

# Agent-based Conceptual Framework for energy and material synergy patterns in a territory with non-cooperative governance

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## ABSTARCT

Circular economy is gaining momentum as an answer for migrating towards a sustainable paradigm. Many literature studies were conducted to assess the feasibility of heating networks based on industrial heat recovery and similarly for material reuse and recycling aiming to propose technical options for energy efficiency and resource use whether on the process scale or on a larger inter-sites level. In addition, reacting conversion systems create new valorization opportunities for the energy or material streams.

In this perspective, a novel conceptual framework, incorporating reacting thermodynamic conversion systems to the material and energy integration problems in non-cooperative economic scheme, was proposed in this work. The application of the proposed methodological framework on a realistic industrial park demonstrated how to implement conversion processes in a territory. The non-usable stream in the investigated park is woody biomass for which three conversion routes were challenged being the wood to hydrogen, methane production and cogeneration.

## Keywords

Industrial Symbiosis, Eco-Industrial Park, Process Integration, Process Design, Reacting Conversion Systems, Multi-agent Systems.

# 1. Introduction

With the unsustainable anthropogenic greenhouse gases (GHG) emissions pressure, stemming from the intense demographic and economic growth since the industrial revolution, intertwining with the prevailing linear production and consumption model, the planet is attaining its limit of natural resources and its capacity to intake waste and pollution. Corollary to being consumed faster than they can be replenished at the current demand, resources are becoming scarcer and thus more expensive. The challenges the world is facing today enjoin an imperative for alteration from the linear economic model towards a sustainable paradigm that ensures meeting the present energy and material demands without jeopardizing the ability of future generations to meet their proper needs.

A global response on global warming was translated in restrictive political regulations<sup>1</sup> on anthropogenic GHG emissions to contend climate change and halt temperature rise through better energy and resource management. The daunting challenge of industries being to cope and comply with the current and upcoming ecological regulations inevitably impacts their economic performances. Nonetheless, by migrating towards Circular Economy, which is regenerative by design as opposed to the extractive linear model, an industrial entity can meet modern ecological standards while jointly cutting down its operating costs as well as its dependency on the fluctuating resources markets. Circular economy, Industrial Symbiosis and Process Integration are concepts developed in relatively separated scientific communities but aim reaching the same global target at different scales with different methodological means and details (Walmesly, et al., 2019). Among these concepts, Process Integration is a thermodynamic and an engineering driven approach allowing to design technical solutions implementing the Circular Economy concept.

At a single process scale, process integration leads to the reuse and recycling of its useless rendered products to be reintroduced back into the production cycle and thus majorly curb both its primary resource demand and waste emissions. On greater scope, partnerships can be made between neighboring industries through resource and waste exchange; one's waste thus becomes another's raw material and thereby evolving towards becoming an eco-industrial park (EIP) that drives economic

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<sup>1</sup> <https://ec.europa.eu/clima/policies/strategies/2020>

development for its participating parties while minifying their environmental footprint. Farel et al. (Farel, et al., 2016) have defined the EIP as the implementation of Industrial Symbiosis and Industrial Ecology. In their paper, they studied the mechanism of creation and governance of the most known EIP and concluded that a top down creation of EIP is less efficient than the bottom up ones. They suggested that a hybrid scenario where a bottom up creation process is organized by the help of a coordinator should achieve the highest integration of industrials. This process is complex since it needs:

- To assess the symbiosis potential
- To assess the infrastructure investment cost and each participant investment cost
- Choose and design waste streams regeneration or conversion process
- Share the costs and benefits among the participant

Indeed, to achieve strongly viable EIP structures, potential synergies that decrease resource usage or waste emission should be assessed to ensure their veritable physical feasibility. However, a company is improbably to adopt an identified synergy incurring additional investment costs unless it proves major cut down in operating expenses. Therefore modeling and optimizing industrial park networks in which energy and material flows circulates entail systematic integrated process design techniques which aggregate the sub-systems components for an overarching functionality. With their emphasis on the efficient use of resources, process integration techniques have resulted in significant benefits to the industrial sector in terms of process improvements, increased productivity, resource management, pollution prevention, and operating cost reductions (Morar & Agachi, 2010).

Even though the most practical and adequate methodology for industrial synergy design is mathematical modeling and optimization, Boix et al. highlighted in their literature review (Boix, et al., 2015) the lack of studies dealing with optimization to design optimal configuration of EIP. In fact, the state of the art territorial energy and mass integration mathematical optimization methods presented here after in section 2 are mostly built with a cooperative decision-making approach that doesn't account for the personal preferences of the actors. They implicitly assume a single economic entity with cooperative partners that exchange the established synergies following a single or multi-objective

global optimization framework, Figure 1. These objectives entail from the assessment of different aspects for the optimization criterion such as environmental objectives, economic gain and resource consumption of the generated results. Therefore, as elaborated these methods cannot be used for the design of an optimal EIP topology. That is because the more realistic version is for EIP industrial actors to share the investment costs and the benefits in a way enabling the accountability of their individual interest. Tan et al. (Tan, et al., 2016) proposed a systematic optimization methodology to propose an allocation of costs and benefits among participants in a cooperative EIP. This approach is interesting in the case of top down EIP creation process where the objective function is unique. However, as discussed earlier by Farel et al. (Farel, et al., 2016), the most promising governance scenario is a bottom up initiated one with most probably a different objective function for every actor.

Actually, in cooperative decision-making governance, industrial actors seek to achieve cooperatively a single shared common goal. Even though each actor may have different individual targets, their primary motivation is the global welfare maximization which consists of the sum of the entire individual profits associated to a given objective. Hence, the execution of an identified synergy is ensured by simply sharing the associated energy and material streams generating a single economic bill for the entire park. However, in non-cooperative decision-making, industrial actors are self-interested each with its own objective. They search to maximize their individual interests irrelevantly of the welfare of the territory and thus they only participate in implementing an agreement if it contributes in increasing their individual interests. For a synergy identified by two actors as more profitable to engage in than it would be for them without participating, the waste and by-products exchange is accomplished through purchase and selling transactions.

The existing process integration models should be amended to account for the costs and/or benefits of non-cooperative actors from participating in an identified exchange and requires to be built in a novel framework based on a non-cooperative decision-making approach that account for multiple objective functions for each participant (Boix, et al., 2015) (Leong, et al., 2017).

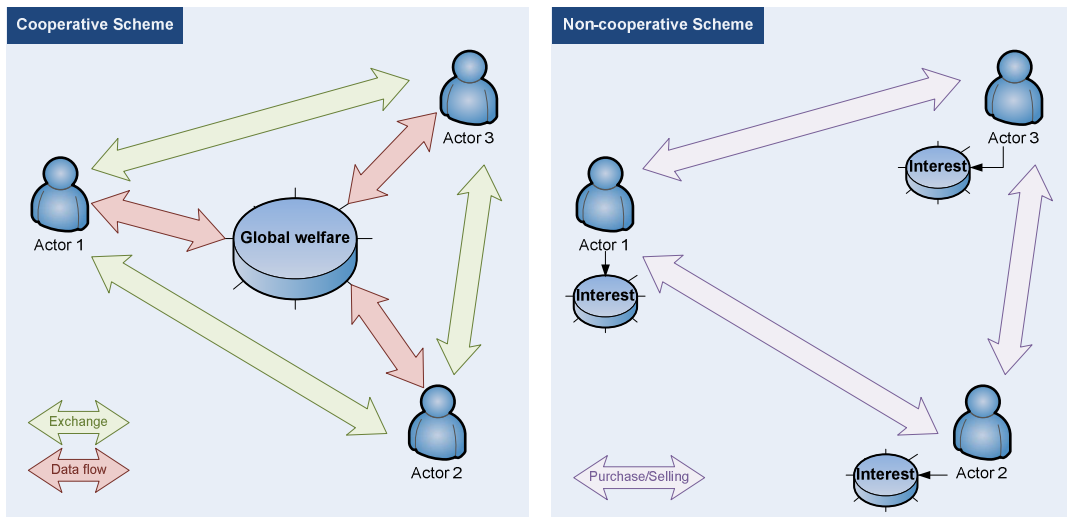


Figure 1. Industrial actors exchange in cooperative and non-cooperative schemes

Some studies employed game theory approach to account for different players interests. For instance, Chew, et al. (Chew, et al., 2009) proposed to post-treat the mathematical problem optimization results and to evaluate the resulting water network configuration based on Nash equilibrium. Nevertheless, being a posteriori approach, it does not guarantee an optimal configuration with multiple interest functions and thus does not overcome the drawback of mathematical modeling and optimization. Ramos et al. (Ramos, et al., 2018) proposed an optimization methodology of a utility network through game theory modeling. Their methodology is limited to the allocation of predefined utilities while taking into account that each actor has an operating cost to minimize. In addition to not accounting for the investment of the heat exchangers or for the transportation networks costs, they do not account for potential synergy between the waste discharge and raw materials of the industrial actors.

This work thus aims on surpassing the state-of-the-art limitations and contributing to the development of a conceptual framework for designing energy and material synergy pattern in an industrial territory with non-cooperative economic scheme governance. The actors' game is actually of great importance and critical to the eco-industrial park's emergence (Mortensen & Kørnø, 2019) and technical and economic feasibility alone is not sufficient. Hence the importance of the methodological framework proposed in this work that combines economic optimization and technical design with actors' personal interests for decision making. Its development encounters three prime methodological challenges:

- First, the process design must append multiple conversion systems of a defined waste with different product options. Not only the energy conversion potential of material is investigated, but other conversion alternatives would as well bring the possibility of turning the non-usable waste into another usable material through chemical processes.
- Secondly, process integration should be intertwined with process design for optimal synergies of both energy and material flows at the conversion system scale. At the inter-sites level, territorial process integration is ought to be carried out while accounting for exchanged streams transport networks. The heat network optimization problem must account for the quality (i.e. temperature) of the exchanged streams.
- Third, the developed methodology should account for the actors' game and thus be based on non-cooperative decision-making approach. In this economic scheme governance, the park's industrial participants manifest individual interests and only accept trading their streams if they believe that it will be more profitable for them to engage in the synergy than it would be without participating; hence waste and by-products exchange is accomplished through negotiated purchase and selling transactions. The problem formulation must account for industrial actors as independent actors each with its own objective function while modeling the interaction between them.

## **2. State of the art of Process integration**

Process integration, which was initiated in the late 1970s, has two main objectives; the first of which is to integrate the use of material (e.g., hydrogen and water) and energy to reduce their consumption, and the second corollary to the first, is to minimize the production of waste and harmful emissions to the environment.

The energy integration and the material integration methodologies investigate using a holistic approach the potential synergies between the resources demand and waste discharge of different process units. The untapped opportunities of the remainders from the local integration to be recovered by geographically proximate industrial sites could be evaluated through the territorial energy and

material integration. Employing these conventional techniques of process integration begets energy efficiency and optimal resource usage. Subsequently, the energy utilities and the raw materials required to meet the local and territorial demands are significantly decreased with the implementation of the identified synergies scenarios.

These integration techniques were extended to the site wide scale. Linhoff and Dhole (Dhole & Linhoff, 1993) introduced the total site analysis method (TSA) to handle energy integration between multiple plants. Similarly further published studies dealt with energy integration of multiple plants but were based on mathematical programming techniques (MILP) (Maréchal & Kalitventzeff, 1998) (Bagajewicz & Rodera, 2002). When multiple industrial sites are involved in the energy integration, the total site analysis (TSA), may encounter complexity imposed by the direct energy integration between the streams of each site. Tertiary heating networks provides the means to accomplish the inter-sites heat recovery. Farhat et al. (Farhat, et al., 2014) proposed a methodology for optimal network synthesis with tertiary network while considering the thermodynamic conversion systems. Their work was further elaborated with the proposition of a heat exchanger network optimization model (Farhat, et al., 2015) which accounts for both exergy and economic aspects of the heat transfer system.

The developed techniques for energy integration underwent extension towards the optimization of the process material exchange. The basic ideas of the thermodynamic heat exchanger network (HEN) analysis were used to introduce the concept of material allocation networks, in which material rich and poor flow (in contaminants) form the composite curves resulting in a material pinch by analogy to the heat pinch (El-Halwagi & Manousiouthakis, 1989). This two-step systematic methodology is designed to transfer material from a rich stream set to a poor stream set in order to reach the required contaminants concentrations while minimizing waste production and fresh resource demand. A significant change in the methodologies of the mass allocation networks synthesis and wastewater discharge minimization was introduced in 1994 (Wang & Smith, 1994). A graphical approach was proposed for targeting the minimum fresh water consumption and consequently the waste water production, through contaminants transfer from the material flow to the fresh water source. This method relies on the principle that concentration is the synergies driving force (El-

Halwagi, et al., 2003). The limitations of mass allocation network methods which are developed for minimizing the discharged and the fresh resources have led to a new way for treating the problem through the source and sinks representation (Dhole, et al., 1996). This representation is appointed by the recycling/reuse problem and it consists on assigning different sources (supply) to sinks (demand) so the fresh source consumption is minimized (El-Halwagi & Spriggs, 1998).

The recycling/reuse based mass integration techniques are limited to the problem governed by the material flow compositions. However, process units are not confined just to this criterion but also to the material stream properties such as pH, density and viscosity. Hence the development of a new generic approach based on the key properties' evolution in addition to the essential components is presented in (Shelley & M. El-Halwagi, 2000). Unlike chemical components, properties are not maintained and thus cannot be traced throughout the process without conducting material balances for each component. Therefore, to overcome this limitation, properties tracing is carried out through the development of conservative quantities, called 'clusters' which substitute the non-conservative properties. These clusters are designed to maintain two basic rules for conservation within and between streams. This new technique of material exchange network design was subsequently generalized to tackle the properties integration problem (El-Halwagi, et al., 2004).

Alternative approaches to that of the material pinch have been developed to formulate network synthesis methods based on mathematical programming techniques. These studies usually consider the contaminants concentration in the material streams as the main limit to be dealt with for the network design. However, these models are applicable to moderate size problems as combinatorial complexity increases exponentially with the number of material flows (Klemeš, et al., 2013). The first mathematical optimization program based on properties tracing for the mass integration networks synthesis was reported in 2009 (Ponce-Ortega, et al., 2009). For the recycling/reuse problems, mathematical programs which consider several components were also developed (Savelski & Bagajewicz, 2001). One of the recent studies of the material allocation networks design which uses mathematical programming is the approach presented by Ghazouani, et al. (Ghazouani, et al., 2015). The network design problem is formulated by a MILP model whose objective function includes fresh resources, waste streams and utilities leading to the minimization of the annual cost. The sources and



sinks composite curves were used to determine the allocation restrictions between the material streams and thus inducing a reduction of the solution's search space. The heat integration of the material streams is conducted simultaneously using an energy cascading model, wherein the temperature scale is discretized in order to linearize the problem. By building a defined temperature scale for the energy cascade model, it became possible to split the main flow into several streams that will first exchange heat through the heat exchanger network and then through their mixture.

The two previously overviewed techniques, which are embedded in the process integration family, allow the identification of potential synergy scenarios whether on the process scale or at the inter-sites level. Subsequently, they design networks to intelligently redistribute energy and material between different sources and sinks to ensure the interchange between the industrial participants. However, these methods may be missing out on prospect synergies as a consequence to the abiding form of the system flows. For further efficient resource management and environmental burden reduction, the form alteration of unrecoverable waste through conversion processes is mandatory to introduce them back into the system under another usable energy or material product more suitable to the system's needs. Consequently, bridging the gap between the mass and heat integration methods by incorporating conversion systems for the non-recoverable streams in their initial form ensues a giant step towards closing the energy and material loops.

The synthesis and design of the synergies resulting from conversion systems implementation can only be achieved after applying process design techniques to systematically identify the optimal system flows. The state of the art of process design in the industrial ecology context is quite recent and limited on several aspects. Hugo and Pistikopoulos (Hugo & Pistikopoulos, 2005) proposed a methodology serving as a decision-support tool for environmentally conscious strategic planning and design of supply chain network. Although their approach optimizes the process design while considering several products and several sources, it does not take into account the energy and material integration on both local and territorial scale. In a similar context, Palazzi, et al. (Palazzi, et al., 2007) have developed a systematic method for the identification of the optimal configuration of an integrated energy system served by a superstructure formed by multiple alternative choices for each step of the system. This superstructure is constructed subsequently to defining the process steps and conducting a

survey of the possible technology options for each of those. However, these options consider converting a source into a defined product, thus for any chosen pathway the end product is the same. Therefore, the scope of this method is limited to the optimization of a conversion system design which generates a beforehand selected product. Gassner and Maréchal (Gassner & Maréchal, 2009) also developed a method for the definition of a conversion system optimal configuration in terms of operating parameters based on splitting the problem into several parts. Their method addresses the problem on the local process level, and it is intended for the optimal design of a conversion process with a single predefined product. Moreover, not only the integration step is limited to the energy aspect, but it does not include the material integration. Gerber, et al. (Gerber, et al., 2011) proposed a methodology for integrating life-cycle assessment (LCA) in a thermo-economic model for energy conversion systems optimal design. To perform this approach, they added a new layer to the methodology developed by Gassner and Marshal (Gassner & Maréchal, 2009). In its original form, the performance evaluation was limited to an economic model. Yet, in order to include environmental indicators, they have developed a life-cycle analysis model with which they amended the previously developed method. In contrast to previously developed methodologies, this methodology considers systems converting a resource to several products and not just into a single one. However, it is limited to the energy demand with no regard to materials product. Moreover, this approach does not consider the integration problem at the material scale. Based on previously developed methodologies, Gerber, et al. (Gerber, et al., 2013) worked on developing a new approach of process design while considering industrial ecology, process integration as well as life-cycle assessment for the identification of optimal conversion systems configurations. While their methodology is promising and enables preliminary system design, it is not suited for eco-industrial parks since their approach requires representing the involved actors' multiplicity and accounting for transportation networks.

Lacking the possibility of identifying economically feasible conversion pathways for the unrecoverable waste from conventional integration methods which is adaptable to the territorial scale demands, a need for a methodology to go one step further in closing the loop towards industrial ecology is compelling. This methodology should be capable of addressing energy and material discharge recovery while encompassing the form alteration of unrecoverable waste via conversion

systems. It will enable to design optimal industrial symbiosis configurations which lead to mitigate waste generation and resource intake of the industrial park for a cleaner production.

### **3. State of the art of agent based modeling**

As opposed to cooperative scheme, in non-cooperative scheme actors constantly explore strategies to find their own individual interests at the expense of the whole territory, i.e., the industrial park. These systems can be difficult to control with a top-down centralized mechanism owing to the autonomy that each actor exhibits; thus, designing energy and material synergy patterns in a territory with self-interested actors requires a different framework. With the need to partition the analysis or synthesis of the system into sub-problems, this system can be defined as a complex system (Bakule, 2008). The aforementioned consists of many components acting and reacting to each other's behavior and whose aggregate activity is nonlinear. To model and simulate complex systems, agent-based models (ABMs) form arguably a generalized framework for this purpose (Sayama, 2015).

Actually ABMs derived from distributed artificial intelligence; the objective shifted from reproducing the knowledge and reasoning of one intelligent agent to several heterogeneous agents each with its own goal and thus need to coordinate actions to meet these goals (Bousquet & Le Page, 2004). They were successfully applied for solving problems that require distributed reasoning, decentralization and coordination. ABMs, also called multi-agent systems (MAS), are systems composed of a collection of interacting computational components known as agents (Bogg, et al., 2008). These agents are capable of controlling their own behavior, i.e., have autonomy of action, with each acting in the furtherance of their own goals while interacting with each other in a shared environment. They are able to achieve this by perceiving their environment through sensors and acting upon that environment through their actuators (or effectors) (Russell & Norvig, 1995).

Typically, agents can only intercept, process and react to their environment but cannot control it. They choose whether to cooperate or to compete based on the payoffs and costs for choosing one of either options. Those payoffs may vary depending on the game they are engaged in with other agents.

Some scenarios have very low incentive for cooperation while favoring competition; these are called zero-sum game, while others have much lower costs and higher payoffs for cooperation.

Wangermann and Stengel proposed a novel method for coordination in MAS using principled negotiation (Wangermann & Stengel, 1999). This negotiation technique is based on the book "Getting to Yes" by Roger Fisher & William Ury, 1991. It focuses on the negotiating parties' interests not positions, generates options for mutual gain and uses objective criteria to evaluate them. This means negotiators should propose new solutions allowing gains for both parties, not fight over the original positions which assume a zero-sum game with only one winner. Using this technique Wangermann and Stengel (Wangermann & Stengel, 1999) developed an iterative optimization method for MAS where an initial master plan formulates each agent's actions before the agents repeatedly search for alternative plans that ensure mutual gain. An agent proposes the option which it finds in the furtherance of its interests and then the others accept or reject it after evaluation. With no rejections the proposed option is implemented. However, if one agent does reject it, it transmits a message with the reasons for rejection to the proposer. This latter enhances its search based on this information. Depending on an agent knowledge about other agents, its options search space could be limited to its own feasible set of plans or may extend to include others action plans. There is no guarantee that its proposed option would not decrease other maximizers' utility functions when it has no knowledge about other agents. Moreover, agent actions are not necessarily affected by every proposed option plan. Therefore, to prevent needless communication between agents while ensuring good coordination when no knowledge is possessed about other agents, the authors proposed the use of a coordinating agent that evaluates proposals and passes them on to the concerned agents. This coordinator only requires the information to be able to assess the agents' interactions and not optimize their actions. The principled negotiation technique is particularly interesting since it does not require any agent to have a global knowledge of the other agents' utility functions.

Romero and Ruiz (Romero & Ruiz, 2014) have put forward an analytical model based on ABMs for the assessment of cooperative relationships among actors in eco-industrial parks (EIPs). They defined the object of the simulation by five indexes that measures the overall system evolution based on environmental and economic criteria. They formulated the agents' structure according to their

proprieties and behaviors rules. The aforementioned considers agents with goal-directed behaviors and thus the satisfaction level of their objectives is the criterion conditioning their actions. Hence the satisfaction level of employing the strategy  $q_x$  is exhibited with the utility function  $P(q_x)$  which is the sum of four indexes evaluating economic profit, social benefit, environmental impact and the advantage strategy degree. Those indexes assess the improvement gained by applying the strategy  $q_x$  relative to the situation where no exchange with other agents is performed. Each index is assigned with a weighting coefficient to adjust its contribution in the utility function. The authors considered the interaction between agents to be conditioned first by the possible substitution of agents flows and then by agents' behavioral rules. Therefore, they established a knowledge database including different flow substitutions that matches resources with wastes that could substitute them. Once the wastes are determined, they serve as searching parameters to identify agents generating such wastes or byproducts and thus may be interested in material exchange. An agreement about the quantity to be exchanged should be settled between seller and buyer agents where the payoffs of each strategy is computed by the utility function  $P(q_x)$ . Based on non-cooperative game theory, each agent proposes four strategies build upon the quantity of exchanged waste  $q_x$  relative to either resources quantity  $rq_j$  for the buyer agent, Eq.(1), or wastes quantity  $wq_k$  for the seller agent, Eq.(2). Nash equilibrium served to define the best strategy of which both parties would not deviate.

$$\text{Buyer : } q_{A_i} = \{q_{A_i}^1 : q_x > rq_j, q_{A_i}^2 : q_x = rq_j, q_{A_i}^3 : q_x < rq_j, q_{A_i}^4 : q_x = 0\} \quad (1)$$

$$\text{Seller : } q_{A_i} = \{q_{A_i}^1 : q_x > wq_k, q_{A_i}^2 : q_x = wq_k, q_{A_i}^3 : q_x < wq_k, q_{A_i}^4 : q_x = 0\} \quad (2)$$

Another application of agent-based systems in the industrial symbiosis context is proposed in the work of Albino et al. (Albino, et al., 2016). Their study aims at exploring the capacity of contractual mechanisms to foster stable industrial symbiosis relationships. They assume that industrial network to be made up of  $N$  firm agents which are defined as production stages. Each of the firm agents is able to choose whether it wants to establish a new synergy or maintain a current symbiotic relation with another firm if its willingness to commit function is above a defined threshold. As in the

previously discussed work an agent decision is driven by a utility function. Their model supposes full disclosure information for the required raw material and produced by-products with exclusive relationships. In other terms a firm can only receive waste from one agent and in return can only transfer its waste to one agent; this aspect limits the opportunities for collaboration and synergies.

From the above exhibited literature work, it can be induced that two main techniques could be employed for self-interested agent strategies establishment: Game theory and coordination techniques. Both of these techniques are further explored in the following sections.

### **3.1. Game Theory – exchanging preferences**

Game theory is the discipline of studying strategic interactions between self-interested actors with respect to their preferences. Its foundation traces back to 1944 to the work of Neumann and Morgenstern (Von Neumann & Morgenstern, 1944). Their analysis was restricted to zero-sum games and was expanded by Nash (Nash, 1951) in the 50s to include wider variety of games.

The two main problems in applying Nash equilibrium is, first that this equilibrium may not exist in some games and second that other games could have multiple Nash equilibrium thus the players will be bewildered on which action to take (Weiss, 1999). The second drawback of Nash equilibrium is that sometimes efficiency goals and stability goals conflicts as exhibited in the canonical prisoner's dilemma which illustrates why intelligent agents might not cooperate even though it is in their best interest to do so.

### **3.2. Coordination techniques**

Agent dynamics are functions of positive and negative feedback loops. Consequently, the actions of one agent in turn have an influence on the future behavior of another. Therefore, agents must coordinate their actions to meet their individual goals mutually. To formalize the coordination strategies among agents three main issues should be addressed: decision-making, control structures and communication (Bousquet & Le Page, 2004). Agents could either have centralized or decentralized control structures that define their hierarchical relationships while a coordinating agent

could also be employed to avoid conflicts or needless communication. The aforementioned can be carried out through passing different sorts of information like data, solutions, constraints and preferences among agents. Different classifications of coordination mechanisms have been proposed in literature for MAS. Shaw and Fox (Shaw & Fox, 1993) proposed a set of coordination mechanisms of which coordination by revising actions, by synchronization, by negotiation, by exchanging preferences (using game theory approach), by structured group mediation, by opportunistic goal satisfaction and by constraints reasoning. Whereas Jennings (Jennings, 1996) considered that the most common mechanisms for managing coordination are confined to three mechanisms: organizational structuring, meta-level information exchange and multi agent planning. Mariano and al. (Mariano, et al., 2001) added contracting approach and reactive tuple spaces (also known as Blackboard) to the classification of Jennings.

In the context of a non-cooperative scheme of the industrial park the most appropriate and realistic mechanism for agents' coordination takes shape in negotiation. Therefore, following Jennings classification (Jennings, 1996), we briefly explore in the following sections organizational structure and multi-agent planning and we go more in depth into the coordination by negotiations.

### **3.2.1. Organizational structure**

This coordination approach consists of organizing agents in a hierarchical community which specifies information and control relationships amongst them. Those control relationships shape the interaction between agents and thus help their coordination. The higher level informs the lower level of the actions to undertake, in contrast to flat structure where this is attainable exclusively by negotiation.

### **3.2.2. Multi-agent Planning**

The coordination by multi-agent planning consists of agents specifying their future actions and interactions in plans to achieve certain objectives. In this approach agents are fully aware of each action they will conduct, and other agents' activities that they will undertake and the interactions that

will occur. The required information involved to constantly reconstruct the plans demand more computational and communication resource than the other two coordination mechanisms.

### **3.2.3. Negotiation mechanisms**

The joint agreement reached by two or more agents each trying to attain its individual goal is called negotiation. The preference of agent  $i$  of agreement  $\alpha$  over an alternative agreement  $\alpha'$  is represented by the preference relation  $\alpha \preceq_i \alpha'$ . Employing utility theory helps mapping an agent interests over a set of available alternatives by real numbers and thus quantifies the agent degree of preference (Shoham & Leyton-Brown, 2009). Hence a utility function  $u_i$  representing the preference relation  $\preceq_i$  is such that:  $\alpha \preceq_i \alpha' \Leftrightarrow u_i(\alpha) \leq u_i(\alpha')$ .

The negotiation is a strategic interaction that follows certain protocols defined by a set of rules such that the available actions for each negotiator and the sequence of their interaction. These protocols can be evaluated according to many criteria governing the choice of the negotiation mechanism according to the desired properties of the system (Weiss, 1999).

- Pareto efficiency: An agreement  $\alpha$  is Pareto Optimal or Pareto efficient if there is no other agreement  $\alpha'$  that would be better for at least one agent without being worse for any other. This criterion has a global perspective and is used to compare the solutions reached by the negotiation protocol.
- Social Welfare: This criterion is employed to evaluate alternative solutions reached by measuring the global good of agents. The sum of all agents' utilities associated to a given agreement is the social welfare. This property forms a subset of Pareto efficiency.
- Rationality: A self-interested agent would not participate in a negotiation if the payoff of the negotiated agreement is not higher than the payoff it would get without participating in the negotiation.
- Stability: Negotiation mechanisms are stable when agents have no incentive deviating from the desired agreement.



- Computational efficiency: Negotiation protocols should be designed with a limited computational burden.

Negotiations can be distinguished in three types according to the number of parties involved in the negotiations: One-to-one, one-to-many and many-to-many negotiators. Some examples of popular negotiation protocols are discussed below according to the aforementioned classification.

### **a) One-to-one negotiation – Bilateral bargaining**

Bilateral bargaining is a socioeconomic problem involving two agents with a common interest to cooperate but with conflicting solutions to achieve this cooperation. The negotiation protocols of non-cooperative bargaining games with complete information can be used by two players to divide a given surplus resulting from the profit of reaching an agreement. Li and al. (Li, et al., 2003) discussed three protocols for such negotiation:

- The ultimatum game: One agent proposes a split of the surplus while the other can either accept or reject the offer. Both players end up with nothing in the case of refusal.
- Monotonic concession protocol: The protocol proceeds in rounds; in each both agents simultaneously make an offer. An agreement is reached when the offer of one player scores at least as high as the counter player current proposal. In the case where both offers hold, the proposal is selected by tossing a coin. If no agreement is reached the players can either concede by proposing a better offer or stand firm.
- Alternating offers: one player offers a fraction of surplus to the other player. This latter can either accept, reject or propose a counter offer. If the player does propose a counter offer, the initial proposal maker can either accept, reject or propose another counter offer. The loop goes on until one player accepts the proposal of its opponent.

Bilateral Bargaining with one sided incomplete information is when the buyer is informed about the seller (the buyer knows the seller's cost price) while the seller has no information about the other party (Li, et al., 2003). Three negotiations protocols for this type of games are the seller-offer

game, the buyer-offer game and the alternating-offer game. In the first game the seller makes an offer that the buyer can either accept or reject. Whereas in a buyer-offer game, the buyer proposes an offer considering the seller's cost since the seller will only accept it if it is higher than its cost. As its name points out, in an alternating-offer game the players keep alternating between proposing and responding until an agreement is reached.

## **b) One-to-many negotiation – Single sided Auctions**

Auction mechanisms provide easily implemented protocols for one-to-many negotiation. They are popularly employed for allocation of tasks, resources and goods. A single sided auction setting is made up of an auctioneer agent (the seller) and a collection of bidders agents (the buyers) with the goal for the auctioneer to allocate an item to one of the bidders (Wooldridge, 2002). The agents are self-interested thus the auctioneer plays to maximize the allocating item price while the bidders try to get it at the lowest price. Auction mechanisms may vary along with three main dimensions (Wooldridge, 2002). The first is the determination of the winner bidder and the price he pays for the allocated item. Protocols where the bidder with the highest bid wins and pays the bid amount for the item are known as first-price auctions. However, there is another type known as second-price auction where the highest bidder wins but pays the amount of the second highest bid. Another dimension is the visibility of bids between bidders. When bidders know each other bids the auction is said open-cry conversely when they are not able to know bids made by other agents it is said sealed-bid auction. The third dimension is how bidding proceeds. If the bidding goes only for one round after which the winner is allocated the item, the auction is a one-shot auction. The second option is for the bidding price to start low and increase in successive rounds, this is an ascending auction. Alternatively, descending auction is when the auctioneer starts with a high price and decrease in successive rounds. Some of the widely known auction protocols are:

- English Auctions: The auctioneer starts with a low reservation price which could be zero. Then in each round agents must bid more than the highest current bid. The auction ends

when no agent is willing to raise the bid and the item is awarded to the highest bidder that pays that amount. English auctions are thus first-price, open cry, ascending auctions.

- Dutch Auctions: The auctioneer starts offering the item for a very high price and lowers it a little bit in each round; first bidder to accept the current offer is allocated the auctioned item. These auctions are open-cry, descending.
- First-price Sealed-Bid Auctions: These are an example of one round auction where bidders submit an offer privately for the item to the auctioneer. This latter award the item to the highest bidder.

### **c) Many-to-many negotiation – Markets**

The business definition of a market is where forces of demand and supply interact to trade goods or services for money. Unlike conventional one-sided auctions with a single, centralized auctioneer and many buyers, double auction markets (two-sided auction) consist of multiple buyers entering in competitive bids to purchase commodities offered by competing sellers that submit simultaneously their ‘ask price’ to the market. Hence double auction markets balance demand and supply efficiently in a decentralized system (Vytelingum, et al., 2008). In a continuous double auction (CDA), bids and asks are matched immediately if possible, otherwise orders are recorded in the order book. A CDA lasts for a certain period of time known as trading period during which offers, and orders are continuously accepted.

Another well-known negotiation mechanism based on market structure is the Contract Net protocol (CNP) defined by Smith and Davis (Smith & Davis, 1981) for task allocation.

## **4. Model Formulation**

The non-cooperative scheme of an industrial park is supposed to be in this research study the situation wherein industries, geographically located in the predefined boundaries, search to increase their personal gain instead of that of the park. This personal interest pursuit associated with a lack of communication engenders a detriment on synergies that eventually could be more beneficial for the park’s industrial actor’s economy if put in place and could thus directly influence their environmental

footprint. To avoid this, we propose a MAS that enables the interaction between actors in the aim of executing potential synergies that are in favor of each of the industries.

Based on the previously explored strategy establishment techniques, game theory is found to be inapplicable in the displayed context in which agents must coordinate their actions to meet their individual goals mutually; since efficiency and stability goals sometimes conflicts in game theory so intelligent agents might not cooperate even though it is in their best interest to do so. Nevertheless, the coordination through the negotiation mechanism is more adapted for self-interested agents, while organizational structure and multi-agent planning suits more non-antagonistic agents (Weiss, 1999).

Consequently, the selected interaction model is based on the negotiation mechanisms with three types of agents involved: network investor, industrial agent, potential agent. The network investor agent negotiates with the other two agents to trade energy and material streams through bilateral bargaining following the alternating offers protocol. It takes in charge the investment and the installation costs of the pipelines that ensure the inter-sites material and energy streams transportation.

Each industry in the predefined boundaries is accounted for as an industrial agent  $IA_i$  which belongs to the industrial agents set  $IA$  defined below. The total number of existing sites is denoted by  $n$ . The third type of agents is the potential agent  $PA_{ik}$  which is an element of the set  $PA$  containing the entire potential agents. As its name states,  $PA_{ik}$  is a potential buyer of  $IA_i$ 's waste  $W_i$ . This type of agents is none-existing in the territory.

$$IA = \{IA_i \mid IA_i \text{ is an industrial site } i \text{ located in the predefined boundaries of the park}\}$$
$$PA = \{PA_{ik} \mid PA_{ik} \text{ is a potential conversion system investor } k \text{ for waste } W_i \text{ of } IA_i\}$$

The potential agents of the same waste first compete to trade  $W_i$  with  $IA_i$  and then the identified winner invests in a conversion system to transform the original form of  $W_i$  into a new product to be sold in the park. Therefore, this winner, as it is appended to the territory, becomes an industrial agent  $IA_{n+1}$ . The conversion system investor can also communicate with the network investor to either buy or sell heat or matter from the network. To identify a  $CS_s$  as a  $PA_{ik}$ , a  $CS$  database containing the resources required by different conversion systems and their products is went through to

find resource matches for each  $W_i$ . The interaction work flow between these agents for the non-cooperative scheme is illustrated in Figure 2.

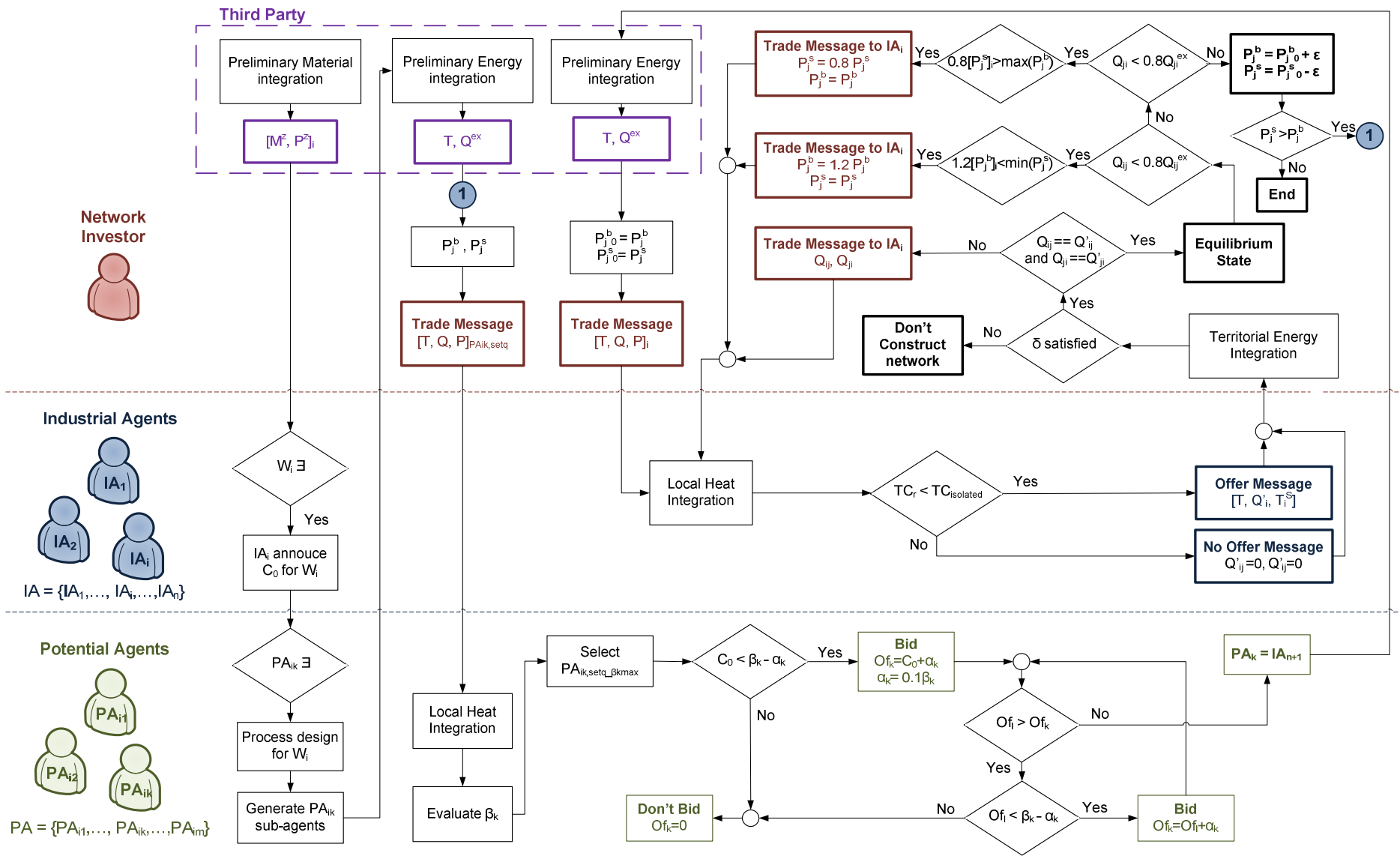


Figure 2. Agent interactions work flow framework for the territorial integration of conversion systems in a non-cooperative scheme

The conceptual framework is based on three primordial methodological bricks which are process design and both process integration on the system level and on the territorial scale. The required models for the integration problems were selected from the state of the art.

Local energy integration is a holistic approach that takes advantage of potential interactions amongst the process units to maximize heat recovery and thus minimize energy consumption. The heat exchanger network synthesis (HENS) manifests as the key step to implement the identified synergies for a given process. It ensures economically optimal design that enables reaching the minimum energy targets computed by the pinch analysis. The limitations tied to the manual calculation procedure that employs the well-known HENS methodologies based on the pinch analysis led to the development of mathematical programming alternatives. These latter can either be formulated using sequential or simultaneous solving strategies. While sequential techniques consist on partitioning the HENS problem, simultaneous methods search for optimal design by solving the entire problem at once. Not decomposing the problem might require using non-linear formulations which may lead to numerical resolution difficulties and for a non-convex problem the resulting solution is probably the local and not the global optimum. Nonetheless, linearizing the problem mainly by creating a discrete temperature scale and approximating the heat exchangers area computation enables employing linear programming optimization techniques to perform a simultaneous resolution of the problem without encountering the non-linear numerical difficulties. Many models using the linearization techniques have been developed in the aim of designing realistic heat exchanger network. Among recent works, the mixed-integer linear (MILP) model that have been proposed by Barbaro & Bagajewicz and which enables the approximation of the heat exchanger areas while handling stream splitting, non-isothermal mixing and permitting multiple matches between two streams (Barbaro & Bagajewicz, 2005). The extension of this MILP was carried out by the research work lead by Zoughaib (Zoughaib, 2017) to additionally feature the incorporation of multiple heat exchanger technologies. The temperature scale is partitioned into several intervals in each zone to ensure the linearity of the problem. Using the temperature intervals, the model, which is actually based on the transshipment-transportation paradigm, is able to generate the energy and flow balances. The objective function of the problem is to minimize the total cost engendered from the installation of the identified synergies in the process. The

total cost includes the heat exchanger costs and the employed utilities to cover the remaining surplus heat and energy deficit after the synergies establishment. The model developed by Zoughaib (Zoughaib, 2017) as an extension of Barbaro and Bagajewicz research work (Barbaro & Bagajewicz, 2005) was selected to be employed as the local energy integration model. As for designing the local material allocation network (MAN), the selected methodology to be employed, which is reported in the work of El-Halawgi (El-Halwagi, 2012), is formulated as a mixed-integer linear problem (MILP) based on the fixed flow rate hypothesis that ensures better flexibility on the sources and sinks quality specifications. The developed models by Farhat, et al. (Farhat, et al., 2015) were chosen to be used in this work for the territorial energy integration. Their work consists of two MILP models which can be resolved either sequentially or simultaneously. The first is based on coupling TSA and exergy analysis in the aim of enhancing the territorial exergy efficiency through optimal heat transfer networks and thermodynamic conversion systems. For a sequential resolution, the networks capacities and temperatures from the first MILP make the input for the second MILP that evaluates the proposed heat exchange economically. It employs an economic objective function considering the network investment that takes account of the industrial sites' geographical positioning to specify the routing, sizes of pipes and the areas of heat exchangers and utilities' operating costs.

In addition to the three aforementioned types of agents, a Third Party intervenes to conduct the preliminary studies of the territory ensuring that no agent possesses an overall knowledge of the circulating energy and material flows in the park. The Third Party collects the industrial agents' energy flow temperatures and heat flux. It then carries out the total site analysis based on exergy evaluation of optimal heat exchanges possibilities between the agents included in the problem. Afterwards, the Third Party transmits to the Network investor the identified steam network temperatures  $T$  and the possible heat to be transferred to and from the network  $Q^{ex}$ . The aforementioned sets are defined hereafter along with two other sets of the problem,  $Q$  and  $P$ . Those are related to the Network Investor trading messages sent to the involved agents and are introduced in the following paragraph.



$T = \{T_j \mid T_j \text{ is the temperature number } j \text{ of the steam network}\}$

$Q^{ex} = \{Q_{ij}^{ex} \mid Q_{ij}^{ex} \text{ is the maximal heat transferred/received from/by agent } i \text{ to/from the network at } T_j\}$

$Q = \{(Q_{ij}, Q_{ji}) \mid Q_{ij}/Q_{ji} \text{ is the heat load transferred/received from/by agent } i \text{ to/from the network at } T_j\}$

$P = \{(P_j^b, P_j^s) \mid P_j^b \text{ is the buying price for heat at } T_j \text{ and } P_j^s \text{ is its selling price proposed by the Network Investor}\}$

According to the received evaluation from the third party, the network investor generates a specific Trade Message for each  $IA_i$  consisting of the network temperatures  $T$  it will construct, the amount of energy  $Q_{ij}$  and  $Q_{ji}$  the Network Investor will buy or sell to Industrial agent  $i$  at the buying and selling prices  $P_j^b$  and  $P_j^s$  respectively. The specific Trade Message sent to  $IA_i$  is therefore constructed using the three sets:  $[T, Q, P]_i$ . At the network temperature  $T_j$ ,  $IA_i$  can either transfer  $Q_{ij}$  to the network or receives  $Q_{ji}$  from it. Consequently, at each network temperature only one of these two quantities can have a positive value. As for the  $P$  set, it is created relative to the Market heat utility price that varies according to the utility's temperature which is in this case  $T_j$ .

The selling and buying prices are reevaluated at each iteration of the entire problem according to the heat utility price and supposing a linear variation slopes formed by a new introduced parameter  $Cost\%$ . The  $P_j^b$  is assumed to be a fraction represented by  $Cost\%$  of the utility price. Since this parameter is defined as being directly proportional to the problem's number of iterations with a 10% step (a parameter that could be altered), the buying price starts from zero and increases progressively in each iteration. As for the selling offer  $P_j^s$ , the network investor proposes to supply heat at the heat utility price and then this offer decreases in the following iterations in function of  $(1 - Cost\%)$ .

Simultaneously to the preliminary energy integration evaluation, the Third Party conducts a preliminary territorial material integration by assessing the resources demand and waste discharge of the  $IA$ . It subsequently informs each concerned agent  $i$  with whom it can trade to get its resources or give its wastes through the Material Message  $[M^z, P^z]_i$ . This latter is formed by the amount  $M^z$  of the exchanged material  $z$  and by the price of  $z$  which is assumed equal to its Market price for both buying and selling agents when both of these  $\in IA$ . The newly introduced sets are defined as follow:

$M^z = \{M_{ip} \mid M_{ip} \text{ is the mass flow of material } z \text{ transferred from agent } i \text{ to agent } p\}$

$P^z = \{(P^{z,b}, P^{z,s}) \mid \text{the buying and selling prices respectively for material } z \}$

However, when a network is required to transport material  $z$  to establish an identified synergy, the Network Investor takes in charge putting in place the pipeline and becomes the intermediate agent for exchanging material  $z$  between two Industrial agents. Therefore, it charges the Market price for selling  $z$  and pays less for the agent from whom it is buying  $z$  in order to achieve a return on its investment. By evaluating the received Material Message and its waste discharge, each  $IA_i$  is able to identify whether or not it has a waste  $W_i$  that has no possible synergy in the territory in its existing form. If that is the case,  $IA_i$  announces the start of a single sided auction for its non-usable amount of  $W_i$  at an initial price  $C_0 \in \mathbb{R}^+$ .

The auction's participants are the potential agents which are identified by running through the CS database searching for the possible  $W_i$  conversion systems. This database consists of physical and economic processes models formulated based on their energy and material balances. According to the auctioned annual quantity of  $W_i$ ,  $PA_{ik}$  evaluates its system design parameters and size it for the complete use of  $W_i$  since the auction is based on the concept of 'Take it or leave it'; meaning that the auction's participants can only place their bids for the entire auctioned quantity of  $W_i$ .

Once the potential agent  $PA_{ik}$  sizes its conversion system, it generates different sub-potential agents by modifying the operating parameters of its process units, thus creating multiple  $PA_{ik, \text{set } q}$ , namely:  $PA_{ik} = \{PA_{ik, \text{set } q} \mid PA_{ik, \text{set } q} \text{ is a sub-agent of } PA_{ik} \text{ with the operating parameters set number } q\}$ . For every created sub-agent in the potential agents' population, which is depicted in Figure 3, the Third Party takes on the energy entailed from the conversion system in order to conduct a territorial exergetic energy integration supposing in its problem  $PA_{ik, \text{set } q}$  an industrial site of the territory along with the existing  $IA$ . It also evaluates the territorial opportunity usage of  $PA_{ik, \text{set } q}$  produced material streams through the territorial material integration. Then the Network Investor employs the transmitted results from the Third Party to generate the specific Trade Message for  $PA_{ik, \text{set } q}$ :  $[T, Q, P]_{PA_{ik, \text{set } q}}$  and its Material Message  $[M^z, P^z]_{PA_{ik, \text{set } q}}$ .

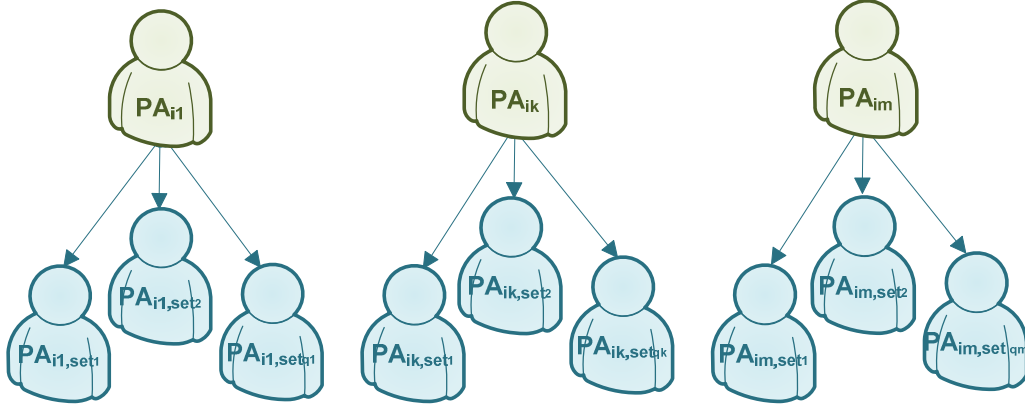


Figure 3. The potential agents' population

Accounting for the received Trade Message,  $PA_{ik,set\ q}$  carries out its local heat integration problem. Actually, each time an agent receives a Trade Message from the Network Investor, it creates new utilities with the proposed network temperatures aiming to incorporate the offered trade in its problem and to eventually evaluate it. When the offered trade at  $T_j$  refers to the amount of heat  $Q_{ij}$  the Network Investor wants to buy from  $IA_i$ , this latter appends this proposition to its problem as a cold utility at  $T_j$  with a negative cost equal to the price  $P_j^b$ ; whereas for an offer from the Network Investor of selling  $Q_{ij}$  at  $T_j$ , a hot utility is created with a cost of  $P_j^s$ .

The sub-potential agents use the results from their local integration to evaluate the highest price they can bid at to get  $W_i$  and reach the return on investment goals. A new set is introduced, namely:  $\beta_k = \left\{ \beta_{kPA_{ik,set\ q}} \mid \beta_{kPA_{ik,set\ q}} \text{ is the maximum amount } PA_{ik} \text{ is willing to bid for } W_i \right\}$ . To assess its bidding limit,  $PA_{ik,set\ q}$  accounts for its entire investment and operating costs according to Eq.(4) and considering a number of operating years manifested in the parameter 'Nbr<sub>year</sub>'.

$$\beta_{kPA_{ik,set\ q}} = - \left[ \text{Opex}_{HEN} + \text{Opex}_{CS} - \text{Revenue}_{CS} + \frac{\text{Capex}_{HEN} + \text{Capex}_{CS}}{\sum_{y=1}^{\text{Nbr}_{year}} (1 + \text{DRate})^{-y}} \right] \quad (4)$$

The operating costs of  $PA_{ik,set\ q}$  cover the resources expenses required to maintain the conversion system operation as well as the local heat utility demands which are assessed during its local energy integration. As for the capital cost, it embeds the investment needed to implement the

conversion system and those to install the heat exchangers needed to establish synergies between its internal heat streams. After evaluating the maximum bidding potentials of its entire sub-agents population,  $PA_{ik}$  selects the agent with the best operating parameters set that results in the uppermost  $\beta_k$ . It hence enters the auction for  $W_i$  with this sub-agent, meaning that  $P_{ik, set q_{\beta kmax}}$  becomes  $PA_{ik}$ .

The agents' interaction during the auction course is based on the one-to-many negotiation based on the English auction protocol. To decide if it is possible for it to place a bid in the auction,  $PA_{ik}$  first examines its  $\beta_k$  compared to the initial announced price  $C_0$  for  $W_i$ . If it manifests as profitable,  $PA_{ik}$  places a bid  $Of_k$  higher than  $C_0$  by  $\alpha_k$  which is defined as ten percent of its  $\beta_k$ . Each potential agent participating in the auction keeps on proposing greater bids than the others' previous offers until it reaches its bidding limit and thus gets out of the auction. This latter ends when no agent is willing to raise the bid and  $W_i$  is awarded to the highest bidder. The winning potential agent becomes a new industrial agent; hence the industrial agents' number increases by the addition of the conversion system agent to the initial  $n$  sites, by that  $IA$  tallies  $N$  elements:  $IA = \{IA_1, IA_2, \dots, IA_n, IA_{n+1}\}$ . The trade the auction's winner is going to establish with  $IA_i$  for its waste is incorporated at the end of the auction in both parties' economic balances. In the first's, this transaction manifests as resource expenses equivalent to the winning bid it made to get  $W_i$ , while it generates a new income source for the second via selling its previously none-usable waste.

When a new agent is appended to the territory, the exergy optimal networks might vary with the introduced streams of that agent. Subsequently, the Network Investor issues a new Trade Message specific for each agent accounting for the updated  $IA$  set. Each industrial agent then carries out a local heat integration for its own streams considering the proposed networks in the Trade Message received from the Network Investor. This is achieved by calling the local HENS algorithm which seeks to design the optimal synergies configuration that enables the minimization of the total cost. Therefore, the self-interested rational agent would not exchange heat with the network for the proposed temperatures and prices if the engendered total cost from participating in the network is not lower than the total cost it would get by exclusively using its own utilities. In the case where  $IA_i$  does not find it lucrative to exchange heat with the network and thus chooses to act as an isolated agent, it sends a No Offer Message to the Network Investor. In contrast, if it does find it profitable,  $IA_i$  transmits an Offer

Message to the Network Investor indicating the amount of heat it wants to sell or buy at the network temperature  $T_j$  for the proffered prices:  $[T, Q'_i, T_i^S]$ . The new sets are introduced as follow:

$$Q'_i = \left\{ (Q_{ij}^s, Q_{ji}^s) \mid Q_{ij}^s / Q_{ji}^s \text{ are the heat loads IA}_i \text{ wants to sell/buy to the network at } T_j \text{ via stream } s \right\}$$

$$T_i^S = \left\{ (T_{in}^{s,j}, T_{out}^{s,j}) \mid (T_{in}^{s,j}, T_{out}^{s,j}) \text{ are the inlet and outlet temperatures of IA}_i \text{'s stream } s \text{ that exchanges with } T_j \right\}$$

Once the network investor receives the Offer Messages from the entire industrial agents, it launches the territorial energy integration. The employed state of the art algorithm of Farhat, et al. (Farhat, et al., 2015) to conduct such integration was amended to be suitable for non-cooperative governance. The buying and selling energy prices are introduced in the algorithm and are set from the sent Trade Messages. It is supposed that no possible utility can be added on the network; meaning that the network only buys from a site offering heat the amount of energy that it can resell to another site according to the received Offer Messages. The objective function of the problem employed in the cooperative scheme and which consists on minimizing the total cost is amended and written as in Eq.(5). It expresses the objective function of the Network Investor which aims at identifying its purchase and sale transactions for an optimal network design. The capital cost is only generated by the pipeline installation costs since the heat exchangers are taken in charge by the industrial agents.

$$\min: \quad \text{totalCost} = \text{Capex}_{\text{pipeline}} + \sum_{y=1}^{\text{Nbr}_{\text{year}}} \frac{1}{(1 + \text{DRate}_{\text{NI}})^y} \times \sum_{i=1}^N \sum_{j=1}^{\text{Networks}} (P_j^b \times Q_{ij} - P_j^s \times Q_{ji}) \quad (5)$$

In the aim of preventing the territorial integration algorithm from numerically adding utilities on a seller site to increase the quantity the network can buy to supply the entire required heat by other sites, since this path decreases the network's total cost, a buying limit variable  $Q_{ij}^{\text{limit}}$  is introduced. A buying limit variable  $Q_{ji}^{\text{limit}}$  is also created to impede transferring heat from a deficit site to a cold utility just to increase the site demand and economically justifying the network's purchase of the complete offered energy of other sites to resell it at a higher price to cover the deficit sites' increment. Both of these variables are set as constraints for the design optimization as expressed in Eq.(6).

$$\begin{cases} Q_{ij} \leq Q_{ij}^{\text{limit}} = \sum_{s=1}^{\text{NbrStoTj}} Q_{ij}^s \\ Q_{ji} \leq Q_{ji}^{\text{limit}} = \sum_{s=1}^{\text{NbrSfromTj}} Q_{ij}^s \end{cases} \quad (6)$$

If the Network Investor does not meet its set return on investment, no network is constructed. Consequently, the negotiations for heat synergies end after informing the industrial agents through an empty Trade Message sent to the entire elements of IA. Otherwise if the heat exchange network took shape from the proposed offered messages, the Network Investor retransmits a new Trade Message to IA with the actual heat amounts it will buy  $Q_{ij}$  or sell  $Q_{ji}$  to  $IA_i$  at the network temperature  $T_j$ . The industrial agents then reevaluate their payoffs from only trading the amount of energy proposed by the Network Investor via the local integration problem. They hence either transfer a new Offer or No Offer Message accordingly to the Network Investor which repeats its network design optimization. The negotiations goes on until the amount of heat each  $IA_i$  wants to trade  $Q'_i$  is identical to the quantities  $Q$  the Network Investor is willing to incorporate in the network. The joint agreement on the energy and material trading reached by the Network Investor and the industrial agents and which contributes in increasing the individual payoffs of the self-interested agents is defined as an equilibrium state. The case in which the territory's agents have no incentive from cooperation and thus none engages in any agreement is also considered as an equilibrium state.

Once an equilibrium point is reached the Network Investor weighs up the resulting exchanged energy amounts in the territory  $Q$  to the maximal synergies  $Q^{\text{ex}}$ . When the heat  $IA_i$  offers to buy or sell to the network is lower than four-fifth of the maximal potential offer, the Network Investor reevaluates the buying and selling prices it have proposed resulting in this income. It actually seeks on finding other equilibrium state in which more synergies can be implemented and that might turn out to be more profitable for it. The price at which the Network Investor buys heat from  $IA_i$  for  $T_j$  is increased by 20% compared to the earlier offer if the energy  $IA_i$  have put to sale is lower than four-fifth of its potential. The selling price is also decreased by the same percentage if  $IA_i$  haven't bought 80% of  $Q_{ij}^{\text{ex}}$ . The amended Trade Messages are resent to IA inducing the necessity for  $IA_i$  to revisit its local HENS and consequently restarting the equilibrium state search engendered from the upgraded prices.

As long as the enhanced heat buying price at  $T_j$  does not surpass the lowest selling price,  $P_j^b$  is increased. And while the altered selling price for  $IA_i$  is still higher than the greatest buying heat price at  $T_j$ ,  $P_j^s$  could be reduced. When the limits in Eq. (7) are reached and no further adjustment can be made to the specific prices, the entire negotiation problem is reiterated.

$$\begin{cases} [P_j^b]_i \times 1.2 < \min(P_j^s) \\ [P_j^s]_i \times 0.8 > \max(P_j^b) \end{cases} \quad (7)$$

Actually in the previous amendment step of the energy selling and buying prices, the changes were carried out specifically for each temperature and for each agent. Meaning, when agent  $IA_i$  have indeed exchanged its full potential with the network, its Trade Message  $[T, Q, P]_i$  is maintained unchanged; while for another industrial agent  $IA_p$  that might offer higher amounts of energy at  $T_j$  for a better pricing, the Network Investor proposes a new Trade Message  $[T, Q, P]_p$  with higher buying or lower selling prices for heat according to the offer Message of  $IA_p$ .

However when for an industrial agent  $IA_i$  the buying price  $P_j^b$  cannot be incremented and selling price  $P_j^s$  cannot be decremented (condition in the upper right of figure 2) the Network investor does not propose a new trade message for  $IA_i$  and if the messages of the entire IA population remain the same meaning that the variation limits are reached, the problem is reiterated with new Trade Messages engendered from resetting the buying and selling prices for the entire IA population according to the heat utility prices with the updated Cost% parameter which varies as described earlier with the number of iterations. Subsequently the auction is repeated since the bidding limits of the potential agents will be influenced by the updated Trade Messages and thus the auction outcome might too. Before the auction is relaunched, the winner of the previously conducted auction is removed from the industrial agents set IA so that the waste  $W_i$  could be put up again for sale. Nevertheless, if the new auction winner has already won in preceding problem iteration, the Network Investor revises in the same manner the Trade Messages to be issued and the auction is restarted since the resulting equilibrium states will definitely be less favorable for the self-interested Network Investor. The reason behind that is the fact that by integrating the same conversion system in the territory the optimal

synergies design will not be affected for the evaluated energy streams remain intact. Consequently, when the Network Investor offers to sell heat at a lower price and to buy it for a higher value for IA, it will be converging towards the similar energy exchange equilibrium state in which its payoff is lower. Therefore resending such Trade Message is contradictory with its objective consisting on increasing its individual interest and thus the Network Investor has no incentive from participating in these negotiations.

The problem number of iterations is restricted to five times limiting the computational burden by dint of the prices amendment method reckoned on the parameter  $Cost\%$ . This latter attain the value of 0.5 at the fifth iteration with the increment step fixed at 0.1. Consequently the buying  $P_j^b$  and selling  $P_j^s$  prices of heat at  $T_j$  both become half the utility price cost. The Network Investor would not accept to buy and sell heat at the same price with the pipeline installation expenses it has to bear, thus a single equilibrium state exists at the fifth iteration and above. This is the state where no heat network is installed meaning that circular economy does not prevail and considerable synergies opportunities between the territory's agents are omitted. Subsequently, the entire problem halts at the fifth iteration.

## 5. Case Study

To demonstrate the application and the potential results of the proposed framework, it was applied on a case study consisting of a virtual industrial park inspired by an existing park in Le Havre France formed by three plants denoted as Site 1, Site 2 and Site 3. Since the case study is virtual, we don't really need to define the exact activity of the sites. Only the process thermal streams and the hydrogen needs are specified. The energy requirements of the three sites are described in the illustrative example of Chew and al. (Chew, et al., 2015). For each site, they are identified according to the circulating streams' inlet and outlet temperatures and heat load capacities. From these data the grand composite curves (GCC) of each site are plotted based on the "Problem Table" method of Linhoff and Flower (Linnhoff & Flower, 1978). They are supposed to be geographically separated as depicted in Figure 4. Site 1 presents a hydrogen demand of 1.5 t/h and it is supposed to also generate 12 t/h of wood waste. The studied park is supposed to have no initial synergies and no valorization



systems for the discharged wood waste. The study aims at finding the best eco-industrial park configuration via optimal synergy patterns. Parenthetically, Figure 4 also illustrates the prospective position of the wood conversion plant relative to the territory's existing industrial sites. The selected placement greatly impacts the territorial integration outcome since the networks investments are directly proportional to the distance of the required pipeline to transfer energy or allocate materials from one site to another.

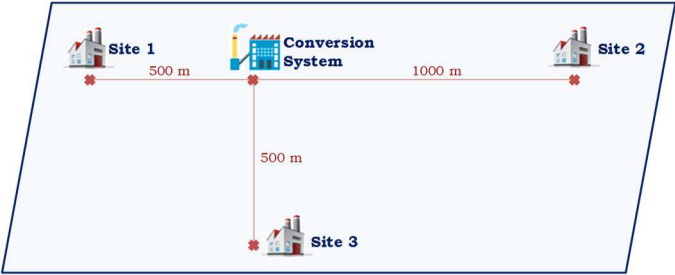


Figure 4. Geographical distance between the industrial actors of the virtual park

Figure 5 shows the GCC for each of the three sites that represents the difference between the heat available from the hot streams and the heat required by the cold streams, relative to the pinch, at a given shifted temperature. Above the pinch point, the net energy represents the heat deficit and below it is the heat surplus. Promising heat synergies could be foreseen from the analysis of the resulting curves.

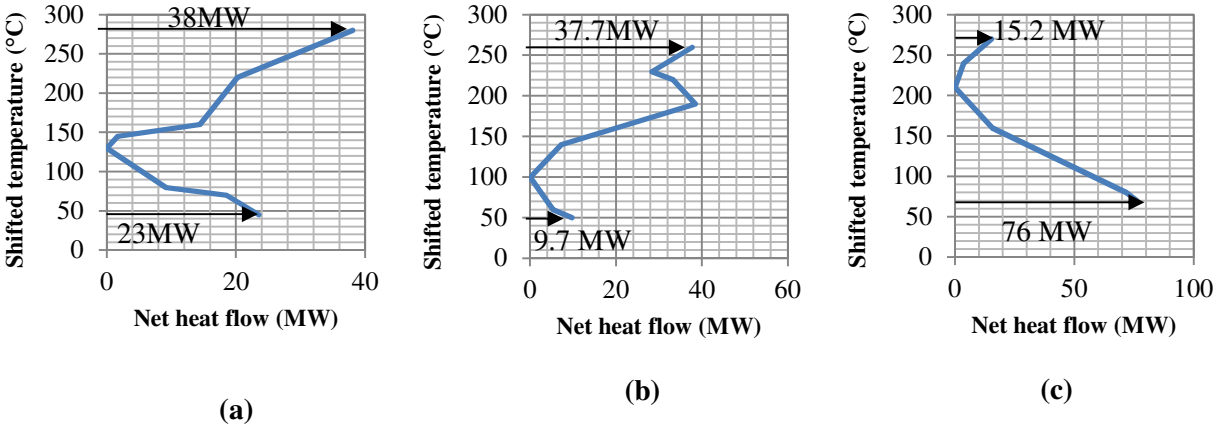


Figure 5. Grand Composite Curves of each actor of the territory (a) Site 1, (b) Site 2, (c) Site 3

## 5.1. Economic data Hypotheses

Before initiating the methodology demonstration, the economic hypotheses concerning the commodities present in the territory should be set. The employed hydrogen price is that generated from a steam methane reformer being the commonly used technology. The ton of hydrogen average price produced from a conventional SMR is actually 1826 € (Mondal & Chandran, 2014) (Laveissiere, 2012). The hydrogen price is thus highly sensitive to methane price which is set by the natural gas market. From the developed relationship of Gray and Tomlinson (Gray & Tomlinson, 2002) between hydrogen and natural gas prices, Eq.(8) was deduced to get the values in the desired units; knowing that the high heating value (HHV) of hydrogen is 142.18 MJ/kg which is equivalent to 39.5 kWh/kg and the HHV of methane is considered to be 15.27 kWh/kg.

$$\text{HydrogenPrice (€/ton)} = 50.2 \times \text{GasPrice (€/MWh)} + 120 \quad (8)$$

The heating price is supposed to be the market price of a heat source produced from a steam generator fueled by natural gas. Subsequently, the heat price tangibly changes with the gas market and it is also supposed to alter according to the temperature at which it is required. The price of natural gas for an average size industrial consumer in the EU is of 34 €/MWh (eurostat, 2016) in the second half of 2015; this price exhibits regular variations by dint of the international market fluctuations. A reference value of 30 €/MWh will be thus considered for the study.

For a reference gas market price 'GasPrice<sub>0</sub>' of 30 €/MWh, the heating cost per kWh is supposed to be at 0.01€ below 150°C and above 300°C the kWh of the heat utility costs 0.03€. In between these two heat levels, the price has an increasing linear function. Consequently, the heat price relationship in function of methane market price and temperature is expressed as in Eq.(9).

$$\text{HeatPrice (GasPrice, T)} = \left( \frac{\text{GasPrice}}{\text{GasPrice}_0} \right) \times \begin{cases} 0.01 & T < 150^\circ\text{C} \\ \frac{0.02}{150} \times T - 0.01 & 150 < T < 300 \\ 0.03 & T > 300^\circ\text{C} \end{cases} \quad (9)$$

The strong assumption intertwining the methane, hydrogen and heat prices entails their simultaneous variation. With the natural gas market fluctuation and to be consistent with the heat price will adopt the price of the reference gas price 'GasPrice<sub>0</sub>'. The methane price is hence supposed to be at 30 €/MWh and the evaluation of Eq.(8) set the hydrogen ton price at 1,626 €. Another worth noting hypothesis lies within the territorial energy integration problem, in which the network is supposed with a monthly discount rate of 0.003%. The heat exchangers investment is supposed to be formed by a fixed cost of 100,965 € and a variable cost of 927.25 €/m<sup>2</sup>.

## **5.2. Reference Scenario**

The reference scenario is considered as the case in which each industrial site of the territory acts as if it is not a part of the territory; meaning as an isolated actor. Consequently, each site conducts its local material and energy integration trying to establish on-site synergies between its process units to make the best out of its streams and reduce as much as possible its resources demand and heat requirements. Every site in the park is supposed to have at disposal enough supply to satisfy its heating and cooling demands. Even though cooling utilities are supposed cost free by dint of the relatively high temperatures of the cooling needs compared to the neighboring environment, the heat utilities come at a cost fixed at the heating market price and which is correlated with their temperature level. The operating hours of the park is set to 6,000 hours per year and each industrial actor is supposed to demand a return on investment after 100 months of the heat exchangers installation. The process are assumed to be operated in continuous mode which is the case of many industrial plants.

The local integration problem for the HEN synthesis was solved using the model of Zoughaib (Zoughaib, 2017) as mentioned in Section 4. The objective function of this problem consists on minimizing the total cost engendered from the installation of the identified heat exchangers and the employed utilities to cover the remaining energy deficits after the synergies establishment.

By locally integrating its energy streams, Site 1 can recover a total of 75 MW through the installation of 19.49 M€ worth of heat exchangers which enable the heat transfer from the streams that need to be cooled to others that should be heated. Consequently reducing its heating utility demand to

29.83 MW which is supplied by its local hot utility at 300°C, resulting in an operating cost of 5.37 M€ per year. This industrial actor also consume 9,000 ton of hydrogen per year, which induces 14.63 M€ yearly operating expenses. Acting as an isolated industrial plant, Site 2 searches to decrease its charges via synergies establishment. The resulting HEN of Site 2 induced from its local integration problem resolution lead to the recuperation of 97 MW of thermal potential and redistribute it internally via 7 heat exchangers, making up grossly 75% decrease in the hot utility uptake for an overall investment of 15.59M€. The third plant of the territory requires a heat subtotal of 43 MW when no integration is performed. However, this is reduced to 11 MW by dint of the established heat synergies through the local HEN synthesis of Site 3, cutting down its annual operating costs from 5.75 to 2 M€. Five heat exchangers were installed generating an investment cost of 9.58 M€. Noting that the minimum temperature difference is set to 20 K for the heat exchangers design. The economic statuses of the industrial actors of the territory when implemented as isolated agents are summarized in Table 1.

Table 1. Economic status of the territory's sites as isolated actors resulting from their local integration

Industrial actor	Fixed Cost (M€)	Variable Cost (M€)	HE area (m <sup>2</sup> )	Hot Utility (MW)	HE Nbr
Site 1	19.49	20.00	20,152	29.83	7
Site 2	15.59	5.90	16,055	32.79	7
Site 3	9.58	2.00	9,788	11.08	5

### 5.3. Problem Statement

The three industrial sites within the predefined boundaries of the studied territory are assumed to be motivated by their individual advantage increase with no regard to the global enhancement of the park's operation. Wherefore the induced payoffs from trading their untapped streams are the only stimulation for them to participate in synergies establishment. In the aim of finding the joint trading agreements which are lucrative for every participating party of the park, the proposed methodological framework is employed. The problem is therefore formulated as a MAS in which the industrial agents set IA consists of the three sites of the park,  $IA = \{IA_1, IA_2, IA_3\}$ . Those transmit their energy and

material requirements and discharges to the third party which exclusively intervenes in the potential assessment of inter-sites synergies based on purely exergy base optimization for the energy integration and consisting of the fresh resource minimizing for the material problem.

The exergy optimal HEN is designed by the minimization of the exergy consumption of the territory which ensue the lowest hot and cold utilities utilization and the highest heat recovery. The GCC of the three industrial sites form the territorial energy integration data input. The employed integration algorithm which is the developed MILP by Farhat and al. (Farhat, et al., 2015) computes the potential synergies between the park's actors by proposing tertiary heating networks to avoid the complexity imposed by the direct energy integration between the streams of each site. It supposes that an ideal local integration is already performed at the site level. The energy transport fluid is supposed to be steam that could circulate at different pressure levels; each network is therefore defined by a specific temperature level with a maximum number of networks limited to four. It is supposed that no heat utilities are allowed to be added on the network, and thus this latter can only intake heat surplus from an industrial site when it can retransfer the recovered heat to another site with deficit. Table 2 exhibits the exergy optimal synergies between the sites of the park resulting from the territorial heat integration problem and carried out by the third party. Three steam networks are proposed, the highest being at 160°C. With the negative sign in the table denoting the heat removed from the corresponding entity, it is noted that the excess heat form Site 3 is collected at the three network levels to be transferred to Site 1 and Site 2. The established synergies enabled a total inter-sites heat recovery of 22.62 MW.

Table 2. Recovery and utility demand found by the territorial Energy integration

Network temperature (°C)	Site 1	Site 2	Site3	Network Capacity(MW)
160	4.88	3.13	-8.01	8.01
155	0	6.25	-6.25	6.25
145	1.14	7.22	-8.36	8.36
Total Recovery(MW)				22.62

Since the only two material streams present in the territory are of different composition, no possible allocation between wood waste and hydrogen is possible. Hydrogen must therefore be purchased from external suppliers to maintain its operation. And even by searching for synergies between the industrial actors, 12 t/h of wood waste are still discharged without any valorization opportunity since none of the sites present such demand. From the empty Material Message  $IA_1$  receives from the third party subsequent to the material flows analysis, it derives that his wood discharge has no recovery opportunities in the territory in its existing form and thus defines its 72 000 annual wood discharge as its waste  $W_1^{\text{wood}}$ . With a view to increase its payoff,  $IA_1$  launches an auction on  $W_1^{\text{wood}}$  for potential investors with a starting price  $C_0$  of 10 € for the ton of biomass; thereby it could raise its yearly revenue by at least 0.72 M€ from selling its waste. Obviously an auction participant will want to invest in a system of processes requiring the auctioned  $W_1^{\text{wood}}$  as resource to generate commodities that can be then resold to other industrial agents of the park in which it is going to be implemented. The reacting processes that involve the destruction and formation of chemical bonds generating a chemical composition change of the woody biomass can be classified under two main categories: thermochemical and biochemical conversion. In thermochemical conversion routes, direct combustion is the most evident pathway to recover the calorific potential of biomass by converting it into heat; steam turbines could as well be added to co-generate electrical power. Wood gasification forms another thermochemical conversion pathway. The resulting gas can be converted into commodities of higher value than wood, such as liquid biofuels through Fischer-Tropsch synthesis, or hydrogen by coupling a steam methane reformer to a Water-Gas Shift reactor, or even to methane by placing a methanation unit downstream of the gasifier. On the other hand, biochemical conversion of biomass consists of the hydrolysis reaction that breaks down the woody biomass into its component sugar molecules which are then transformed via fermentation to produce ethanol. Since the park has hydrogen and heat demand and assuming that electricity can be sold to the national power grid and methane to the gas network, hydrogen, methane, heat and electricity are the commodities judged to be most interesting for the park. Consequently the auction bidders which compose the potential agents PA of the problem are identified from the conversion systems database CS which is formed by the

three wood conversion pathways that enable respectively hydrogen, methane and energy generation, thus:  $CS = \{CS_1^{\text{wood}}, CS_2^{\text{wood}}, CS_3^{\text{wood}}\}$  and  $PA = \{PA_{1,1}, PA_{1,2}, PA_{1,3}\}$ . A more in depth description of these three conversion routes can be found in the paper of Abi Chahla et al. (Abi Chahla, et al., 2016a).

Each element in PA generates its sub-population by altering the operating parameters of its process units and creating different sets of parameters; hence a sub-potential agent of  $PA_{1,1}$  with set q is denoted as  $PA_{1,1,\text{set } q}$ . The workable parameters of a PA are identified from the conversion process degree of freedom. For the wood to hydrogen conversion system, which is the  $PA_{1,1}$ , the sets of parameters with sporadic values selected amidst their established limits are presented in the parametric study of Abi Chahla, et al. (Abi Chahla, et al., 2016b). A similar studies were conducted for the two other conversion pathways to generate the different sub-potential agents.

From its created population, a potential agent k selects the sub-agent having the highest bidding potential  $PA_{1,k,\text{set } q_{\beta k \max}}$  to enter the auction with. The evaluation of their bidding potentials are conducted according to the investment strategy they follow. Similarly for the industrial agents that evaluate their received Trade Messages from the Network Investor (NI) based on the time they are willing to wait for prior to their net profit generation. The case study was carried out considering the self-interested agents of the studied territory having a 100 months long term investment plan.

## 5.4. Results for long term investment strategies

The first auction is launched with the NI proposing the buying and selling prices of heat respectively at 10% and 90% of the heat utility market price when the MWh of natural gas is at 30€. The auction ends by  $IA_1$  allocating its  $W_1^{\text{wood}}$  to the highest bidder which was  $PA_{1,1}$  for the amount of 85.35€ for the ton of wood. The wood to hydrogen conversion system investor actually entered the bidding with its  $PA_{1,1,\text{set } 10}$  that exhibited the highest bidding potential amongst its sub-agents; it could have raised its bid for the ton of wood up until its  $\beta_k$  of 193 €.  $PA_{1,1}$  was faced by another bidder that is  $PA_{1,2}$  with its  $PA_{1,2,\text{set } 5}$ . However the latter could not bid higher than the winning agent since it was unable to raise the final bid by  $0.1\beta_{k PA_{1,2,\text{set } 5}}$  which is equivalent to 8.68 € since it surpasses the

cost for the ton of wood it could afford to reimburse its investment in less than 100 months. As for the cogeneration pathway that is the third potential agent  $PA_{1,3}$  it does not even enter the auction by dint of its limited bidding potential  $\beta_k$  of 2.21 € for the ton of wood which is less than the initial reservation price of 10€ per ton. Subsequently, the auction winner is appended to the industrial actors and takes part in the negotiations for heat trading with the NI; thereby  $PA_{1,1}$  becomes  $IA_4$ .

On the basis of the exergy based territorial HEN synthesis conducted by the third party with the updated industrial agents list, the NI establishes its first specific Trade Message destined to each IA. Those are expressed below in degree Celsius for the network temperatures in MW for the heat load and in Euros per MWh the buying and selling prices.

$$TM_1 = [\{T_1, T_2\}, \{Q_{11}, Q_{21}\}, \{P_1^s, P_2^s\}]_1 = [\{155, 150\}, \{4.23, 1.70\}, \{9.6, 9\}]$$

$$TM_2 = [\{T_1, T_2, T_3\}, \{Q_{12}, Q_{22}, Q_{32}\}, \{P_1^s, P_2^s, P_3^s\}]_2 = [\{155, 150, 145\}, \{3.13, 3.13, 7.22\}, \{9.6, 9, 9\}]$$

$$TM_3 = [\{T_1, T_2, T_3\}, \{Q_{13}, Q_{23}, Q_{33}\}, \{P_1^b, P_2^b, P_3^b\}]_3 = [\{155, 150, 145\}, \{7.36, 4.83, 10.42\}, \{1.07, 1, 1\}]$$

$$TM_4 = [\{T_3\}, \{Q_{34}\}, \{P_3^s\}]_4 = [\{145\}, \{3.20\}, \{9\}]$$

The industrial agents then evaluate their TM and send back an offer message to the NI. This is repeated until joint agreements are established between the entire agents of the territory which defines an equilibrium state. Noting that the decision of participating or not in a negotiated agreement is based on the agent *rationality* since a self-interested agent will only be part of an agreement if it gets him higher payoffs. From the resulting equilibrium state and based on the offer messages it received, the NI gradually increases the buying price or decreases the selling price for certain networks' temperatures at which the intended industrial agent did not exchange its full potential. The NI takes this action in the aim of motivating the industrial agent to trade greater amounts which might increase its own profit. Consequently, a new equilibrium state is determined for each TM with amended offers.

Ten distinct equilibrium states of EIP configurations are actually found for the studied territory. The NPV of each industrial agent are evaluated at the 100 months of operation to examine the profitability of each state at the date of their established investment horizon in reference to their



economic statuses when acting as isolated agents. Figure 6 till Figure 10 illustrate the NPV for the ten given equilibrium states of the NI and of the four industrial agents, the fourth agent being the wood to hydrogen conversion system investor. By examining the outcomes of the first industrial agent, Figure 6, it can be noticed that IA<sub>1</sub> presents in the ten states consistent annual profits of 6.14 M€ generated from selling its 72 000 ton of wood waste to IA<sub>4</sub>. It does not however participate in the heat network except in two equilibrium states 3 and 5 which induces a 6% raise in its profitability. This increase is due to the saved amount from buying 3.9 MW of heat at a 10% lower price than the market. It should be noted that even when trading heat with the NI the heat exchangers costs are still taken in charge by the industrial agent. For the similar reasons related to the energy exchange with the NI, IA<sub>2</sub> has an income in the equilibrium states 2, 4 and 7 being the only three in which it buys heat from the NI. Nonetheless in both states 4 and 7, IA<sub>2</sub> generates the same profits by dint of the identical amount of 7.22 MW of heat that it purchases at the same price from IA.

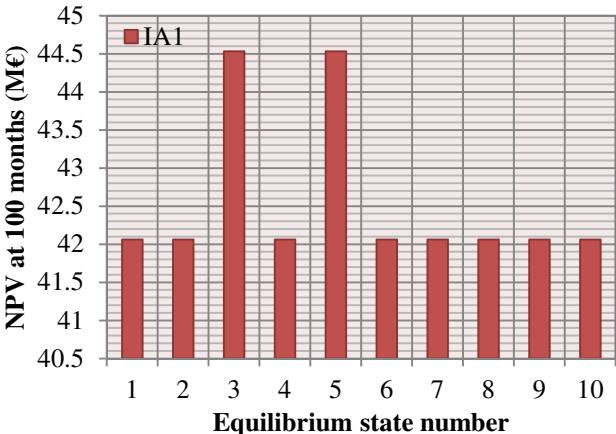


Figure 6. NPV at 100 months of operation of IA<sub>1</sub>

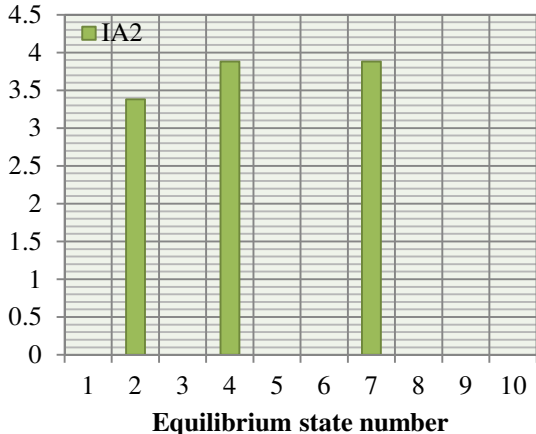


Figure 7. NPV at 100 months of IA<sub>2</sub>

The only heat seller between the territory’s agents and thus the main contributor is IA<sub>3</sub>; hence it generates gains by trading its untapped heat surplus to the NI. From its NPV at 100 months of operation, Figure 8, it can be induced that the most lucrative state for IA<sub>3</sub> is state 7. Nonetheless through comparing the HEN configurations ensued from state 4 and state 7, it is perceived that both heat streams circulating patterns are identical except for the buying price the NI offers for the 10.42

MW of IA<sub>3</sub> at 145°C which is 44% higher in state 7. Therefore state 4 and 7 are with similar benefits for IA<sub>2</sub> while the latter results in greater payoffs than the former state for IA<sub>3</sub>. Consequently, with the same quantities being sold to the NI by IA<sub>3</sub>, the buyer will definitely get the lower price. Therefore state 7 is not *stable* in the presence of equilibrium state 4 since the NI decision weighs the most in the network construction and it will deviate from the established agreement towards the state that will add an incentive to its profit.

With the same reasoning another equilibrium state could as well be eliminated between state 3 and state 5 which results in the highest profitability for IA<sub>1</sub>. In both equilibriums, the NI buys 3.91 MW of heat at 155 °C from IA<sub>3</sub> and then resells it for IA<sub>1</sub>. Nevertheless, the heat purchase transactions from IA<sub>3</sub> are different. The NI pays 20% less in state 3 than it does in state 5 for getting the same amount of energy; the NI will favor the lower suggested buying value from the industrial agent when getting the exact product and hence the equilibrium state 3 is more *stable* than state 5.

Moreover, the EIP configuration in the equilibrium states 8, 9 and 10 only have one distinction being the heat buying price the NI pays to get 3.2 MW at 145 °C from IA<sub>3</sub>. Between the three states the NI increases by 20% the buying price it offers for IA<sub>3</sub> with the aim of pushing this latter to sell more heat since its potential at this temperature is of 10.42 MW. However IA<sub>3</sub> trade exclusively 3.2 MW in this equilibrium states. Consequently, state 8 manifests as being of higher *stability* compared to the other two and hence it is, among the *stable* states, the most profitable one for IA<sub>3</sub>.

The fourth industrial agent IA<sub>4</sub> is the bio-refinery that buys the wood from IA<sub>1</sub> and converts it mainly into hydrogen which it sells back to IA<sub>1</sub>. It thus has a substantial trading income from its annual 8,700 ton of hydrogen sold at the market price. As it can be seen from the NPV chart in Figure 9, IA<sub>4</sub> generates the highest gains in most of the equilibrium states except in states 1, 3 and 5 since in these latter states either no network is constructed (state 1) or the IA<sub>4</sub> is not offered to participate in it (state 3 and 5). Actually, IA<sub>4</sub> has to purchase its 3.2 MW heat demand at the market price when it does not buy its heat from the NI.

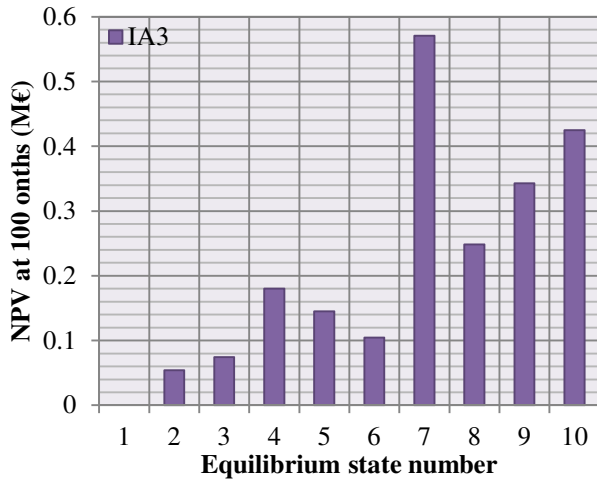


Figure 8. NPV at 100 months of operation of IA<sub>3</sub>

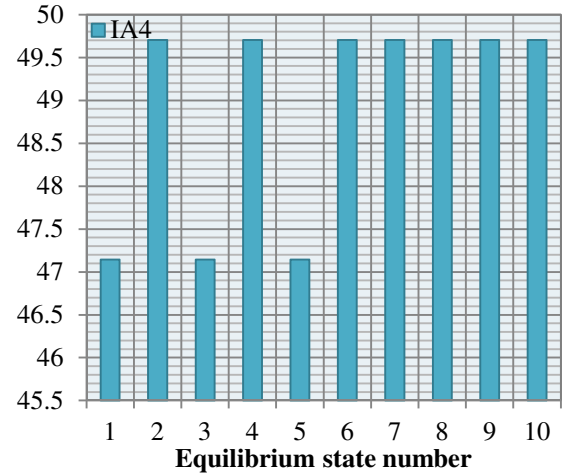


Figure 9. NPV at 100 months of IA<sub>4</sub>

This latter generates the most profits in the equilibrium state number 4 in which the entire industrial agents of the territory except IA<sub>1</sub> take part in exchanging heat through the suggested network at 145°C. Those also participate in the heat synergies in the equilibrium states 2 and 7.

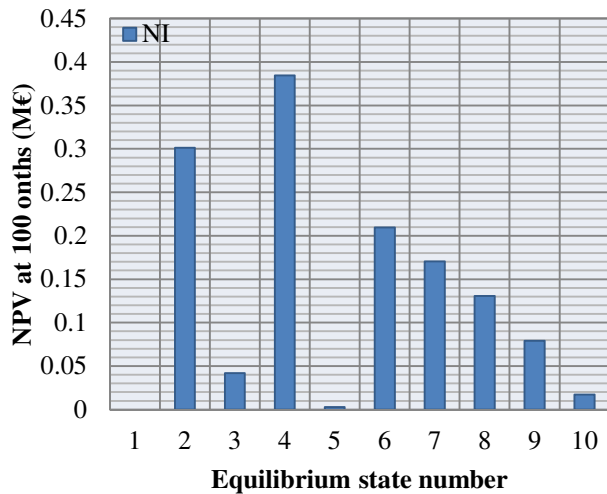


Figure 10. NPV at 100 months of the NI

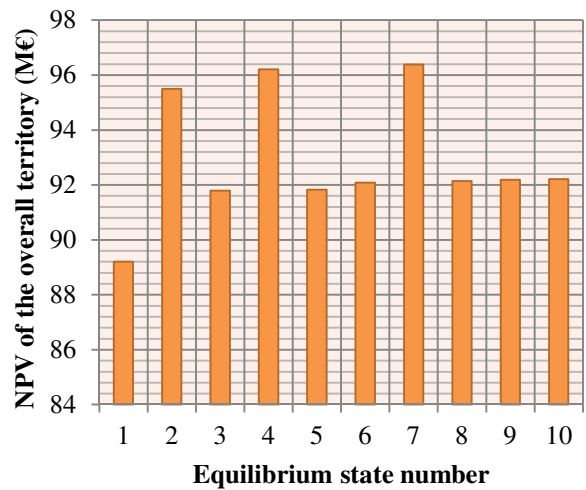


Figure 11. The equilibrium states social welfare

From the above results it can be noted the absence of a consensus for one equilibrium state. While IA<sub>1</sub> finds state 3 to be most lucrative, IA<sub>2</sub> generates its highest gains in state 4. Then again for IA<sub>3</sub> state 8 manifests as being its greatest profitable *stable* equilibrium. As for IA<sub>4</sub> it does not have a single favorite but instead has several. Yet, the NI does have a preferable state, this is state 4.

Consequently to select an EIP configuration for which the whole agents are satisfied from its implementation, the criterion of *social welfare* is employed. It is evaluated by the aggregation of the NPV at 100 months of the four industrial agents as well as that of the NI for each corresponding equilibrium state since the *social welfare* is defined by the sum of payoffs associated to a given agreement. As it can be seen from Figure 11, the three uppermost states are those in which the entire agents are involved in a certain material or heat synergy. From these three, state 7 induces the highest *social welfare*. Nonetheless as discussed earlier, this equilibrium state being unstable, from the NI perspective, the second best choice is state 4 and therefore it is considered as the most adequate equilibrium to be established.

It should be pointed out that the stable states were assessed considering the NI as being the single investor in the transport networks infrastructure which buys and sells heat through its constructed network. However, when competition does exist for buying and selling energy between multiple agents, the NI should assess the risk related to favoring a negotiated agreement over another which might influence the decision of the involved industrial agent. As for instance in equilibrium states 4 and 7 in which IA<sub>3</sub> prefers the negotiated agreement in state 7, whereas the NI has higher gains from state 4. Therefore with several involved agents for buying the heat from IA<sub>3</sub>, the NI has interest in establishing the agreement in state 7 even if it is for less profit in order to ensure that IA<sub>3</sub> will not deviate towards selling its 10.42 MW to another heat buyer with a better proposal. In this case study the NI is indeed the only agent taking in charge the heat purchase and sales and thus state 4 is most likely to be the established agreement between the industrial agents of the territory in non-cooperative governance. The EIP configuration resulting from this equilibrium is depicted in Figure 12 which shows the purchase and sales transaction between the agents of the territory.

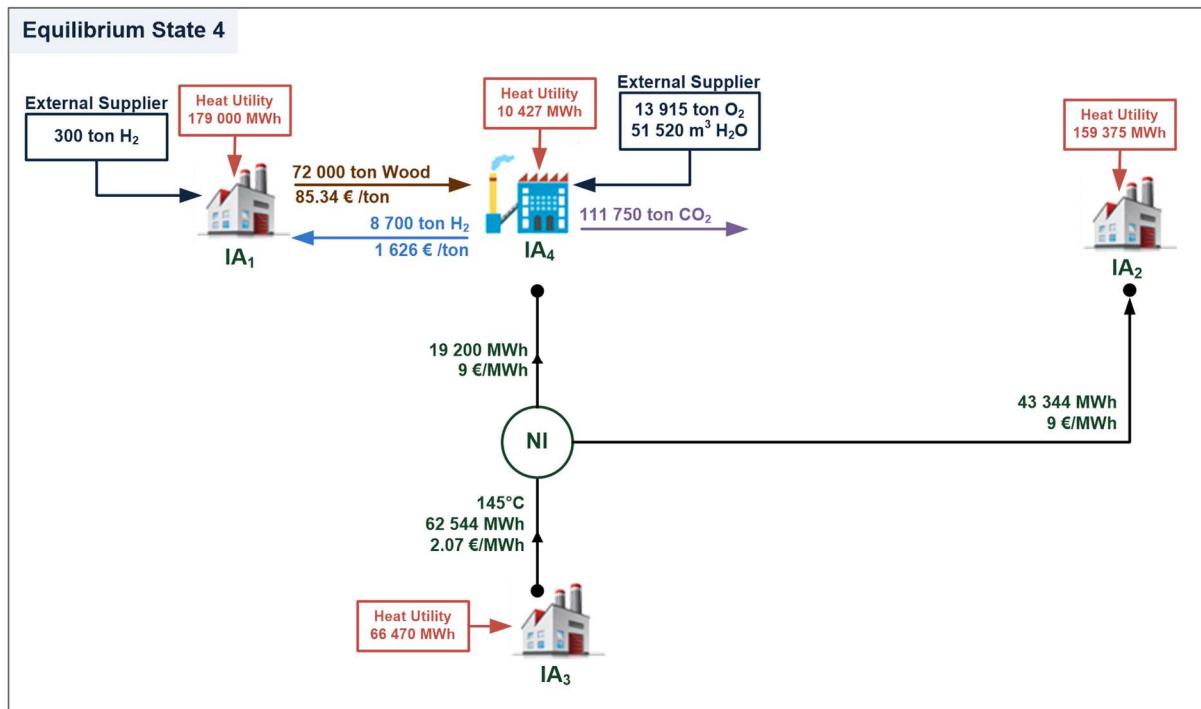


Figure 12. EIP configuration of the most adequate equilibrium state in non-cooperative scheme

The adjunction of the wood conversion system created new synergies opportunities for a more dynamic territory. IA<sub>4</sub> is the bio-refinery formed by the series of the wood to hydrogen processes. This sub-agent won the auction for wood and participates in the non-cooperative negotiations because it has the combination of parameters which consists of the lowest studied feed steam to biomass ratio and the highest gasifier and steam methane reformer temperatures, thus maximizing hydrogen production. This emphasizes on the importance of assessing the required resource of the park when selecting the conversion systems to be further investigated.

The equilibrium states of the negotiations between the agents of the territory are highly dependent on the strategy an agent has set for its investment to start inducing profits. The previous transactions pattern resulted from long term investment strategies in which the corresponding agents would not mind their gain to be initiated 100 months after the installation of the negotiated EIP configuration. With a view to evaluate the agents alterations of profitability as well as the impact on the energy and material equilibrium transactions, a sensitivity analysis for short and medium term investment strategies was conducted. Further analyses were as well carried out to investigate the gas market fluctuations effect on the auction winner and the induced states equilibrium.

From the results and analysis of the sensitivity assessments over the agents' investment strategies and the gas market price it can be stated that the wood to hydrogen conversion is the most profitable wood pathway to invest in its implementation in the investigated park compared to the wood to methane or wood cogeneration routes. Indeed,  $CS_{1, \text{set } 10}^{\text{wood}}$  withstands the gas market fluctuations as well as the desired investment reimbursement plans alterations by preserving its first ranking for the highest bidding potential. Therefore it ensures for the entire collection of equilibrium states the upgrade of the previously non-usable wood into a commodity of higher value and thus creating unprecedented synergies in the park which are otherwise unattainable.

The established heat synergies in the territory are highly impacted by the set target for the uttermost allowable return on investment to the extent where short and medium term investment strategies could be the detriment for heat trading opportunities. The reason behind this is the small disposable period to assert the investment reimbursement of the larger heat exchangers for the industrial agents or of the pipeline for the network investor. On the other hand, the gas market price plays a major role in the offered buying and selling prices by the network investor. Therefore higher gas prices entail more gains for the industrial agents thus they exchange more heat which results in greater network capacities.

As a conclusion, this case study shows how the proposed methodology enables the establishment of the strategic decisions to be implemented by each self-interested agent in a territory with non-cooperative governance by identifying the optimal synergy creation and their equilibrium prices for the purchase and sale flows between agents. Among these equilibrium points some shows higher robustness since the benefits are better distributed avoiding any disengagement from the agreement. This also shows from the case study that one actor may be a key player for the success of the synergy in our case it is IA3. As discussed market price conditions may influence the results however a complementary sensitivity analysis should be performed.

## 6. Conclusion and Outlook

In this study, a novel conceptual framework for the design of energy and material synergy patterns of an industrial park was proposed in the context of circular economy and sustainability. The novelty of this framework consists first in the formulation of the problem using agent-based modeling enabling to account for several heterogeneous agents each with its own objective function and that acts and reacts to each other's behavior. This framework was mandatory since formulating the problem using centralized mechanism with a single objective was found to be complex considering the non-linearity of the actors' aggregate activities. State of the art MILP optimization algorithms were adapted to be used in the proposed framework for the on-site and inter-site level integration. These algorithms take into account the investment cost of the transportation networks and the heat exchangers allowing their design. This entails a strongly viable EIP topology with ensured physical feasibility that decrease resource usage and waste emission for cleaner production. The strength of this framework is that the coordination between agents is based on the negotiation mechanism. This latter work flow is developed to ensure optimal synergies creation for an equilibrium purchase and selling transactions. The self-interested actors negotiate through bilateral bargaining with the network investor to reach an agreement on the purchase and selling transactions for energy and material trading. Another novel feature of this framework is incorporating reacting thermodynamic conversion systems that allow creating new valorization opportunities for the non-recoverable discharged material by conventional integration techniques and thus improving circular economy. This was achieved through the problem formulation by introducing potential agents that represent possible buyers of an existing industrial agent's waste and which will compete in an auction to win the raw material for their conversion system in which they will invest. The proposed framework combines economic optimization and technical design with actors' personal interests for decision making. Even though the agents' objective functions, on which they act upon, are only based on their economic interest, these could evolve to the sum of an agent economic profit, social benefit and environmental impact with a weighting coefficient of each to adjust their impact degree.

The proposed framework was applied on a virtual park in which the agents are rational and self-interested acting upon their payoffs to engage in a negotiated agreement for energy and material trading; each agent has its individual economic status. The prime inferences ensued from the application of the proposed methodology are:

- The integration of reacting conversion systems in a territory to upgrade non-usable streams into another form of greater opportunities for reuse in the park entails major enhancement in the energy and material synergy patterns.
- The outcome of the most profitable conversion system is highly impacted by two main factors; the first being the resources requirements of the park in which it is going to be implemented and the second is the upgraded new product value.
- The monopolistic position of a single network investor might lead to higher risk for industrial agents breaking a joint agreement for another more lucrative forthcoming offer. The NI should therefore carry out risk assessment and consider lowering its payoff for the benefit of the industrial agents by for instance opting for the equilibrium state inducing the highest *social welfare* that could considerably lower its risks.
- Short and medium term investment strategies could lead to limited heat recovery opportunities due to the transport network and heat exchanger substantial costs.
- The increase in natural gas market price stimulate self-interested agents to bear the additional investment expenses to trade their surplus heat with the network investor by dint of the greater profits induced from the higher heat price.
- The wood to hydrogen conversion system investor manages to place the highest bid in the wood auction with the same sub-agent. It is thus the most profitable wood pathway to invest in its implementation in the investigated park.

This demonstration study proved the capabilities and the possible outcome of the novel developed methodology that enable going further towards closing the energy and material loops. They serve as decision support tools for neighboring industries searching to evolve towards becoming an EIP by proposing strongly viable EIP topology including the best design and technical options of the



non-usable streams conversion systems. Nonetheless some limitations still need to be addressed to strengthen their potential outcomes.

The impact of data uncertainties on the resulting EIP topology robustness is still to be assessed before implementing the energy and material synergies. This could be carried out by fluctuating the process parameters to evaluate if any operation limitation for the proposed design does exist. Moreover, the models of HEN and MAN designs employed in the developed frameworks in this thesis are contend to continuous operating mode. Although substantial number of industrial processes do operate in such mode, others run in batch. Therefore, to account for both type of processes, the network design models should be extended to subjoin the time dimension.

Also, the monopolistic position of a single network investor might lead to higher risk for industrial agents breaking a negotiated agreement for another more lucrative forthcoming offer. To prevent such situations, the methodology for a territory with self-interested actors could be extended to include several network investors that compete to transfer resources and energy through their constructed transport network. The industrial agents thus receive multiple offers from which to choose ensuing energy and material transactions patterns of higher stability.

## **Acknowledgments**

This work has benefited from state aid managed by the National Research Agency under the Investments for the future program with the reference ANR-10-IEED-0012-03.

## **References**

Abi Chahla, G., Zoughaib, A., Tran, C.-T. & Farel, R., 2016a. Is Wood Waste Only for Burning? A Methodology for Best Pathway Identification of Waste Recovery. *Computer Aided Chemical Engineering*, Volume 38, pp. 199-204.

Abi Chahla, G., Zoughaib, A., Tran, C.-T. & Farel, R., 2016b. *Design of an Integrated Waste Wood to Heat and Hydrogen Conversion System: A Parametric Study*. Portoroz, The 29th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems (ECOS).

Abi Chahla, G., Zoughaib, A., Tran, C.-T. & Farel, R., 2016b. *Design of an Integrated Waste Wood to Heat and Hydrogen Conversion System: A Parametric Study*. Portoroz, THE 29TH

INTERNATIONAL CONFERENCE ON EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS (ECOS).

Albino, V., Fraccascia, L. & Giannoccaro, I., 2016. Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: an agent-based simulation study. *Journal of Cleaner Production*, Volume 112, pp. 4353-4366.

Bagajewicz, M. & Rodera, H., 2002. Multiple Plant Heat Integration in a Total Site. *AIChE Journal*, 48(10), pp. 2255-2270.

Bakule, L., 2008. Decentralized control: An overview. *Annual Reviews in Control*, Volume 32, pp. 87-98.

Barbaro, A. & Bagajewicz, M. J., 2005. New rigorous one-step MILP formulation for heat exchanger network synthesis. *Computers and Chemical Engineering*, 29(9), pp. 1945-1976.

Bogg, P., Beydoun, G. & Low, G., 2008. When to Use a Multi-Agent System?. *Springer Berlin Heidelberg*, pp. 98-108.

Boix, M., Montastruc, L., Azzaro-Pantel, C. & Domenech, S., 2015. Optimization methods applied to the design of eco-industrial parks: a literature review. *Journal of Cleaner Production*, Volume 87, pp. 303-317.

Bousquet, F. & Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. *Ecological Modelling*, 176(3-4), pp. 313-332.

Chew, I. M. L., Tan, R. R., Foo, D. C. Y. & Chiu, A. S. F., 2009. Game theory approach to the analysis of inter-plant water integration in eco-industrial park. *Journal of cleaner production*, 17(18), pp. 1611-1619.

Chew, K. H., Klemeš, J. J., Wan Alwi, S. R. & Abdul Manan, Z., 2015. Process modifications to maximise energy savings in total site heat integration. *Applied Thermal Engineering*, Volume 78, p. 731e739.

Dhole, V. R. & Linnhoff, B., 1993. Total site targets for fuel, co-generation, emissions, and cooling. *Computers & Chemical Engineering*, 17, Supplement 1(0), pp. S101 - S109.

Dhole, V. R., Ramchandani, N., Tainsh, R. A. & Wasilewski, M., 1996. Make your process water pay for itself. *Chemical Engineering*, Volume 103, pp. 100-103.

El-Halwagi, M. M., 2012. *Sustainable Design through process integration*. Waltham, USA: ELSEVIER.

El-Halwagi, M. M., Gabriel, F. & Harell, D., 2003. Rigorous Graphical Targeting for Resource Conservation via Material Recycle/Reuse Networks. *Ind. Eng. Chem. Res*, 42(19), pp. 4319-4328.

El-Halwagi, M. M., Glasgow, I. M., Qin, X. & Eden, M. R., 2004. Property integration: Componentless design techniques and visualization tools. *AIChE Journal*, 50(8), p. 1854-1869.

El-Halwagi, M. M. & Manousiouthakis, V., 1989. Synthesis of mass exchange networks. *AIChE Journal*, 35(8), pp. 1233-1244.

El-Halwagi, M. M. & Spriggs, H. D., 1998. Solve design puzzles with mass integration. *Chem Eng Prog*, 94(8), pp. 25-44.

eurostat, 2016. *Energy price statistics*. [Online] Available at: [http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy\\_price\\_statistics](http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics) [Accessed 2016].

Farel, R., Charrière, B., Thevenet, C. & Yune, J., 2016. Sustainable Manufacturing Through Creation and Governance of Eco-Industrial Parks. *Journal of Manufacturing Science and Engineering*, 138(10).

Farhat, A., Zoughaib, A. & El Khoury, K., 2014. *Etude de l'extension de la méthode d'intégration énergétique de l'échelle locale à l'échelle territoriale*. Lyon France, Congrès Français de Thermique 2014: Approches Multi-Échelle.

Farhat, A., Zoughaib, A. & El Khoury, K., 2015. *Heating and cooling networks design algorithm for site wide energy integration*. Pau- France, ECOS 2015 - The 28th international conference.

Fazlollahi, S. & Maréchal, F., 2013. Multi-objective, multi-period optimization of biomass conversion technologies using evolutionary algorithms and mixed integer linear programming (MILP). *Applied Thermal Engineering*, 50(2), pp. 1504 - 1513.

Gassner, M. & Maréchal, F., 2009. Methodology for the optimal thermo-economic, multi-objective design of thermochemical fuel production from biomass. *Computers & Chemical Engineering*, 33(3), pp. 769-781.

Gerber, L., Fazlollahi, S. & Maréchal, F., 2013. A systematic methodology for the environomic design and synthesis of energy systems combining process integration, Life Cycle Assessment and industrial ecology. *Computers & Chemical Engineering*, 59(0), pp. 2 - 16.

Gerber, L., Gassner, M. & Maréchal, F., 2011. Systematic integration of LCA in process systems design: Application to combined fuel and electricity production from lignocellulosic biomass. *Computers & Chemical Engineering*, 35(7), pp. 1265 - 1280.

Ghazouani, S., Zoughaib, ., A. & Pelloux-Prayer, S., 2015. *Coupled heat and resource allocation network design considering multi-contaminants, properties and non-isothermal mixing*. Pau - France, ECOS 2015 - The 28th international conference.

Gray, D. & Tomlinson, G., 2002. *Hydrogen from coal*, s.l.: Mitretek. MTR 2002-31.

Hugo, A. & Pistikopoulos, E., 2005. Environmentally conscious long-range planning and design of supply chain networks. *Journal of Cleaner Production*, 13(15), pp. 1471 - 1491.

Jennings, N., 1996. *Coordination techniques for distributed artificial intelligence*, IN Greg O'Hare, Nicholas Jennings, editors, *Foundations of Distributed Artificial Intelligence*, New York: Jhon Wiley and Sons.

Klemeš, J. J., Varbanov, P. S. & Kravanja, Z., 2013. Recent developments in Process Integration. *Chemical Engineering Research and Design*, 91(10), pp. 2037 - 2053.

Laveissiere, S., 2012. *Les technologies de l'hydrogène au CEA*, Saclay: CEA.

Leong, Y. et al., 2017. Multi-objective optimization for resource network synthesis in eco-industrial parks using an integrated analytic hierarchy process. *Journal of Cleaner Production*, Volume 143, pp. 1268-1283.

Li, C., Giampapa, J. & Sycara-Cyranski, K., 2003. *A Review of Research Literature on Bilateral Negotiations*, Pittsburgh: Carnegie Mellon University, Robotics Institute.

Maréchal, F. & Kalitventzeff, B., 1998. Energy integration of industrial sites: tools, methodology and application. *Applied Thermal Engineering*, 18(11), pp. 921-933.

Mariano, P. et al., 2001. *Simulation of a trading multi-agent system*. s.l., IEEE International Conference.

Mondal, K. C. & Chandran, S. R., 2014. Evaluation of the economic impact of hydrogen production by methane decomposition with steam reforming of methane process. *International Journal of Hydrogen Energy*, 39(18), pp. 9670-9674.

Morar, M. & Agachi, P. S., 2010. Review: Important contributions in development and improvement of the heat integration techniques. *Computers and Chemical Engineering*, 34(8), pp. 1171-1179.

- Mortensen, L. & Kørnøv, L., 2019. Critical factors for industrial symbiosis emergence process. *Journal of Cleaner Production*, Volume 212, pp. 56-69.
- Nash, J., 1951. Non-cooperative games. *Annals of Mathematics*, 54(2), pp. 286-295.
- Palazzi, F., Autissier, N., Marechal, F. M. & Favrat, D., 2007. A methodology for thermo-economic modeling and optimization of solid oxide fuel cell systems. *Applied Thermal Engineering*, 27(16), pp. 2703 - 2712.
- Ponce-Ortega, J. M., Hortua, A. C., El-Halwagi, M. & Jiménez-Gutiérrez, A., 2009. A property-based optimization of direct recycle networks and wastewater treatment processes. *AIChE Journal*, 55(9), pp. 2329-2344.
- Ramos, M. A. et al., 2018. Utility network optimization in eco-industrial parks by a multi-leaderfollower game methodology. *Computers and Chemical Engineering*, Volume 112, pp. 132-153.
- Romero, E. & Ruiz, M. C., 2014. Proposal of an agent based analytical model to convert industrial areas in industrial eco-systems. *Science of the total environment*, 468-469(15), pp. 394-405.
- Russell, S. & Norvig, P., 1995. *Artificial Intelligence (Book)*, New Jersey: Prentice Hall, Englewood Cliffs.
- Savelski, M. J. & Bagajewicz, M. J., 2001. Algorithmic procedure to design water utilization systems featuring a single contaminant in process plants. *Chemical Engineering Science*, 56(5), pp. 1897 - 1911.
- Sayama, H., 2015. *Introduction to the Modeling and Analysis of Complex Systems (Book)*, Geneseo, NY: Open SUNY Textbooks, Milne Library.
- Shaw, M. & Fox, M., 1993. Distributed artificial intelligence for group decision support: Integration of problem solving, coordination, and learning. *Decision support system*, 9(4), pp. 349-367.
- Shelley, M. D. & M. El-Halwagi, M., 2000. Component-less design of recovery and allocation systems: a functionality-based clustering approach. *Computers & Chemical Engineering*, 24(9-10), pp. 2081 - 2091.
- Shoham, Y. & Leyton-Brown, K., 2009. *Multiagent Systems: Algorithmic, Game-Theoretic, and Logical Foundations*, New York: Cambridge University press.
- Tan, R. et al., 2016. An optimization-based cooperative game approach for systematic allocation of costs and benefits in interplant process integration. *Chemical Engineering Research and Design*, Issue 106, pp. 43-58.
- Von Neumann, J. & Morgenstern, O., 1944. *Theory of Games and Economic Behavior*, USA: Princeton University Press.
- Vytelingum, P., Cliff, D. & Jennings, N., 2008. Strategic bidding in continuous double auctions. *Artificial Intelligence*, 172(14), p. 1700-1729.
- Walmesly, T. et al., 2019. Circular Integration of processes, industries, and economies. *Renewable and Sustainable Energy Reviews*, Volume 107, pp. 507-515.
- Wangemann, J. & Stengel, R., 1999. Optimization and coordination of multiagent systems using principled negotiation. *Journal of guidance, control, and dynamics*, 22(1), pp. 43-50.
- Wang, Y. & Smith, R., 1994. Wastewater minimisation. *Chemical Engineering Science*, 49(7), pp. 981 - 1006.
- Weiss, G., 1999. *Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence*, Cambridge, MA: The MIT press.
- Wooldridge, M., 2002. *An Introduction to MultiAgent Systems*, UK: Department of Computer Science, University of Liverpool. WILEY & SON, LTD..

Zoughaib, A., 2017. *From Pinch Methodology to Pinch-Exergy Integration of Flexible Systems [Book]*, Oxford, UK: Elsevier Ltd.