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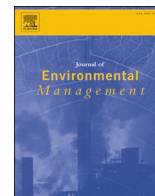
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Research article

A sustainability assessment model for industrial parks: A Choquet integral aggregation approach



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ABSTRACT

This study deals with subject sustainability assessment for industrial parks which are seen as systems of inter-related companies and infrastructures. Although sustainability was introduced into mainstream policy discourse several decades ago, it remains complex to assess, and thus to improve in an integrated way. This is particularly true for such elaborate structures as industrial parks. However, the literature has made little effort to present tools for industrial parks managers to take decisions towards sustainability. The paper develops a sustainability assessment framework aimed at industrial parks' managers. The model is based on a multi-criteria compromise aggregation principle and relies on a preliminary systemic deployment of industrial park sustainability. The presented assessment uses a double aggregation mechanism using the weighted arithmetic mean (WAM) and the Choquet integral (CI) to account for the interrelations between stakeholders involved in an industrial park. This double aggregation results in two level of assessment, offering a more comprehensive view of the examined industrial park. A first level of assessment allows managers to control and improve the performance of their industrial parks in each pillar of sustainability. The second level is the assessment of the overall sustainability, which supports the managers' analysis of their strategy to achieve sustainability. As an illustration, the model is used to assess the sustainability of a Canadian industrial park. Application of the model shows that the completion of the studied industrial park's action plan results in reaching a 54% sustainability performance considering the managers' long-term sustainability strategy and that their vision of sustainability moderately favors the simultaneous satisfaction of economic criteria with environmental or social criteria. These results illustrates the capacity of the model to guide managers in the sustainable development of their industrial parks.

1. Introduction

Industrial activities seek proximity with one another in order to benefit from easy access to materials, logistics and clients and to take advantage from their complementarity. Historically, their gathering place used to be the city but this solution found its limit because of the nuisances caused by the closeness between industrial and residential activities. It is in this context that the industrial park emerged in North America and Europe in the 1950's. Nowadays, industrial parks are tools of planned economic development in industrialized countries (Peddle and Feb, 1993). They can be described as "a large tract of land, subdivided and developed for the use of several firms simultaneously, distinguished by its shareable infrastructure and close proximity of firms" (United Nations Industrial Development Organization, 1997).

Today, industrial parks face various challenges, depending on their geographic, economic and social environment (Lambert and Boons, 2002). Some of these challenges, such as infrastructure aging, road congestion, land rarefaction, or labor shortage, impact their attractiveness. Other challenges such as waste handling, pollution, or intensive resource and land consumption are related to the environmental impact of industrial parks and their resident companies. As a consequence, local authorities and planners are rethinking the design and development of these parks by introducing environmental and social considerations so as to improve their sustainability. In order to do so, local authorities need to assess the sustainability of industrial parks, taking environmental, social and economic criteria into account.

Against this background, a new archetype of sustainable industrial park has been introduced: the mixed-use ecopark (MUE) (Le Tellier

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et al., 2019). This archetype provides answers to the sustainability challenges faced by traditional industrial parks, notably in Europe and North America. Essentially, the MUE philosophy is based on the belief that sustainable planning and inter-company collaboration are important assets for creating sustainable industrial parks that are beneficial to their community. At its highest level of abstraction, the MUE's mission, the so-called finality, is its sustainability. In itself, sustainability is a complex concept (Pope et al., 2004) that cannot be reduced to a set of rules and formulas unless applied in a specific context. In the MUE's context, additional complexity arises from the inherent intricacies of the MUE and the diversity of its instances. Therefore, sustainable industrial parks that aims to become MUE need an assessment tool that is able to deal with this complexity.

The global scope of this paper is the development of methods for environmental quality management, more particularly, it deals with the subject of industrial park's sustainability assessment. Previous research on this subject have focused on another well-known concept that is the eco-industrial park and therefore mostly tried to assess the performance and sustainable gains of industrial symbiosis rather than overall sustainability Valenzuela-Venegas et al. (2016); Zhao et al. (2018); van Beers et al. (2020); Fan and Fang (2020); Hu et al. (2021). As far as we know, no study to date has presented overall industrial parks' sustainability assessment tools, which represents a research gap. Therefore, our research objectives is the development of such a tool in order to guide managers with the development and control of their MUE, no matter their size, maturity, type of resident companies etc.

In order to predict or to assess the sustainability of MUEs, an assessment model is proposed. Indeed, in a proactive way, the prediction of MUE sustainability can guide its manager with clearly defined action plans. In a reactive way, the assessment of MUE sustainability can support its manager in updating or redefining action plans. Moreover, information about the expected versus the attained sustainability states offers an overview of the MUE performance. This results in an easy, direct, and comprehensive way of communicating. Local authorities can thus display the results and improvements achieved through visual management. Information about sustainability can be used to promote the MUE to potential resident companies. Finally, information on sustainability may be used for benchmark studies and comparisons between several MUEs.

Because of its complexity as an objective, MUE sustainability cannot be directly assessed. It needs to be deployed into so-called elementary objectives, whose achievement can be directly assessed, resulting in the so-called elementary expressions. The proposed approach is based on the aggregation, at any given point in time, of these elementary expressions in a multi-criteria context (Figueira et al., 2005). Two different assessments of sustainability are expected: an assessment with regards to each of the three pillars of sustainability and an overall assessment. Therefore, the approach comprises several steps and relies on mathematical tools that take into account the specificities of this problem. From a formal point of view, it uses two operators from the compromise aggregation family: the weighted arithmetic mean (WAM) and the Choquet integral (CI). The WAM is used to handle the varying relative importance of the objectives and the CI is used to handle the interactions between them. The Measuring Attractiveness through a Categorical-Based Evaluation TechNique (MACBETH) framework is used to ensure mathematical consistency. In a nutshell, the innovative elements of this study is the operationalisation of sustainability assessment through a double aggregation mechanism.

This article is structured as follows. In Section 2, the intricacies of MUE sustainability are presented based on the definition of an MUE and of sustainability as a general concept. After presenting the outline, the aggregation procedure is introduced in Section 3. In Section 4, the model is applied to a Canadian MUE whose manager wants an assessment of the sustainability improvement during the execution of its action plan. Section 5 analyses the results of this case study and the perspectives of this work. Finally, Section 6 concludes this work.

2. The MUE and its sustainability

2.1. The MUE

2.1.1. Definition

One of the oldest and most traditional forms of planned economic development in developed countries is the industrial park. In recent decades, the challenges for sustainable development have become inseparable from industrial parks (United Nations Environment Programme, 2001). Indeed, the design, development, management, and retrofit of industrial parks are cross-sector endeavors involving a variety of stakeholders.

With the goal of spurring on the development of sustainable industrial parks, a new archetype called mixed-use ecopark (MUE) has been introduced. The MUE is a sustainable industrial park that is planned and built with respect to principles of sustainable urban development, where companies collaborate in order to gain economic, environmental, and social advancements for themselves, their employees, and the community. This concept is derived from another established concept: the eco-industrial park (EIP). An EIP is an industrial park where a community of industries take part in a network of collaborative relationships, exchanging resources such as energy, water, materials, and by-products, in order to increase their economic performance by minimizing the environmental impact and creating benefits for the local community (Côté and Hall, 1995; U.S President's Council on Sustainable Development, 1997; Côté and Cohen-Rosenthal, 1998). The origins of the EIP can be traced back to the emergence of industrial ecology and circular economy (Li, 2011; Saavedra et al., 2018; Belaud et al., 2019). The main difference between an MUE and an EIP is that the focus of an EIP is on the creation of physical exchanges between industries, also called industrial symbiosis (Chertow, 2000). On the other hand, the MUE strategy for sustainability focuses on urban planning practices and collaboration between companies to foster eco-innovations, sustainable business practices, improved work conditions for employees, and economic and social advancement for the community.

The MUE is traditionally controlled by a designated manager. This manager is a legal entity that can be a combination of several stakeholders such as public or private investors, local authorities, planners, developers, etc. (Lowe, 1997; van Leeuwen et al., 2003; Heeres et al., 2004; Tessitore et al., 2015). As described before, the manager is tasked with the general operation of the MUE, including activities such as defining strategy, overseeing the execution of the sustainability action plans, as well as communicating about the park and promoting it.

2.1.2. Systemic modeling

By definition, the MUE is an open system that exchanges material, energy, people, capital, and information with its environment. A system is defined as "a regularly interacting or interdependent group of items forming a unified whole" (Merriam-Webster.com, 2020). Systemic analysis considers a system as a whole and adopts diverse perspectives and organizational levels, looking at interactions between its constituent sub-systems (Bertalanffy, 1950). The systemic modeling of an entity consists in the characterization of its finality, its environment and observer, its structure, its objectives, and its two behaviors: normal operation and transformation (Le Moigne, 1994). Like other types of modeling, systemic modeling is described through a defined perspective, which is that of the observer of the system, namely, the MUE manager. The manager is a particular entity found on the border between the system and its environment.

The systemic modeling of the MUE is presented in Table 1. Additional details are found in (Le Tellier et al., 2019).

In particular, a system's finality reflects the observer's idea of the mission of a system at its highest level of abstraction. The MUE finality is its sustainability. Indeed, sustainability fits Le Moigne's idea of finality perfectly, since it is a process of continuous improvement through decision-making and interactive learning (Le Moigne, 1994;

Table 1
Systemic modeling characteristics of the MUE.

Characteristics		Modeling of the MUE
1	Finality	Sustainability
2	Environment	Suppliers, Clients of the resident companies Natural Environment Local community
3	Structure	Observer Entities Manager Companies Buildings Infrastructures
		Interactions Inter-company collaboration Eco-Industrial Synergies Deployment of the finality
4	Objectives	Operation of the entities
5	Behavior	Operation Transformation Evolution of the MUE structure

Siebenhüner and Arnold, 2007).

2.2. Sustainability

2.2.1. Definition

One of the most cited definitions of sustainable development is from the Brundtland Report, which defines it as a “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” (World Commission On Environment and Development, 1987). Completing the Brundtland Report, the Rio Declaration consists of 27 principles intending to guide future sustainable development, and Agenda 21, which articulates a plan for putting these principles into practice (United Nations, 1992). Both the Rio Declaration and Brundtland Report have facilitated the introduction of sustainability into mainstream policy discourse. Nevertheless, since then, various interpretations of the definition found in the Brundtland Report have been proposed, which shows that sustainability and sustainable development remain ambiguous and complex concepts ((Pope et al., 2004; Johnston et al., 2007) among many others).

A common interpretation of the concept is through its three interconnected pillars, which each include economic, social, and environmental objectives. In its most consensual paradigm, sustainability is often represented at the intersection of these three pillars. Sustainability emerges when balancing trade-offs between seemingly equally desirable goals within these categorizations (see (Purvis et al., 2019) for an extensive analysis of the definition of the three pillars). While it has been criticized for its lack of theoretical development (Redclift, 2005), this popular and engaging description is successful in illustrating the complexity of sustainability that should emerge from the achievement of interconnected conflicting objectives (Cocklin, 1989). Two other paradigms are weak sustainability and strong sustainability. These paradigms are based on the notions of manmade capital, expressed by the ability to produce economic value, and natural capital, corresponding to the world’s stock of natural resources. Strong sustainability assumes that manmade and natural capital are complimentary but cannot be substituted and that sustainability is equivalent to “*leaving the future generations a stock of natural capital not smaller than the one enjoyed by the present generation*” (Cabeza Gutiérrez, 1996). On the other hand, weak sustainability assumes that natural and manmade capital can be substituted, and that sustainability is equivalent to non-decreasing total capital stock (Daly and Cobb, 1994; Figge, 2005; Dietz and Neumayer, 2007; Chandrakumar and McLaren, 2018). Both paradigms have been criticized because their concept of sustainability lacks resilience (Atkinson et al., 2007) and practicability, respectively (Beckerman, 1994). However, Neumayer argues that both paradigms are scientifically compelling since they both rest on claims about the future that are irrefutable (Neumayer, 2010). The disparities in balance between the paradigms of weak and strong sustainability perfectly illustrate the ambiguity and complexity surrounding the concept of sustainable

development. Hence, these disparities lead to different visions of sustainability, which translates into varying importance attributed to each pillar and into diverse approaches to dealing with the trade-offs.

2.2.2. Assessment

Sustainability assessment can be defined as “*a tool that can help decision-makers and policy-makers decide what actions they should take and should not take in an attempt to make society more sustainable*” (Devuyst, 2001). Various sustainability assessment tools have been developed and several overviews and typologies of these tools are found in the literature (Singh et al., 2009; Kaufmann-Hayoz et al., 2001; Sharifi and Murayama, 2013).

For instance, a categorization of tools that is worth mentioning is the one proposed by Ness et al. (2007). This categorization considers the focus of the tools (*i.e.*, product, organization, region, or policy), their temporal characteristics (*i.e.*, if they are used retrospectively or prospectively of the assessed project, of the introduction of the assessed policies, or of the design of the assessed product) and the integration of the pillars (*i.e.*, to what extent the tools combine environmental, social, and/or economic aspects). Sustainability assessment tools are then distinguished into the following three categories:

- Indicators and indices, which are retrospective tools that can focus on a wide array of systems and are either integrated or non-integrated.
- Product-related tools, which are both retrospective and prospective tools that focus exclusively on products and are non integrated.
- Integrated tools, which are prospective tools that focus on projects or policies (most of them are established tools but do not necessarily pertain directly to sustainability issues only).

As we can see from Ness et al. (2007), various tools exist for assessing sustainability, whether they integrate its three pillars or not. Our work is consistent with this logic since it consists in an integrated tool for the assessment of the overall sustainability of a MUE, but doesn’t focus on details.

2.3. MUE sustainability

In the context of an MUE, sustainability is naturally defined through its three interconnected pillars. As a generic concept, MUE sustainability is complex because of the intrinsic complexity of the MUE. Certain elements of the complexity of MUE sustainability can be highlighted.

1. MUE sustainability is complex because it can be defined through numerous perspectives. Some of these perspectives are the entities of the MUE and the entities constituting its environment (see Table 1).
2. Because of the systemic nature of MUEs, their entities and stakeholders interact with each other. Similar to the interconnectedness of the pillars of sustainability, the interactions between the MUE entities increase the complexity of its sustainability.
3. Different MUEs may encompass different visions of sustainability. Just like regular industrial parks, MUEs can differ for a variety of reasons: their size, their juridical status, the type of companies they welcome, the life cycle stage they are at, the local culture, their natural environment, their resources, their manager etc. These characteristics impact both the development strategy adopted by the manager of the MUE and the visions of sustainability.

The deployment of MUE sustainability is based on the systemic modeling. Because of its complexity, MUE sustainability cannot be directly assessed and needs to be deployed into smaller objectives which can be directly achieved and assessed. This deployment draws on similar works with EIPs and urban sustainability (Verma and Raghubanshi, 2018; Valenzuela-Venegas et al., 2016; Zhao et al., 2017) and was validated through observations of MUEs (see (Le Tellier et al., 2019) for

details on the MUEs observed). The elementary objectives resulting from the deployment are directly related to the entities of the system and their interactions, as detailed in Table 1. Fig. 1 shows the proposal for MUE sustainability deployment. The results of this deployment are a hierarchy of criteria that are used to describe objectives. The first deployment level draws upon the definitions of the MUE and of the pillars of sustainability. At this level, the finality is deployed into three criteria matching the three pillars. At the second level, these criteria are further deployed. Each criterion is associated with one of the entities or interactions of the structure of the MUE (see Table 1). Criteria associated with entities of the MUE are *EnBui*, *EcLan*, and *ScArc*, with the *Building* entity, *EnInf*, *EnTrs*, *EnNat*, and *ScAcs*, with the *Infrastructure* entity, and *ScJob* with the *Company* entity. Criteria associated with interactions between entities are *EnSyn*, with the *Eco-Industrial Synergies* interaction, and *EcCol* and *ScSrv*, with the *Intercompany Collaboration* interaction.

3. A model for the assessment of MUE sustainability

3.1. Outline

The assessment amounts to expressing a performance, defined as the satisfaction of an objective. As mentioned earlier, the MUE sustainability assessment is provided by a (deployment, aggregation) mechanism. Once the deployment has been performed (see Fig. 1), three successive steps have to be followed (Fig. 2). The first step is the determination of the elementary performance expressions. Then, the elementary expressions are aggregated into the so-called three-pillar performance expressions. Finally, the three-pillar performance expressions are aggregated into the overall sustainability expression.

The performance aggregation must comply with the following properties:

- Each criterion has a varying relative importance. This importance depends on the strategy of the MUE. Therefore, the sustainability assessment must be able to account for the relative importance of each criterion. For example, in the early stages of development of an MUE, its manager may decide that economic criteria are more important than environmental and social criteria in order to ensure the project's financial viability.
- The MUE entities and stakeholders interact with each other, and the pillars of sustainability are interconnected. Therefore, the criteria are not independent and the assessment must be able to account for these

interactions. There are two types of interactions: the first type occurs when the simultaneous satisfaction of two objectives is preferred over a unilateral satisfaction; the second occurs when the satisfaction of either one of a pair of objectives is preferred to their simultaneous satisfaction. In more concrete terms, when the managers prefer the simultaneous satisfaction of objectives, it means that their MUE's assessed overall sustainability may be higher with moderate performance in each of the three-pillars than with only exceptional performance and two mediocre performances.

It is important to note at this point that we hypothesize that, within one pillar, the elementary performance expressions compensate each other and that therefore the interactions between the elementary objectives are negligible. From now on, the model will consider the interactions between the three pillars.

Two operators from the compromise aggregation family are chosen for the aggregations: the WAM, which uses weights as required by our aggregation problem, and the CI, which handles interactions (see Fig. 3). It should be noted that the CI has frequently been used to evaluate sustainability (Bottero et al., 2013, 2014; Merad et al., 2013; Pinar et al., 2014; Zhang et al., 2014, 2016; Karnib, 2016; Angilella et al., 2018). The MACBETH framework is chosen for the sustainability assessment model in order to ensure mathematical consistency when aggregating.

3.2. Aggregation: weighted arithmetic mean & Choquet integral

Having presented the outline of the assessment model and its mathematical tools, we now provide details on these tools. From a general point of view, aggregation can be seen as an operation that synthesizes pieces of information into an overall expression, according to the following mapping (Berrah et al., 2004):

$$Ag : E_1 \times E_2 \times \dots \times E_i \times \dots \times E_n \rightarrow E$$

$$(p_1, p_2, \dots, p_i, \dots, p_n) \rightarrow p_{Ag} = Ag(p_1, p_2, \dots, p_i, \dots, p_n)$$

E_i is the universe of discourse of elementary expressions p_i and E is the universe of discourse of the overall performance expression p_{Ag} . The mathematical consistency of the aggregation requires the satisfaction of two conditions (Grabisch, 1997):

- **Commensurability.** The elementary expressions must be commensurate. This means that two identical values (e.g., 0.64) according to

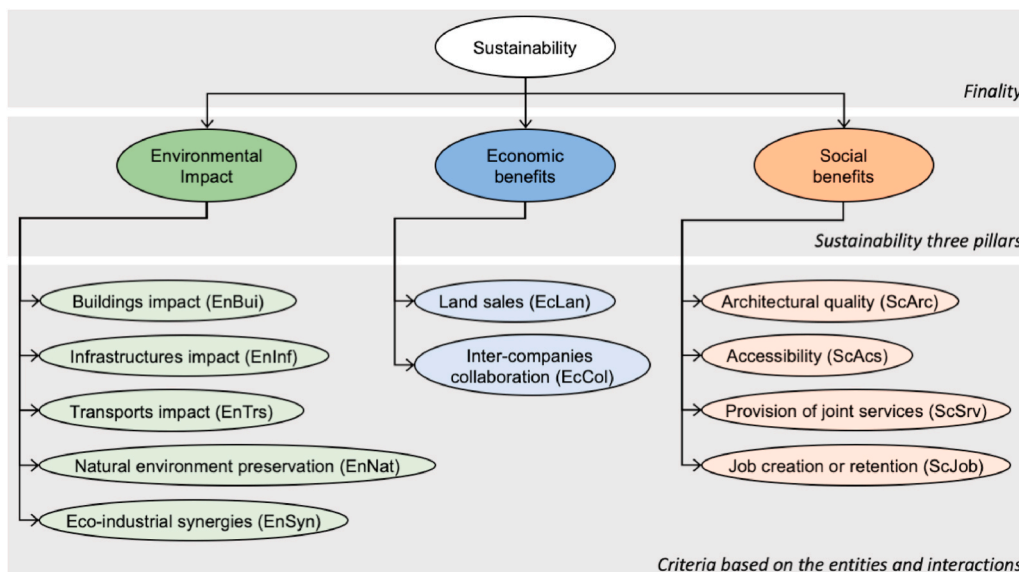


Fig. 1. Proposal of a deployment of MUE sustainability.

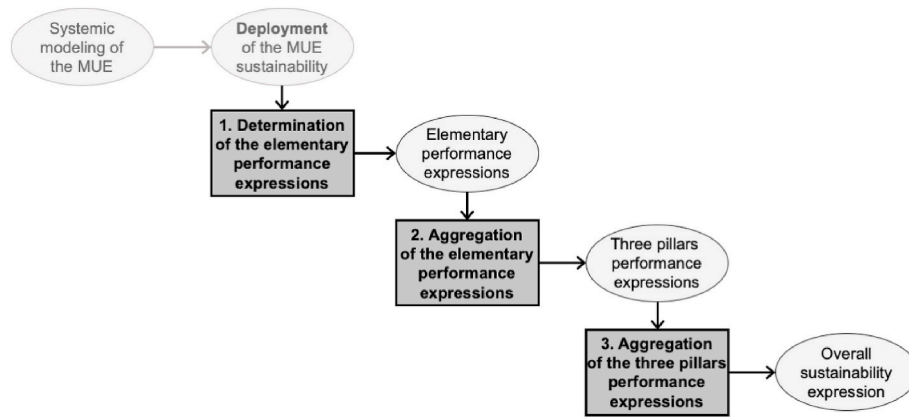


Fig. 2. MUE sustainability assessment steps.

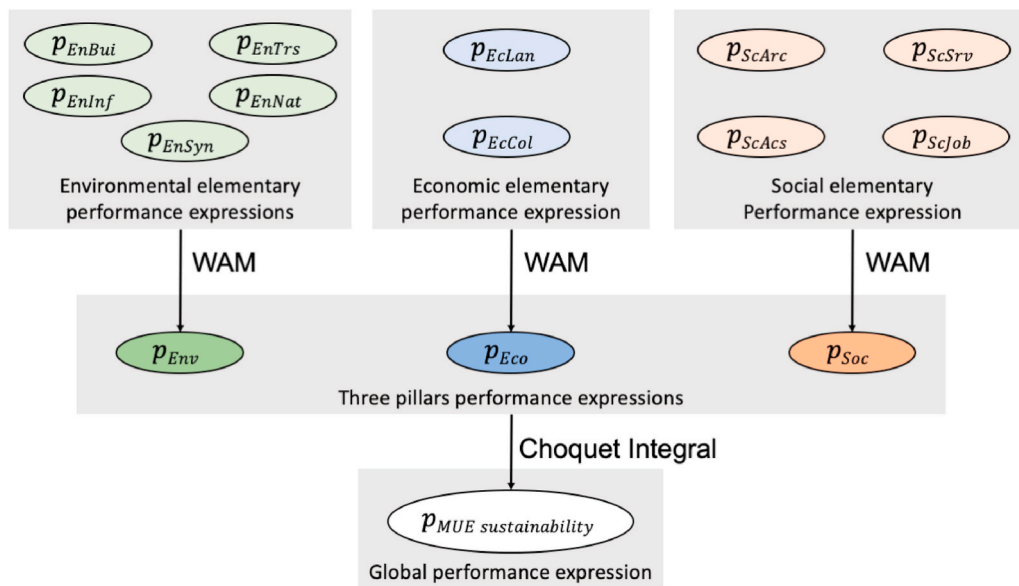


Fig. 3. Aggregation mechanism (p_i is the elementary performance expression associated to criterion i , p_{Env} , p_{Eco} and p_{Sc} are the three pillars performance expressions and $p_{MUE\ sustainability}$ is the aggregated sustainability expression of the MUE).

two different criteria (e.g., environmental impact of the infrastructures and creation of eco-industrial synergies) have the same meaning.

- **Significance.** The aggregation operator must be significant for the elementary expressions. The significance ensures that an elementary expression can be compensated by another one (Choo et al., 1999). For example, for the family of mean operators (arithmetic mean, WAM, CI, etc.), for each criterion, the same difference between two values (e.g., (0.70–0.55) and (0.34–0.19)) has the same meaning. When the aggregation operator is the product, this condition applies to the ratio.

The WAM has the form:

$$\sum_{i=1}^n p_i \times w_i \tag{1}$$

with w_i the weight associated with the criterion i such as $\sum_{i=1}^n w_i = 1$. It is appropriate for the aggregation of independent criteria.

The CI has the form (Grabisch, 1997):

$$p_{Ag} = \sum_{i=1}^n \nu_i p_i - \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n I_{ij} |p_i - p_j| \tag{2}$$

where $(p_1, \dots, p_i, \dots, p_n)$ is the vector of elementary expressions such that:

$$\left(\nu_i p_i - \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n I_{ij} |p_i - p_j| \right) \geq 0 \quad \forall i \in [1, n] \text{ and } i \neq j \tag{3}$$

- ν_i is the Shapley parameter. It represents the weight of each elementary expression in relation to all the other contributions to the overall expression. It satisfies $\sum_{i=1}^n \nu_i = 1$.
- I_{ij} is the interaction parameter of any pair of criteria i and j . It ranges between [-1; 1].
 - a positive I_{ij} implies a synergy between objectives o_i and o_j (the objectives, respectively, associated with the criteria i and j).
 - a negative I_{ij} implies that o_i or o_j is redundant.
 - a null I_{ij} implies that no interaction exists; thus ν_i acts as the weights in a WAM.

3.3. MACBETH

3.3.1. Definition

The MACBETH framework is a multi-criteria decision analysis method introduced in the 1990s (Bana e Costa and Vansnick, 1997). In this model, MACBETH is used to express the elementary expressions and

to determine the parameters of the aggregation operators. Its underlying principle is to translate the expertise of the manager into useful coherent information (Bana e Costa et al., 2005). MACBETH allows the assessment of situations that are significant or well-known by the manager against multiple criteria. MACBETH also requires the use of particular and possibly fictive situations (Labreuche et al., 2003). These situations are known through their elementary expressions $(p_1, p_2, \dots, p_i, \dots, p_n)$ and the associated aggregated expressions $p_{Ag}^{(p_1, p_2, \dots, p_i, \dots, p_n)}$ where $\forall i, p_i \in \mathbb{N}$ and $p_i \in [0, 1]$. To ensure commensurability, two fictive situations need to be set and act as references: one that is simply satisfying, associated with the performance value of 0, also called “Neutral,” and one that is fully satisfying, associated with the performance value of 1, also called “Good”.

MACBETH is based on pairwise comparisons. Considering each criterion and for each pair of situations, the manager is asked to give their preference. They are also encouraged to characterize the intensity of their preferences thanks to semantic judgment (*null, very weak, weak, moderate, strong, very strong, extreme*) (Karande and Chakraborty, 2013).

For the sake of conciseness, the detailed MACBETH procedure is described in the MUE sustainability assessment context.

3.3.2. Procedure

Beyond a preliminary step of describing the assessment problem, MACBETH’s procedure follows three steps. In the particular MUE case, four steps are involved, due to the double aggregation (see Fig. 2).

Description of the assessment problem: The description of an assessment problem consists in the identification of the criteria and the situations. As seen earlier, the criteria are provided by the deployment of the MUE sustainability (Fig. 1). The considered situations correspond to the MUE assessed at different points in time. For example, a situation that is considered may be the current state of an MUE. Their number can vary depending on the assessment problem.

Determination of the elementary expressions: MACBETH’s scales (which allow the aggregation) are elaborated thanks to the manager’s preferences and the intensities of the preferences. Some formal elements that will be applied in Section 4 are given here:

- Let S_k and S_l be two compared situations and p_k and p_l be their respective performance expressions. If $S_k \geq S_l$ (i.e., for a criterion i , the manager prefers situation S_k to situation S_l) then $p_k \geq p_l$.
- If $S_k = S_l$ (i.e., for a criterion i , the manager considers that S_k is equivalent to S_l) then $p_k = p_l$.

The intensity of a preference is denoted by h , which can take seven values, from 0 for *null* strength, to 6 for *extreme* strength. In this case:

- If $S_k \geq_h S_l$ (i.e., for criterion i , the manager prefers situation S_k to situation S_l with a strength h) then $\alpha(h - 1) \leq p_k - p_l \leq \alpha(h + 1)$ where α is a coefficient necessary to meet the condition p_k and $p_l \in [0, 1]$.

The elementary expressions are determined by solving the system of inequations issued from the expression of all the intensities of preference h between S_k and S_l .

Aggregation of the elementary expressions: This aggregation is the first of the two aggregations of the model. This aggregation of elementary expressions within the three pillars into three-pillar performance expressions is made with the WAM. The WAM weights are determined through the pairwise comparison of particular situations. These situations are associated with elementary expression vectors such as $(0, \dots, 0, 1, 0, \dots, 0)$. Hence, the aggregated expression becomes: $p_i^{Ag} = w_i$ where p_i^{Ag} is the aggregated expression from the vector where $p_i = 1$ and all the other elementary expressions $p_g = 0$ with $g = 1$ to n and $g \neq i$. To determine the n weights w_i ’s (related to the n criteria involved), the manager has to make n pairwise comparisons between the particular

situations. The result of each comparison is an inequation taking the following form:

$$\alpha(h - 1) \leq p_i^{Ag} - p_g^{Ag} = w_i - w_g \leq \alpha(h + 1) \tag{4}$$

The n pairwise comparisons lead to a system of n equations whose unique solution is the weights (w_1, w_2, \dots, w_n) .

Therefore, the aggregation of the elementary expressions within the three pillars is straightforward with the WAM function (Equation (1)).

Aggregation of the three-pillar expressions: The aggregation of the three-pillar expressions into the overall sustainability expression is made with the CI. The determination of the CI parameters is similar to that of the weights for the WAM. The difference is that more parameters have to be determined and that, therefore, the manager is asked to consider additional fictive situations. In the considered case, there are six CI parameters to be determined: three Shapley parameters $\nu_1 = \nu_{Env}$; $\nu_2 = \nu_{Eco}$; $\nu_3 = \nu_{Soc}$ and three interaction coefficients I_{12}, I_{13}, I_{23} .

The aggregation is straightforward with the CI function (Equation (2)).

An illustration of the complete procedure is provided in Fig. 4.

4. Case study

4.1. Daniel Gaudreau Industrial Ecopark

The Daniel Gaudreau Industrial Ecopark (DGIE) is an MUE located in Victoriaville, a town in central Quebec in Canada. Victoriaville is a medium-sized town with 46,000 inhabitants and an area of 86 km². The DGIE was inaugurated in 2013, following the identification of wetlands in one of the town’s industrial parks. Since wetlands are protected by Quebec law, this discovery hindered the development of the industrial park. However, Victoriaville decided to transform this constraint into an opportunity to develop an industrial park that integrates and promotes the unique ecosystem of wetlands. The DGIE was planned and built in a sustainable way and welcomes companies that adopt sustainable business practices. These companies are required to participate in a local label certification process. The DGIE is a small industrial park with 22 lots for sale, representing an area of 111,400 m² and 93,000 m² of wetlands. The manager is the Corporation of Economic Development of Victoriaville and its Region (CEDVR), which acts on behalf of the municipal council.

In 2016, the CEDVR published an action plan whose goal was to make the DGIE an example of an innovative and sustainable industrial park. This action plan consisted of eight global actions, subdivided into a total of 31 actions, organized over a 4-year schedule. In the second half of 2019, the DGIE took part in a study on the definition of an MUE action plan and its control (Le Tellier et al., 2021). The deployment of MUE sustainability resulted from this study. At the beginning of 2020, the action plan was almost completed and as a logical continuation of the 2019 study, the CEDVR requested more global information on DGIE sustainability. This information will aid in defining the subsequent action plan. It will also be used to communicate with the Victoriaville municipal council.

The sustainability assessment model was applied to express DGIE’s sustainability at three different points in time, corresponding to three different rates of execution of the action plan. This allowed us to assess the improvements in DGIE sustainability that were achieved during the entire execution of its action plan. The sustainability assessment was conducted with three members of the CEDVR in charge of DGIE development: Victoriaville’s industrial commissioner, an advisor on sustainable development, and a sustainable development officer. These tactical managers have different roles but equivalent importance in DGIE development.

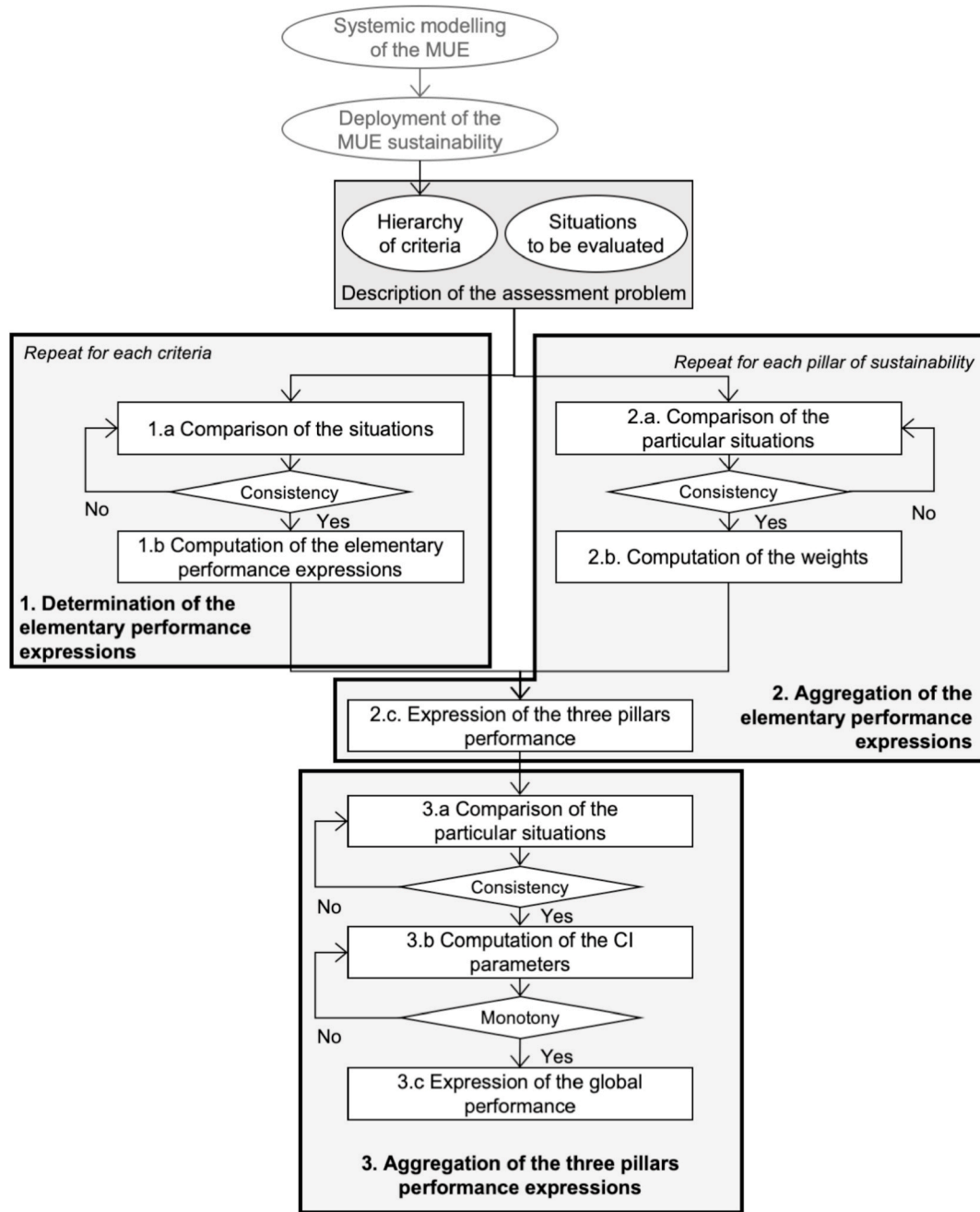


Fig. 4. Complete procedure for the sustainability assessment of the MUE.

4.2. Description of the DGIE assessment problem

The description of the DGIE assessment problem requires the definition of respective criteria (Fig. 1) and situations to be considered (Section 3.3.2). To represent the entirety of the DGIE development during the past 4 years, three situations were assessed (Table 3). These situations correspond to the results achieved at different execution rates of the action plan, described in Table 2, which are the ratio of achieved actions against the total of actions. As explained earlier, these three situations are also compared with a good situation and a neutral situation. The neutral situation corresponds to the situation before the beginning of the action plan and, therefore, to an execution rate of 0%. The good situation cannot be expressed in terms of execution rates since it corresponds to an ideal that goes beyond the action plan.

Table 2
Summary DGIE action plan.

Code	Global Action
A1	Demystify DGIE to influential socio-economic stakeholder and prospected companies
A2	Evaluate the possibility to build new building to offer turnkey solutions to prospected companies
A3	Create a financial incentive to attract companies
A4	Promote DGIE
A5	Enable mixed-use developments in order to offer services to the companies employees and create a pleasant living environment
A6	Make DGIE accessible and known by the citizens in order to make it a source of regional pride
A7	Highlight the wet lands of DGIE
A8	Differentiate DGIE with a certification

Table 3
Characteristics of the considered situations.

Situation	Execution rate (Achieved actions)	Milestone
Neutral	0% (None)	January 2017
S ₁	38% (Actions A1, A2 and A4)	January 2018
S ₂	63% (Actions A1, A2, A3, A4 and A5)	January 2020
S ₃	100% (Actions A1, A2, A3, A4, A5, A6, A7 and A8)	January 2021
Good	N/a	N/a

4.3. Determination of DGIE elementary expressions

This step was carried out with Victoriaville’s industrial commissioner and the advisor on sustainable development. For each criterion, the two members of the CEDVR were asked about their preferences and the intensities of the preferences, with respect to the situations listed in Table 3. The resulting elementary expressions are provided in Table 4.

4.4. Aggregation of DGIE elementary expressions: Three-pillar performance expressions

The three-pillar expressions are provided by three aggregations with the WAM, whose weights have to be determined through a comparison of fictive situations corresponding to the satisfaction of a sole criterion (see Fig. 5).

Like the previous step, this one was carried out with Victoriaville’s industrial commissioner and the advisor on sustainable development. The three-pillar expressions are computed as shown in Table 5.

4.5. Aggregation of DGIE three-pillar performance expressions: Overall sustainability expression

This step was carried out with the CEDVR sustainable development officer. To determine the six parameters of the CI (three Shapley parameters $\nu_1 = \nu_{Env}$; $\nu_2 = \nu_{Eco}$; $\nu_3 = \nu_{Soc}$ and three interaction coefficients

I_{12}, I_{13}, I_{23}), the sustainable development officer supplied information about six particular situations known through the three-pillar expression vectors ($P_{Env}, P_{Eco}, P_{Soc}$). The associated vectors are: (1, 0, 0), (0, 1, 0), (0, 0, 1), (0, 1, 1), (1, 0, 1) and (1, 1, 0).

The associated matrix of the complete system is given in Appendix A.

Table 5
DGIE three pillars performance expressions.

Situation	P_{Env}	P_{Eco}	P_{Soc}
S ₁	0.19	0.06	0.08
S ₂	0.27	0.21	0.21
S ₃	0.34	0.35	0.37

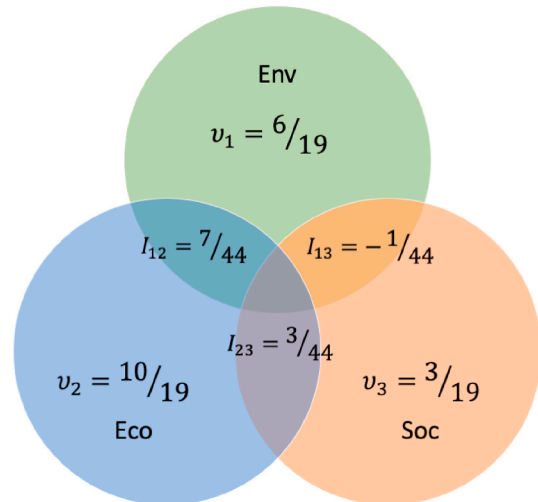


Fig. 6. CI parameters for DGIE.

Table 4
DGIE elementary performance expression.

Situation	P_{EnBui}	P_{EnInf}	P_{EnTrs}	P_{EnNat}	P_{EnSyn}	P_{EcLan}	P_{EcCol}	P_{ScArc}	P_{ScAcs}	P_{ScSrv}	P_{ScJob}
S ₁	0	0	0	0	0.17	0.35	0.25	0	0.11	0.15	0.08
S ₂	0.43	0	0.05	0	0.25	0.47	0.38	0.50	0.22	0.45	0.21
S ₃	0.57	0	0.33	0.67	0.33	0.65	0.38	0.50	0.44	0.55	0.62

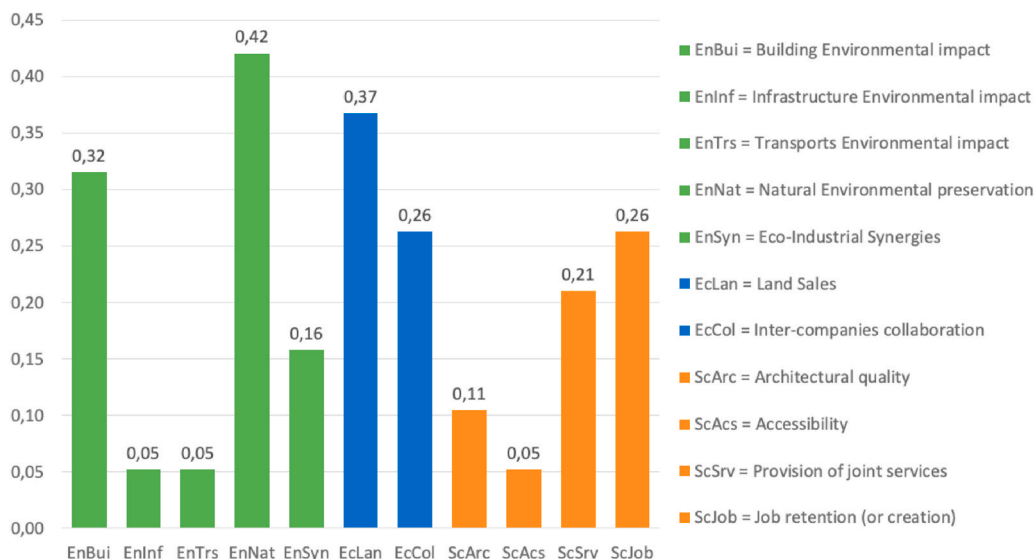


Fig. 5. WAM weights for DGIE.

The results of the parameter determination are synthesized in Fig. 6. Let us note that the interaction parameters I_{12} and I_{23} are both positive. This means that the satisfaction of economic criteria cannot be compensated by the satisfaction of environmental or social criteria. On the other hand, the interaction parameter I_{13} is negative, which means that the CEDVR considers that simultaneous satisfaction of environmental and social criteria is not required. This result was expected by the three members of the CEDVR since they are aware that their strategy is currently heavily focused on attracting new companies to the DGIE.

With the three-pillar expressions and the parameters of the CI being defined, the overall sustainability expressions are computed. The DGIE three pillars and the overall sustainable expressions are summarized in Table 6.

The overall sustainability expression reached in the third situation is 53%. This means that the CDEVVR considered that at the end of their action plan, the DGIE will have reached half of what they consider to be ideal. As we can see, for all situations, the interaction is detrimental to the overall sustainability expression. The interactions have an influence on the overall sustainability expression of S_2 and S_3 of approximately 10% of their respective performance. This influence is even greater for S_1 (50%). Therefore, the influence of the interaction is non-negligible.

5. Discussion and outlook

As requested by the CEDVR, the overall sustainability of the DGIE was assessed throughout the execution of their action plan. Let us reflect on this application and the prospects of this study.

From a general standpoint, the three members of the CEDVR believed that the model was useful to assess the impact of their action plan. They were satisfied with the simplicity and clarity of the proposed procedure, which facilitate its adoption. In the future, they plan to use the results from this application of the model as an input for the update and redesign of the DGIE action plan. Moreover, they plan to use the model as a way of communicating with Victoriaville’s local council, by displaying the results and improvements achieved.

An advantage of the model for the DGIE managers is that it helped them to reflect on their own interpretation of the sustainability paradigm by the actions decided in their strategic plan. Fig. 7 illustrates estimates of potential CI parameters and performance expressions for each of the “traditional” sustainability paradigms described in Section 2.2. These estimates are based on the definition of the three paradigms. To be more precise, “weak” sustainability interaction parameters between the three pillars are null, because it is based on the assumption that manmade and natural capital can be substituted. Regarding “balanced” sustainability, the Shapley parameters and performance expressions are equal because it is based on the assumption that the three pillars have the same importance. The balanced sustainability interaction parameters are positive because this paradigm favors the simultaneous satisfaction of objectives in the three pillars. The “strong” sustainability is based on the assumption that manmade and natural capital cannot be substituted and that natural capital should not be depleted; therefore, it favors the environmental pillar, which leads to a higher Shapley parameter and performance expression.

As shown in Fig. 6, the DGIE paradigm moderately favors the simultaneous satisfaction of economic criteria with environmental or social criteria. Therefore, we can infer that the DGIE sustainability paradigm is a combination between the weak and balanced paradigms, which can be explained by the fact that the DGIE is still a developing

Table 6
DGIE three pillars and overall sustainable performance expressions.

Situation	$P_{Sustainability}$	Part of interaction
S_1	0.03	0.04
S_2	0.18	0.02
S_3	0.53	0.03

MUE.

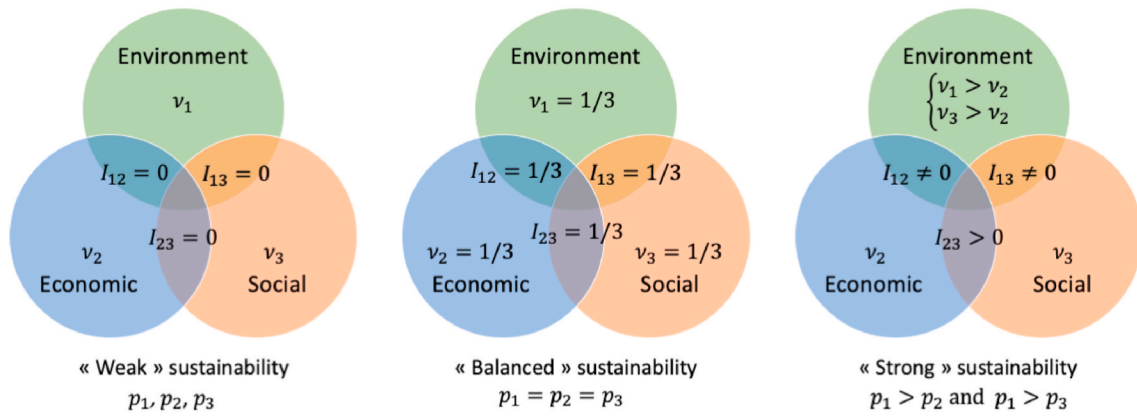
An unused capacity of the model is that it can be used by several managers. Indeed, let us recall that the aggregation model consists of four aggregation sub-models: three aggregation sub-models, one for each of the three pillars, and one global aggregation sub-model. Thus, if the MUE is managed by a team, each sub-model can be delegated to the manager that has the most expertise or involvement in the pillar under assessment. The final aggregation could be delegated to a strategy manager while the three lower aggregation sub-models could be delegated to more tactical or operational managers. In other words, the aggregation model allows for a systemic assessment of the MUE.

In its actual form, the model does not bind managers to subscribe to all the principles of sustainable development and every characteristics of the MUE, the proposed approach is descriptive and offers guidelines. Another potential of the model is that it could be used as a benchmarking tool to help managers compare their industrial park with other ones presenting some similarities. Using the model for benchmark would essentially mean that it should impose a typical behavior that all industrial parks should try to emulate. In that sense, the model could be used to conduct certification audits. A first step to this approach would be to apply the presented model to a wide variety of industrial parks in order to draw a common ideal MUE. Over a certain time, this common reference will possibly evolve as more MUE managers use this approach. The definition of a reference could also be an iterative process based on participatory research approaches such as the one proposed by Rosano and Schianetz (2014) for the Kwinana Industrial Park. Eventually, the definition of a reference could eventually lead to policy changes propositions (Pilouk and Koottatep, 2017).

Finally, future work will reconsider the industrial park boundaries of the model. Since this research was limited to the perimeter of an industrial park, the reflection should be expanded to a greater scale, such as a region where entities of the systemic models are companies but also industrial parks and cities Martin and Harris (2018). A promising idea in order to model an industrial park into its environment is to use social network analysis in addition to the systemic modeling. As demonstrated by Song et al. (2018); Genc et al. (2019), social network analysis can be used to understand the internal industrial symbiosis interrelations of an industrial park from both ecological and sociological perspectives. Through social network analysis, one can identify key stakeholders of an industrial park and assess its resilience (Domenech and Davies, 2009), in other words, its capacity to absorb internal and external perturbations while preserving its structure, its self-adaptation capacity and its capacity to adapt to stress and change. Using social network analysis in addition to our model could help managers understand the dynamic nature of their industrial park and its relationship with its environment. Such understanding could help them with the definition of their strategy and action plan by answering questions such as “how will this action impact the resilience of the system?” or “how will this action impact the sustainability of other industrial parks and companies of the region?”. The addition of social network analysis would therefore enrich the proposed model so that it is able to take the idea of risk into account, such as suggested by Neise et al. (2018) with the IARD framework.

6. Conclusion

The benefits of sustainability assessment are today acknowledged as a matter of fact, but the question of a sound processing of the set of environmental, economic, and social measurements is still open. In this sense, the present study deals with the sustainability assessment of a particular type of industrial park, that is, the MUE. The proposed model is based on the broad framework of integrated sustainability assessment and is complementary to reflections on indicators, which deal with quantitative assessment of the respective environmental, economic, and social pillars. The postulates underlying the proposal are that the assessment of sustainability is achieved via an expression of each pillar, on the one hand, and a global expression, on the other hand. Since the



Where $\forall i \in [1,3]$ and $i \neq j$, v_i , p_i and I_{ij} such as :

- $(v_i p_i - \frac{1}{2} \sum_{i=1}^3 I_{ij} |p_i - p_j|) \geq 0$
- $\sum_{i=1}^3 v_i = 1$
- $I_{ij} \in [-1,1]$

Fig. 7. Estimates of potential CI parameters for the three sustainability paradigms.

three pillars are interconnected in their associated objectives and actions, this overall assessment represents more than a synthetic value, as it also conveys all the interactions involved.

Sustainability cannot be assessed by applying an aggregation formula without variants. Hence, according to the complexity of the MUE and the multi-criteria characteristic of sustainability, the main idea of this work is to study MUE sustainability assessment in the context of multi-criteria decision analysis through a deployment/aggregation mechanism. Systemic deployment of MUE sustainability has thus been considered along with two aggregation operators from the compromise family. The WAM was chosen to handle the varying relative importance of criteria and the Choquet integral to handle the varying relative importance and interactions between the three pillars.

The presented aggregation model, is the first, to our knowledge, sustainability assessment tool designed for industrial parks managers. Moreover, this model is intended to be used on any kind of industrial park, no matter its size, maturity, geographic location, or type of resident companies. The aggregation model was used to assess the sustainability of the Canadian MUE Daniel Gaudreau Industrial Ecopark (DGIE). The economic performance expression supported the DGIE in the definition and management of actions to improve the attractiveness of the ecopark, and the environmental performance and overall sustainability expressions have offered the DGIE a tool for communicating with local authorities. An unexpected finding of this study is that using the CI encouraged the DGIE managers to reflect on their own appropriation of the sustainability paradigm by the actions decided in their strategic plan. They realized that their current vision of sustainability is not balanced, as it is heavily focused on economic performance and attractiveness; however, when DGIE occupancy reaches a satisfying rate, they plan to improve this balance.

Regarding short-term perspectives, the model is to be implemented in a single software. Indeed, three different data-processing tools are currently needed for its application: UML, for the systemic modeling, MACBETH, for the three-pillars expressions, and a spreadsheet for the aggregation with the CI. A single user-friendly tool will greatly improve the adoption of the model through MUE managers.

Credit author statement

Mathilde Le Tellier: Conceptualization, Methodology, Data curation, Investigation, Writing – original draft, Lamia Berrah: Conceptualization, Writing – review & editing, Jean-François Audy: Conceptualization, Investigation, Benoit Stutz: Supervision, Funding acquisition, Simon Barnabé: Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Matrix for determination of the Choquet integral parameters

$$\begin{bmatrix} 1 & 0 & -1 & 0.5 & 0 & -0.5 & -5 \\ -1 & 1 & 0 & 0 & -0.5 & 0.5 & -6 \\ 1 & -1 & 1 & 0 & 0 & 0 & 1 \\ -1 & 1 & 0 & 0 & 0.5 & -0.5 & -2 \\ 1 & 0 & -1 & -0.5 & 0 & 0.5 & -1 \\ 0 & 0 & 1 & 0 & -0.5 & -0.5 & -2 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} \nu_{Env} \\ \nu_{Eco} \\ \nu_{Soc} \\ I_{EnvEco} \\ IE_{EnvSoc} \\ I_{EcoSoc} \\ \alpha \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

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