SUSTAINABLE SELECTION OF A MANUFACTURING FACILITY LOCATION USING SMAA-PROMETHEE

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ABSTRACT

The location of manufacturing facilities is one of the most important strategic decisions in supply chain design. Moreover, as the concern for sustainability grows, sustainability issues have been included in decision-making. In this context, the following article deals with the problem of selecting a manufacturing facility location from a set of candidates, with the consideration of sustainability-related criteria. Twelve main criteria and twenty-three sub-criteria extracted from the literature and framed under three bottom line dimensions of sustainability were selected. Due to the lack of information about the preferences, scenarios formed with different weights preferences were proposed. SMAA was used in scenarios where complete preference ranking of groups weights was elicited and ranking and selection of the alternatives for each scenario were performed using PROMETHEE-II. Results were analyzed comparing the results of each of the scenarios and further research directions on sustainable manufacturing facility location with multi-criteria decision-making were finally proposed.

KEYWORDS. Multi-criteria decision making, Location selection, sustainability, SMAA, PROMETHEE.

1. Introduction

The decision of where to locate facilities, such as plants, hospitals, distribution centers among others, is one of the most relevant in the strategic planning of supply chains. In addition, the development or acquisition of new facilities is a project that generally requires the use of large resources and involves the consideration of different criteria that tend to be of conflicting nature, which makes facility location a complex task.

Traditionally, as the economic performance has implicitly been the central dimension when addressing location problems, related economic criteria have been taken as drivers of location success [Chen et al., 2014]. However, in recent years, the world has directed its efforts towards sustainability, and environmental and social problems have gained relevance in business research and practice [Govindan et al., 2013]. This has led decision makers (DMs) to consider the inclusion of criteria in the different dimensions of sustainability (economic, environmental, and social) into their decision-making as they become important to develop competitive advantages [Dou & Sarkis, 2010]. In particular, manufacturing companies look forward to expand their network, as technology and geopolitics advance making markets become global, which leads to the need of the inclusion of sustainability aspects in facility location decisions [Chen et al., 2014].

Multi-criteria decision aiding (MCDA) methods have shown its applicability in real-life problems in a variety of fields [Greco et al., 2016]. As sustainability is a multidimensional concept MCDA methods become a suitable approach to deal with sustainability where multiple criteria are framed into the famously known three bottom line. In the present work, we use multi-criteria decision methods known as SMAA and PROMETHEE-II to deal with a sustainable manufacturing location selection problem. Criteria obtained from the literature review framed within the three dimensions of sustainability are taken into account for the selection. An exploratory case is proposed and finally results analyzed. In general, this paper is divided as follows: section 2 presents a literature review focused on sustainable facility location and articles that addressed this problem with MCDA methods. Then, section 3 will present the methodology focusing on detailing the PROMETHEE and SMAA methods, how the scenarios and simulation were configured and criteria selected. Afterwards, section 4 will show and comment on the results, and finally, conclusions on the work will be shown in section 5.

2. Literature Review

Due to its practical importance the problem of locating facilities has been widely studied over the years. In general, as noted by [Chen et al., 2014] the literature on the problem can be classified in two areas, namely factor assessment and mathematical approaches. In this brief review, we will focus on articles dealing with sustainable facility location addressed with multi-criteria decision aid (MCDA) methods. To have more information about the definitions, solution methods and more aspects about the facility location problem the reader might refer to [Zeinab and Ensiyeh, 2009] and [Melo et al., 2009]. Terouhid et al. [2012] defined sustainable facility location models as those that include requirements for sustainable development. In their review, they propose a framework for the classification of sustainability characteristics and show insights on the integration of sustainability and facility location. In a most recent review, Chen et al. [2014] identified environmental, social and economic factors that have an influence in location decisions. To synthetize, they proposed a framework for sustainable facility location. In the present work, we will use their work as a base to extract the main sustainability related criteria in manufacturing facility location.

Regarding applications of sustainable facility locations with MCDA, Sumathi et al. [2008] dealt with the siting of a landfill using MCDA and geographic information systems (GIS). In their study, economic and environmental sustainability are the focus and the Analytic Hierarchy Process (AHP) was used to obtain weights of criteria and later rank alternatives. Fernandez and Ruiz [2009] proposed a conceptual descriptive model to locate industrial areas considering sustainability factors. AHP is used in this study to establish the location model through three distinctive phases. In addition, fuzzy logic is applied to obtain the evaluations given the complexity and uncertainty of their criteria. Dou e Sarkis [2010] developed a study to make offshoring decisions integrating facility location, supplier, and sustainability factors. They use the Analytical Network Process (ANP), a generalized form of the AHP, to propose their decision making framework. Banias et al. [2010] proposed a methodological framework to locate units of alternative construction and demolition waste. ELECTRE III was selected as solution method in their paper to rank seven alternative locations considering 19 criteria.

In most recent years, Chauhan and Singh [2016] proposed a hybrid MCDM method to select a sustainable location of a healthcare waste disposal facility. A combination of interpretive structural modelling (ISM), fuzzy AHP and fuzzy technique for order preference similar to TOPSIS was applied in their study. Anvari and Turkay [2017] present a decision support framework to facility location incorporating the three bottom line of sustainability. They show a case study to illustrate how their framework works by combining Process Analysis Method (PAM) through AHP for criteria validation and weight assignment, optimization modelling and final selection using weighted sum method and AHP. Finally, Sennaroglu and Varlik Celebi [2018] works with a selection location problem for a military airport considering nine main criteria, thirty-three sub-criteria, and taking into account location requirements, environmental and social effects. Weights were found using AHP, and ranking and selection were performed using PROMETHEE and VIKOR methods, which are later compared with other selection methods.

3. Methodology and application

This article will consider a global location problem where the alternative locations are represented by seven candidate countries. The final objective is to select the best location of a new manufacturing facility considering sustainability criteria. The following subsections explain the used multi-criteria methods and give details on the experiments.

3.1 SMAA and PROMETHEE

The Stochastic multi-criteria acceptability analysis (SMAA) is a method developed by Lahdelma et al. [1998] to assist DMs when there is little information on the weights and/or the criteria values are not totally accurate. SMAA allows DMs to explore the weight space through an inverse analysis; this is, describing the preference that would make each alternative to be the first in the ordering. This is done using three main description measures for each alternative Ehrgott et al.[2010]; Pelissari [2019]:

- Acceptability index (b_i^s): Describes the probability of an alternative x_i of being accepted to occupy the position s in the ranking.
- Central weight vector (w_i^c): Describes the preferences (criteria weight vector) of a typical decision maker that supports alternative x_i.
- Confidence factor (p_i^c): The probability of an alternative to be preferred with the weights given in its central weight vector.

Algorithm 1 shows the generic simulation of SMAA from Ehrgott et al., (2010) that will be used in this study.

Algorithm 1. Generic SMAA simulation

Assume a decision model M(**x**,**w**) for ranking or classifying the alternatives using precise information (criteria matrix **x** and preference parameter vector **w**)
{Use Monte-Carlo simulation to treat stochastic weights:}
repeat
    Draw <x,w> from their distributions
    Rank, sort or classify the alternatives using M(**x**,**w**)
    Update
Until Repeated K times
Compute results based on the collected statistics

The PROMETHEE I (partial ranking) and PROMETHEE II, that will be used in this article, were methods originally proposed by Mareschal et al. [1984] . These methods are based on pairwise comparisons and the deviation between the evaluations of two alternatives within criteria is considered. Small deviations will translate in small preference, and larger deviations in larger preferences. To do so, for each one of the criteria the DM will have to consider a preference function [Brans and De Smet, 2016]:

$$P_j(a, b) = F_j[d_j(a,b)] \; \forall (a, b) \in A$$

where:

$$d_j(a, b) = g_j(a) - g_j(b)$$

and

$$0 \leq P_j(a, b) \leq 1$$

In this study, we have chosen to use PROMETHEE II that provides a complete ranking through the calculus of net flows. The usual function will be used for each one of the pairwise comparisons:

$$P(d) = \begin{cases} 0 \; if \; d \leq 0 \\ 1 \; if \; d \geq 0 \end{cases}$$

For criteria to be minimized the preference function will be reversed. For detailed explanations on the PROMETHEE methods the reader may refer to [Brans and De Smet, 2016].

3.2 Scenarios

Due to the lack of information about the preferences, nine scenarios representing different preferences were created. In scenario 1, the weights are considered equal for each sub-criteria, this is $w_i = 1/n$, where n is the number of sub-criteria. Scenario 2 will consider equal weights by group of criteria, this is, $w_{Gk} = 1/k$ where G_k corresponds to the sustainability groups (1 - Environmental, 2 - Social, 3 - Economic) the weight for each sub-criteria within a group will be the weight of the group divided by the number of sub-criteria. Scenario 3 will let the weights to be random without a particular order. Scenarios from four to nine will represent complete preference ranking weights among groups. Table 3 shows the order of scenarios.

In general, for all scenarios considering non-negative and normalized weights, the feasible weight space will be given by:

$$W = \{w \in R^n : w \geq 0 \; and \; \sum_{j=1}^{n} w_j = 1\}$$

Table 3. *Scenarios and corresponding weights*

Scenario	*Preference representation*
1	$w_i = 1/n$
2	$w_{G_k} = 1/k$
3	$0 \leq w_{G_k} \leq 1$
4	$w_{G_1} > w_{G_2} > w_{G_3}$
5	$w_{G_1} > w_{G_3} > w_{G_2}$
6	$w_{G_2} > w_{G_1} > w_{G_3}$
7	$w_{G_2} > w_{G_3} > w_{G_1}$
8	$w_{G_3} > w_{G_1} > w_{G_2}$
9	$w_{G_3} > w_{G_2} > w_{G_1}$

Scenario 3 will correspond to the particular case where there is total lack of information on the preferences and it is possible to represent W with the uniform weight distribution:

$$f_W(w) = 1/vol(W)$$

Scenarios 4 to 9 will represent the elicit of some preference information from de Decision Makers (DMs). These scenarios will correspond to the case where a complete ranking of the weights for groups is given. Results on the first two scenarios will yield a complete ranking. However, the rest of the scenarios will be analyzed according to two descriptive indices, namely rank acceptability indices and central weight vectors. The confidence factor will not be analyzed as the reader can deduce that given the deterministic nature of the data in the decision matrix the confidence factor will be one for all alternatives. Finally, the experiments will be programmed and executed in MATLAB R2014a according to algorithm 1. Simulations of 10000 iterations will run for each scenario.

3.3 Selection of criteria

A total of 12 criteria and 23 sub-criteria for sustainable manufacturing facility location were extracted from the work of Chen et al., [2014]. In general, the 12 main criteria and sub-criteria were classified in the environmental, social and economic dimensions of sustainability. As no standard measures for each of the criteria were detailed in the literature, in order to obtain the units and values of each criteria different sources were revised. Appendix 1 table (a) provides a brief description of the each sub-criteria as well as the objective and source. Table (b) shows the final decision matrix.

4. Results

For scenario one the final ranking was CHI>COL>MEX>BRA>PAM>URU>ARG and for scenario two CHI>PAM>COL>URU>MEX>BRA>ARG. It can be noted that the extreme alternatives remained unchanged in both scenarios. As it can be seen in figure 1, in the first two scenarios Chile is remarkably the best location (almost 0.1 points of net flow above the second) as it occupies the first place in the rankings. Figure 1 shows how the net flow for each alternative behaves for both scenarios, and how changing the weights from scenario one to two causes an slight improvement in the net flow of Chile, and also positive changes in Argentina, Panamá and Uruguay.

The acceptability indices for scenario 3 are shown in figure 2. It can be perceived that Chile has the higher probability to remain in the first place of the ranking. In particular, if a ranking is made considering the probability of each alternative to stay in the first place the final order would be the same as scenario one CHI>COL>MEX>BRA>PAM>URU>ARG.

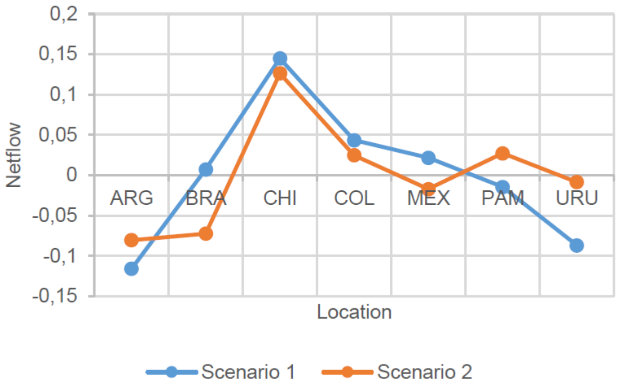

Figure 1. Net flow for scenarios 1 and 2.

The acceptability indices for scenarios 4 to 9 are shown in figure 3. As expected, different preferences resulted in changes along the acceptability indices. Overall, Chile had probability to stay in the first place of the ranking in every scenario. This is not true for the other candidate locations, which showed to have zero probability to occupy the first place in at least one of the scenarios. In scenarios 4 and 5, where environmental criteria were preferred over the other two groups of criteria, Panamá clearly outranked the remaining locations with almost 60% probability to be in first place.

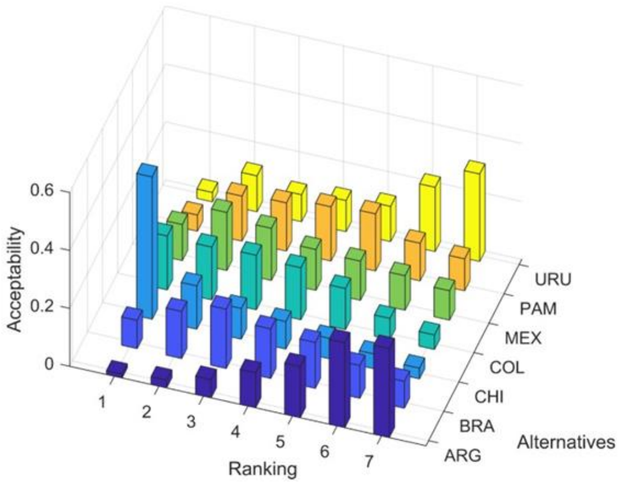

Figure 2. Acceptability indices for scenario 3

Scenarios 6 and 7, where the social criteria has the greater weight, show Uruguay and Chile as the locations with probability to be first in the ranking. In scenario 6, Uruguay has more probability to be first in the ranking while in seven, where the weights for economic criteria are greater than social, Chile is by far the most probable option to be first. Finally, in the last two scenarios with the economic criteria leading over the other dimensions, Chile is still the location with more probability to be in ranking one. However, scenario 8 is the scenario where more locations have probability to be ranked first. Chile, Brazil, Colombia and Panamá can occupy the first position in the ordering in this scenario if certain combination of weights is selected.

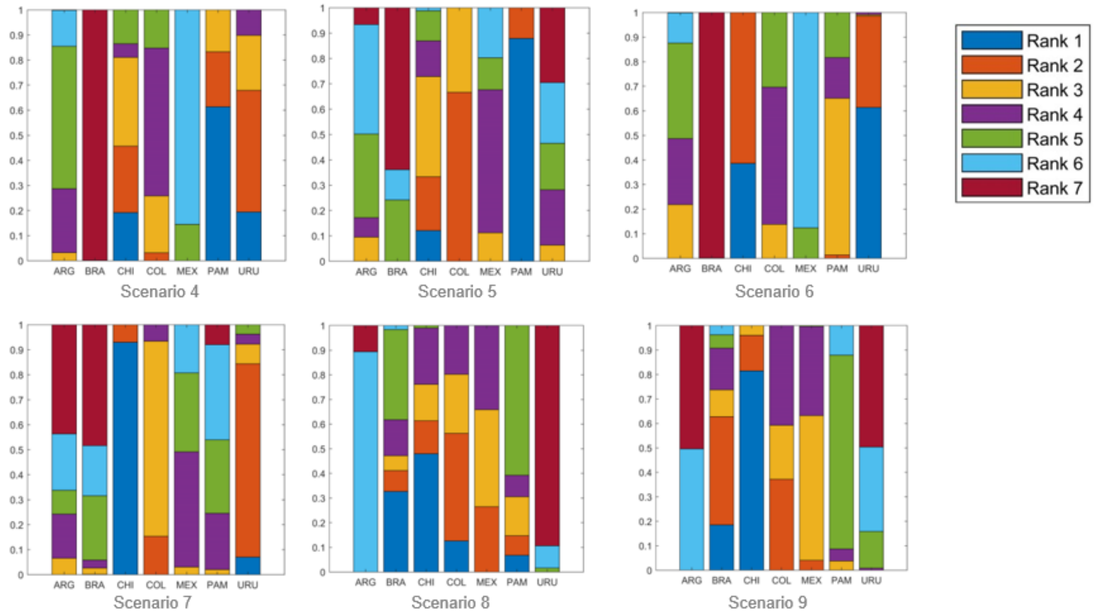

Figure 3. Rank acceptability indices for scenarios 4 to 9

Together with the acceptability indices, the weight vectors were obtained for scenarios 3 to 9. Table 3 shows the distribution of weights for scenario 3 and Figure 4 for scenarios 4 to 9. In table 3 we see that for Argentina to be selected a higher importance would have to be given to C1 and C17. Similarly, if Panamá and Uruguay were to be selected more weight should be assigned to certain environmental criteria, this fact is also supported by the acceptability indices under scenarios 4,5 and 6 where Chile is no longer the choice with more probability to be first in the rank.

Regarding the central weight vectors for scenarios 4 to 9, we can deduce which locations perform better in each sustainability group. For example, Panamá generally performs well when high weights were assigned to environmental criteria and lower values to economic and social sub-criteria. Brazil only comes into picture when the economic performance is more important, like in the last two scenarios, and Uruguay performs well when social criteria become more relevant.

In table 4, a summary on the results for each scenario is presented. Overall, Chile seems to be the best choice in the majority of scenarios (1, 2,3,7,8 and 9) positioning itself as the alternative with the higher chance to be in the first place of the rank most of the times. In scenarios where it does not have the greatest probability (4, 5 and 6), Chile still remains in the top 3. Nevertheless, the final selection will depend on the weights for each criteria, because as seen in scenario 3, each one of the locations can occupy the first place in the ranking with a particular weight vector.

5. Conclusions

This article proposed a facility location problem with 7 different alternatives and 23 sub-criteria embedded into the sustainability dimensions. Through the combination of multi-criteria decision-making methods, nine different scenarios each corresponding to possible weights elicitation from DMs, were analyzed considering the acceptability indices and central weight vectors. The results showed Chile as the alternative with more probability to be selected as the best in most of the scenarios, and with an overall good probability to be in first places in the remaining scenarios. However, under different preference information from the DMs, Chile might not always be the best choice. The selection when strict preference is given for each dimension can change, turning for example Panamá in the best choice under scenario 5.

The present study was limited to a global scale as alternatives were represented by countries. However, only Latin-American region countries were picked as alternatives. Future studies could consider alternatives from other regions with other market qualities. In addition, no specific criteria or weights were studied for specific industries and it could be expected to have additional criteria or not to have the same weights for a company that manufactures technology and other that manufacture food products, bio-fuel among others. Additionally, it could be interesting to explore more multi-criteria decision-making methods for the ranking and then compare the results with the PROMETHEE-II. Finally, the influence of the stochastic nature of some of the selected criteria like the demand could also be studied with the help of SMAA.

Figure 4. Central weight vector for scenarios 4 to 9

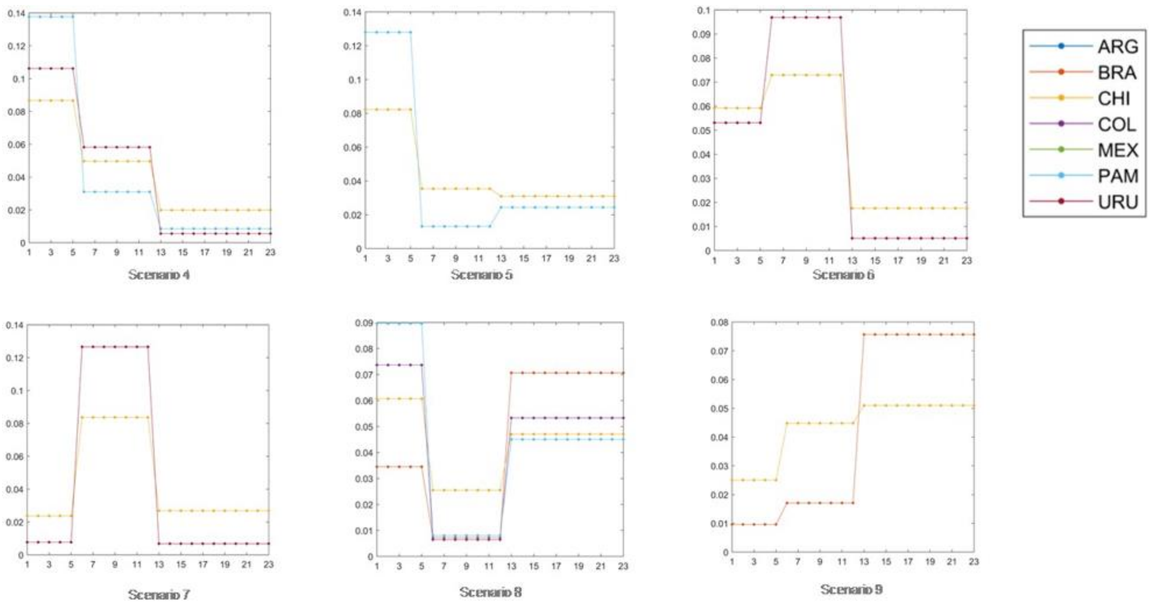

***Table 3**. Central weight vectors for scenario 3*

	Argentina	Brazil	Chile	Colombia	México	Panamá	Uruguay
C1	0,096	0,050	0,035	0,035	0,042	0,108	0,068
C2	0,032	0,053	0,034	0,063	0,030	0,046	0,095
C3	0,025	0,041	0,049	0,031	0,049	0,035	0,024
C4	0,056	0,024	0,051	0,030	0,057	0,036	0,031
C5	0,043	0,026	0,039	0,069	0,031	0,059	0,042
C6	0,050	0,032	0,049	0,038	0,028	0,039	0,062
C7	0,036	0,039	0,050	0,030	0,034	0,052	0,076
C8	0,043	0,032	0,033	0,054	0,070	0,054	0,034
C9	0,038	0,024	0,052	0,049	0,035	0,025	0,043
C10	0,029	0,043	0,050	0,032	0,029	0,047	0,063
C11	0,032	0,049	0,051	0,029	0,038	0,024	0,052
C12	0,037	0,046	0,034	0,065	0,056	0,035	0,034
C13	0,037	0,054	0,037	0,062	0,046	0,036	0,026
C14	0,031	0,043	0,034	0,053	0,072	0,030	0,050
C15	0,026	0,037	0,050	0,033	0,044	0,052	0,023
C16	0,026	0,023	0,051	0,048	0,034	0,034	0,046
C17	0,124	0,041	0,045	0,043	0,032	0,025	0,062
C18	0,040	0,052	0,045	0,034	0,063	0,029	0,025
C19	0,054	0,074	0,040	0,040	0,051	0,028	0,028
C20	0,081	0,084	0,034	0,048	0,035	0,047	0,035
C21	0,022	0,045	0,046	0,038	0,032	0,068	0,024
C22	0,023	0,052	0,042	0,032	0,065	0,042	0,024
C23	0,021	0,033	0,049	0,044	0,028	0,049	0,033

Table 4. *Results Summary by scenario*

Scenario	*Preference information*	*Best options*
1	$w_i = 1/n$	CHI
2	$w_{G_k} = 1/k$	CHI
3	$0 \leq w_{G_k} \leq 1$	CHI
4	$w_{G_1} > w_{G_2} > w_{G_3}$	PAM, URU,CHI
5	$w_{G_1} > w_{G_3} > w_{G_2}$	PAM, CHI
6	$w_{G_2} > w_{G_1} > w_{G_3}$	URU,CHI
7	$w_{G_2} > w_{G_3} > w_{G_1}$	CHI, URU
8	$w_{G_3} > w_{G_1} > w_{G_2}$	CHI, BRA, COL, PAM
9	$w_{G_3} > w_{G_2} > w_{G_1}$	CHI, BRA

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Appendix 1. **Table a**. *Detailed description of each criteria*

Group	*Main Criteria*	*Label*	*Sub-Criteria*	*Sub-criteria Description*	*Objective*	*Source*
Environmental (G_1)	Ecosystem vitality	C1	Air pollution Related to the ecosystem	Annual mean concentration of particulate matter of less than 2.5 microns (PM2.5) (ug/m3).	min	(World Health Orgnization, 2018)
		C2	Climate change vulnerability	The index assesses global variations in vulnerability to climate change by gauging each country's vulnerability to three main potential impacts of global warming: increase in weather-related disasters, sea levels rise and loss of agricultural productivity. (best 0-100)	min	(Sachs, Schmidt-Traub, Kroll, Lafortune, & Fuller, 2018)
		C3	Waste water treatment	Percentage of wastewater that undergoes at least primary treatment in each country, normalized by the proportion of the population connected to a municipal wastewater collection system. (0-100%)	max	(Wendling, Z. A., Emerson, J. W., Esty, D. C., Levy, M. A., de Sherbinin, A., 2018)
	Environmental Health	C4	Environmental Burden of disease	Quantifies the amount of disease caused by environmental risks. Disease attributable to the environment can be expressed in deaths and in Disability-Adjusted Life Years (DALYs) (DALYs/1000 cap)	min	(World Health Orgnization, 2014)
	Environmental factors within production	C5	Recycling of material energy and waste	Total adequate disposal of solid waste (%)	max	(Waste Atlas, 2018)
Social (G_2)	Governance	C6	Incidence of corruption	Score on the Corruption Perceptions Index, which measures perceptions of corruption in the public sector. This is a composite indicator, and the scale ranges from 0 (highly corrupt) to 100 (very clean) | 2018 edition Transparency International, Corruption Perceptions Index	max	(Transparency International, 2018)
		C7	Political stability	Measures perceptions of the likelihood of political instability and/or politically motivated violence, including terrorism. Ranging from approximately -2.5 to 2.5.	max	(The World Bank, 2010)
		C8	Trade and tariff Barriers	Weighted average applied tariff rate, expressed in percentage points | 2018 or most recent period available. (%)	min	(Schwab, 2019)
	Education	C9	Skillset of graduates	Extend at which the graduated population possesses the skills needed by businesses. (1-7)	max	(Schwab, 2019)
	Individual	C10	Civil liberties	A country or territory's political rights and civil liberties ratings then determine whether it has an overall status of Free, Partly Free, or Not Free.	min	("Freedom in the World Countries | Freedom House," 2019)
	Community	C11	Local technology	Total number of patent family applications per million population.	max	(Schwab, 2019)
		C12	Safety	Based on the global peace index independent states and territories according to their level of peacefulness.	max	(Institute for Economics & Peace, 2019)

Table a. *Detailed description of each criteria (Continued)*

Economic (G_3)	Cost	C13	Labor Cost	Average Monthly wage in USD	min	World Data [2018]
		C14	Facility Cost	Cost of square meter of industrial construction. (USD/m2)	min	Turner&Townsend [2017]
		C15	Logistic performance	The efficiency of countries to move goods across and within borders (domestic and international) provided by the world bank.	max	The WorldBank [2018]
		C16	Labor Tax rate	Labour tax and contributions are the amount of taxes (at any level—federal, state or local) and mandatory contributions on labour paid by the business, expressed as a percentage of commercial profits. (%)	min	Schwab [2019]
		C17	Energy Cost	Price of electricity for businesses in over 100 countries (USD/KWh)	min	Global Petrol Prices [2019]
	Market	C18	International markets	Total of exports in USD millions.	max	Central Intelligence Agency [2017]
		C19	Potential demand	Sum of gross domestic product plus value of imports of goods and services, minus value of exports of goods and services. (1-7)	max	The WorldBank [2019a]
	Economic stability	C20	Favorable tax	Distortive effect of taxes and subsidies on competition	min	Schwab [2019]
		C21	Exchange rate fluctuations	Annual percentage change in the Consumer Price Index	min	Schwab [2019]
	Suppliers	C22	Proximity to key suppliers	How widespread are well-developed and deep clusters (geographic concentrations of firms, suppliers, producers of related products and services, and specialized institutions in a particular field).	max	Schwab [2019]
	Growth	C23	Industry growth	Annual growth rate for industrial value added based on constant local currency.	max	The World Bank [2019b]

Table b. *Decision Matrix for the sustainable location problem*

	Environmental					Social							Economic										
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**	**C19**	**C20**	**C21**	**C22**	**C23**
Argentina	16,44	87,57	72,13	24	0,05*	40	0,05	6,60	4,20	2,0	1,44	1,99	12370	3488	2,89	29,30	0,07	59,69	4,86	2,60	30,00	3,40	-3,10
Brazil	19,16	84,32	81,08	36	0,01	35	-0,37	6,60	3,20	2,0	1,93	2,27	9140	1553	2,99	39,40	0,15	217,20	5,71	2,50	3,60	3,90	0,40
Chile	24,85	90,00	98,55	19	0,04	67	0,42	7,00	4,60	1,0	4,13	1,63	14670	3849	3,32	5,10	0,14	64,51	4,39	4,90	2,30	3,70	4,30
Colombia	22,97	83,51	77,21	31	0,20	36	-0,81	6,40	4,30	3,0	0,79	2,66	6190	971	2,94	18,60	0,15	34,30	4,73	3,00	3,80	3,60	1,10
México	22,22	88,65	91,48	23	0,03	28	-0,60	6,30	4,10	3,0	1,84	2,60	9180	750	3,05	26,90	0,17	406,50	5,53	3,40	5,50	4,30	0,20
Panamá	13,20	87,30	78,12	25	0,06*	37	0,30	6,50	3,80	1,5	0,57	1,80	14370	3606	3,28	20,00	0,20	15,48	3,34	3,30	0,80	3,70	2,60
Uruguay	18,00	83,51	58,85	25	0,05*	70	1,05	6,70	4,30	1,0	1,98	1,71	15650	1932	2,69	15,60	0,10	8,98	3,19	3,70	6,90	3,40	0,70

* Data not found in main database, estimated respectively from the following informal sources:
https://www.sudestada.com.uy/10893/Detalle-de-Noticia?articleId=efbc9cd9-a075-451d-ba8c-a38a77d9720f
https://www.lanacion.com.ar/buenos-aires/reciclado-solo-se-recupera-el-6-de-los-residuos-que-produce-la-ciudad-nid2033330
https://impresa.prensa.com/panorama/basura-recicla