Infrastructure Sharing Synergies and Industrial Symbiosis: Optimal Capacity Oversizing and Pricing

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Abstract—**In this paper we show that Industrial Symbiosis (IS) being implemented in Eco-Industrial Parks (EIP) deals with both substitution synergies (exchange of waste materials, fatal energy and/or utilities as resources for production) and infrastructure/service sharing synergies. The latter is based on the intensification of use of an asset and thus requires to balance capital costs increase with economies of scale for its implementation. Initial investors must specify ex-ante arrangements (cost sharing and pricing schedule) to commit toward investments in infrastructure capacity and the associated transactions. In this way we propose a model that investigates the decision of 3 actors, 2 trying to choose cooperatively a level of infrastructure capacity oversizing to set a plug-and-play offer to 1 potential entrant. The latter has a capacity requirement which is randomly distributed. Capacity cost exhibits sub-additive property so that there is room for profitable overcapacity setting. The entrant's willingness-to-pay for the access to the infrastructure depends on its standalone cost and the capacity gap that must be completed in case the available capacity is insufficient ex-post (the back-up cost). Since initial capacity choices are driven by the ex-ante (expected) entrant's willingness-to-pay we derive the expected complement cost function which helps us to define the investor's objective function. We first show that this curve is decreasing and convex in the capacity increments and that it is shaped by the distribution function of the potential entrant's requirements. We then derive the general form of solutions and solve the model for uniform distribution. Depending on the requirements volumes and the cost assumptions different capacity levels are set.**

Index Terms—**industrial symbiosis, capacity, optimization**

I. Introduction

Y During the two last decades Industrial Ecology (I.E) status evolved from a rather confidential paradigm to an institutionalized interdisciplinary field ([1]). Its seminal idea is to draw on insights from establishing structural parallels between socio-technic systems (supply chains, complex plants...) and biological systems(trophic chains, populations) putting emphasis on valuable materials and energy exchanges denoted as symbioses ([2]) leading to economic and environmental benefits. The conversion of I.E principles into concrete industrial symbioses requires cross-organizational cooperation to gain access to useful information for such symbioses to emerge. The set of actors trying to generate such synergies is denoted as an eco-industrial park. Following Chertow [3] a distinction can be made between 3 modes of synergistic "opportunities" in industrial symbioses: "by-product exchanges" (the use of waste as resource), "infrastructure/utility sharing" and "joint provision of services". The first set of strategies to improve the industrial eco-system efficiency consists in substituting the use of virgin resources by resources recovered from the diversion of waste disposal streams from another actor activities (including in particular fatal heat and water). In addition to the latter, the second and third types of synergistic strategies developed in eco-industrial parks consists in the sharing of infrastructures and services in line with the performance economy principles. In order to explore the actual role played by infrastructure sharing synergies in eco-industrial parks we survey literature on eco-industrial parks and industrial symbioses. Heeres *et al* in [4] showed that utility sharing is easier to implement than waste-as-input flows. Therefore utility sharing often generate the first step cooperation framework to initiate a wider set of symbiotic exchanges. Drawing on the "anchor tenant model" of IS deployment ([1]) Korhonen [5] argued that the role of "anchor tenant" for industrial symbioses can be fulfilled by common Combined Heat and Power (CHP) plants. His central argument is that such installations can use and supply a diversity of flows. In [6] Eilering and Vermeulen focus on utility sharing synergies and insists on the joint exploitation of wastewater treatment plants and CHP plants. Moreover in their study the authors put emphasis on the role played by government in stimulating I.S, notably utility sharing practices in the Netherlands. Regarding the concept of eco-industrial development, literature distinguishes eco-industrial parks and industrial symbiosis networks from other forms of (green) networked businesses ([7]). As stated in ([8]) "to be able to speak about a real eco-industrial park, a development should be bigger than: a single by-product exchange or network of exchange, a recycling business cluster, environmental technology companies, companies making 'green' products, an

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industrial park designed around a single environment theme (for example a solar energy-driven park), a park with environment friendly infrastructure, a mixed-use development (industrial, commercial, and residential)". Several patterns have been identified in the literature regarding eco-industrial development processes in different real world cases ([9]) notably in Northern Europe and Asia. A major stream of research in I.E investigates how does the degree of involvement of "planners" (public institutions, industrial associations...) affects actual outcomes. Coordination body implication ranges from "planned" EIP (top-down) to "self-organized" ones (bottom-up) with intermediate forms of project support. Top-down planning has exhibited limits ([10]) whereas self-organization limits the scope of cooperation. It leads to different deployment patterns tested with complex adaptive systems modelling ([11]; [12]), social network analysis ([13], [14]) and agent-based models ([15], [16]). In line with the so called top-down approach many contributions on optimization methods for I.S deployment adopt a design perspective. Assimilation of I.S network deployment to technical process integration forgoes the nature of EIP actors ([17]-[19]). A limitation of such top-down models is the lack of consideration on bottom-up motives underpinning network deployment. Notably the inclusion of individual rationality constraints (basically the need for positive benefit derived from participation to exchanges) is poorly envisaged and induce global solutions with potentially local imbalances with bad outcomes for some individual actors. Moreover those models do not account for risk taking regarding the symbiosis operational conditions in the future ([20], [21]). Nevertheless a recent stream in the I.S literature analyze I.S as using game theoretic tools ([22]-[24]) In order to cope with those issues, micro founded models would rather require to take into account individual preferences and rent seeking behavior on each potential project ([25]) within a risky environment. In order to cope with these issues a shift in the line of inquiry is proposed in our contribution .We formulate a microeconomic model in a cooperative game setting with stochastic characteristic of one actor (the entrant). By doing so we explicitly consider individual actors decision making in presence of risks. In a first section we propose a taxonomy of infrastructure sharing symbioses based on a literature review on eco-industrial parks and industrial symbioses, then we derive economic foundations for the synergy strategies insisting on infrastructure sharing and in a third section we present a model analyzing the design and the investment decisions of actors anticipating the entry of a partner in the infrastructure sharing synergy. Results are presented and discussed in the fourth section. The last section concludes.

II. A Taxonomy of Infrastructure Sharing Cases

A pool of 25 eco-industrial parks (EIP) is retained for analysis in our study (Table I). We indeed limited our attention to EIP cases with available academic (and institutional) references and information on existing symbioses (not projects).

A. Eco-industrial Parks in the World

General lessons about what is an EIP lead us to notice that EIPs exist in several regions of the world, mainly Asia and Europe. Moreover a diversity of industries from various sectors are involved in EIPs (power generation, refining, pulp and paper mills...). The territorial scale at which EIP are functioning can vary from industrial estate wide (Guitang, Kymi...) to regional networks interlinking multiple sites and municipal areas (Styria, Kalundborg...). In line with the cost killing philosophy of industrial symbioses mature industrial sectors are involved and usual assets are used to support exchanges. Innovative technologies are less frequently part of EIP. We then restricted our attention to infrastructure sharing practices in order to obtain a "real-world" description of the generic instance we will analyze in our model. Over the referenced cases of infrastructure sharing in industrial symbioses we must also indicate that other types of cooperative strategies to reduce global costs do exist and are treated in other streams of literature (Supply chain). At this point it is worth noting that infrastructure sharing can be associated with resource substitution synergies as we will show that those two modes of cooperation do interact strongly.

TABLE I. List of EIP in the World

Eco-industrial park (Country, initiation/discovery)	**References (see supplemental list in annex)**
Green Valley (France,2013)	[owncasestudy];[26]
Dunkerque (France,1999)	[27];[26]
Le Havre (France,1977)	[26],[28]
Pomacle (France,1990)	[26], [29],
Kaisersbaracke(Belgium,2006)	[30], [26]
Terneusen(Netherlands,2007)	[31]; [32]; [26]
MontheyChabalais(Switzerland,2007)	[26], [36]
Styria (Austria, 1993)	[3]; [26]
Nanjangund (India,2007)	[26], [33], [28]
Kalundborg(Denmark,1961)	[2], [10], [3]; [26]
Kymi (Finland,1914)	[34],[26]
Jyvaskyla(Finland,1986)	[5]
Uimaharju (Finland,1967)	[35]
NorkopingLinkkoping(Sweden,2008)	[26], [36], [37]
Gladstone (Australia,2004)	[37]; [26]
Kwinana(Australia,2000)	[3]; [26]
Central Gulf coast (USA,mid-1990's)	[2]-[4]; [26]
Barceloneta (Porto-Rico,1970's)	[2]-[10][11]-[3]; [26]
Guyama (Porto-Rico,2002)	[2]-[10][11]-[3]; [26]
Kawasaki(Japan,1997)	[38]; [26]
Shenyang Teixi (China,2002)	[39]; [26]
TEDA (China,2000)	[39]-[3]
Guitang (China,2001)	[3]-[39]-[11]; [26]
Lubei (China,2003)	[39]; [26]
Ulsan (Korea,2005)	[3]; [26]

B. Proposed Taxonomy of Infrastructure Sharing

Our taxonomy is divided in two categories ("Autoproduction" and "Treatment") relative to the functionality which is at stake when sharing a collective installation. Then for each category the infrastructure type is depicted with its occurrences in the reviewed EIPs.

Autoproduction consists in the design and building of energy/utility production plants and/or (modular) distribution networks (power cables, piping) systems to achieve Capex and Opex reduction.

The most frequent infrastructure sharing practice is the common use of CHP plants. 18 cases are in function over the 25 reviewed parks and its interest is to be "two-sided" since 12/18 also induces a waste treatment synergy. It confirms the importance of such installations in industrial symbiosis as proposed by Korhonen in [5]. With 9 cases water exchange network is the second practice. It is used for energetic purposes (district heating and cooling) and reuse of process water from one firm for other processes requiring lower quality thus saving fresh water use from groundwater sources. In addition to water and steam supplies infrastructure sharing does relate to specific conversion platforms in 5 cases (Zinc powder, CO_2 , bio-fuels and solvents regeneration). The "Treatment" side targets Capex and Opex costs reduction from the design and sharing of effuents, waste water, sludges and hazardous/non-hazardous waste. Typical installations includes water treatment/purification plants for which 12 cases have been identified in our survey. It is an important symbiosis scheme since it bridges public (municipalities) and private actors. As for CHP plants, common wastewater treatment plants do provide a two-sided synergy since sludges are used as fuels for CHP plants or valuable substitution resources for fertilizer production. Incinerators and CHP plants sharing represent a second typical case. In 12 cases the CHP plants do perform a collective waste treatment service by burning sludges, wood residuals or organic waste. In 2 cases incinerators do burn hazardous waste from industries and supplies steam to other firms. Additional synergies not specific to eco-industrial symbioses but with sound business interest include Purchasing consortia for order pooling. It is an Opex reduction strategy from Bulk purchasing (leveraging non-linear tarification schemes) for utilities, energy vectors, consumable supplies, transportation and treatment services. A taxonomy of organizations supporting those arrangements is available in [40]. Logistics is another vector for multilateral cooperation with inventory pooling that lowers the global carrying costs. Savings are driven by coordinating over depletion rates and replenishment policies ([41]). Warehouses sharing for Capex and Opex reduction from optimization of in-bound or out-bound logistics activities stems from the intensification of use of available storage space ([42]). Transportation is a last category. For the latter synergies occurs from the optimization of for inbound or out-bound transportation schemes in order maximize the use of available capacities (freight consolidation) and negotiate an agreement with logistics service providers ([43]). In the next section we analyze the economics of "Autoproduction" and "Treatment" cooperative strategies in the context of industrial symbiosis following the models proposed in the literature. Exploration of cost and value drivers will help us to base our model assumptions and scope regarding these elements.

TABLE II. TAXONOMY OF SHARING-BASED SYMBIOSES

Infrastructure-service sharing practices	**Functionality**
eco-industrial:	
Auto-Production	
CHP plants	steam and electricity supply
Water exchange network	fresh water, cooling, low grade heat
Conversion platforms	supply of: CO_2, bio-fuels, Zinc, solvents
Treatment	
Waste water treatment plant	elimination + sludge supply
Incineration/CHP boiler	elimination + ash and heat supply
other:	
Purchasing	various supplies or services
Logistics	
Inventory pooling	various resources
Freight consolidation	transport and storage

III. How Infrastructure Sharing Generate Value

A. The Value of Sharing Practices Types

Along with resource substitution the second type of synergistic strategy to be developed in eco-industrial parks consists in the sharing of infrastructures and services. In the generic labelling of infrastructures and services, we can find a variety of systems and devices as productive assets, utilities-energy generation plants (and the associated transmission systems), industrial water network, waste treatment units, logistics warehouses, site roads and buildings for the most prominent (Table II). The specificity of those installations is that it provides homogenous services to the actors. Most of such services are cost components for the actors core production activities. By adopting sharing practices over such infrastructures, cost cutting synergies are generated. This is a key difference with R&D departments or laboratories alliances which may improve substantially core products strategic market position as in sectoral clusters. Efficiency gains over supply cost components can be achieved by appropriate cooperation among actors in the eco-industrial park. The economic advantages of such strategies can be decomposed in several dimensions as investments budget (Capex) reduction ([44]; [45]), bargaining position enhancement ([46]; [47]) or resources/capabilities consolidation for example in conversion platforms ([48], [49]). The extent of such gains depends upon various contextual patterns. Each actor faces its own constraints and opportunities in relation with its sourcing strategy, market conditions and technological environment which in combination will affect the value of collective action. Production assets can be networked in order to handle cost reductions (inventory) and risks. On the risk dimension, collective networking can be used as a diversification of sources and demands to hedge against risks ([50]). Order pooling and collective arrangements like purchasing consortia for service contracting or items purchasing can provide benefits (see [46]). By pooling their orders collaborating actors can achieve cost reductions through the effect of price discounts on purchases due to bulk pricing policies of item providers stemming from combination of competition in the upstream market and economies of scale (the upstream cost reductions for service or items provision are at least partly transferred to the collaborating actors due to competitive pressure). Service contracts can also be priced down by contractors since the bargaining position of the pool increases. Order pooling for service can be used to optimize import/export logistics freight consolidation or warehouse infrastructure sharing. Such practices requires a certain amount of information sharing for coordination and collective arrangement setting among participating actors. Another operational strategy is resource pooling. By cooperating for pooling common resources actors can achieve various benefits. For instance inventories of spare parts can be shared and managed to minimize inventory levels ([51]). Capacity sizing for installations (design phase) like resource generators (CHP plants) or treatment units (incinerators, water purification) and piping systems for carrying utilities (industrial water, heat transfers, industrial gases) is a key lever to benefit from infrastructure sharing. Regarding energy-utility generation plants or treatment units the costs drivers are capacity (quantitative) and capability (qualitative). Qualitative aspects determines the technical specifications of the plant and thus will structure the cost of purchased equipments since it specifies the suitable technical combinations.

B. Capacity and Economies of Scale

The quantitative cost driver that is the capacity is of first interest when analyzing infrastructure sharing opportunities. Particular statistical relationship have been estimated by industrial engineers and reported in the literature on plants capital cost estimation methodologies (see [52]). The baseline formulation of the capital cost estimates rely on a relationship between the capacity of needed equipments and their purchased cost. The total capital cost is standardly estimated using a scaling exponent which allow to derive the (estimated) cost of a plant or an equipment from its capacity. Reference [53] provides scaling exponents estimated using statistical techniques on empirical production processes at two levels of aggregation -from plant to equipments can be used to estimate the cost of a plant (or an equipment) in function of its capacity level. Mathematically the scaling exponent is the power at which the capacity requirement is raised in order to obtain the efficient "physical" infrastructure scale needed to perform the function (i.e: the capacity requirement). In most cases this scaling factor is lower than one meaning that it is preferable (in terms of cost) to scale-up the equipment rather than buying several ones. After equipment system choice and the sum-up of the associated costs one can recover an estimate of the purchased cost for the whole infrastructure. A distinction is usually made between inside battery limits estimates dealing with core process equipment and outside battery limits consisting in the estimation of land and yard improvements, roads, buildings but also service facilities for utilities generation ([52], [53]). The latter is of first importance in industrial ecology. To complete the total capital cost (Capex) estimate the equipment purchasing costs (for both inside and outside battery limits) have to be scaled using additional coefficients to account for other direct costs such as delivery, installation, add-ons (piping, instrumentation…). Indirect costs (or construction overhead costs) must also be added (using percentages of the delivered equipment or total fixed-capital investment whose it is part of). In addition to the fixed capital costs the working capital requirements must be considered for an exhaustive total capital investment estimation. In terms of infrastructure sharing synergies capacity choices dramatically drives expanses.

C. Act on Cost Drivers through Cooperation

Cooperation among actors in the eco-industrial park can allow for substantial gains in terms of capital investment as long as the cost for a given aggregated service or production level can be globally reduced. In fact if the cooperating actors can pool their demands(for a utility or an input production) and in case their demands exhibit synergistic patterns according to their profiles the capacity cost for the common unit can be lower than the sum of the capacity needed for individual units. This is due to the fact that the capital investment depends on the total capacity required. As long as the equipment costs (and thus the total costs of capital) are concave in the capacity requirement (which is the case for scaling factors lower than 1 then it is optimal to share a larger unit and not developing several parallel units. In consequence the final induced cost then can be shared among participants depending on their contributions to cost. The key point here to achieve effective gains is the adequation of demand profiles. Indeed in case the sum of demands (loads for the production unit) reaches levels above the maximum among each actors demands (or the corresponding load) then the required capacity under cooperation should increase. For illustration if each actor would have perfectly synergistic profiles then the capacity required for the pool will not have to be set above the maximal individually required capacity. In the worst case the peak load is attained simultaneously by all the actors so that the capacity needs will increase dramatically lowering the gains from cooperation. If the cost function is concave in the capacity (and the same applies for each actor) pooling is still synergistic but appropriate cost sharing should be performed. In addition to capital expenditures, operating fixed costs can be further split among the actors leading to savings in those fixed expanses leading to global cost savings. The same principle holds for treatment units in terms of treatment capacity setting. Implementing collaborative practices to decrease the peak loads can further reduce capacity requirements. Since it requires accurate data on load profiles those strategies are more intensive in terms of information sharing and complex in terms of coordination. In case of synergies requiring piping network setting the piping system can be the main capital cost to consider. The main Piping cost components are purchased equipment, installation costs and maintenance. Purchased equipment cost drivers for piping is the length of pipes and their diameter. As those drivers are dependent upon the network topography, complexity and density (for length) and throughput (for diameter) substantial gains can be achieved by appropriate technical optimization and common network optimization (for a literature review see [54]). Nevertheless some actors might contribute more or less than other to the corresponding costs since their positioning (length) and requirements (diameter) will impact total cost. A right assessment of these contribution should be performed in order to properly define contributions in order to implement a cost sharing rule. Installation and maintenance tasks are contracted with some energy or utility service provider thus gains can be done by sharing this fixed cost among several participants. In case of connection of an actor to an existing installation is possible it is a factor of dynamism in eco-industrial cooperation. Connection to an existing (pre-designed) system can raise issues such as congestion effects since the capacity ca not be sufficient for some periods with an additional participant but it allows to transfer a part of fixed operating expenditures and initial capital investment to the prospective actor. Once again the question of the new entrant's profile is of first importance. Arrangements for common infrastructure setting and use are then dependent upon exogenous characteristics of the project and endogenous patterns related to actor's objectives.

Those arrangements must be structured in contracts that specify procedures, cost sharing rules and various constraints to coordinate actors. Gains drivers are dependent upon demand or supply profiles (load curves/supply curves) in interaction with underlying (exogenous) cost structures for investments. Synergies thus arise from appropriate design and capacity choices as well as the ability to ex-post share part of the incurred costs. To sum-up infrastructure (and service) sharing synergies arises from decreasing global (peak) capacity needs or resource availability costs (inventory pooling). On the other hand the associated interaction costs includes intrinsic downside risks of synergies like congestion (less availability) implying more back-up purchasing (less availability trigger back-up recourse) and quality concerns. Both must be minimized to ensure mutual profitability and commitment to the implementation of the sharing strategy. Following this, investigating the articulation of capacity design, infrastructure building and operation with designers' prospects about potential entrants is of first importance. In the next section a model is formulated to analyze the implementation of such infrastructure sharing synergies.

IV. Model: Optimal Capacity Oversizing

A. *Model: Business Case Description*

In order to analyze the decision of investing in additional capacities to attract future partners a 2 periods model is formulated. The timing is as follows: in t_0 2 actors A and B (the incumbents) pool their capacity requirements and decide cooperatively what capacity level to set. Capacity level K corresponds to the sum of individual i requirements (q_i) pooled ($K = \sum_i q_i$). In real instances these requirements can represent input/utilities supplies or effluents treatment volumes. The cost of investment is driven by the infrastructure capacity ($I(K)$) and is described by the formula $I(K) = (1 + \alpha)\, K^{\beta}$ where K is the infrastructure capacity (it is the direct cost driver), β is the scaling factor, (β < 1) (linking capacity requirement to equipments needed) and α is the total cost of equipments and associated costs (linking equipments to cost). The investment cost function exhibits economies of scale so that $\sum_i I(q_i) > I(\sum_i q_i)$. To take their decision the incumbents share information on their respective requirement level q_A and q_B and they form a common prospect about future sharing opportunities. Regarding further sharing opportunities they anticipate the demand of an entrant whose capacity requirement q_C is randomly distributed over (0,1) with distribution $f(x)$ (and c.d.f $F(x)$). Due to economies of scale the decision of incumbents on what capacity level to set is equivalent to the decision on additional capacity over their own requirements k (with $Q(k) = k + q_A + q_B$). In t_1 after investment in $K + k$ had occurred (and the incumbents have paid the corresponding amount) an entrant addresses a demand for the access to the infrastructure available capacity k. Access is conditional upon a payment $T(k)$ that C should transfer to the incumbents A and B. This access price is set by private negotiations between C and the allied incumbents who owns the infrastructure so that in t1 the entrant's willingness-to-pay is bounded by its standalone cost ($I(q_C)$) if $k \geq q_C$. In case $k < q_C$ the entrant's willingness-to-pay is decreased by the back-up costs (B) he should incur to fill the capacity gap during exploitation ($q_C - k$). If the back-up cost is incurred by the incumbents they will transfer it to the entrant in the exploitation phase so that the reasoning is symmetric and the consequence is the same. The formula linking the additional capacity setting with the decrease in the willingness-to-pay is the following:

$$\mathrm{B}\,(q_C; k) = \mathrm{B} \cdot \mathrm{Max}\,(q_C - k\,; 0)$$

B. *Model: Behavioral Considerations*

Ex-post entrant rationality constraint: $\mathrm{T} \leq I(q_C) - \mathrm{B}(q_C; k)$, Where T is the tariff proposed by the incumbents to the entrant. Assuming that if the entrant decides to connect to the incumbent's infrastructure he cannot build its own and must use the back-up solution in case of capacity shortage. The entrant is willing to accept the offer if he derives a cost advantage from it. Thus the payment made to the incumbents and the back-up cost to be incurred must not exceed its standalone cost. Otherwise he would prefer to build its own infrastructure. Ex-post incumbents rationality constraint: $0 \leq \mathrm{T}$, Where T is the tariff proposed by the incumbents to the entrant. After the entrant's requirement is known incumbents must have non negative revenue from the offer they make to the entrant. Ex-post bargaining set non-emptiness condition:

Trade will occur in period 2 if and only if:

$$0 \leq \mathrm{T} \leq I(q_C) - \mathrm{B}(q_C; k)$$

Note there is no consideration for incumbent's incurred cost increments since it is sunk in period 2. Ex-ante incumbents rationality constraint (iRC): $0 \leq I(K+k) - I(K) \leq E(T(k))$, Where K is the optimal capacity level for incumbents requirements ($K = q_A + q_B$) and k is the extra capacity available to the entrant ex-post. Before uncertainty is resolved about the entrants' requirement level the incumbents should decide the level of overcapacity they will set. Thus they seek to maximize their Expected profit regarding their overinvestment decision that is the (deterministic) investment cost increment to incur in comparison with the expected payment they anticipate (E(T(k))). It follows that the expected profit for the incumbents is:

$E(T(k)) - [I(K+k) - I(K)] = E(I(q_C)) + I(K) - [E(B(k)) + I(K+k)]$ with $E(T(k)) = E(I(q_C)) - E(B(k))$,

Thus the incumbents ex-ante rationality constraint can be reformulated as:

$$0 \leq I(K+k) - I(K) \leq E(I(q_C)) - E(B(k))$$

Equivalent to :

$$I(K) + E(B(k)) \leq I(K+k) + E(B(k)) \leq E(I(q_C)) + I(K)$$

C. Model: Optimization Programm

Profit maximization is equivalent to the minimization of: $O(k) = E(B(k)) + I(K+k)$.

Thus the incumbents optimization programm is:

$$\min_k \{I(K+k) + E(B(k))\}$$

s.t: $I(K) + E(B(k)) \leq I(K+k) + E(B(k)) \leq E(I(q_C)) + I(K)$,
(let's call this constraint "cap")
with: $O(k) = I(K+k) + E(B(k))$
$= (1+\alpha)(K+k)^{\beta} + B\cdot\int_k^1 f(x)(x-k)dx$

Under some circumstances that we will investigate, the minimal expected cost of the sharing agreement may not generate sufficient savings regarding the global expected costs without additional capacity setting. In that case there will be no overcapacity setting ex-ante ($k^* = 0$) so that the solution of the programm is given by:

$$k^* = \begin{cases} argmin\{O(k)\}, & if\, cap\, holds \\ 0, & otherwise \end{cases}$$

V. Results and Discussion

A. General Formulation

1) Assumptions

Our baseline assumption is that it is preferable to build an infrastructure rather than using the "back-up" solution when standing alone: $\forall\, q_C \geq 0$; $B \cdot q_C \geq I(q_C)$
Corollary:
for $k = 0$, $E(B(0)) \geq E(I(q_C))$
since, $O(0) = I(K+0) + E(B(0)) = I(K) + B\cdot\mu$, $O(0) >$ cap (a null over-investment do not induce any expected savings).

2) Analysis of the Expected Back-up Cost

$E(B(0)) = B\cdot\mu$, $E(B(1)) = 0$

Proposition: E(B(k)) is decreasing and convex in k

(decreasing) : $\frac{\partial E(B(k))}{\partial k}(k) = -B\cdot(1 - F(k)) < 0$
(convex): $\frac{\partial^2 E(B(k))}{\partial k^2}(k) = B \cdot f(k) > 0$

3) Analysis of the Objective Function

A minimizer of the objective function is given by the first order condition when O is convex in k:
Proposition:

$\forall\, k : k\, f(k)^{\frac{1}{2-\beta}} \geq (B/(1+\alpha)\beta(1-\beta))^{1/(\beta-2)} - K$,

$O(k)$ is convex
and we have:

$$argmin\{O(k)\} \begin{cases} k\,(1 - F(k))^{1/(1-\beta)} = (\frac{B}{(1+\alpha)\beta})^{1/(\beta-1)} - K \\ k\, f(k) \geq (\frac{B}{(1+\alpha)\beta(1-\beta)})^{1/(\beta-2)} - K \end{cases}$$

B. Numerical Application: Uniform Distribution

For simplicity we will assume that the entrant's requirement follows a uniform distribution over (0,1). This choice lead to have the following:
Assumptions:

$q_C \sim U(0;1)$
it follows that: $\mu = E(q_C) = 0.5$ and $\forall 0 \leq q_C \leq 1$; $F(q_C) = q_C - 0/1 - 0 = q_C$; $f(q_C) = 1$

From our baseline assumption on cost functions we have:

$$B \geq (1+\alpha)/(1+\beta) \cdot 1/\mu$$

Objective function:

$$O(k) = (1+\alpha)(K+k)^{\beta} + B \cdot (0.5 + k^2/2 - k)$$

Optimization:

$$argmin\{O(k)\} \begin{cases} k(1-k)^{1/(1-\beta)} = (\frac{B}{(1+\alpha)\beta})^{1/(\beta-1)} - K \\ k \geq (\frac{B}{(1+\alpha)\beta(1-\beta)})^{1/(\beta-2)} - K \end{cases}$$

In $\tilde{k} = (\frac{B}{(1+\alpha)\beta(1-\beta)})^{1/(\beta-2)} - K$, O admits an inflection point.

Holding our assumptions (requiring $\forall\beta, B \geq (1+\alpha)\cdot\frac{1}{\mu}$, uniqueness of the minimizer is ensured by the fact that: $\frac{\partial O(k)}{\partial k}(\tilde{k}) < 0$.

C. Results Discussion

In order to explore the overinvestment decision of incumbents in different contexts we will optimize the objective function and remove solutions at which the "cap" constraint is violated. We perform such a task using standard Python optimization tools (Scipy). We generate instances by varying the 3 key parameters that are the unit back-up cost level (B), the scaling factor β (see Fig. 1 and Fig. 2) and the incumbents' capacity requirement K (see Fig. 3 and Fig. 4). In this article we focus on the impact of unit back-up cost and we investigate the effects of different levels of β and K on the incumbents' overcapacity choices.

Case 1: Influence of back-up costs depending on β for low/high K ($K < 1$ /$K > 1$)

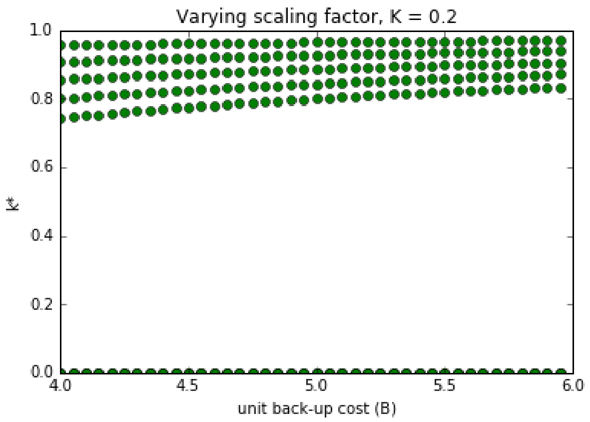

Figure 1. Influence of unit back-up cost for low K

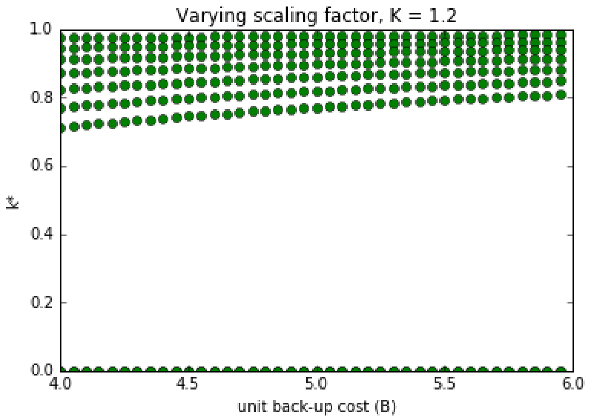

Figure 2. Influence of unit back-up cost for high K

Observations: The larger is K positive overinvestment occur for larger range of β (less favorable scaling factors). The higher β is the less overinvestment is. Moreover, for higher scaling factors overinvestment is more sensitive in low values of B.

Case 2: Influence of back-up costs depending on K for low/high β ($\beta < 0.5$ / $\beta > 0.5$)

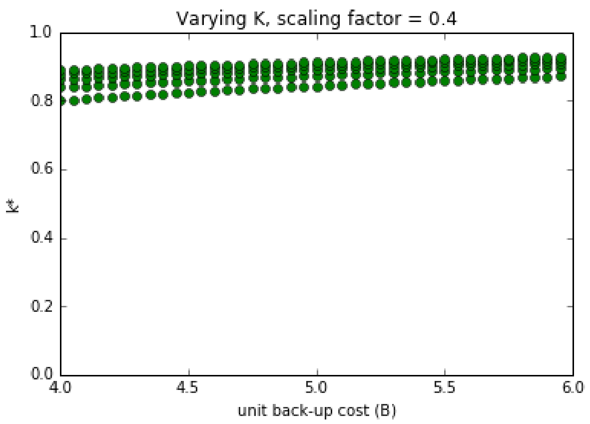

Figure 3. Influence of unit back-up cost for low β

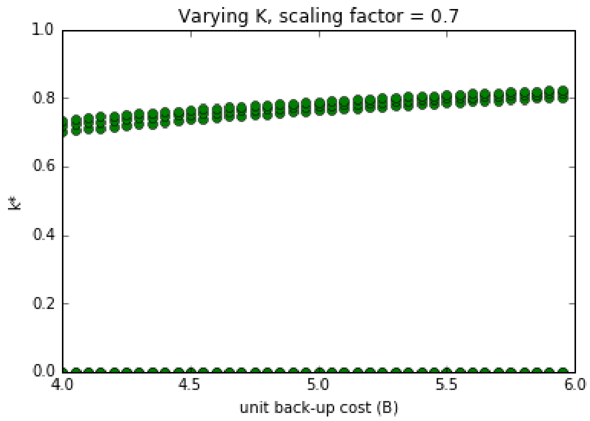

Figure 4. Influence of unit back-up cost for high β

Observations: The larger β is the lower overinvestment is. For β ranging above 0.5 investment is null whenever K is low. Regarding the influence of K, the higher it is the higher the overinvestment is.

The lower K is, the more overinvestment is sensitive in lower ranges of B.

VI. Conclusion

In this article we propose a review of infrastructure sharing practices in eco-industrial parks referenced in the literature. A taxonomy is proposed along the function that is performed by the infrastructure and we show that autoproduction and treatment can interact. Then we explain the business model of such practices leading to cost cutting synergies for participating actors. The importance of capacity choices in the design phase is shown to be a key cost driver for this type of synergy. Insisting on the fact that cooperating actors must set appropriate arrangements for such projects to be completed we formulate a model to analyze the sharing opportunities in a dynamic context in presence of economies of scale and uncertainty regarding future needs for capacity. A first insight is that the decision to overinvest must be analyzed in two parts: the level of overinvestment (efficiency) and the occurrence of it (effectiveness). While back-up costs increases the value of over capacities (in a convex and decreasing manner) it discards positive solutions in not favorable contexts (low K and low economies of scale). In further studies we can consider alternative formulations for back-up costs considering it as the entrant's cost for infrastructure building so that it would be of the form of the investment cost function. Moreover we could waive our assumption about the superiority of infrastructure over "back-up" solution for standalone costs. Indeed a market segmentation could be added in which back-up is better for actors with low needs and (over a certain threshold) the best standalone solution is to build an infrastructure (due to economies of scale). Regarding extensions we could investigate the effect of public interventions the effect in two ways. A lump sum subsidy would induce positive overinvestment in more cases while per-unit subsidies increase the value of it and induce a higher overinvestment level. Another extension of our research would also add a non-cooperative branch to the game in which incumbents could compete in period 2 for the entrant's connection. Understanding the repartitions of expected value to sustain cooperation would be an interesting insight in terms of access pricing.

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