Sewage Co.	Radin Protein,		Kashan Yalda Kavir Carpet	Feedlots	Sahand Co.
	Tavazoe Co.	Mahyar Construction	Mahmood Tea		Atlas Pood	Tire recycling plant	Mahyar Construction
	Behnoush Co.	Sabzineh Farm Co.	Tavazoe Co.		SAIran Electronics Co.	Aburihan Pharmaceutical Co.	Hasan Abad Fish Farm
	Sahand Co.,	1&1 Products	Sina Co.		Iran Tejarat Co.	Hegmatan Concrete	Aria Parto Co.
	Irankhodro Co.	Barekat Farm	Negin Darya Protein		Alumtechnic	Aida Co.	Plastic Plant
	Mahyar Construction		Radin Protein		Sial Co.	Nooshineh Khoram Co.	Ladan Plant
	Asphalt Tous Co.				Vazin Plast	Mani Electronics Co.	Avin Pack Co.
					Mahdineh Co.	Ladan Plant	Iran Plastic Recycling
					Tavazoe Co.	Hegmatan Concrete Factory	Shamsabad glass Recycling Co.

Table 5 - Potential New Synergies for the Shamsabad EIP (Table by the Researcher)

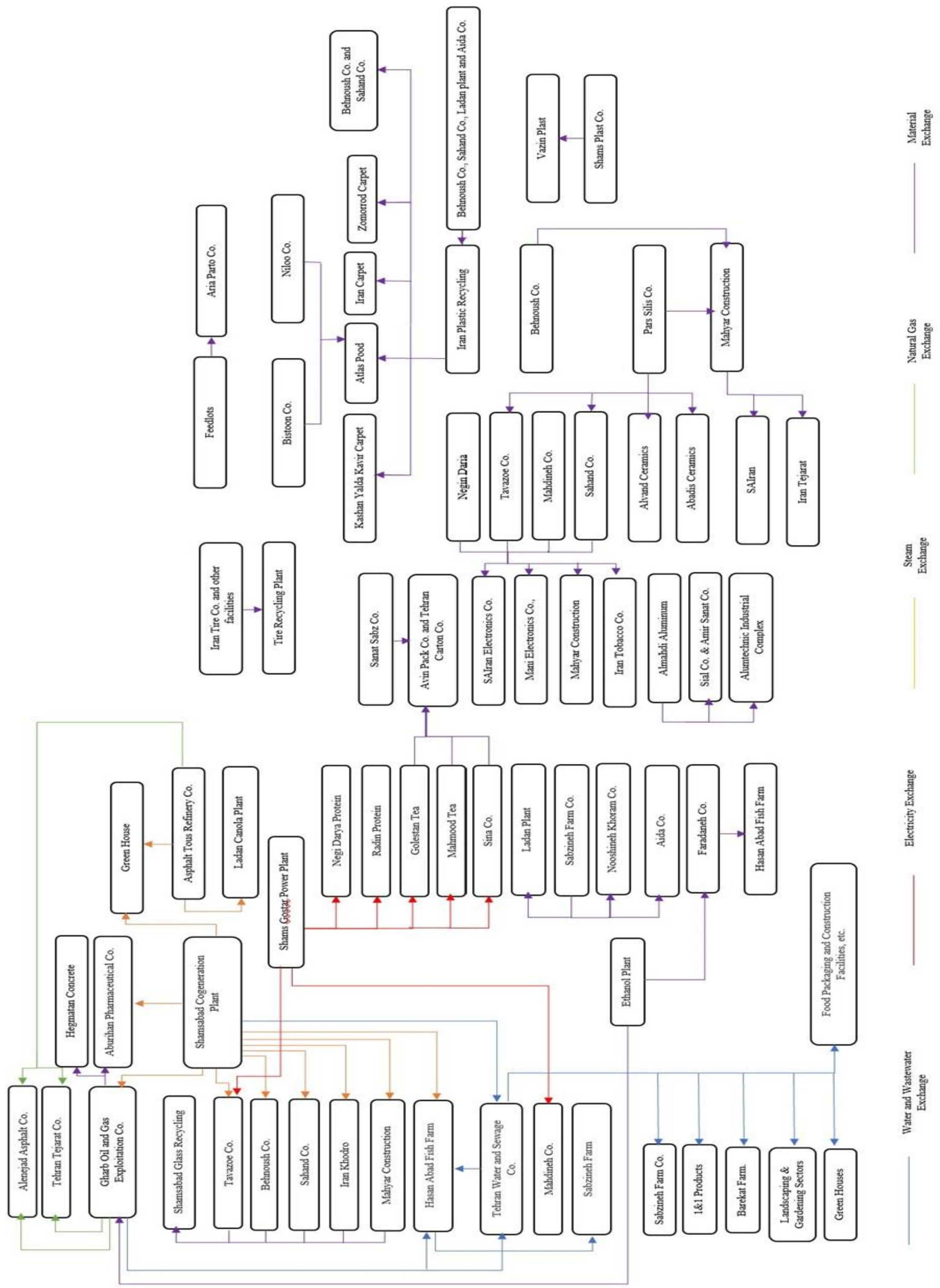


Figure 14 - Potential New Synergies for the Shamsabad EIP (Figure by the Researcher)

The following is a brief description of each of the potential synergies:

- Shamsabad Cogeneration Plant: Shamsabad Cogeneration Plant is a 984 MW combined cycle cogeneration plant. The construction phase of the plant will be completed in 2024 by MAPNA Group Company. The main fuel of this power plant will be natural gas (DOE, 2020). The high-pressure waste steam (3,450,630 t/yr) and low-pressure waste steam (1,205,700 t/yr) provided by the Shamsabad Cogeneration plant will be an ideal source that could be utilized by other industrial facilities. The high-pressure steam could be provided to Gharb Oil and Gas Exploitation Co. to be used in the heavy oil upgrading process. Also, high- and low-pressure steam could be offered to other industrial facilities, including Behnoush Co. and Sahand Co. for heating purposes, which will significantly reduce energy utilization and the associated costs. Applying sustainable design solutions, including installing solar panel networks, using anti-heat options, and sustainable materials in this facility, is suggested by the researcher for promoting the environmental and economic performance of the industrial facility.

- Gharb Oil and Gas Exploitation Co.: Gharb Oil and Gas Exploitation Co., for which the construction phase will be completed in 2024, will be a heavy oil upgrading plant which processes the heavy oil feedstock into light sweet synthetic crude oil. It will have the capacity to provide low pressure steam (670,500 t/yr) to other industrial facilities for heating purposes.

- Aburihan Pharmaceutical Co. could obtain high-pressure steam (250,000 t/yr) from Gharb Oil and Gas Exploitation Co.

- Asphalt Tous Refinery Co., which processes heavy oil to produce asphalt, generates low-pressure steam (92 t/yr) that could be used by the Ladan Canola Plant and Hasan Abad Fish Farm.

- Hasan Abad Fish Farm, which is planned to relocate to Shamsabad IP, could use the waste low-pressure steam (400 t/yr) provided by Gharb Oil and Gas Exploitation Co. Also, the Fish Farm could purchase wastewater (2,400 m^3/yr) from the Gharb Oil and Gas Exploitation Co. or directly from the Tehran Water and Sewage Company. The Fish Farm is a sustainable business because it provides an edible product that will be used by the people of Tehran and surrounding cities and because it uses a water recirculation system making it efficient and cost-effective.

- Food packaging facilities, including Tavazoe Co., Sahand Co., and construction and automotive industries, including Irankhodro Co. and Mahyar Construction which produce glass, could use the high-pressure steam (3,200 t/yr) provided by the Shamsabad plant.

- Three greenhouses, each with an area of 1200 m^2, could use low pressure steam (1,020 t/yr) provided by the Gharb Oil and Gas Exploitation and the Shamsabad cogeneration plant for heating. Also, they could purchase water (1,800 m^3/yr) from the Gharb Oil and Gas Exploitation Co. or directly from the Tehran Water and Sewage Company. The market for vegetables is fairly good in the study area, and the products could be sold at low prices.

- Shams Gostar power plant, which is under construction to produce surplus heat, will have the capacity to burn 600 tons of solid waste per day. It could provide 150 MW of electricity per day to Tavazoe Co., Mahdineh Co., Negin Darya Protein, and Radin Protein for dried fruits, nuts, Saffron and meat packaging. The excess electrical power that could be provided by this power plant could be used by Mahmood Tea Co. This electrical power could be supplied at a reduced cost compared to the cost charged by the Iranian Ministry of Power. Applying sustainable design solutions, including installing solar panel networks, using anti-heat options, and sustainable materials in Shams Gostar Power Plant, is suggested by the researcher for promoting the environmental and economic performance of the industrial facility.

- Official units in the Shamsabad park could obtain natural gas (2,340 GJ/yr) from Gharb Oil and Gas Exploitation Co. as a backup source of steam and natural gas for heating.

- Alinejad Asphalt Co. and Tehran Tejarat Co., which processes heavy oil to produce asphalt, could purchase the extra natural gas (2,480,277 GJ/yr) supplied to Gharb Oil and Gas Exploitation Co. and the Asphalt Tous Refinery Co. at a lower cost than that supplied by the pipelines. The market price for natural gas is lower because the companies purchase it in bulk. Applying sustainable design solutions, including installing solar panel networks, using anti-heat options, and sustainable materials in Asphalt Tous Refinery Co. is suggested by the researcher for promoting the environmental and economic performance of the industrial facility.

- Ladan Plant which uses canola grain (18 t/yr) provided by Sabzineh Farm Co. Also, Sabzineh Farm sends wheat grain (33 t/yr) to Nooshineh Khoram Co. and Aida Co. Poor quality wheat, and canola grain (weather damaged or immature) could also be used as material input for a planned Ethanol Plant.

- Faradaneh Co., which currently provides feed to the Feedlots (430 t/yr) inside and nearby the Shamsabad IP, could also provide feed to the Hasan Abad Fish Farm (93 t/yr).

- Iran Tire Co., which was launched in 1965 under the name of General Tire and Rubber of Iran, has the capacity to produce 2800 tons of automobile rubber per year. Damaged tires of the Iran Tire Co. and other facilities in the study area could be collected and brought to the potential tire recycling plant instead of landfills to be used in road stabilization, playgrounds, sports, etc.

- Sulfur from Gharb Oil and Gas Exploitation Co. (314 t/yr) could be used as input for the Aburihan Pharmaceutical Co. In addition, sulfur could be used in the production of concrete admixtures in Hegmatan Concrete.

- Manure from the feedlots (225 t/yr) could be collected and anaerobically digested to produce methane, known as biogas in Aria Parto Co. for street lighting.

- Naphtha produced by Gharb Oil and Gas Exploitation Co. (102 t/yr) could be used in the process of producing plastics at the Plastic Plant. The produced plastics could be used in food packaging and other industrial facilities.

- Distiller's Dried Grains with Solubles (DDGS), known as mash, which could be produced at the planned Ethanol Plant (48 t/yr), could be used as a high protein supplement to produce feed at Faradaneh Co.

- The Ethanol Plant could utilize poor grains in the area (62 t/yr) to produce Ethanol. The Ethanol could be used by Gharb Oil and Gas Exploitation Co. to produce Ethanol blended gasoline.

- Hasan Abad Fish Farm, which produces clarifier sludge as a byproduct (230 t/yr), could provide it to Sabzineh Farm Co. and other croplands for soil amendment and improvement of land quality in the study area.

- Wastewater produced in several industrial facilities, including Gharb Oil and Gas Exploitation Co., food packaging, power plants, and construction facilities (2,460,000 m^3), could be used after treatment in Tehran Water and Sewage Co. in place of fresh water to irrigate croplands of Sabzineh Farm Co., 1&1 Products, and Barekat Farm, and be used in greenhouses, and landscaping and gardening sectors. Excess treated wastewater could be exchanged between these enterprises.

- Gharb Oil and Gas Exploitation Co. produces hydrocracking residue (pitch), which is currently being coked with a 1.5/3 return and a low-value byproduct (coke). The pitch could be used by construction facilities, such as Hegmatan Concrete Factory, in the production of concrete admixtures to reduce water. The information is not available regarding the amount of pitch the Gharb Oil and Gas Exploitation Co. could supply to Hegmatan concrete.

- Avin Pack Co. and Tehran Carton Co., which produce cartons and boxes (2,700 t/yr), could use the waste of paper and paperboard and corrugated fiberboard produced by food packaging (Golestan Tea, Mahmood Tea, and Sina Co.), textile and clothing, and other industrial facilities.

- Electricity generating and electronics facilities, including SAIran Electronics Co. and Mani Electronics Co., could use the waste of aluminum foil (52 t/yr) produced by Negin Daria, Tavazoe Co., Mahdineh Co., Sahand Co., and Radin Protein. Aluminum foil comes in a wide range of thicknesses and is used for thermal insulation, moisture barrier, electrical cables, electronics, etc. According to the European Aluminum Foil Association, reusing and recycling aluminum foil means an equivalent reduction of demand for virgin aluminum in industrial facilities and significant energy savings equivalent to 95% (Tong et al., 2016). As the management and executive team of the Shamsabad IP stated, currently, the average reuse rate of aluminum packaging in the Shamsabad IP is estimated at 18%.

- Mahyar Construction and the construction sector of the Shamsabad IP could use the waste of aluminum foil (47 t/yr) produced by food packaging and other industrial facilities. Aluminum foil is used as a top layer for insulating materials such as stone wool, foam insulation panels and lamellar mats in the insulation of buildings. It is an effective vapor barrier that ensures the prevention of moisture damage to the installation material. Also, it is used for thermal insulation because it reflects approximately 96% of radiant heat. Moreover, it is used as an easy-handling material that allows fast installation even in large buildings such as warehouses. Furthermore, aluminum foil is used as an ideal material for the insulation of power cables. Finally, it is used as a protection against electrical shock caused by damaged cables (Haupt et al., 2017).

- The tobacco industry could use aluminum waste produced by food packaging (8 t/yr). Aluminum foil is used as the preferred barrier material for the inner liner of cigarette packets and other purposes.

- Tinplate waste produced by Tavazoe Co., Mahdineh Co., and Sahand Co. (52 t/yr) could be recycled and re-used in the facilities or be supplied to SAIran Electronics, Mani Electronics, and metal and machinery facilities. Tinplate is extremely sustainable and environmentally friendly as a packaging material. It is a suitable product for sterilization because it is a heat-treated and sealed product. Also, it is highly resistant to moisture, odors, light, microorganisms, and air (Haupt et al., 2017). Tinplate cans and boxes are used in cosmetics, chemicals, paints and oil production industries. Alumtechnic Industrial Complex is an aluminum production and recycling complex located in the Shamsabad IP, which recycles aluminum waste. Recycling aluminum waste significantly reduces energy use (95%) and cuts down greenhouse gas emissions by 97% compared to raw aluminum production. According to Schlesinger (2014), the production of aluminum from raw materials results in 14.1% of greenhouse gases emitted each year. Also, recycling aluminum helps reduce 97% of water pollution than producing new aluminum products.

- Excess silica (32 t/yr) produced by Pars Silis Co., one of the main suppliers of silica in Iran, could be provided to food packaging facilities, including Tavazoe Co., Sahand Co., and other facilities such as Alvand Ceramics and Abadis Ceramics. Excess silica that could be supplied to construction facilities (14 t/yr) such as Mahyar construction could be provided to electronic facilities, e.g., SAIRAN and Iran Tejarat Co., for water filter production.

- Food packaging facilities, including Tavazoe Co., Behnoush Co., Sahand Co., and construction and automotive industry, including Irankhodro Co. and Mahyar Construction could supply glass waste (182 t/yr) to other facilities. Most of the glass waste produced, specifically in food packaging facilities, is recyclable (Zorpas, 2015). Shamsabad Glass Recycling Co. is responsible for recycling glass waste. The recycled glass could be used by Behnoush Co. and Sahand Co. for beverage packaging and Tavazoe Co. for dried fruits, nuts and Saffron Packaging. Also, it could be used by Mahyar Construction to produce concrete, road pavement, cement, noise barriers, and fiberglass insulation products. About 1650 hectares of the Shamsabad IP were put into operation, of which 900 hectares are in the existing plans, and 750 hectares are in the development plans. Therefore, recycled glass could be used for the sustainable construction of the industrial park.

- Behnoush Co., Sahand Co., Ladan plant and Aida Co. could supply PET waste (63 t/yr) to other facilities for manufacturing fiber material for carpeting, textile, thermo-forming of insulation materials, industrial strapping, automotive parts, construction materials, and food packaging. Several industrial facilities in Shamsabad IP import and use 30.000-

40.000 tons of PET annually as a raw material. Recycling PET could significantly reduce PET waste. Iran Plastic Recycling is currently responsible for recycling plastics. Iran Carpet, Zomorrod Carpet, Kashan Yalda Kavir Carpet., Atlas Pood, Behnoush Co. and Sahand Co. could be the primary consumers of recycled PET in Shamsabad IP.

3.4. Conclusion

Establishing a case-specific framework, the main outcome of this research study, necessitated a multi-dimensional analysis of the case study to deliver thorough comprehension of the existing conditions/characteristics. This chapter was dedicated to identifying and analyzing the Shamsabad IP's significant features, identifying the EIP's enterprises and their motivations, identifying sharable material, energy and waste of the enterprises, and forming the EIP's industrial symbiosis. In this respect, a series of design considerations and straightforward steps for EIP designers and decision-makers were recommended by the researcher to develop EIPs conveniently.

The features of Shamsabad IP were discussed from a structural and environmental point of view in this chapter. In this respect, the economic, social and environmental specifications of the IP were highlighted. The IP's potential to be transformed into an EIP was examined by forming an effective industrial symbiosis through linking the existing and potential enterprises. In this respect, design considerations and straightforward steps were determined by analyzing the form, structure, and functions of discussed successful EIPs and how the EIPs were developed. They were used to create Shamsabad EIP's industrial symbiosis to benefit from the complete potential of participating (existing and new) enterprises and sharing material, waste and energy. The private, government and government-cum-private industrial facilities, which could optimize industrial processes and provide/use underutilized resources (such as materials, energy, water, or other by-products), were identified. An innovative approach was adopted using the heterogeneity of the context of Shamsabad IP. The highly polluting industries and industries with the potential to have the most exchange-flow types, including Shams Gostar Power Plant, Shamsabad Cogeneration Plant, and Gharb Oil and Gas Exploitation Co. were considered as the cores of industrial symbiosis for capturing and exploiting effective new synergies at a large scale. The structural characteristics of the industrial facilities were considered to create multiple connections between various facilities to increase the efficiency of different flow types. In this regard, the Gharb Oil and Gas Exploitation Co., Hasan Abad Fish Farm, Asphalt Tous Refinery Co., food packaging facilities (e.g., Tavazoe Co., Sahand Co.), automotive industries (e.g., IranKhodro Co., and Mahyar construction, and greenhouses, which have suitable structures such as steam pipelines, vapor chambers and heat pipes, were connected to share steams and energy.

The researcher took advantage of the synergistic possibilities offered by close proximity for reducing costs associated with transporting raw material, waste, and buy-product, minimizing energy waste, and improving process efficiency and productivity. Also, the researcher suggested applying sustainable design solutions, including installing solar panel networks, using anti-heat options, and sustainable materials in Shams Gostar Power Plant, Shamsabad Cogeneration Plant, greenhouses, Asphalt Tous Refinery Co., for promoting the environmental performance of the industrial facilities, resulting in improving the social and economic performance of the Shamsabad EIP.

By promoting industrial process efficiency and increasing the re-use of material, water, energy and waste, the total environmental performance of the Shamsabad EIP will be enhanced. The researcher brought 56 EIP enterprises which together with the existing enterprises formed a circular model, a kind of ecosystem with closed loop flows of energy, water, materials, wastes at the scale of an EIP. The collective collaboration of the EIP enterprises exchanging large quantities of water, steam, electricity, natural gas, and materials including waste, could result in a significant reduction of the total environmental impact of the Shamsabad EIP. Therefore, it contributes to mitigating climate change at the national and global levels. This functioning industrial symbiosis could encourage new industrial facilities to join the selected enterprises and work together for their benefit, the sake of each other, the environment, and a better way of doing business. Providing tax exemptions as financial incentives, as demanded in the interviews with the executive and management team of the Shamsabad IP, could provide great opportunities for startups, new businesses, and local job opportunities. Also, setting up digital platforms to identify reserves of materials and waste and their sources could encourage new EIP enterprises and local businesses to participate in promoting the industrial symbiosis, which was discussed in several meetings with the IP representatives.

So far, the industrial symbiosis of the Shamsabad EIP was formed based on the theoretical foundation of this research, the critical characteristics of the Shamsabad IP, and the recommended design considerations and straightforward steps for developing EIPs. The next chapter is dedicated to evaluating and promoting industrial symbiosis.

Chapter 4: Life Cycle Assessment of Carbon and Water

4.1. Introduction

As highlighted in the previous chapters, this research aims to develop a practical EIP framework, supporting EIP developers at the first stages of transforming IPs. So far, the theoretical foundation of the research has been created by reviewing the literature and analyzing several successful EIPs. The Shamabad IP was analyzed as a case study from environmental and structural points of view to form an industrial symbiosis based on the potential of the existing and new enterprises for optimum energy, raw/used resources, and waste saving. For this purpose, the researcher recommended a set of design considerations and straightforward steps for EIP designers and decision-makers, presented in the previous chapter. The IP pattern showing the spatial arrangement and proximity of the enterprises, their structures, and physical specifications, and supporting platforms for the enterprise's engagement were considered to create the list. The design considerations and steps were used to form the industrial symbiosis according to the above-mentioned criteria. This chapter examines the effectiveness of industrial symbiosis in minimizing the environmental impacts of the Shamsabad IP and improving the life cycle sustainability performance of carbon and water via Life Cycle Assessment (LCA) in beverage packaging systems.

4.2. Life Cycle Assessment (LCA) of Glass and PET in Food Packaging Systems

During the last few decades, environmental awareness has increased due to the harmful environmental impacts of industrial sectors and the depletion of water and non-renewable energy sources. To resolve global environmental problems, countries in the middle east region also need to take necessary actions (Juaidi et al., 2016). In this regard, environmental regulations and standards should be issued to control environmental pollution by obliging industrial sectors (Choi, 1995). Also, the manufacturing process should be designed to minimize energy, water and raw material consumption, and products should be designed to be recyclable during their life cycle. The methodology called Life Cycle Assessment (LA) refers to studying the direct and indirect environmental effects of products and their manufacturing, distribution, and disposal process (Saleh, 2016).

In this research study, the LCA methodology was used to conduct a comparative life cycle assessment in a beverage packaging facility which produces glass and polyethylene terephthalate (PET). The aim of LCA was to evaluate the effectiveness of the industrial symbiosis formed for reducing/saving water, carbon, and waste. The LCA was in accordance with the International Standardization Organization (ISO) standard. The target factory was Behnoush beverage packaging Co. which produces 330 ml glass bottles and 1000 ml PET bottles. For the LCA, four environmental items, including water, solid waste, recycling rate, and energy, which are important at the country level were considered (Table 6).

Environmental item	Status description
Water	One of the most critical problems in Iran is having adequate fresh water. Industries are one of the major consumers of fresh water in Iran, with 19% water consumption, and their untreated wastewater has contaminated fresh waters and reduced water quality.
Solid waste	Annually, about 21 million tons of urban waste are produced in Iran. Also, Iran produces 32 million tons of industrial waste and eight million tons of dangerous waste annually. Industrial facilities in Iran are still underdeveloped. Several facilities show environmental problems, such as solid waste generation and carbon emissions.
Recycling	The scale of recycling waste in Iran is at 20%. The amount of waste recycling is planned to increase from 20 to 60% by 2030.
Energy	Although Iran is a country with a high potential for producing biomass or solar energy, about 90% of the energy used is provided by electricity and fossil fuels.

Table 6 - Current Status of Relevant Environmental Categories in Iran (Table by the Researcher)

Four significant environmental impact categories were considered in this study, according to the Impact 2002+ method (Jolliet et al., 2003), which include water consumption, non-renewable energy, solid waste, and global warming potential. The LCA conducted in this research was an ISO-based LCA, presenting comparative environmental results based on life cycle inventory (LCI) and life cycle impact assessment (LCIA) phases. The results of this LCA study contribute to the current literature on LCA in the middle east, specifically Iran, by presenting LCA with a comparative environmental impact assessment approach which shows a significant difference between two popular food packaging systems in Iran. Moreover, the results contribute to promoting the evaluation methods for the effectiveness of the industrial symbiosis formed to develop EIPs. The approach presented by this research could be applied to the LCA of other products and processes in other countries.

4.3. Methodology

The technical methodological framework for LCA consists of four components: goal and scope definition, inventory analysis, impact assessment, and interpretation. These components closely correlate throughout the assessment and follow ISO standards (ISO, 2016; ISO, 2006a) (figure 15). The following sections present the results of each of the main components of the LCA methodology applied to the glass bottles and PET bottles packaging systems.

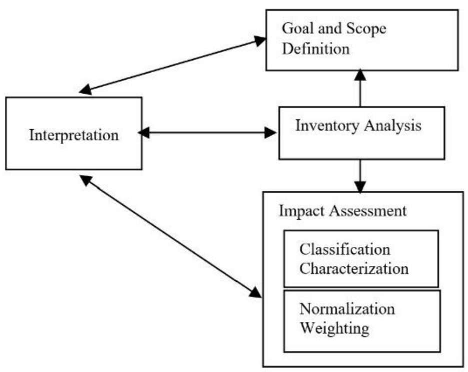


Figure 15- Components of LCA, Figure by the Researcher

4.4. Goal and Scope Definition

The LCA aims to identify and compare the environmental impacts associated with each of the selected packaging systems. The scope of this research is defined as 330 ml glass bottles and 1000 ml PET bottles used for holding beverages (product) (figure 16). The weight of an empty 330 ml glass bottle is 250 g and the weight of an empty 1000 ml PET bottle is 35 g. The comparative environmental LCA is based on a functional unit of 1000 L of beverages. It should be noted that the primary packaging function of the glass and PET systems is to contain the beverage safely until reaching the consumer.

To conduct the LCA, many data categories were used as a basis for the LCA calculations and comparisons between glass and PET packaging. These categories included: inputs from nature (resources, fuels), outputs to nature (emissions to air, emissions to water, solid wastes), and products (main products: primary packages of beverages). The information was collected from the DOE (2022) and internal auditing report (Environmental Office of the Ministry of Industry, Mine and Trade, 2022a). The target food packaging facility for the LCA was Behnoush Co., one of the main beverage and beverage packaging facilities in Iran which has nine industrial facility and 18 production line. The LCA included primary packaging of beverages, including auxiliary materials of caps and labels. Also, the LCA focused on cradle-to-grave scope and included the point of manufacturing glass and PET from their direct raw material (glass preforms and PET preforms), filling, distribution, use, and disposal.

Figure 16 - 330 ml Glass Bottle and 1000 ml PET Bottle of Behnoush Co., (Behnoush Co., 2022)

4.5. Life Cycle Inventory (LCI) Analysis

"Life cycle inventory analysis (LCI) is concerned with collecting, analyzing, and validating data that quantify the appropriate inputs and outputs of a product system. The results include all environmental inventories (inventory table), which are associated with the products under study" (Saleh, 2016, p. 32). The computations of LCI data for the glass and PET packaging materials were carried out using the EXCEL software package, encompassing all production, rejection, and environmental data for the selected two food packaging systems in the covered periods.

4.5.1. LCI of 330 ml Glass Bottles

The LCI of the environmental burdens associated with the 330 ml glass bottle packaging system was analyzed by considering the product's entire life cycle and related processes (Table 7). The LCI required information, including values of inputs and outputs obtained from the mentioned data sources, were measured to produce the life cycle model. Figure 17 presents the summary of the LCI conducted for the 330 ml glass bottles per 1000 L of beverages. It shows the information on environmental burdens presented in the International System (SI) of units, over the entire life cycle, including the consumption of water, energy, materials, and the emissions and wastes generated from the unit processes.

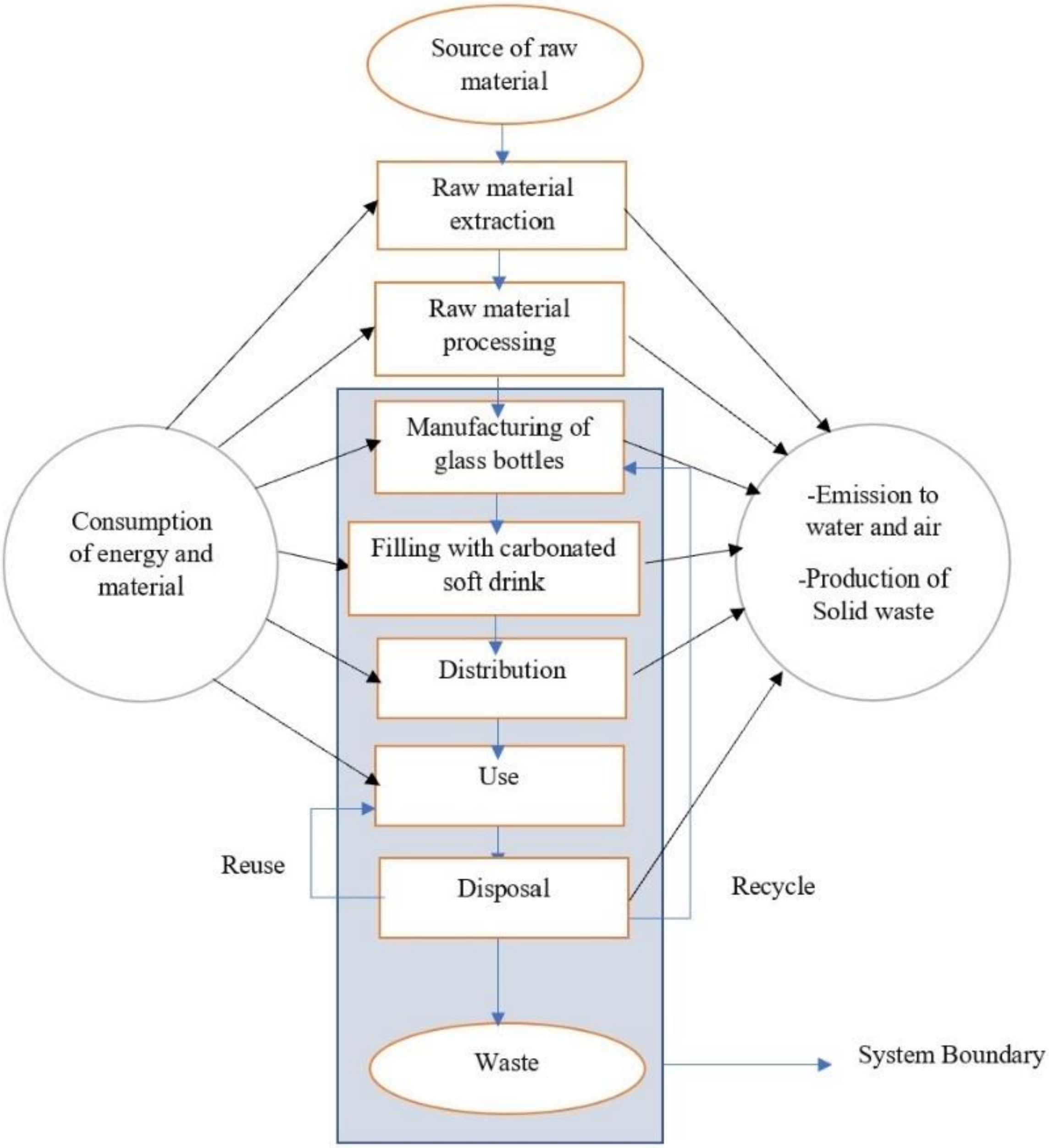


Figure 17 - System boundary of glass bottles packaging system (Figure by the Researcher)

Environmental Burden	Unit	Value
Consumed water	M^3	8.876
Consumed energy	MJ	8218.9
Wasted and disposed industrial wastes		
• Glass	kg	584
• Metal (caps)	kg	5.5
Recycled solid wastes		
• Glass	kg	21.2
• Metal (caps)	kg	1.3
Current recycling rate = [(21.2+ 1.3)/(584+ 5.5)] x 100% =4%		
Released atmospheric emissions		
CO_2	kg	667.512
N_2O	kg	6.942

Table 7- LCI of the 330 ml Glass Bottle per 1000 L of Beverages for the Year 2022 (Table by the Researcher)

4.5.2. LCI of 1000 ml PET Bottles

The LCI of all environmental burdens associated with the 1000 ml PET bottles packaging system was conducted based on the 1000 L functional unit (Table 8). In this regard, environmental burdens, presented in International System units, refer to water, energy, and materials consumption and the emissions and wastes generated from different unit processes (figure 18). The LCI required information, including values of inputs and outputs, were obtained from the mentioned data sources.

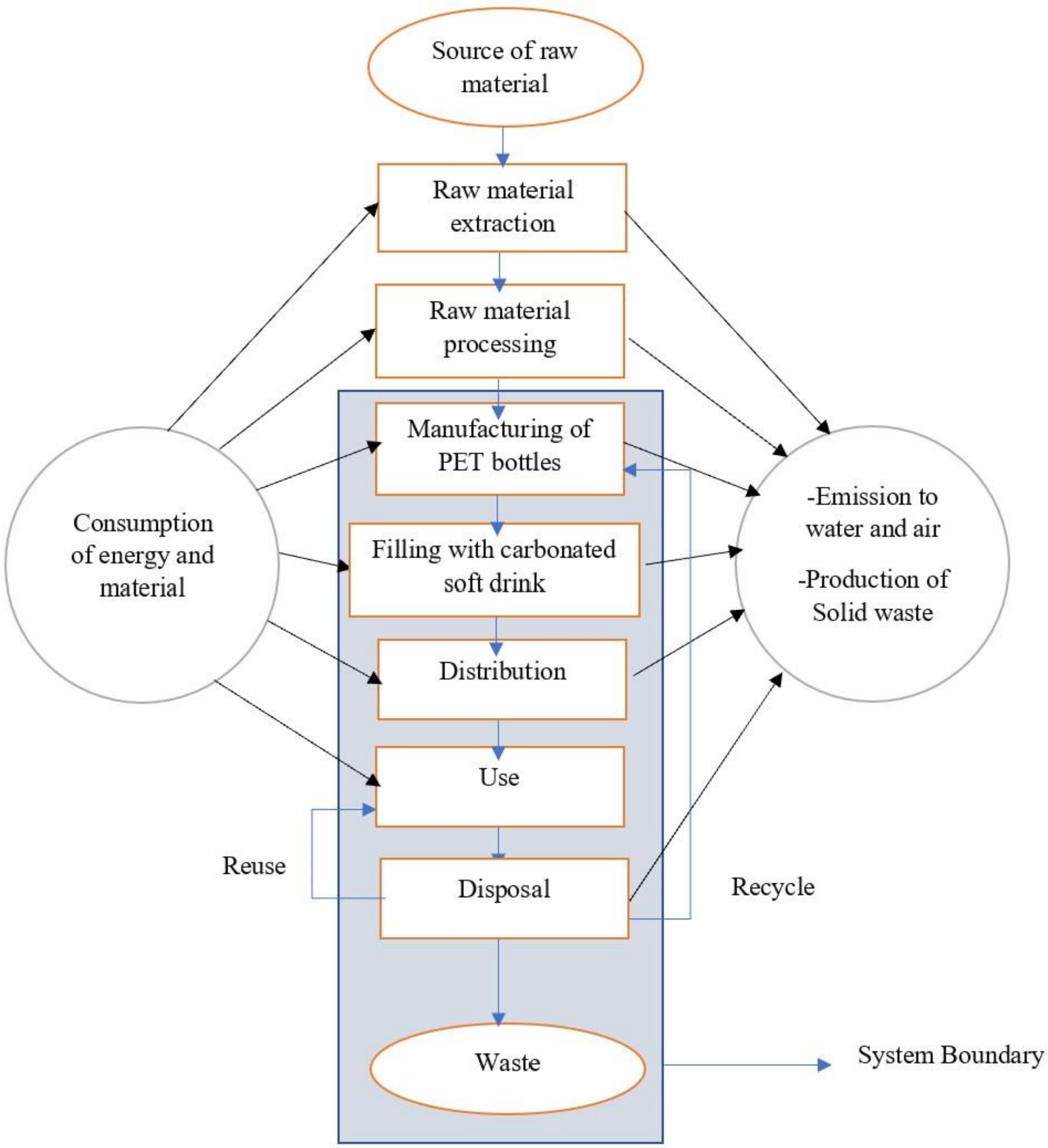


Figure 18 - System boundary of PET bottles packaging system (Figure by the Researcher)

Environmental Burden	Unit	Value
Consumed water	M^3	4.922
Consumed energy	MJ	681.7
Generated and disposed plastic solid waste	kg	53.12
Recycled plastic solid wastes Current recycling rate= [(7.06)/(53.12)] x 100% = 13%	kg	7.06
Released atmospheric emissions CO_2 N_2O	 kg kg	 27.11 0.141

Table 8- LCI of the 1000 ml PET bottles per 1000 L of beverages for the year 2022. (Table by the Researcher)

4.6. Life Cycle Impact Assessment (LCIA)

"The primary aim of life cycle impact assessment (LCIA) is to identify and establish a linkage between the product's life cycle and the potential environmental impacts associated with it" (Saleh, 2016, p. 35). Two factors were considered in selecting impact categories: the LCI results; and the significance of these categories in the Iranian context. According to an impact model called IMPACT 2002+ and based on the LCI results for glass and PET, the most relevant impacts selected for this study were water consumption, non-renewable energy, solid waste, and global warming potential (Jolliet et al., 2003; International Organization for Standardization (ISO), 2006b) (Table 9). Solid waste, considered in this study, is a significant impact category in the Iranian context and related to the research topic, although it is not a formal category in IMPACT 2002+.

Environmental impact category	**Description**
Water consumption (M^3)	Water usage is critical in the Iranian context. Water is an essential factor for ecosystem functioning. Iran faces several environmental problems due to the lack of water resources in dry lands, where most industrial parks are located. Therefore, all forms of freshwater consumption are considered in this study.
Non-renewable energy (MJ)	Electricity, gas, oil, fuel (diesel), liquefied petroleum gas (LPG), and kerosene reserves, raw material processing energy, and recycling energy is considered for the systems undergoing comparison. Energy use causes depletion of energy resources.
Solid waste (kg)	Solid waste, considered in this study, is recognized as a valuable indicator for measuring disposal and, therefore, developing strategies for waste reduction. All solid wastes from production both disposed and recycled is considered for the impact assessment because waste disposal causes low ecosystem quality.
Global warning potential (kg CO_2-eq.)	CO_2 and N_2O contribute to global warming potential. The global warming was calculated in CO_2 equivalents (kg) using the greenhouse gas equivalencies calculator tool (www.epa.gov). Climate change is recognized as the effect of the global warming.

Table 9 – Environmental Impact Categories (Table by the Researcher).

4.6.1. Classification

In this phase, classification was made by defining the impact categories and assigning the exchange from the glass and PET packaging inventory to the impact categories. By the classification, the contribution of the material to different problem areas was reflected. Table 10 presents the result of the quantitative classification of the LCI data for the glass and PET packaging processes with the selected midpoint impact categories.

LCI results	Impact Categories			
	Water consumption (m^3)	Non-renewable energy (MJ)	Solid waste (kg)	Global warming potential (kg CO_2-eq.)
Water	x			
Energy		x		
Solid Wastes			x	
CO_2				x
N_2O				x
Damage Category	Ecosystem Quality, Resources, Human Health	Energy resources	Ecosystem quality	Climate Change (Life Support System)

Table 10 - Classification of LCI Results to Midpoint Impact Categories. (Table by the Researcher)

4.6.2. Characterization

The purpose of characterization is "to determine how big are the impacts?" In this phase, quantitative modelling for the contribution of each exchange was conducted. Then, the contribution of the exchanges was aggregated within each category. The results showed resource consumption, environmental impact potentials, and working environment in producing glass and PET bottles. "The characterization process is multiplying the emitted quantities with equivalence factors of reach impact category. The calculation created the environmental profile of each system under consideration" (Saleh, 2016, p. 35). Table 11 presents the characterized impact categories for the glass and PET bottles.

Packaging system	**Impact Categories**						
	Water consumption (m^3)	Non-renewable energy (MJ)			Solid wastes (kg)		Global warming potential (kg CO_2 equiv.)
		Non-renewable energy (MJ)	Energy needed for producing packaging from (MJ)				
			Virgin sources	Recycled materials	Disposed (kg)	Recycled (kg)	
330 ml glass bottles	8.876	8218.9	5912	1024	589.5	22.5	2736
1000 ml PET bottles	4.922	681.7	1011	341	53.12	7.06	69.1
Total	13.798	8900.6	6923	1365	642.62	29.56	2805.1

Global warming was calculated in CO_2 equivalents (kg) using the greenhouse gas equivalencies calculator tool (www.epa.gov).

Table 11 - Characterized Impact Categories of Glass and PET Packaging Systems Per 1000 L of Beverages for the Year 2022. (Table by the Researcher)

In this research study, the energy consumed and saved by using virgin sources and recycled sources were also calculated based on the 2022 statistics on glass and PET production systems of Behnoush Co. (DOE, 2022; Environmental Office of the Ministry of Industry, Mine and Trade, 2022a), and Hekkert and Worrell (1999), DECCW (2010), and Nori (2000) (Table 12).

Packaging system	**Required Energy (MJ) to produce primary package from**		**Energy saving (%)**
	Virgin sources	Recycled sources	
Glass	5912	1024	83%
PET	1011	341	67%

Table 12 -Energy Requirements to Produce Primary Packages Per 1000 L of Beverages (Table by the Researcher).

The table compares the results of the energy savings in the production processes of glass and PET bottles for a 1000 L functional unit. The table shows more energy saved by producing glass from recycled glass (83%) compared to producing PET from recycled material (67%) compared to producing Also, it presents that producing glass and PET requires more energy when using virgin sources than recycled sources. Recycling glass bottles is highly recommended in many countries for energy saving purposes (Edgar et al., 2008). According to Department of Environment, Climate Change and Water (DECCW) (2010), making one ton of glass bottles from their virgin sources needs (7.33 GJ) energy compared to about (1.27 GJ) energy required for recycling glass cullet. Also, according to Nori (2000), producing one ton of PET bottles from its virgin source (ethyl glycol and terephthalic acid) requires about (74.9 GJ) of energy compared to about (25.3 GJ) of energy for producing PET bottles from recycled PET.

4.6.3. Normalization

Normalization is conducted to understand better the order of magnitude for the glass and PET packing system indicators. In ISO 2000, the normalization step is considered an optional element of LCIA, which is not a measure of impact severity or importance, but merely a common reference point (ISO, 2000 cited in Grant et al., 2001). Therefore, normalization was excluded from the conducted LCIA.

4.6.4. Weighting

Weights were assigned to different impact categories to reflect the specific importance of the impact categories. For weighting, several studies, such as Komly et al. (2011, 2012), Adedeji (2006), Rowley and Peters (2009) and Ahmadi and Barna (2015), which elaborated on the weighting process, were used. This research study used the preferred weighting value presented in the DOE (2022) and confirmed by a group of environmental science researchers and practitioners of the DOE and the Environment Office of the Ministry of Industry, Mines, and Trade in Iran. Therefore, the weighting results may differ from other studies despite having the same indicator result (ISO, 2000; Saleh, 2016). For the weighting phase a scale from 0 to 10 was considered in the weighting phase. The scores considered for weighting included score 9 (water consumption), score 8 (non-renewable energy), score 7 (solid waste), and score 6 (global warming). The values for each impact category were multiplied by the chosen values. The total value for glass and PET packaging systems was obtained by adding all weighted values across the impact categories (Table 13).

Packaging system	**Impact Categories**						
	Water consumption (m^3)	Non-renewable energy (MJ)			Solid wastes (kg)		Global warming potential (kg CO_2 equiv.)
		Non-renewable energy (MJ)	Energy needed for producing packaging from (MJ)				
			Virgin sources	Recycled materials	Disposed (kg)	Recycled (kg)	
330 ml glass bottles	8.876	8218.9	5912	1024	589.5	22.5	2736
1000 ml PET bottles	4.922	681.7	1011	341	53.12	7.06	69.1
Total	13.798	8900.6	6923	1365	642.62	29.56	2805.1
Weight	9	8	8	8	7	7	6
Weighted Values of 330 ml glass bottles	79.884	65751.2	47296	8192	4126.5	157.5	16416
Weighted values of 1000 ml PET bottle	44.298	5453.6	8088	2728	371.84	49.42	414.6
Weighted Total	124.182	71204.8	55384	10920	4498.34	206.92	16830.6
Score of 330 ml glass bottles	142019						
Score of 1000 ml PET bottles	17149						
Score of packaging systems	159168						

Table 13- Weighted Values of Impact Categories of the Investigated Systems Per 1000 L of Beverages for the Year 2022 (Table by the Researcher)

4.7. Interpretation

Interpretation refers to extracting information from the LCA inventory and impact assessment results to find answers to the questions related to the goal and scope of the research. "A series of checks (identification of significant issues and sensitivity analyses) are used in the interpretation to determine if significant issues, which were identified in the inventory and impact assessment, were supportable, given the data accuracy and boundary conditions and assumptions made throughout the study" (Saleh, 2016, p. 38).

4.7.1. Identification of Significant Issues

To identify the significant issues, the weighted values of the impact categories, including water consumption, non-renewable energy, solid waste, and global warming potential, were compared between glass and PET packaging systems. Figures 19, 20, 21, and 22 illustrate the comparison of the impact categories between glass and PET. According to the figures, water consumption, disposal of solid and recycled solid wastes and global warming potential in glass packaging systems were higher than in the PET packaging system. The glass system exhibited higher weighted values of the total required non-renewable energy over the life cycle model compared to the PET system.

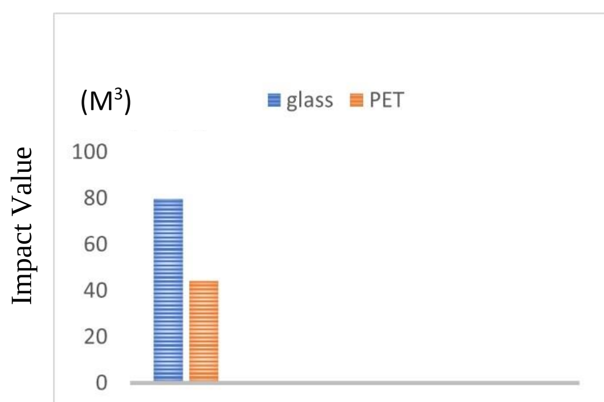


Figure 19- Comparison of Water Consumption Between Glass and PET Systems (Figure by the Researcher)

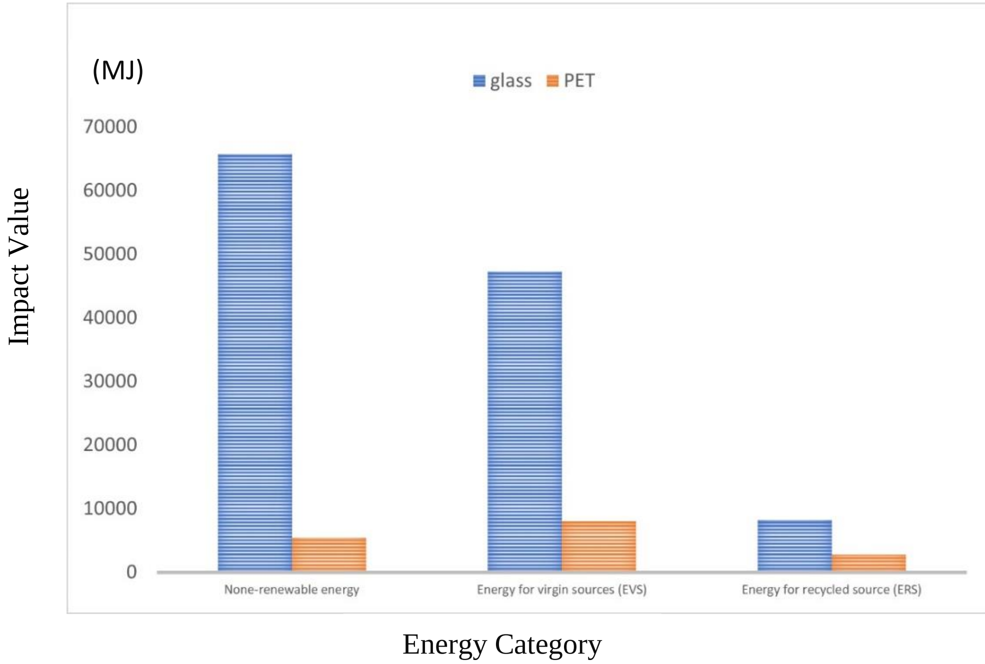


Figure 20– Comparison of Energy Consumption Effects Between Glass and PET Systems (Figure by the Researcher)

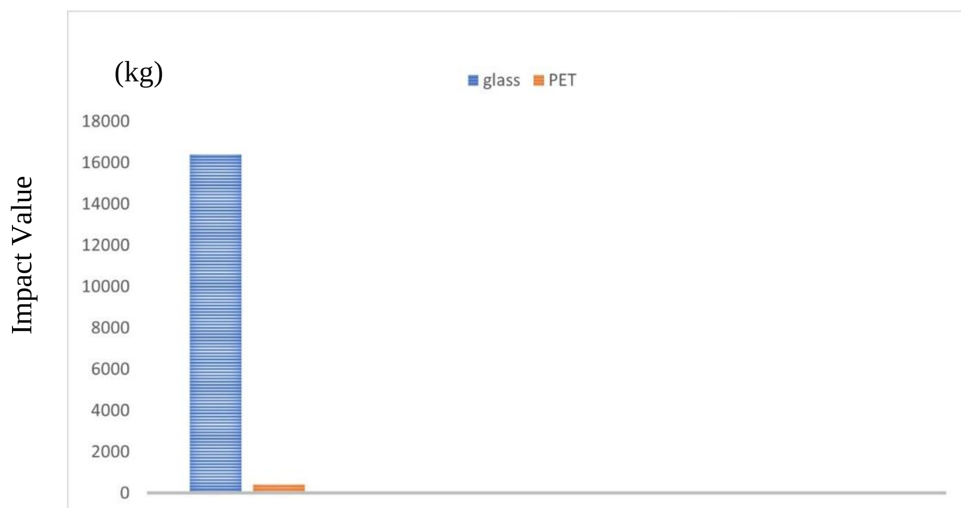
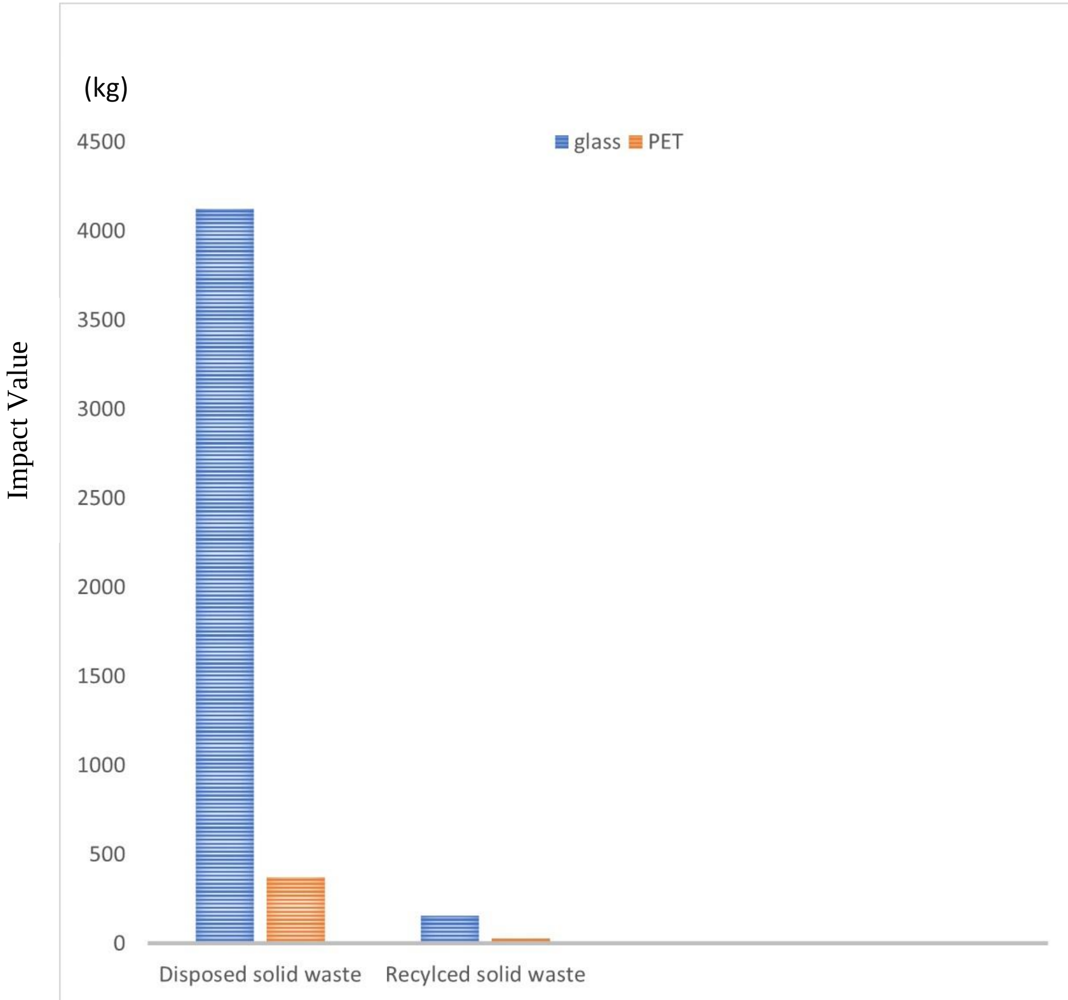


Figure 21 - Comparison of Global Warming Effects Between Glass and PET Systems (Figure by the Researcher)



Solid Waste Category

Figure 22- Comparison of Solid Waste Effects Between Glass and PET Systems (Figure by the Researcher)

The overall environmental score for glass and PET packaging systems was calculated by adding the weighted environmental values for all respective impact categories and illustrated in figure 23. Overall, the glass packaging system had the most considerable contribution to all evaluated impact categories compared to the PET packaging system.

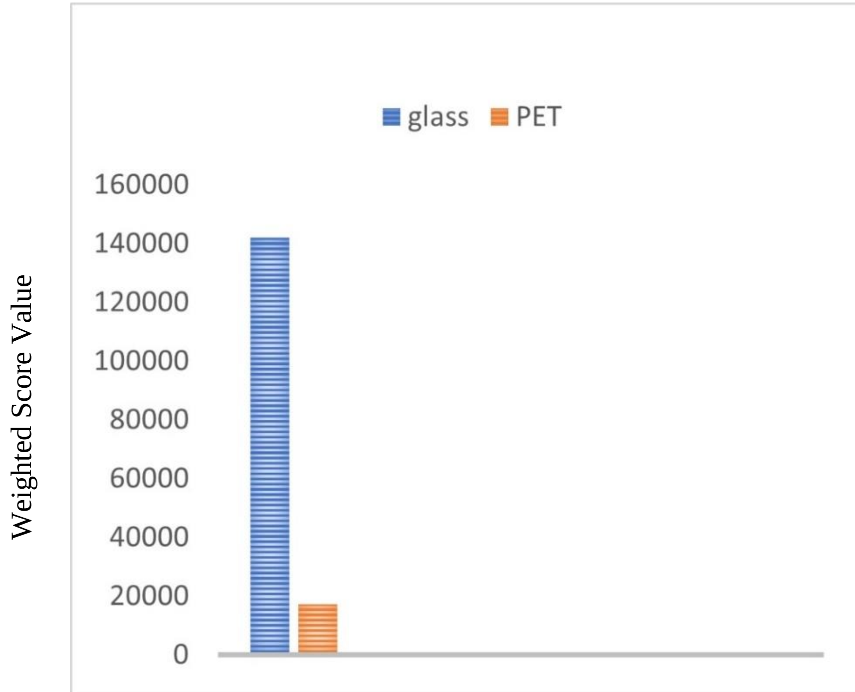


Figure 23 – Comparison of Weighted Environmental Scores of Glass and PET Packaging Systems (Figure by the Researcher)

4.7.2. Sensitivity Analysis

The effects of the designed exchange-flows and new recycling rates of the glass and PET packaging systems on the total environmental score of each packaging system are evaluated by sensitivity analysis.

- **Effects of Designed Exchange-Flows on Total Environmental Score of Glass Packaging**

The effects of the designed exchange-flows on the weighted impact categories of 330 ml glass bottles were investigated. To calculate the environmental effects based on the recycling rate, values provided by Amienyo et al. (2013), EIA report (DOE, 2022), Iran's Small Industries and Industrial Parks Organization (2012b), and Environmental Office of the Ministry of Industry, Mine and Trade (2022a) were used as references. These values included water consumption, energy saving, and carbon emission, based on the designed exchange-flow types and new recycling rate. These values are as follows:

1. 30% non-renewable energy saving by using the high-pressure steam supplied by the Shamsabad Cogeneration Plant
2. 40% increase of recycled glass waste provided by Tehran glass recycling plant
3. 20% reduction of carbon emissions by 40% increase of using recycled glass
4. 20% water saving by 40% increase of using recycled glass

A quantitative representation of the effect of varying the recycling rate for the glass system was provided. In this regard, each impact category and the total environmental score for the glass system were considered in the determination. Increasing, decreasing, and zero effects on the impact value were indicated by (+), (-), and (N) signs. All weighted values for each recycling rate were added to reach the total environmental score.

The sensitivity analysis of the glass system showed a total value of 101764, which demonstrated the total environmental score of 330 ml glass bottles resulted by the new recycling rate and designed exchange flows. A significant energy saving was attained by using recycled glass and wasted high-pressure steam and heat, which could be used for heating storage areas, cooling energy, and the process uses (i.e., cullet drying and sand storage heating). Moreover, a considerable decrease in water consumption, solid waste disposal, and carbon emission was achieved in the glass packaging system (Table 14).

Recycling rate (%)		Impact Categories							
		Resources				Solid wastes		Global warming potential	Total score
		Water	Energy	EVS	ERS	Disposed	Recycled		
4%	Effect value	N 80	N 65751	N 47296	N 8192	N 4126	N 157	N 16416	N 142018
44%	Effect value	- 64	- 46026	- 28378	+ 11468	- 2476	+ 219	- 13133	- 101764

Table 14- Effects of the Created Exchange-Flows on Total Environmental Score of Glass Packaging (Rounded up to Largest Integer) (Table by the Researcher)

- Effects of Designed Exchange-Flows on Total Environmental Score of PET Packaging

The same computation procedure, used to calculate the total score of the 330 ml glass packaging system, was used for calculating the total score of the 1000 ml PET packaging system. To calculate the environmental effects based on the recycling rate, values provided by EIA report (DOE, 2022), Iran's Small Industries and Industrial Parks Organization (2012b), Environmental Office of the Ministry of Industry, Mine and Trade (2022a), and Shen et al. (2011) were used as references. The values included water consumption, energy saving, and carbon emission, based on the designed exchange-flow types and new recycling rate.

These values are as follows:

1. 10% non-renewable energy saving by using the high-pressure steam supplied by the Shamsabad Cogeneration Plant
2. 30% increase of recycled PET supplied by Tehran Plastic Recycling
3. 8% reduction of carbon emissions by 30% increase of using recycled PET
4. 32% water saving by 30% increase of using recycled PET

The sensitivity analysis of the PET packaging system showed a value of 14850 as the total environmental score of 1000 ml PET bottles resulted by the new recycling rate and designed exchange flows. Similar to the glass packaging system, significant water, energy and carbon saving and waste reduction were achieved in the PET packaging system by increasing the waste recycling and the new exchange-flow types among the Behnoush food packaging Co. and other EIP enterprises (table 15).

Recycling rate (%)		Impact Categories							
		Resources				Solid wastes		Global warming potential	Total score
		Water	Energy	EVS	ERS	Disposed	Recycled		
13%	Effect value	N 44	N 5453	N 8088	N 2728	N 371	N 49	N 414	N 17147
43%	Effect value	- 30	- 4908	- 5662	+ 3546	- 260	+ 63	- 381	- 14850

Table 15- Effects of the Created Exchange-Flows on Total Environmental Score of PET Packaging (Rounded up to Largest Integer) (Table by the Researcher)

Considering all this, the sensitivity analyses of the two packaging systems revealed that the new exchange-flow types between the selected enterprises for the Shamsabad EIP development contributed to more reduction/saving of water, carbon, and waste in glass packaging than PET packaging, and therefore, higher level of environmental benefits for the people and the living environment. Within the limitations of the conducted LCA, the 1000 ml PET bottles outperformed the 330 ml glass bottles in terms of scoring the lowest total weighted environmental score. Moreover, recycling was found to be an effective approach to reducing the respective total environmental scores, and therefore, it is highly recommended for the future environmental plan of the Shamsabad EIP (figure 24).

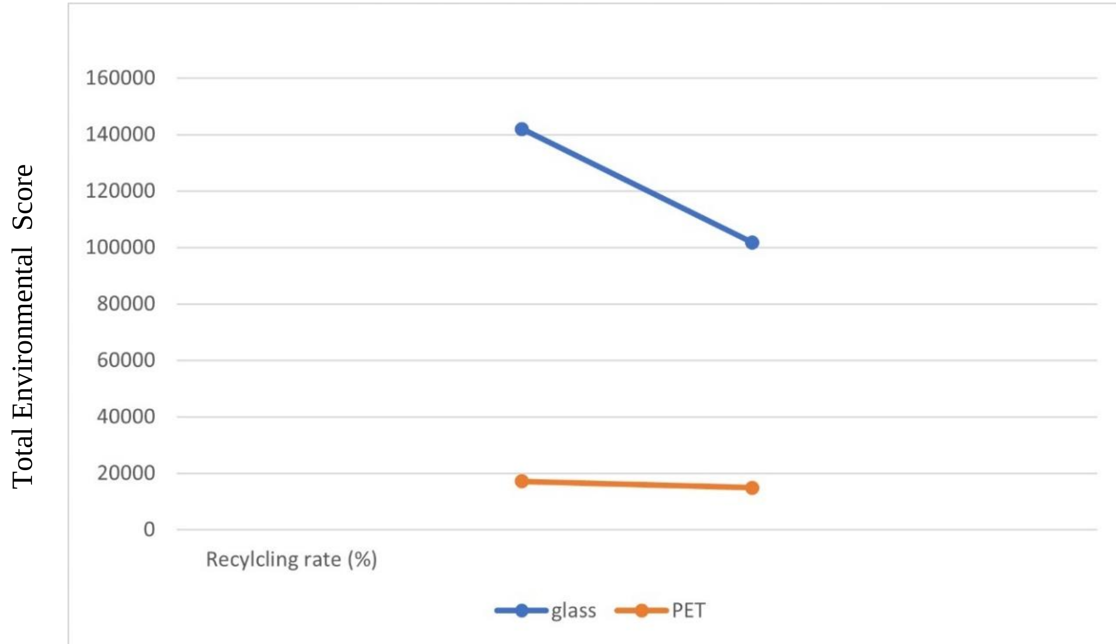


Figure 24 - Sensitivity Analysis of Glass and PET Systems and the total Environmental Score (Thousands) (Figure by the Researcher)

4.8. Optimization of Industrial Symbiosis

The key to industrial symbiosis is a collaboration between enterprises resulting in synergistic effects. LCA contributes to optimizing industrial symbiosis by providing complete knowledge of industrial processes, inputs and outputs, and associated environmental impacts. Based on this knowledge, EIP developers could optimize material and energy flows within different symbiosis scenarios and increase the enterprise collaboration performance.

It is possible to promote the collaborations between Behnoush Co. and other industrial facilities and local businesses for the purpose of reducing/saving carbon, water and waste and improving the synergistic effects of industrial symbiosis. The LCA results achieved through the previous steps helped the researcher to recognize potential new synergies. The designer recommended establishing a new collaboration between Behnoosh Co. and the steel industry network, especially the Iran Steel Co., located in the northern area of Shamsabad IP, close to the Behnoush Co. The collaboration focuses on addressing water scarcity and non-renewable energy consumption challenges. The steel industries significantly consume water and energy; however, it was impossible to discuss creating exchange flow types at the time of data collection due to the government ownership and the confidentiality of the data. The fundamental solution to this problem is to notify industrial facilities/businesses collaborating with Iran Steel through the digital platform mentioned in the previous chapter. This platform will share information on the reserves of materials, waste, energy and their sources. The wastewater supplied to the enterprises could be used in both the glass and PET packaging systems of Behnoush Co. to reduce the freshwater demand. Also, by sharing the extra electricity supplied by the Regional Electric Company to Iran Steel Company, it will be possible to reduce the energy cost. Moreover, by installing rooftop solar panels, renewable energy will be produced and replaced with the non-renewable energy required for lighting and heating, significantly improving carbon reduction.

4.9. Conclusion

To achieve the long-term benefits of EIPs, practical frameworks presenting design considerations and steps for the transition of IPs into EIPs are essential. These frameworks serve as guidelines for stakeholders and decision-makers during the first stages of developing new EIPs.

As mentioned in the previous chapters, this research aims to establish a similar case-specific framework. In this research, the LCA methodology was applied as a useful means to evaluate and promote the efficiency of the formed industrial symbiosis. The results of the LCA revealed the effectiveness of the formed industrial symbiosis, and therefore, it proved the performance of the intended framework in resolving the environmental impacts of the Shamsabad IP. According to the LCA results, the life cycle sustainability performance of carbon and water related to industrial processes was improved via increasing the recycling rate and collective collaboration of EIP enterprises for sharing services, energy, by-products, and waste resources. The LCA results showed a total environmental score drop for both glass and PET packaging. Reduction in natural resources use for inputs, reduction in air, water and soil pollution, reduction in energy use and waste disposal, and increase in value of non-product outputs are some of the environmental benefits achieved from improving the life cycle sustainability performance of carbon and water. Reduced costs associated with by-product transfer and waste disposal, reduced landfill waste, improved environmental health and habitat environment, and improved aesthetics are other environmental benefits achieved by the transformation of the Shamsabad IP into an EIP.

Thus far, the theoretical foundation of this research was formulated, and the industrial symbiosis of the Shamsabad EIP was formed, evaluated, and promoted. The next chapter debates the effectiveness of the legal and regulatory framework which supports or hinders the EIP establishment.

Chapter 5: National Laws, Policies, and Plans

5.1. Introduction

As mentioned in the previous chapters, this research aims to develop a case-specific framework for the first stages of EIP establishment. Recently, a variety of EIP frameworks with focus on different areas have been developed. This research focuses on laws, regulations, policies and plans in addition to design considerations and LCA for ensuring the framework's efficiency and guaranteeing the long-term environmental, social and economic values of the Shamsabad EIP. So far, the industrial symbiosis formed to develop Shamsabad EIP was formed and evaluated by LCA. This chapter elaborates on regulations, policies and plans that hinder or promote the development of the Shamsabad EIP and guarantee its efficient social, environmental, and economic performance. These significant factors influence the effectiveness of the framework developed in this research study by securing the commitment of enterprises in EIP formation. According to the World Bank Group (2018), “the lack of sufficient, appropriate and effective regulations limits the push for traditional IPs and their resident businesses to transform their operations into sustainable production centers” (p. 25).

5.2. Environmental Protection Laws

The Environmental Protection Laws that specify rules and measures for the protection and management of the environment support developing EIPs in Iran. The objectives of this Law, consisting of 21 articles, are the protection and improvement of the environment. According to the laws, The Department of Environment (DOE) takes measures to preserve the ecological balance, prevent and control harmful waste and air, water, and soil pollution, and arrange public training courses to raise awareness about environmental protection. The Clean Air Law and Waste Management Law are the most relevant environmental protection laws supporting EIP development in Iran.

- **Clean Air Law**

The Clean Air Law, enacted in 2017, defines air pollution and the permissible limits for the pollution released by natural and man-made resources. The DOE cooperates with the Ministry of Industry, Mine and Trade to monitor the proper implementation of this law. According to this law, large and medium-sized projects that are subject to environmental impact assessment are required to install online monitoring systems and send up-to-date information to the monitoring center of the DOE.

In this regard, the industrial facilities designated by the DOE are required to sample and measure air pollution in determined time periods. Industrial facilities with pollution above the allowable level should take action to eliminate pollution, change production processes or used materials, or shut down their work and activities (depending on the pollution types). Issuance and renewal of operation licenses of these industrial facilities are subject to elimination or reduction of pollution to the extent allowed. According to the law, a penalty is imposed for stopping the activities of polluting industrial facilities that have not taken the necessary measures to reduce pollution. In case of non-payment of penalties and elimination of pollution by the end of the deadline, the polluting facilities, in addition to compensating the damages, are obliged to pay the penalty equal to three to five times the damages to the environment. In this regard, a decision to stop activities of industrial facilities with destructive environmental effects is made by a team of the Minister of Industry, Mine and Trade, the head of the DOE, the governor, and the highest authority. According to the law, in case of endangering public health in residential areas, all or part of production lines or facilities must be transferred to appropriate locations to reduce or eliminate the pollution caused by the industrial facilities. The owners and managers of industrial facilities are obliged to transfer the facilities within the set deadline.

- **Waste Management Law**

The Waste Management Law, enacted in 2004, protects the environment from the harmful effects of industrial waste. The management and executive teams of IPs and manager of industrial facilities can entrust all or part of the collection, separation, transportation, disposal, and recycling of industrial waste to verified individuals or companies. The DOE is responsible for overseeing the implementation of the waste management law. The executive and management teams of IPs and the manager of industrial facilities are responsible for using methods that lead to the production of less waste and their consumption. Storage, mixing, collection, transportation, purchase, sale, disposal, and export of waste are in accordance with the provisions of this law. As well as education and information in this field, the government is obliged to provide facilities to ensure the production and consumption of goods that are easier to recycle. Also, it is obliged to limit the production and import of products whose waste is more difficult to dispose of and recycle and to take measures to increase the use of recycled raw materials in production. A penalty of up to 10 million rials is considered for violators of this law.

5.3. Sustainable Development Policy

The sustainable development policy focuses on the improvement of science and technology, promotion of innovation, resource use efficiency, action on climate change, and investment in green production to address the environmental problems caused by city development in Iran. In line with this policy and with the purpose of decreasing environmental pollution, industrial facilities were forced nearly ten years ago to leave Tehran and settle in the suburbs. Also, transforming IPs into EIPs was put on the agenda of the relevant organizations and institutions to spark economic growth while reducing environmental and social impacts.

5.4. Tehran Comprehensive Plan

The Tehran Comprehensive Plan, which proposes the future 15 years of growth of Tehran, brings new order to its irregular urban expansion and responds to the growing population. Based on the plan, the Shamsabad IP is set to become an EIP to provide significant environmental, social and economic benefits to the people and the living environment (Iran small industries and industrial parks organization, 2012b, 2013a).

5.5. Barriers to the National EIP Development

Identification of the significant barriers to EIP development in Iran is necessary to facilitate the design of national EIPs. These barriers can hinder the implementation of the framework developed in this research and the transformation of the IPs into EIPs. In this regard, several barriers to the development of the Shamsabad IP were identified by reviewing the regulations, policies and plans, which include:

- Ineffectiveness of environmental laws and policies due to light penalties awarded for violating the laws and the fact that some government and government-private industries have exceptions to the implementation of clean air and waste management laws.
- Lack of suitable policies to encourage EIP development through command and control and fiscal incentives
- Lack of familiarity of policymakers with EIP and industrial ecology concepts
- Lack of general awareness about EIPs among industrial firms and economic development professionals of local communities
- Lack of liabilities associated with disposal and re-use of industrial waste
- Lack of long-term financial support required to promote industrial symbiosis

It should be noted that economic sanctions have led to recessions, especially in industrial sectors, which have brought decreased economic output, lower consumer demand, and high unemployment, and as a result, violations in compliance with environmental laws, policies, and sustainable development programs.

5.6. Solutions for EIP Development

According to Peck and Callaghan (2018), "increasing support for the implementation of EIPs provides governments with a new opportunity to achieve multiple environmental and economic objectives" (p. 57). The following measures/strategies for the progress of developing the Shamsabad EIP and other EIPs in Iran are recommended:

- Developing programs by the government to help make strategic investments in technologies needed to improve the linkages between major industrial processes used in different industrial facilities, e.g., recycling programs, water conservation programs, wastewater treatment and industrial waste management programs.
- Establishing an ad hoc interdepartmental committee between management and executive teams of IPs to coordinate programs that support EIP development.
- Developing a program budget supporting local EIP development projects over ten years that will clearly demonstrate the environmental, economic, and social benefits and build a stronger constituency. The budget should be provided by the local and provincial resources and be allocated to management and executive teams of IPs for planning and establishment of EIPs.
- Providing facilities to ensure the production and consumption of goods that are easier to recycle.
- Supporting the development of an industrial ecology website to develop awareness among local and regional industrial and economic development officials and policymakers of the EIPs.
- Engaging in park-level dialogue and enterprise training to improve awareness of the cost-effective and advanced solutions associated with EIPs.
- Promoting the introduction of industrial ecology and EIP concepts into teaching programs through partnerships in environmental engineering, business, planning, and design disciplines.

- Providing political, financial, and strategic support for developing a national conference, workshops, and briefing sessions on EIP development to broaden awareness and facilitate further action.
- Increasing penalties for violating environmental laws, including clean air law and waste management law.
- Increasing tax on the purchase of polluting raw materials for industrial production.
- Providing rent subsidies to industrial facilities which use each other's waste and energy.
- Encouraging local and national authorities to establish tax incentives.
- Creating financing mechanisms and making it easier for the Shamsabad EIP to share the lessons learned between enterprises.

5.7. Conclusion

To establish the EIP framework aimed in this research study, the existing Iranian laws, policies and regulations associated with the EIP development were reviewed in this chapter to identify their gaps, weaknesses, and strengths. Such information facilitates the better design of the targeted framework and, therefore, the development of EIPs in Iran. According to the reviews, the current laws, policies, and plans associated with EIP development entail revisions. More attention should be devoted to their specification, operation, details and efficiency to facilitate the establishment of EIPs in Iran and guarantee their integrated long-term environmental, social, and economic benefits. In this regard, supporting programs should be provided to raise awareness of EIPs and their environmental, social, and economic performance and encourage the participation of enterprises by offering funding subsidies in the formation of industrial symbiosis at different levels. Funds under local and provincial sustainable development programs, e.g., energy and waste-related programs designed to improve energy efficiency and waste reduction, should be offered to business associations, local round tables, and community organizations to encourage the enterprises and EIP development in Iran. In this respect, research and development (R&D) are necessary to help develop new technologies that will allow for economically viable linkage between enterprises. The local, provincial, and federal programs dealing with water, waste, energy, and manufacturing should support research and development (Peck & Associates, 1997).

Chapter 6: Conclusion and the Future of Shamsabad EIP

6.1. Review of Ground Covered and Lesson Learned

The aim of this research study was developing a comprehensive case-specific framework, known as the main outcome of the study which serves as a guideline for stakeholders and decision-makers during the first stages of developing new EIPs in Iran using Shamsabad IP, one of the most extensive IPs in the Middle East as the case study. The framework is simple, requiring primary data that can easily be collected from each enterprise forming EIPs. It is composed of two dimensions: organizational, legal and regulatory. On the one hand, the organizational dimension emphasizes that EIPs are networks of enterprises with various interests/motivations sharing energy, material and waste. On the other hand, the legal and regulatory dimension reflects the significant aspects of the current and future policies, plans and regulations in forming EIPs and their sustainable performance. The framework consists of four steps:

1. Identifying EIP enterprises and their motivations
2. Forming industrial symbiosis based on the interests/motivations of enterprises
3. Evaluating the effectiveness of industrial symbiosis in resolving environmental impacts by LCA
4. Identifying regulations, policies and plans supporting the development and performance of the new EIP

Figure 25 illustrates the framework and step-by-step approaches for the Shamsabad EIP establishment. According to the figure 25, the outputs of using the framework include (1) enterprises forming the EIP, (2) exchange-flow types of material, energy, and waste, (3) new exchange-flow types based on the LCA results for improved results and future EIP development if necessary, (4) measures and strategies for the development of EIPs.

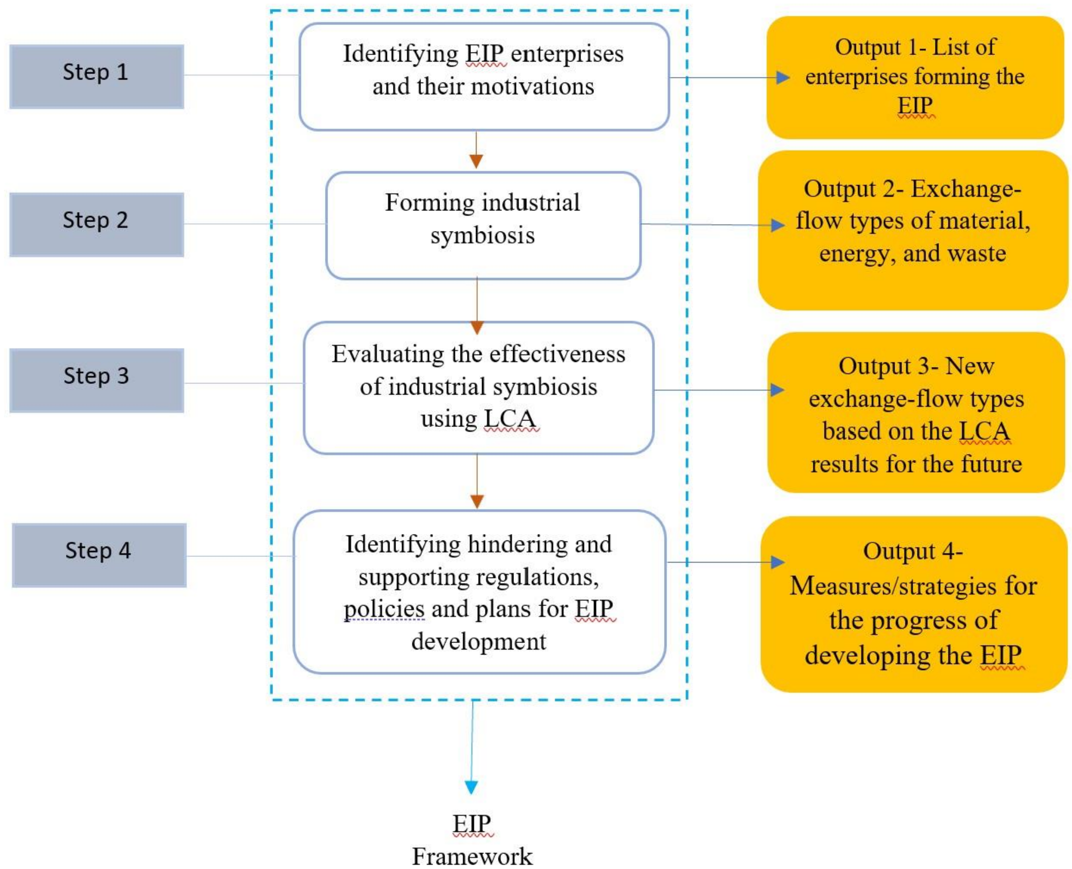


Figure 25- Framework for Developing Shamsabad EIP (Figure by the Researcher)

Over five chapters, the researcher provided answers to the seven research questions to develop and examine the framework, which is as follows:

1. What are the economic, environmental, and social motivations for designing the Shamsabad EIP?
2. What are the entities forming the EIP?
3. Where is the most carbon and water footprint coming from?

4. Where are the most waste materials coming from?
5. What are the possible exchange flows between entities?
6. How much potential for reduction/saving of water, carbon and waste can be achieved by transforming to EIP?
7. What policies and regulations support transforming the IP into an EIP?

The following information was obtained by the researcher through answering the questions elaborated over the thesis chapters:

Chapter two was dedicated to reviewing the literature to build a theoretical foundation for the research study. The theoretical foundation of the project was built by exploring the main concepts, including the circular economy (CE), life cycle assessment (LCA), eco-industrial park (EIP), and EIP framework. The systematic literature review conducted by the researcher contributed to identifying the characteristics of best practice examples of EIPs and an efficient framework for developing such an EIP. According to the research achievements, an EIP is defined as an industrial system of enterprises that derives the integrated environmental, social, and economic benefits from creating a circular model similar to the natural one where the material is recycled, energy is cascaded, and waste is re-used. An interesting EIP plan accelerates the collective collaboration of enterprises to fulfill a country's national sustainable development goals by addressing the environmental challenges of IPs, such as air, water, and soil pollution, water scarcity, and waste production. This plan meets various enterprises' needs which engages their collaboration in the EIP plan over the years.

The researcher explored several international practice examples of EIPs to extract information on the key environmental, social, and economic drivers and barriers to developing EIPs. The researcher also used statements from several relevant research studies, EIP handbooks and government reports. It was obtained from reviewing literature that it is necessary to establish comprehensive and case-specific frameworks to be used in the first stages of developing EIPs. The framework should present the performance requirements for transforming an IP into an EIP to derive long-term environmental, social, and economic benefits. The step-by-step actions illustrated by the framework help establish the fundamental structure of the EIPs by creating the collective collaboration of industrial facilities for sharing services, utilities, energy, and by-product resources, known as industrial symbiosis. Also, it should guarantee the secure commitment of the EIP enterprises in creating the EIPs and their sustainable performance.

The first question was answered in chapter three by retrieving information from the interpretation of 25 interviews with ten representatives and stakeholders of the Shamsabad IP. The interviews covered in-person, phone, and videoconference interviews. The information indicated nine environmental, social and economic motivations for the Shamsabad EIP. The researcher explored that the EIP enterprises have relevant solid environmental, social, and economic motivations which ensure the secure commitment of the enterprises in forming the industrial symbiosis and guarantee the promotion of industrial symbiosis in the future. According to the interview participant's statements, the economic sanctions have led to recessions, especially in industrial sectors, decreased economic output, high unemployment, and violations in compliance with environmental laws, policies, and sustainable development programs. Therefore, considering the social and economic motivations could result in environmental condition improvements and high environmental performance of industrial facilities.

The researcher answered the second research question in chapter three by retrieving information from the interpretation of 25 interviews. Based on the interpretations, a list of enterprises that showed interest in participating in forming Shamsabad EIP. The list of enterprises was classified into existing and potential enterprises and producers and consumers for creating an effective industrial symbiosis based on the potential and needs of the enterprises. The list showed the heterogenous context of the Shamsabad EIP in terms of enterprises which are the key beneficiaries of the EIP. The heterogeneous context could significantly contribute to forming a functioning industrial symbiosis which allows for sharing of a variety of materials, utilities, and services among the enterprises at the EIP scale. The collaboration of the EIP enterprises, which behave like a natural ecosystem sharing by-products and waste, derives long-term environmental, social, and economic benefits and, therefore, meets the broad, diverse needs of the EIP enterprises.

In chapter three, answers to questions three and four were provided. The researcher extracted information on the contribution of the diverse industries in the Shamsabad IP's environmental problems by reviewing governmental reports. According to the 2022 statistics on CO_2 emission, water consumption and waste production (Environmental Office of the Ministry of Industry, Mine and Trade, 2022a), the energy industry, with 21.4%, was the highest source of CO_2 emissions in the Shamsabad IP. Other facilities groups, including construction, textile, wood products, and food packaging, showed 14.8% of the CO_2 emission. Also, chemical and petrochemical industries had the most significant industrial water consumption, with a share of

28.2%. Moreover, machinery and metal industries, with a share of 35%, were the highest source of waste production.

To answer question five, the researcher initially determined a series of design considerations and straightforward steps for EIP developers and decision-makers. For this, the significant characteristics of the best practice examples of EIPs (such as Kalundborg, Taiga Nova, and Burnside Park), including pattern, form, structure, and their associations with the functionality of the EIPs and how successful EIPs were developed, were retrieved from studies such as MOTIE (2011), Massard et al. (2014) and Hollander (2000). According to the information extracted from these studies, proximity, variety, and distribution of industrial facilities across EIPs, ties between managers of industrial facilities, digital platforms for shareable materials, waste and energy, and financial support for the engagement of enterprises were the significant factors for creating effective industrial symbiosis. To determine the design considerations, the specific characteristics of the Shamsabad IP were also considered. These included the significant size and heterogenous context of the Shamsabad IP, the proximity of industrial facilities and their access to utilities, the number of highly pollutant industrial facilities and their distribution across the IP, and the potential of specific facilities for accommodating sustainable design solutions. The researcher determined ten design considerations for developing Shamsabad EIP based on the abovementioned factors.

Then, the researcher determined and followed four straightforward steps to transition IPs into EIPs, used to build effective collaborations between various industrial facilities and generate a kind of ecosystem with closed-loop flows of energy, water, materials, and wastes in Shamsabad IP. These steps consist of: (1) establishing a platform for EIP enterprises to collect information concerning material, waste, and energy, (2) categorizing enterprises into consumers and producers based on shareable material, energy, and wastewater, (3) forming initial cores of the industrial symbiosis by high-polluting enterprises and enterprises with the potential to have the most exchange flow types, and (4) connecting producers and consumers to the initial cores and other enterprises based on proximity and flow-type needs.

In the next step, the design considerations and straightforward steps, recommended by the researcher to develop EIPs, were contemplated by the researcher to form Shamsabad industrial symbiosis. The maximum potential of the industrial facilities was employed for sharing the by-products, utilities, and services to meet the diverse demands of the facilities. This strategy could encourage collaborations between industrial facilities that increase the competitiveness and the associated benefits, such as maintaining the value of the products, materials, and resources for the maximum possible time period, saving the utilities and materials cost, and achieving environmental protection. This EIP concept follows a variety of advantages at different levels, and therefore, it accelerates the transformation of the Shamsabad IP into an EIP and guarantees its future sustainable performance.

The researcher answered question six in chapter four by examining LCA as a systematic decision and support tool for forming, evaluating, and improving the industrial symbiosis developed in this research. The application of LCA makes the proposed framework specific and distinctive compared with other frameworks, such as the international framework for EIP (World Bank Group, 2018) and the generalized framework for designing eco-industrial parks (Al-Quradaghi, 2020). The researcher defined LCA as a method based on the correct understanding of industrial processes holistically for measuring various environmental impacts. By reviewing the literature on the application of LCA in promoting industrial ecology, the researcher recognized the comparative approach and function of LCA that support identifying contaminating industrial facilities/processes and classifying them based on the level of environmental effects. Therefore, LCA plays a distinctive role in identifying the industrial facilities/processes which require improvement through sharing energy, waste, water, raw material, and by-products to reduce environmental effects. Hence, the designer used this LCA's specification to form, evaluate, and improve the industrial symbiosis based on the LCA results, which helped resolve the direct and indirect environmental problems, including resource depletion, air pollution, and waste disposal arising from the industrial processes of the Shamsabad EIP.

The LCA was conducted with a comparative environmental impact assessment approach in the Behnoush food packaging facility, one of Iran's significant beverage and beverage packaging producers, which manufactures beverage glass and PET bottles. The LCA results indicated that the generated EIP's circular model, which represents the collocative collaborations between the industrial facilities and the designed exchange-flow types, was effective in reducing/saving water, waste and carbon. In this regard, a series of checks (identification of significant issues and sensitivity analyses) for glass and PET systems were conducted. The information retrieved from the identification of significant issues step showed that the glass system exhibited higher water consumption, disposal of solid and recycled solid wastes, energy consumption and global warming potential over the life cycle model compared to the PET system. In this regard, the diagrams of the investigated systems revealed a major difference in the statistics of global warming, disposed solid waste, and non-renewable energy use, which proved the lack of strategies/plans for energy saving, sustainable energy use and waste reduction in the glass and PET systems.

By contrast, the information retrieved from the sensitivity analyses step displayed a significant energy saving and a considerable decrease in water consumption, solid waste disposal, and carbon emission in the glass and PET packaging systems. The proposed strategies, including increasing the rates of recycling (40% in glass systems and 30% in PET systems) and using energy waste (30% in glass systems and 10% in PET systems), significantly contributed to addressing water scarcity, waste production and global warming effects. According to the quantitative analysis and comparison of the glass and PET systems, the total environmental score of the glass packaging system dropped from 142018 to 101764. Also, the total environmental score of the PET system dropped from 17147 to 14850. Therefore, the industrial symbiosis effectively reduced the significant environmental problems of the Shamsabad IP. Nevertheless, it is still possible to promote industrial symbiosis by taking advantage of other IP levels and their structural facilities.

Therefore, in the end, the researcher used the LCA results to optimize the industrial symbiosis determined in the previous steps. For this step, the results of LCA sensitivity analysis in the Behnoush food packaging facility were used to provide solutions for improving and implementing industrial symbiosis. For this purpose, the feasible future development of the Shamsabad EIP and the capability of industrial facilities were considered. To increase enterprise collaboration performance, the researcher constructed scenarios between Behnoush Co. and the steel industry network, especially Iran Steel Co. The collaboration concentrated on water scarcity and non-renewable energy consumption challenges these two industrial facilities faces. The researcher highlighted the role of digital platforms in informing other facilities concerning existing wastewater and material resources and sustainable designs (installing rooftop solar panels) to save non-renewable energy for production and maintenance and CO_2 reduction. It was concluded from the LCA results that applying LCA as part of the targeted EIP framework guarantees the formation of new effective synergies which promote collaboration between enterprises purposefully and improve the share of material, waste, and energy based on the environmental performance of the industrial facilities.

The researcher answered the final research question in chapter five by recognizing the existing laws, regulations, policies, plans and strategies related to EIP development in Iran and evaluating their implementation mechanism. This approach allowed for strategic solutions that improved the current legal and regulatory framework. The information required for recognizing the existing gaps and inefficiencies of the existing legal and regulatory framework was retrieved from DOE (2022) and DOE (2020). Environmental protection laws, including the clean air and water management laws, sustainable development policy, and Tehran comprehensive plan, were recognized as relevant legal and regulatory factors supporting the development of Iranian EIPs. According to the information obtained from analyzing these factors, there is a noticeable lack of effectiveness in legal and regulatory framework. Enforcement weaknesses of the laws, policies and plans could be evidently seen at various levels, which is the consequence of several factors, such as the lack of severe penalties for disobedience of laws, lack of familiarity with the EIP concept and industrial ecology, especially at the management and executive level of IPs, and the lack of programs for supplying financial supports required to form and extend industrial symbiosis.

The researcher concluded that the EIP framework would be implemented effectively with the support of local, regional, and national influencing factors.

The researcher offered strategic solutions for improving the legal and regulatory framework to support the Shamsabad EIP establishment and its long-term sustainable performance. In this regard, the researcher highlighted the effects of economic sanctions on decreased economic output, lower consumer demand, and high unemployment, resulting in violations in compliance with environmental laws, policies, and sustainable development programs. Therefore, the researcher recommended alternative solutions to guarantee the effectiveness of the targeted EIP framework, which focused on increasing penalties and taxes for non-compliance with laws, policies, and plans, use of polluting raw materials and waste production, designing programs for strategic investment technologies and committees, and developing sustainable development programs.

The researcher learned lessons from developing the EIP framework for designers and decision-makers through establishing Shamsabad EIP. More attention should be devoted to the specifications of IPs to facilitate the establishment of EIPs in Iran and guarantee their integrated long-term environmental, social, and economic benefits. Indeed, practical EIP frameworks are essential to give direct attention to the details of forming an efficient industrial symbiosis and guarantee its long-term sustainable performance. These frameworks focused on important areas including design considerations, easy steps for the transition of IPs into EIPs, LCA, and legal and regulatory factors (figure 26). As a result of applying the determined design considerations, following the transition steps, and using LCA, the existing significant structural, environmental, social, and economic factors are used to create and promote a functioning industrial symbiosis. The central cores of the industrial symbiosis formed by polluting industrial facilities and facilities with the potential to have the most exchange-flow types play significant roles in sharing material sources, energy and waste. The close proximity of enterprises accelerates and expands the creation of industrial synergies by linking core enterprises and small and local businesses. Specific structural characteristics of the industrial facilities increase the chances of forming synergies quantitatively and qualitatively.

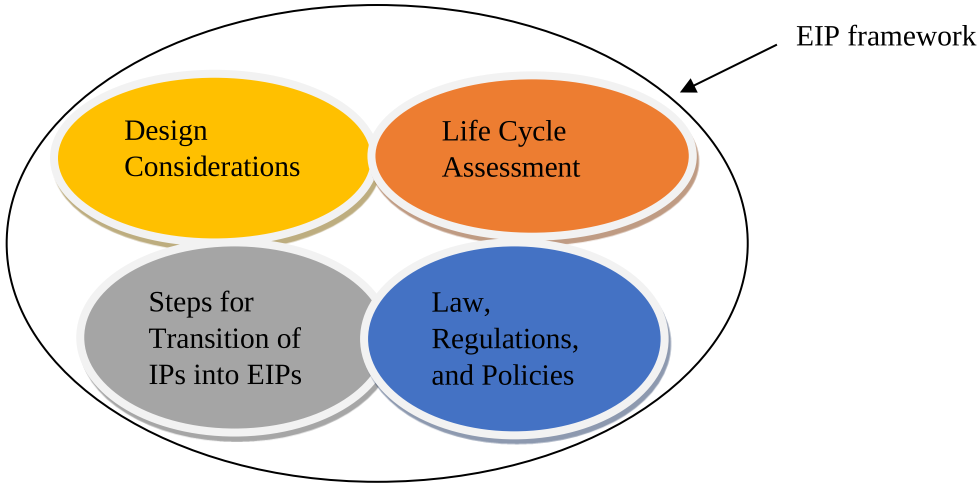


Figure 26- Focused Areas of EIP framework (Figure by the Researcher)

Sustainable design solutions promote overall environmental performance and bring social and economic benefits. LCA is a fundamental component of the targeted EIP framework, used as a tool to form, evaluate, and improve industrial symbiosis. Identification of the polluting industrial processes/sectors and their associated environmental impact help the decision makers and EIP developers to check the efficiency of the industrial symbiosis in addressing challenges such as global warming and water scarcity and to promote it purposefully. Solutions for forming a broader industrial symbiosis should be offered based on the current barriers to national EIP development. In this respect, the creation of an electronic platform is highly recommended. This platform provides information about the product's origin and available by-products and waste reserves. Also, it exchanges information regarding raw materials, energy and water at a competitive price to enable supply synergies and co-location of suppliers and clients and utility, service, by-product, and waste exchanges. Moreover, EIP programs for budget allocations and tax revenues are suggested to guarantee the formation, performance, and sustainability of EIPs in the future. Finally, attention to the legal and regulatory framework associated with EIP establishment consolidates the secure commitment of enterprises to EIPs formation and improvement of the environmental, social, and economic performance of industrial facilities. In this respect, identification and revisions of laws, policies and plans are crucial to fill the gaps in legal and regulatory frameworks that support the establishment of future EIPs.

6.2. Towards the Development of EIPs

The overall aim of the framework established in this research study was to assist EIP developers and decision-makers with the practical design considerations in the initial stages of EIP development. Compared to the comprehensive frameworks for EIPs provided in the literature, this framework is specific and answers fundamental questions of the executive and management team of the Shamsabad IP and other IPs in Iran regarding EIP development. The lessons learned from using the framework for transforming the Shamsabad IP into EIP will help national and international governments raise awareness of the integrated benefits and significant values of EIPs, including alignment with sustainable development goals and climate change mitigation. These lessons will contribute to establishing new local frameworks and promoting EIP development in the Middle East and other geographical areas.

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8. Appendix

8.1. Interview Questions

Shamsabad Industrial City Interview – Experts/Operators/Managers

Interview General Information
Interviewee Code: -----------------   Interview Date and Time: ------------------------------------   Interview Place: --

Dear Expert/Operator/Manager,

Thank you for agreeing to talk to me and be part of my research study. My study explores design considerations for water and carbon life cycle sustainability performance in Shamsabad industrial city which is planned to be transformed into an Eco-Industrial Park (EIP). The interview consists of several questions regarding the materials and processes, and regulations and policies associated with the industrial city. It will produce information that can help transform the industrial city into an Eco-Industrial Park, provide integrated social, environmental, and economic benefits, and resolve significant environmental problems. I promise that no names will be mentioned when I write the master thesis, and I will record this interview as part of the research. Your time and assistance in the successful completion of this project are very much appreciated.

Experts/Operators/Managers Personal Information
1. Full Name: --   2. Official job title: --   3. Responsibilities: --   2. Phone Number: ----------------------------------   3. Email Address: ------------------

1. Who are the stakeholders of the industrial park?
2. What are the current interests of the stakeholders regarding an eco-industrial park development?
3. What government agencies or departments are the most relevant and capable of making decisions, and developing policies for eco-industrial park development?
4. What are the national and regional government regulations and policies related to the industrial park?