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# Shaping cities: A proposal for an integrative FEW nexus model

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ABSTRACT

Advances to better understand the food, energy and water (FEW) nexus are still needed since most available approaches are non-integrated, complex, and focused on large scale, which makes them difficult in supporting public policies on small scales. This work proposes the FEW nexus cube model, a quantitative and integrated model to evaluate the FEW nexus of municipalities. FEW flows are independently quantified to show their demand by each municipality, they are then graphically represented in a 3-D cube to allow a criteriously-based integrated performance final rank that supports the identification of strengths and weaknesses for the municipality. The cube model is applied in nine Brazilian municipalities as case studies to show its potential for comparative assessments. Santos municipality is in the top ranking according to the criteria behind the cube model, being located in the so-called security cube region, without limiting FEW factor, and 0.80 for the FEW vector length. In 2018, Santos demanded 9.73E+ 07 $m^3H_2O_{eq.}$, 2.08E+ 10 $MJ_{fossil\text{-}eq}$., and 6.87E+ 08 $kgCO_{2eq}$., of which food & energy were the FEW flows that most influenced $CO_2$ emissions and fossil energy demand, while food & water FEW flows have influence on the embodied water demand. Although outside the scope of this study, general policy recommendations are suggested for effective developing plans. This work contributes to the advancement of FEW nexus studies by providing an integrated, non-complex, and small-scale based model to achieve more resilient municipalities as emphasized by the United Nations in several of its 17 goals.

## 1. Introduction

Even recognizing the importance of the "peak everything", as coined by Hall and Day (2009) about the scarcity of water, soil, biodiversity, and a series of other natural resources not accounted for by conventional economic theory, the population continues to grow at the expense of reducing the availability of natural resources. According to World Oil Outlook (2018), global demand for primary energy will grow by 33% for the period between 2015 and 2040. By 2050, energy demand will almost double, and water and food demand is expected to increase by more than 50% (Ferroukhi et al., 2015). According to UNESCO (2015), global water consumption is expected to increase by 55% by 2050, mainly due to the increasing demands on manufacturing, electricity generation and domestic use. Between 60%– 80% of global anthropogenic water use is devoted to irrigation for food production (Gerbens-Leenes et al., 2009). These numbers indicate that the greater the population growth and lifestyle, the greater the demand on resources, and this trend is unlikely to change in the short and medium term.

Every process involving water resources, including capture, transport, distribution, wastewater collection, treatment for disposal, and reuse of water, depends on energy (Meng et al., 2019). Similarly, the high energy demand scenario for the coming decades will culminate in a considerable increase in water consumption, either in fuel extraction and processing processes or even in the electricity generation from hydropower plants (Tidwell and Moreland, 2016). Furthermore, energy and water are crucial inputs for the production, processing, transport, and preparation of food (Ferroukhi et al., 2015). This dependency relationship provides evidence for the existence of a nexus, an interdependent relationship between food, energy and water (FEW).

The FEW nexus was first discussed in 2008 during an annual meeting of the World Economic Forum (WEF World Economic Forum, 2011) and it has been identified as a global risk (Van der Elst and Dave, 2011). It was understood that the need for security between the three FEW resources should be considered in an integrated way, and that this

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interdependence guarantee should be identified and considered in decision-making (Hoff, 2011), emphasizing the need to develop strategies that show a comprehensive and integrative approach to the FEW nexus. For the Food and Agriculture Organization of the United Nations, the approach to studying the FEW nexus should consider the different dimensions of the three factors and recognizes the interdependence of these resource uses for sustainable development (FAO, 2014).

Many works that focus on the FEW nexus theme are available in the scientific literature and can be classified as: (i) literature review (Ghodsvali et al., 2019; Zhang et al., 2019); (ii) principles and concepts (Liu et al., 2017; Albrecht et al., 2018); (iii) relationship with sustainability and the SDGs (Stephan et al., 2018; Yuan et al., 2021); (iv) methods and tools (Daher and Mohtar, 2015; Ermolieva et al., 2015; Kraucunas et al., 2015); (v) modeling and evaluating the nexus (Abulibdeh and Zaidan, 2020; Djehdian et al., 2019; Mahjabin et al., 2020); and, (vi) nexus in government (Voelker et al., 2019). Even though providing important contributions, the vast majority discuss definitions and concepts, existing a scientific gap on its quantitative aspects. For instance, the few studies that aim at quantifying the FEW nexus focus on specific regions and/or different assessment scales, and do not integrate the three FEW resources into the discussions. Among others, Al-Ansari et al. (2015) studied the food production sector in Qatar, showing that the implementation of a photovoltaic system could reduce the global warming potential by 30% and have a return on investment after three years. Frankowska et al. (2019) assessed the environmental impacts of the eight most consumed vegetables in the UK, emphasizing that the demand on primary energy ranged from 12 to 36 MJ/kg, and 40% of imported vegetables came from countries with water problems, resulting in a footprint several times higher than in vegetables grown in the United Kingdom. Schlör et al. (2018) calculated the resilience index of 69 cities in the world. Other works can be mentioned, such as those by Mohtar and Daher (2012), Allouche et al. (2014), Flammini et al. (2014), Ringler et al. (2016), Miller-Robbie et al. (2017), Owen et al. (2018), Mahlknecht and González-Bravo (2018) and Mercure et al. (2019), each considering different assessment scales (countries, regions, industries, etc.), in which FEW resources are assessed separately rather than interrelated, and focusing on conceptual and/or qualitative aspects of the FEW. However, none of these are based on or present a quantitative and integrative evaluation of the FEW nexus, not achieving the inherent objectives of its own definition.

Regarding the assessment scale, urbanized centers deserve special attention as they are home to 55% of the world's population (DESA, 2018; with the potential to reach 68% in 2050) and are a net consumer of energy and materials, in addition to generating large amounts of waste. Jenerette and Larsen (2006) estimate that the urban centers of the world demand from 27 to 621 times their physical area to be able to supply/capture their water needs in a sustainable way. The focus on municipalities is important in order to operationalize the suggestions for a more sustainable future, a condition that hardly occurs when large-scale systems are studied. Thus, urbanized centers show up as potential systems to be considered in the FEW nexus evaluations. This is especially true when the city mayor is the one with power to implement public policies. According to Artioli et al. (2017), municipalities are an intertwined part of the interdependencies of the nexus but remain on the sidelines of research and policy, which claims for more 'urbanizations' for FEW studies.

Even though FEW nexus studies in municipalities are gaining more and more importance (e.g., Gondhalekar and Ramsauer, 2017; Rodrigues, 2017; Giatti et al., 2016), until now a suggested standard procedure (metrics, indicators and analysis) to be used in studies of the FEW nexus in municipalities has not been found in the scientific literature. Similarly, Rising (2020) explains that there is inconsistency in all the proposed FEW models and it is necessary to establish criteria and follow steps before decision making to avoid mistakes. Due to the importance of evaluating the FEW nexus of urbanized centers, simultaneously with the absence of publications and standardized procedures existing in the scientific literature, it is understood as important to propose procedures to evaluate the FEW nexus of municipalities, carefully explaining the models and indicators used.

This work proposes a quantitative and integrated evaluation model of the FEW nexus and applies it in detail for a Brazilian municipality. An additional 8 Brazilian municipalities are also considered as case studies to obtain a larger sample and verify the potential of applying the proposed evaluation model. It is expected that the proposed FEW model can be useful to support, in a scientific way, more robust decisions about the planning of municipalities in search of their resilience over the years, as advocated by the sustainable development goals (SDGs; specifically goals 2, 6 and 7) of the 2030 Agenda.

## 2. Proposal of a quantitative and integrated evaluation model of the FEW nexus in municipalities

### 2.1. Modeling the FEW resources

The absence of a suggested standardized procedure for evaluating the FEW nexus could be its 'Achilles heel', the weakness in spite of overall strength which makes it difficult to model and choose suitable indicators to represent its goals. To overcome this obstacle, the model and indicators presented in Fig. 1 as proposed by Zhang et al. (2019) are considered in this work. Initially, the spatial and temporal analysis window is established; as the focus is on municipalities (including urban and rural areas), the spatial window comprises the physical-political limits of the municipality, and the usual time window is one year. Then a complete inventory of the municipality's demand on food, energy and water (types and quantities) is obtained.

To calculate the indirect resources that support FEW flows, the life cycle assessment (LCA; International Organization for Standardization - ISO, 2006a, b) is considered as method to obtain the indicators of climate change ($kgCO_{2\text{-eq.}}$), cumulative fossil energy demand ($MJ_{fossil\text{-eq.}}$), and water depletion ($m^3H_2O_{eq}$). LCA is a method used to quantify the FEW nexus, advocated by Zhang et al. (2019) as a typical method to quantify the environmental impacts of a given product or process throughout its life cycle. The Ecoinvent® database, version 3.6 2019, is considered as a data source for the conversion factors used in LCA, considering the methods "cumulative energy demand, fossil" to obtain $MJ_{fossil\text{-eq.}}$, "CML2001, climate change, 20 yrs" (GWP20 is adopted since decisions are made focusing on short time, being more suitable for strategic planning for municipal development) to obtain $kgCO_{2\text{-eq.}}$, and the method "ReCiPe Midpoint (H) V1.13, water depletion" to obtain

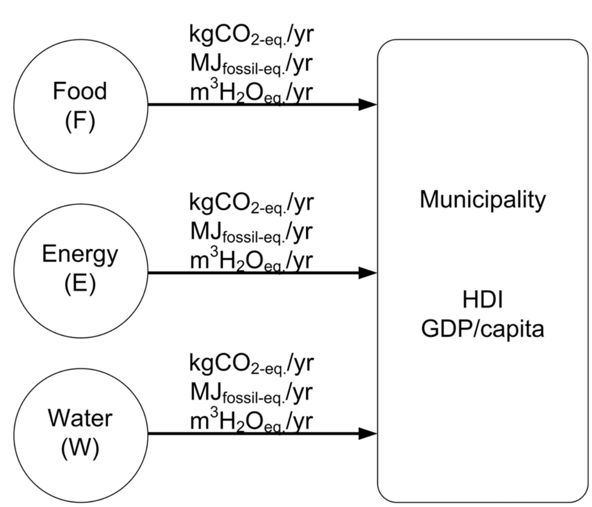


**Fig. 1.** Conceptual model of the nexus between food, energy and water, and their respective indicators.
Adapted from Zhang et al. (2019).

$m^3H_2O_{eq}$. Although these LCA methods are used here, it is understood that other methods can be used and that this choice will not significantly influence the comparative results of the proposed model, it being up to the analyst to choose the LCA methods that he/she deems most appropriate.

Conceptually, the food, energy and water nexus implies the recognition that these three variables are dependent. Similar to the work by Frankowska et al. (2019), after calculating the indicators $kgCO_{2\text{-eq}}$., $MJ_{fossil\text{-eq}}$., and $m^3H_2O_{eq}$., they are normalized and analyzed by a triangular radar graph, which represents the overall municipal performance including local and regional/national footprints due to consumption of FEW flows. Comparatively, the area of the radar diagram indicates the overall performance of the system, as the smaller the area, the less pressure on the environment due to the demand on resources. In this analysis, all three indicators are considered to have the same importance (or weight). The logarithm in base 10 (Log10) is used to make the indicators comparable, and the results are normalized by the Standard score method: $Z = (x-\mu)/\sigma$; where "x" is the value to be normalized, "μ" is the mean of "x", "σ" is the standard deviation of "x".

Although important, the analysis carried out through the quantitative assessment of the performance indicators for the FEW nexus is seen separately and still lacks an integrative approach as emphasized by the own nexus definition. This is nothing new, as there are some studies in the scientific literature (Kibler et al., 2018; Bergendahl et al., 2018; Djehdian et al., 2019; Mahjabin et al., 2020) that used this quantitative approach but did not integrate the FEW nexus. In this sense, the greatest contribution of this present study is the integrative aspect of the FEW nexus model, which is presented in the following subitem.

### 2.2. FEW nexus quantitative and integrated evaluation model: the cube model

Fig. 2 shows the cube model considered in this work to graphically represent and allow the integrative analysis of the FEW nexus of municipalities. The model presents the FEW flows individually in plans, two by two, and thresholds are established according to the scientific literature and/or government reports to create internal regions in the cube model that help in the diagnosis of the FEW nexus of the municipalities in an integrated way.

To define each of the thresholds, a sample of 189 countries and their respective Human Development Index (HDI) is used. Information is collected from the United Nations (2019) and the values are for the year 2019, but may be updated as new versions become available. Data is classified into two groups: the first (group 1), with countries with a high and very high HDI above 0.7, and the other (group 2), with countries with medium and low HDI below 0.7. It is assumed as a proxy that the HDI indirectly represents the level of consumption in each country, which is supported by the Wackernagel et al. (2017) findings; whether other criteria than HDI becomes available and shown higher accuracy for clustering purposes according to countries consumption for FEW resources, then the cube model can be revisited. For example, countries with an HDI> 0.7 show greater development and, for this reason, the consumption of FEW resources is assumed to be higher in order to achieve the highest HDI (more infrastructure, provision of goods and services for schools and hospitals, and greater GDP generation). Similarly, countries with an HDI< 0.7 that show less development would indicate lower consumption of food, energy and water. It is important to emphasize that a higher HDI does not necessarily express higher consumption, as the education variable, for instance, can help the population to improve their food consumption practices (more balanced, without waste and without excess of animal proteins), use energy in a sustainable way (using sunlight, when possible, renewable sources, etc.), and avoid wasting water. However, for this work, this indicator was used as a criterion due to its importance, representativeness, and availability.

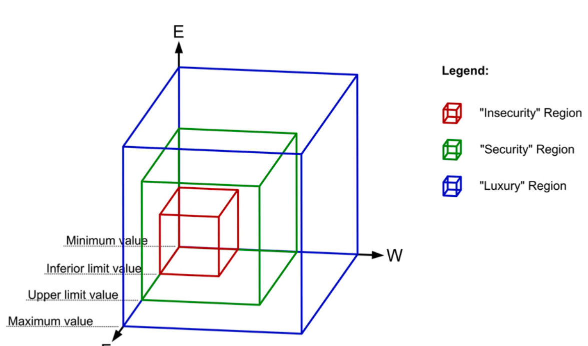


**Fig. 2.** Graphical visualization of the proposed FEW nexus cube model.

After separating the countries into groups, an inventory is drawn up with all per capita consumption of food (F), energy (E) and water (W) to know the amount that countries consume of each resource. As available in the Supplementary Material A, information is collected from Our World in Data (2020); food in kcal/person day), The World Factbook (2020); energy, sum of electricity in kWh/person yr, natural gas in m3/person yr and oil derivates in bbl/person day), and Worldometer (2020); water in L/person day), to establish the following limits used in the cube model: (a) minimum value: the value obtained for the country with the lowest consumption per inhabitant among countries in group 2; (b) inferior limit value: the median of consumption per inhabitant among countries within group 2; (c) upper limit value: the median of FEW consumption per inhabitant among countries within group 1; (d) maximum value: the value obtained for the country with the highest FEW consumption per inhabitant among the countries in group 1. To insert these values into the FEW nexus cube model, they are normalized between 0 and 1, by the method of Normalization Minimum and Maximum Feature Scaling, or Unit-based Normalization (Eq. 1). The terms 'insecurity', 'security', and 'luxury' refer to the living conditions related to the consumption of FEW resources in a municipality. It is understood that security refers to an ideal living standard, where the population has access to resources to maintain life, avoiding a scenario of insecurity (insufficient consumption of FEW resources to maintain life), while luxury means there is excessive or unnecessary consumption for the well-being of society. In order for there to be symmetry between the data and the cube design, the limits are pre-determined as being: 0 (zero) to the minimum value; 0.33 for the inferior limit value; 0.66 for the upper limit value; and 1 (one) to the maximum value.

$$X' = a + \frac{(X - X_{minimum}) \; . \; (b-a)}{(X_{maximum} - X_{minimum})} \tag{1}$$

where:

"X" is the value to be normalized;.

"$X_{minimum}$" is the inferior limit value closest to X;.

"$X_{maximum}$" is the upper limit value closest to X;.

"b" is the normalized value of $X_{maximum}$;.

"a" is the normalized value of $X_{minimum}$.

Table 1 presents the cube limits. Values are in annual consumption units per person and must be used by the real data of the municipalities to be evaluated, making it possible to compare the limits and the consumption obtained for the municipality, leaving them in the same order of magnitude for each FEW flow.

### 2.3. Interpreting the FEW nexus cube model

Three steps are performed to classify and quantify the FEW nexus. This procedure allows the system to be analyzed in an integrated way, represented through classification of the region in the cube, the analysis of the flows limiting factor, and the length of the FEW vector. For an efficient application of the cube model, one criterion at a time must be considered according to the following priority order: 1st. Classify the

**Table 1**
Limits established for the cube model.

| Cube limits | Quantity[a] | Normalization |
|---|---|---|
| Food (kcal/person yr) | | |
| Minimum value | 6.4E+ 05 | 0 |
| Inferior limit value | 9.0E+ 05 | 0.33 |
| Upper limit value | 1.1E+ 06 | 0.66 |
| Maximum value | 1.4E+ 06 | 1 |
| Energy (kWh/person yr) | | |
| Minimum value | 1.1E+ 02 | 0 |
| Inferior limit value | 2.0E+ 03 | 0.33 |
| Upper limit value | 1.7E+ 04 | 0.66 |
| Maximum value | 5.8E+ 04 | 1 |
| Water (L/person yr) | | |
| Minimum value | 1.2E+ 04 | 0 |
| Inferior limit value | 1.2E+ 05 | 0.33 |
| Upper limit value | 4.3E+ 05 | 0.66 |
| Maximum value | 1.6E+ 06 | 1 |

[a] Raw data available in Supplementary Material A.

region where the FEW vector is found: security, luxury or insecurity; 2nd. Analyze the limiting factor: stable, semi-stable or unstable; 3rd. Quantify the FEW vector length. These criteria are presented in detail in the following subsections.

#### 2.3.1. Region classification

The classification of the region in which the FEW flows are located allows us to know the current consumption status of the studied municipality. The classification step allows for the evaluation of the performance of the FEW in two ways: (a) each FEW flow is evaluated individually; (b) the municipality's FEW nexus is assessed in full.

The individual assessment focuses on the position where each indicator representing the FEW is positioned in the pre-established regions. The criteria for evaluating the FEW nexus performance for municipalities are judged according to the model proposed in Fig. 2: (i) when the value of a FEW flow is between the inferior and upper limits values, it will be in the region called "security"; (ii) above the upper limit value, it will be in the region known as "luxury"; and (iii) below the inferior limit value, it will be in the "insecurity" region.

The integral form of evaluation of the FEW nexus, on the other hand, is the result of the relationship between the three FEW resources, using the 'vector principle', called 'FEW vector', to determine the meeting point or resultant between the three flows FEW. The FEW nexus performance can be interpreted according to the spatial position of the FEW vector, including the regions of insecurity, security and luxury.

#### 2.3.2. Limiting factor analysis

Using resilience assessment criteria based on the limiting factor concept is important to verify the balance between FEW resources. The limiting factor is any condition that approaches or exceeds the tolerance limits of life in general, as an ecosystem, of an animal or plant organism (Odum, 1988). This principle developed from Liebig's "Law of the Minimum" and Shelford's "Law of Tolerance". The Law of the Minimum reveals the indispensable conditions to subsidize life, and the Law of Tolerance refers to life support capacities and can be adapted to the environment in which a given species inhabits. A limiting condition can exist not only because of the unavailability of a resource, as Liebig proposes, but also because of the excess. This circumstance meets the criteria established to define the regions of the cube model and, therefore, they are used in this work. The central idea is that there is a balance between the FEW flows to avoid the existence of limiting factors.

Based on these concepts, the criteria adopted in the cube model for this analysis are: (i) when all three FEW flows are in the same region, it will be called 'Stable Condition', as the FEW flows are quantitatively similar, with no limiting factor: (ii) when each of the three FEW flows is in a different region, or two FEW flows are in a region and the other flow is in the neighboring region, there is the so-called 'Semi-stable Condition', because, in this case, one or two FEW flows cross the boundary of the limiting condition to minimum or maximum; (iii) when two of the three FEW flows are in an extreme region of the cube and the other FEW flow is in the other extreme region, there is the so-called 'Unstable Condition', this reveals an adverse situation, as the three FEW flows exceed the boundary of the limiting condition (inferior and upper limits).

#### 2.3.3. Quantification of vector length

While the previous two steps classify the FEW nexus, this step is important to quantify it. The vector principle for this work is fundamental to represent the resulting point of FEW flows, where the FEW vector $= (F^2 + E^2 + W^2)^{1/2}$, with FEW flows already normalized. The main characteristic of this step is the verification of the vector length, starting from the origin of the cube p(0,0,0). The vector length in the cube can vary from 0 to 1.73, where, for the latter, the consumption of FEW resources must be the maximum possible for all flows. The highest performance for vector length corresponds to 1.14, reaching the inner edge of the security region. It is worth noting that the direction of the vector is not a crucial condition in this evaluation, since the quantification using the FEW vector length is the last step considered in the ranking of municipalities according to their FEW nexus. In other words, this is a 'tie-breaker' aspect, occurring when the previous rankings are similar for two or more municipalities.

For example, if municipality A is classified in the same region and limiting factor as municipality B, the length of its FEW vectors will show which one has better performance than the other related to FEW consumptions. In this case, the classification shows that the municipalities have similar conditions, differing only in relation to the length of their FEW vectors. In general, when the classification region is insecurity or security, the greatest possible vector is sought to leverage the municipality's power or capacity to demand on FEW resources, in order to support its development. Moreover, if the region is luxury, the smallest possible vector is sought, so that the municipality can get closer to the security region.

### 2.4. Steps to apply the proposed model: an overview

The first step includes obtaining consumption data for the municipalities, here called direct consumption (Fig. 3). Values for food consumption are established by the amount a person consumes per day, as commonly found in databases. Important to highlight that food consumption refers to the amount of food that crosses the boundaries of the municipality and becomes available to feed the population, disregarding the existing potential wastes that occurs within the municipalities boundaries; the same meaning is also applied to water and energy resources. For water and energy FEW flows, the total consumed within the municipalities is considered, including quantities destined for industrial, commercial, domestic and agricultural sectors. Food and energy resources are separated into food and energy subgroups (Appendix A and Supplementary Material C), respectively, to better represent their specificities relating to demand on water, energy, and causing global warming.

The second step "estimating indirect consumption" is carried out only for the individual assessment, that is, when the objective is to obtain the radar diagram to assess which of the FEW flows has the greatest influence on the performance indicators. At this point, the database transformation coefficients are collected to obtain the indicators $kgCO_{2\text{-eq}}$., $MJ_{fossil\text{-eq}}$., and $m^3H_2O_{eq}$ (Supplementary Material B). The third step is the conversion of direct and indirect consumption data into performance indicators; at this point, a previous analysis of the results can be done in a comparative way. The fourth step consists of the conversions or normalizations of this data to be placed into each evaluation tool, triangular radar graph or cube model. The fifth and last step is the method evaluation phase: for the radar diagram, the visual and individual reading and interpretation of the quantities presented in the graph are performed, while for the cube analysis, the procedures

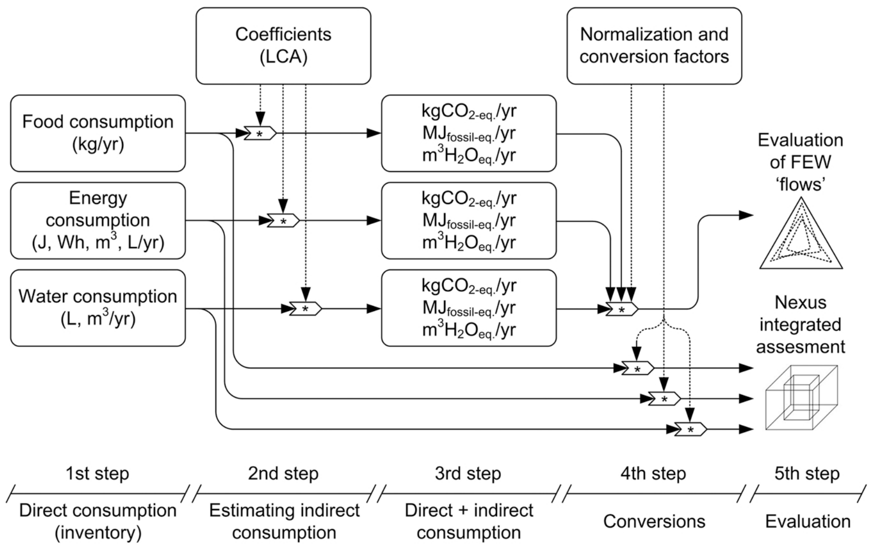


**Fig. 3.** Flowchart for the steps behind the FEW nexus cube model.

described above are considered.

It is important to emphasize that proposed framework should be used in its totality, i.e. the cube model must be used together with the radar-triangle diagram. Decision maker must firstly consider the cube to sustain a decision focused on short-time period and under the municipality scale, identifying whether one or more FEW flows should be reduced or increased to achieve the best performance in the cube security region. When replacing a resource by other is identified as option to reduce or increase FEW flows (e.g. substituting a food type by another, or one energy source by another), than the radar diagram is used to sustain an effective decision about what should be done to implement the decision. Using the radar diagram for substitution purposes is important because a choice impact indirectly on FEW nexus, e.g. choosing one kind of food impacts indirectly on the $CO_2$ emissions, water and energy demand.

### *2.5. Sustainability versus resilience: the scope of FEW nexus cube model*

In some FEW nexus studies (Zhang et al., 2019; Chirisa and Bandauko, 2015; Yang et al., 2018; Nhamo et al., 2020) it was possible to verify that both the words sustainability and resilience are commonly used with the objective to show what is proposed in the nexus approach. Although the nexus between food, energy and water was set out to show the interactions and dependence of the three FEW flows, it is still not clear in the scientific literature which of the concepts would be the most appropriate to include in the study of the FEW nexus, as there is a relationship between the definitions of sustainability and resilience, and may even in some cases be complementary.

Specifically for the FEW nexus evaluation model proposed in this work, the biophysical sustainability aspect makes sense when the municipality is classified in the luxury region, thus having to reduce its consumption of FEW flows to move towards the security region. A consequence of this would also be the reduction of waste, an important aspect when discussing sustainability. However, when municipalities are classified in the region of insecurity or security, it is suggested that the consumption of FEW flows be increased until reaching their maximum performance (vector length of 1.14). This approach is contrary to what is proposed by the definition of biophysical sustainability (consuming and generating waste within the regeneration capacity of the environment). Thus, it would not be appropriate to relate the cube assessment model with sustainability, unless the replacement from one region to another happens, solely and exclusively, based on the consumption of renewable resources. Other conceptual sustainability models include three different pillars (social, environmental and economic; e.g. Sporchia et al., 2021), but these models could hardly be applied in the proposed FEW cube because the social aspect could be included only indirectly when targeting the security region to promote a better quality of life for the population.

In a study by Olsson et al. (2015), investigating the lack of relationship between resilience and social sciences, it is clear that resilience thinking describes important attributes of ecosystems, materials and human beings, that is, the ability to cope with and recover after disturbances, shocks and stress. The concept of resilience is related to the ability to deal with and remain in a given situation even after fluctuations and stresses. Thus, it is understood that this condition is directly related to the cube model, as it seeks to reach the "ideal" security region for the three FEW flows. Thus, unlike expressing sustainability, the proposed cube model shows the municipality's capacity to maintain itself in a condition of resilience, trying to avoid low and/or exaggerated consumption of FEW flows, or even aiming to obtain them in a quantitatively similar way.

## 3. Applying the FEW nexus cube model into Brazilian municipalities as case study

Among more than 5500 municipalities in Brazil, Santos, located on the São Paulo state coast deserves special attention. It is a heavily urbanized municipality comprising the largest port in Latin America, has a high Human Development Index (HDI) of 0.84, the 6th best position in the country (IBGE, 2018). Santos has a territorial area of 281 km$^2$, 7 km of coastline and a population of around 433,000 people (IBGE, 2018). Its main economic activity is related to its port, tourism, services and fishing sectors, achieving a gross domestic product (GDP) per capita of 9200 USD in 2018 (IBGE, 2018). Highly dependent on external FEW resources and essential for its development, the municipality of Santos is undergoing an expansion phase in its infrastructure and population, making it an excellent case study about its FEW nexus to support its strategic planning. In addition to the municipality of Santos, which is assessed in more detail, another 8 municipalities in the state of São Paulo with different characteristics are considered, to compare and rank them according to what is proposed by the cube assessment model. Highly urbanized regions were randomly selected, and others were almost entirely rural, some with high HDI and others low. In the following section, the evaluation model was first applied to all 9 studied municipalities and, later, detailed for Santos.

### 3.1. Quantitative and integrative evaluation

Initially, the inventory with consumption data of FEW flows for the municipalities is obtained. This inventory is essential for all subsequent impact analyses that are carried out in parallel and independently, ensuring maximum consistency of input data. Consumption data can be viewed in Appendix A (regional data were used for food, while municipal data were used for energy and water FEW flows), which is then normalized (4th step of Fig. 3) to obtain the cube. An Excel® file was prepared and used to facilitate the procedure, which is found in Supplementary Material C and can be used in other municipalities. Fig. 4 shows variations of the FEW performances among the municipalities considered as a case study. Overall, 3 out of 9 municipalities studied were classified in the luxury region (dots in blue), while the other 6 were in the security region (dots in green).

Although it is important to visualize the spatial distribution of the FEW nexus of municipalities, Fig. 5 presents the cube in two dimensions, allowing the analysis of each flow individually and in a comparative way between two flows. In Fig. 5a it is possible to identify that the food has similar consumption for all studied cities, which is explained by the fact that the database used in this work provides values by regions of Brazil, and in this case all cities are from the same Southeast region. However, this does not interfere with the quality of the proposed model, as when more accurate and individualized data on food consumption in these municipalities is available, the calculations can be revisited.

The vertical axis of Fig. 5a and b shows energy consumption, where the municipality of Cubatão reached the maximum possible value, that is, its energy use is equal to or higher than the average consumption for the country that consumes the most energy in the world. This can be explained by the characteristics of this municipality, known as an industrial hub, close to a port region and oil hubs that have refineries installed in the municipality. The municipalities of São Caetano do Sul, Santos, Nova Campina, São Paulo, Diadema and Ribeirão Branco are located within the security region (thresholds between 0.33 and 0.66). The same vertical axis for the energy FEW flow is visualized in Fig. 5b, however, there are now variations according to the water FEW flow. Only the municipalities of Santos, Águas de São Pedro and Cubatão have water consumption above the inferior limit value (0.33), while Barra do Turvo and Nova Campina have consumption close to the minimum value (0.00). Finally, Fig. 5c shows the food-water interface, which has the same behavior as the previous ones.

Table 2 shows the hierarchy and final classification of the sample of municipalities, obtained through the graphical analysis and classifications for each municipality, including the region and the limiting factor. None of the municipalities were classified in the region of insecurity, which is seen as a positive aspect. Likewise, no municipality resulted in an unstable condition. However, for 1 out of 9 municipalities, each flow was found in a different region. The municipality of Barra do Turvo was classified in the luxury region due to its high energy consumption and presented a semi-stable condition. Figs. 5b and 5c reveal the low water consumerism for the municipality. For this situation, it is essential to establish measures to increase water consumption. After the practices to improve water consumption in Barra do Turvo, policies are suggested to reduce energy consumption in the municipality, which in some way characterizes it as a high consumer.

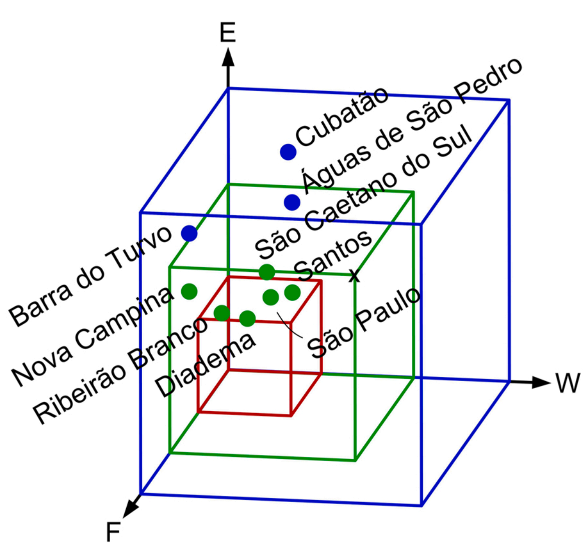


**Fig. 4.** FEW nexus cube model applied to 9 Brazilian municipalities. The ‘x’ indicates the best performance target. Data refers to 2018.

Table 2 shows a relationship in the hierarchy of municipalities with that established by the HDI, with the exception of the municipalities of Águas de São Pedro and Cubatão. Due to the existence of large water dams in some municipalities such as Águas de São Pedro and Nova Campina, they could consume water not accounted for by official data, which must be taken into account before making a decision to encourage or reduce local consumerism. Amaral et al. (2021) found that highly urbanized municipalities that demand more resources such as food, energy and water benefit from a better quality of life for their population, when compared to those that simply provide natural resources. São Caetano do Sul, for example, is highly urbanized and very dependent on the importation of FEW resources, but at the same time it is considered one of the most important municipalities in Brazil in terms of human development index. Unlike the municipality of Natividade, provider of ecosystem services with a small population and a very low HDI.

This extends to the municipalities that occupy the first four positions of the hierarchy set out from the three forms of classification and quantification of the cube model. The municipalities of Santos, São Caetano do Sul, São Paulo and Diadema are highly dependent on resources from other areas: there is no local food production and water collection, or even energy generation. As a result of this assessment, the municipality of Santos shows an ideal performance, located in a security region and in a stable condition; although there is space to increase its FEW vector from actual 0.80–1.14 (the point ‘x’ in Figs. 4 and 5). The municipalities of São Caetano do Sul, São Paulo and Diadema require efforts related to increase water consumption in order to move the water FEW flow from the insecurity region to the security region.

### 3.2. Main outcomes from the FEW nexus cube model applied to Santos municipality

The detailed application of the proposed model considers the municipality of Santos as a case study, but any other municipality is a potential candidate to be evaluated in future works. Table 3 presents the results for the FEW flows from Santos. The groups provided by IBGE (2020) were adapted to the food groups proposed by the Food and Agriculture Organization (FAO, 2017), understanding that this standardized approach can be used in studies of the nexus in other regions of the world. The indicators obtained for the food FEW flow are 2.15E+ 07 $m^3H_2O_{eq}$./yr, 1.30E+ 09 $MJ_{fossil\text{-}eq}$./yr, and 5.19E+ 08 $kgCO_{2\text{-}eq}$./yr. For the energy FEW flow, the indicators are 2.64E+ 06 $m^3H_2O_{eq}$./year, 1.93E+ 10 $MJ_{fossil\text{-}eq}$./year and 1.51E+ 08 $kgCO_{2\text{-}eq}$./year. Similarly, the water FEW flow obtained 7.32E+ 07 $m^3H_2O_{eq}$./year, 1.74E+ 08 $MJ_{fossil\text{-}eq}$./year and 1.67E+ 07 $kgCO_{2\text{-}eq}$./year.

By comparing the indicators in Table 3 there is a high amount of direct and indirect water used throughout the water processes, considering its entire life cycle up to the final consumer in the municipality of Santos. The value of 7.32E+ 07 $m^3H_2O_{eq}$./yr is approximately 3.4 times greater than the consumption of water for food production, and 28 times greater than the use of water for energy generation. Even though it is not directly perceived in the water itself, a lot of water is used indirectly in the catchment, making it an imperative condition to be considered in future development plans for the municipality of Santos. In other words,

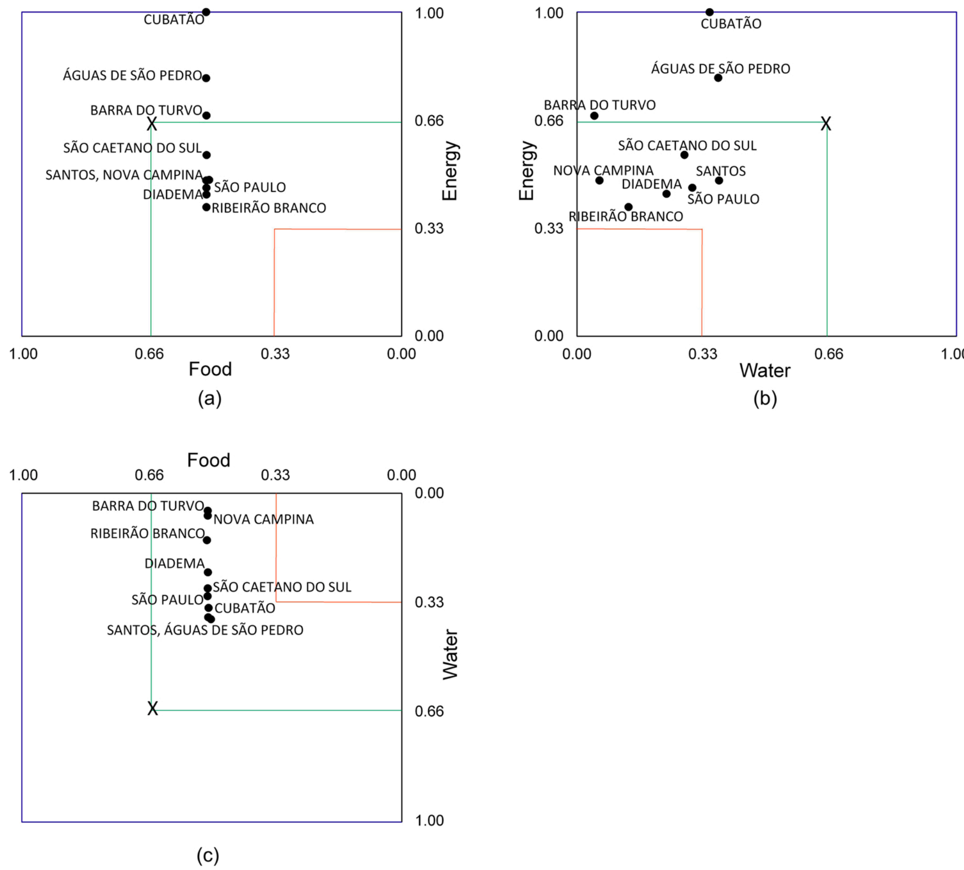


**Fig. 5.** Orthogonal projections of the cube model in Fig. 4 for the 9 municipalities studied. (a) food-energy interface (F-E); (b) energy-water (E-W) interface; (c) food-water interface (F-W). The 'x' indicates the best performance target. Data refers to 2018.

**Table 2**
Final classification of municipalities evaluated according to the FEW nexus cube model. Data refers to 2018.

| Rank | Municipalities | Individual FEW Flows | | | Integrated classification | | | HDI[a] |
|---|---|---|---|---|---|---|---|---|
| | | Food | Energy | Water | Region | Limiting factor | Vector Length | |
| 1st | Santos | Security | Security | Security | Security | Stable | 0.80 | 0.840 |
| 2nd | São Caetano do Sul | Security | Security | Insecurity | Security | Semi-stable | 0.81 | 0.862 |
| 3rd | São Paulo | Security | Security | Insecurity | Security | Semi-stable | 0.75 | 0.805 |
| 4th | Diadema | Security | Security | Insecurity | Security | Semi-stable | 0.71 | 0.757 |
| 5th | Nova Campina | Security | Security | Insecurity | Security | Semi-stable | 0.70 | 0.651 |
| 6th | Ribeirão Branco | Security | Security | Insecurity | Security | Semi-stable | 0.66 | 0.639 |
| 7th | Barra do Turvo | Security | Luxury | Insecurity | Luxury | Semi-stable | 0.85 | 0.641 |
| 8th | Águas de São Pedro | Security | Luxury | Security | Luxury | Semi-stable | 1.02 | 0.854 |
| 9th | Cubatão | Security | Luxury | Security | Luxury | Semi-stable | 1.18 | 0.737 |

[a] Source: IBGE (2018).

focusing on the direct and indirect water consumption indicator, the water FEW flow should be prioritized, as it is the biggest consumer of this resource.

The incorporated fossil energy indicator proved to be significant in the energy FEW flow, whose value of 1.93E+ 10 $MJ_{fossil\text{-}eq\text{.}}$/yr is approximately 15 times higher than the energy indicator for the food flow, and approximately 110 times higher than that found for the water FEW flow (1.74E+08 $MJ_{fossil\text{-}eq\text{.}}$/yr). Thus, focusing on the incorporated energy indicator, the energy FEW flow should be prioritized in public policies. The global warming potential (GWP) indicates that the food FEW flow is the most impactful, with a GWP of 5.19E+ 08 $kgCO_{2\text{-}eq\text{.}}$/yr. This result is 31 times greater than that obtained by the water FEW flow and 3 times greater than that obtained by the energy FEW flow. The food FEW flow should be a priority in planning when it comes to reducing the GWP.

Fig. 6 presents the radar diagram with the normalized results from Table 3. The reduction in the food consumption (perhaps combined with lifestyle) should be prioritized when related to global warming potential, since the food FEW flow is, comparatively, what most cause global warming. Regarding the energy FEW flow, the fossil energy indicator appears as the most impacting one, and the embodied water shows highest impact for the water FEW flow. Results shown that actions are needed for all three FEW flows to increase the resilience of the Santos municipality, with special attention to food FEW flow.

As presented before, the food (1.04E+06 kcal/person yr; 0.51), energy (9.12E+03 kWh/person yr; 0.48) and water (1.67E+05 L/person yr; 0.38) flows to Santos are in a security region of the cube model. Classifying the nexus between FEW flows in an integrated way, the FEW vector obtained for the municipality in 2018 is in the region known as security. SDG11, Sustainable Cities and Communities, set out as a goal

**Table 3**
Demand on FEW resources by Santos municipality in 2018.

| FEW flows and their items | Consume | Unity/ year | Annual indicators of FEW flows | | |
|---|---|---|---|---|---|
| | | | $m^3H_2O_{eq.}$ | $MJ_{fos.-eq.}$ | $kgCO_{2-eq.}$ |
| Food FEW flow[a] | | | 2.15E+ 07 | 1.30E+ 09 | 5.19E+ 08 |
| Cereals | 1.57E+ 07 | kg | 5.44E+ 06 | 9.26E+ 07 | 2.00E+ 07 |
| Meat | 1.42E+ 07 | kg | 5.09E+ 06 | 2.01E+ 08 | 2.67E+ 08 |
| Fruits and vegetables | 1.17E+ 07 | kg | 3.82E+ 06 | 8.04E+ 07 | 1.52E+ 07 |
| Fish | 5.92E+ 05 | kg | 9.08E+ 02 | 2.10E+ 07 | 1.69E+ 06 |
| Dairy | 1.66E+ 07 | kg | 2.13E+ 06 | 5.06E+ 08 | 1.33E+ 08 |
| Legumes | 1.14E+ 07 | kg | 3.07E+ 05 | 1.50E+ 08 | 2.13E+ 07 |
| Roots and tubers | 1.08E+ 07 | kg | 7.76E+ 05 | 2.95E+ 07 | 3.77E+ 06 |
| Sugars | 2.66E+ 07 | kg | 3.72E+ 06 | 1.39E+ 08 | 2.78E+ 07 |
| Vegetable oils | 3.12E+ 06 | kg | 2.34E+ 05 | 7.77E+ 07 | 2.95E+ 07 |
| Energy FEW flow | | | 2.64E+ 06 | 1.93E+ 10 | 1.51E+ 08 |
| Electricity (BR) | 1.39E+ 06 | MWh | 1.35E+ 00 | 1.00E+ 09 | 8.23E+ 02 |
| Natural gas | 1.40E+ 07 | $m^3$ | 5.28E+ 03 | 1.13E+ 09 | 8.98E+ 06 |
| Ethanol | 5.81E+ 07 | L | 2.32E+ 06 | 1.51E+ 08 | 3.38E+ 07 |
| Oil derivates | 1.74E+ 05 | toe[b] | 3.15E+ 05 | 1.70E+ 10 | 1.08E+ 08 |
| Coal | 0.00E+ 00 | kg | 0.00E+ 00 | 0.00E+ 00 | 0.00E+ 00 |
| Water FEW flow | | | 7.32E+ 07 | 1.74E+ 08 | 1.67E+ 07 |
| Water | 7.22E+ 10 | L | 7.32E+ 07 | 1.74E+ 08 | 1.67E+ 07 |

[a] IBGE (2020);
[b] tonne of oil equivalent.

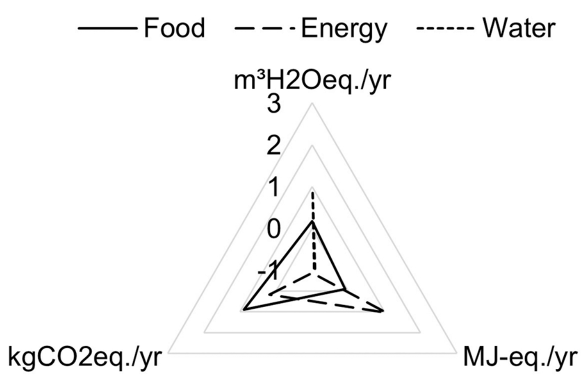


**Fig. 6.** Graphic representation of FEW flows performance indicators for Santos in 2018. Data from Table 3 normalized.

for sustainable development (SDG; UN, 2020) seeking to make cities and human settlements inclusive, safe, resilient and sustainable. Among the studies that used sustainability approaches to characterize the FEW nexus, few of them relate or use the SDGs as a conceptual guide. For example, Yuan et al. (2021) considered the sub-indicators present in each SDG that would be directly related to the FEW nexus, while Mohtar (2016) emphasizes that, besides SDG11, the FEW studies also covers SDG2, SDG6 and SDG7. However, additional studies are needed to assess what SDGs are strongly related to FEW nexus studies. Ensuring access to housing and basic services are goals of the SDG11, as well as reducing the per capita negative environmental impact of cities, including paying special attention to air quality and municipal waste management. Some of these characteristics are related to FEW resources and the results obtained in this work. Santos, highly urbanized, has characteristics of consumption of food, energy and water that place it in a security region under stable condition.

### *3.3. Public policies suggestions*

The two evaluation approaches considered in this work (radar graph and cube) provide essential aspects for decision making. Verifying the existing relationships among the three FEW flows using the cube model allows to characterize the studied cities by their level of internal consumption on FEW flows as well by the classification resulting from the cube. The desired result is obtained when there is a consumption balance among the three FEW flows, which leads to a security region and stable condition. However, the following general recommendations are provided for those cases with asymmetrical FEW flows consumption levels:

a) Leaving the insecurity region without worrying about the balance between FEW flows (limiting factor) at that time. This is a 'quick win' public policy.
b) If the vector is not in the insecurity region and none of FEW flows are in this region, then action should be applied on FEW flows to leave the luxury region and go to the security region. Initially, it seeks to act on that FEW flow, which will result in greater stability, and then on the other flows gradually. This is a 'best buy' public policy.
c) Pursuing the security region and with stable condition. This is a 'game-changer' public policy.

Although these are general suggestions to guide public policies, it is recognized that more specific ones can be provided for each case study. The use of the triangular radar diagram can be used as an important tool to indicate which variable (direct or indirect) is affecting the level of utilization of a given FEW flow. It is necessary to highlight that is not enough to act on only one FEW flow, because other factors (and their interaction) can still be considered in the final assessment to suggest public policies, including the means of transport used, improvements in housing conditions, enhanced health and well-being, digital infrastructure, and electronic services, in addition to better governance of the city and protection of natural resources. As an example, water management is dependent on the efficient use of energy and food, while the type of transport is related to energy consumption and $CO_2$ emissions. It is not intended to exhaust the subject here as it is well known that the most efficient way of proposing public policies is through participatory meetings (Smith et al., 2010) with decision makers and stakeholders, in which the applicability of alternatives is discussed so that collective efforts are able to put the suggestions into practice.

## 4. Simplicity-complexity analysis

Dargin et al. (2019) developed an index that verifies the complexity or simplicity of the metrics available in the literature, addressing 8 criteria that support the selection/choice of the appropriate tool (Supplementary Material D). Complexity subjectively depends on data availability, accessibility, user history, goals and time constraints. The index ranges on a scale of 5–19, where the highest index value correlates to a more complex tool. After analyzing the proposed cube model by the tool proposed by Dargin et al. (2019), a score equal to 7 was obtained, indicating that the cube model has a low level of complexity. This can be considered positive because, in addition to its scientific importance, perhaps the most imperative thing is the results obtained by applying the cube model used in practice to support public policies. It is known that the vast majority of decision makers do not have a scientific profile, so the reduced complexity of the cube model would be an advantage. Comparatively, Dargin et al. (2019) obtained a complexity index of 16 for the WEAP-LEAP Integrated Model tool, 15.5 for CLEWS, 15 for MuSIASEM, 6 for the World Bank Climate and Disaster Risk Screening Tools, and 8 for WEF Nexus Rapid Appraisal.

While more complex tools often allow for more detailed analysis and include more advanced features to accommodate scenario development, this comes at the cost of restricting the analysis to certain sub-nexuses (binomial relationships such as water-energy) and increases the need for more data and highly skilled users to understand the food-energy-water relationship. The proposed cube model corroborates the thinking of integrated policies, providing multi-sector solutions, which in accordance with Yillia (2016) and Märker et al. (2018) have been a barrier to decision-making, mainly due to the current management model in 'silos'.

Comparatively, the cube used as a geometric figure has an advantage over other models available in the literature as it graphically shows different performance regions of the FEW nexus of the evaluated municipalities, providing information in a fast and easy-to-understand manner. Additionally, the procedures for evaluating the FEW nexus through the cube model have been standardized so that it can be used in several cities around the world. However, it still needs a considerable amount of data on food, energy and water consumption, including the amount consumed and the type of resource used. Anyway, the proposal of the model has been achieved, and with the availability of more robust databases in the future, its applicability will also become easier.

## 5. Limitations of the proposed FEW nexus cube model

Even with all of its advantages, which include easy use and interpretation, quantitative integration of the FEW nexus, the fact that it can be used to support public policies, and the fact that it is applied on small scales (for municipalities) which other tools find difficult to achieve, the proposed model still has some limitations which require future efforts to overcome.

Initially it can be said that the cube thresholds were obtained from country data, so they may change over the years. Thus, analyses and discussions become comparative between the considered sample, and analyses from different years must be done carefully; this is also discussed by Sporchia et al. (2021) when making over time comparisons of European countries sustainability. It is known that from year to year the variation in consumption of FEW flows is not so high, but depending on the case study, these variations can be significant. Another limitation identified was the data collection for the food FEW flow, as specifically for the Brazilian case, data was only available at a regional scale instead of at a municipal level. This may be a problem unique to existing databases in Brazil, anyway, the findings of this study can be revisited as soon as more specific data is available.

Regarding the interpretation of results and suggestions for public policies, a municipality that achieves the maximum value does not necessarily mean that it needs actions to reduce the consumption of some FEW flows. For example, even though Cubatão is the municipality with the highest energy consumption, this is a characteristic of the municipality that perhaps should not be changed, as its function is to have essential industries for the development of other Brazilian municipalities. Thus, depending on the objectives of the study, maybe it is recommended to make comparisons between municipalities that have the same pattern of development and characteristics, rather than comparing the larger and different samples without clustering them.

Finally, a validation analysis was not performed at this point because the proposed model is innovative and there are no references (data and/or benchmarks) available in the scientific literature for comparisons. Probably, with the advance of FEW nexus studies and model proposals, larger amount of data would become available, and a validation of the cube model can be implemented.

## 6. Concluding remarks

The use of the proposed cube model is imperative to graphically indicate different performance regions of the FEW nexus, providing quick and easy-to-interpret information about the quantitative and integrated performance of FEW flows and their nexus (represented by the FEW vector). These characteristics are an advance in relation to the evaluation methods available in the literature, which generally evaluate FEW flows separately and present very complex graphical relationships that are difficult to interpret by decision makers (such as the usual Sankey diagrams). The cube model overcomes (i) the lack of a quantitative and integrated assessment method, and (ii) the lack of a tool to assess the nexus in municipalities (small scales). With that being said, like any other tool, a complete database is needed to feed the model.

To assess the applicability of the proposed cube model, conclusions can be provided about the case studies, although emphasizing that the same number for food consumption were assumed for all the evaluated municipalities. Data shows that $CO2_{eq.}$ measured by the municipality of Santos is strongly related to the food FEW flow. Thus, the search for strategies to reduce the environmental load due to the direct consumption of food is essential. This can be achieved by reducing consumption, changing lifestyles, or replacing foods with others that put less pressure on the environment. In addition to the food FEW flow, the energy FEW flow also proved to be critical in terms of $CO2_{eq.}$ emissions, emphasizing that actions should be taken in order to reduce direct energy consumption in the municipality. Focusing on the direct and indirect demand for $m^3H_2O_{eq}$. and $MJ_{fossil\text{-}eq}$., actions to reduce water and energy FEW flows should be implemented, respectively.

The municipality of Santos presents a demand on resources for its development that classifies the food, energy and water nexus in the security region. Comparatively, the top 3 municipalities considered as a case study in this work are shown in the following hierarchy in relation to their respective FEW nexus: 1st place for Santos (security region, stable condition and 0.80 for its FEW vector), 2nd place for São Caetano do Sul (security, semi-stable condition, 0.81), and 3rd place for São Paulo (security, semi-stable condition, 0.75). Although recognizing the limitations of the case study comparative results due to restriction on raw data availability that feeds the cube model, this classification is important for municipalities to understand the reasons why they are performing poorly, providing crucial information on where to act (benchmarks) to improve their indicators.

After showing the potential of the proposed cube model in providing FEW diagnosis, effective public policies must be individually developed by the stakeholders of different spheres that operate in the municipality to achieve more resilient development patterns.

## CRediT authorship contribution statement

**A.P Clasen**: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **F. Agostinho:** Conceptualization, Project administration, Supervision, Writing – review & editing. **C. Teodosiu:** Supervision, Writing – review & editing. **C.M.V.B. Almeida:** Methodology, Writing – review & editing. **B.F. Giannetti:** Conceptualization, Formal analysis.

## 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. Food, Energy and Water consumption for the studied municipalities. Data refers to 2018

| FEW resources | Unity | Municipalities | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Santos | São Paulo | São Caetano do Sul | Cubatão | Diadema | Águas de São Pedro | Ribeirão Branco | Barra do Turvo | Nova Campina |
| Food | | | | | | | | | | |
| Cereals | kg/yr | 1.57E+ 07 | 4.43E+ 08 | 5.83E+ 06 | 4.72E+ 06 | 1.53E+ 07 | 1.23E+ 05 | 6.07E+ 05 | 2.80E+ 05 | 3.51E+ 05 |
| Meat | kg/yr | 1.42E+ 07 | 4.00E+ 08 | 5.27E+ 06 | 4.26E+ 06 | 1.38E+ 07 | 1.11E+ 05 | 5.48E+ 05 | 2.53E+ 05 | 3.17E+ 05 |
| Fruits and vegetables | kg/yr | 1.17E+ 07 | 3.28E+ 08 | 4.32E+ 06 | 3.50E+ 06 | 1.13E+ 07 | 9.11E+ 04 | 4.50E+ 05 | 2.07E+ 05 | 2.60E+ 05 |
| Fish | kg/yr | 5.92E+ 05 | 1.66E+ 07 | 2.19E+ 05 | 1.77E+ 05 | 5.75E+ 05 | 4.62E+ 03 | 2.28E+ 04 | 1.05E+ 04 | 1.32E+ 04 |
| Dairy | kg/yr | 1.66E+ 07 | 4.68E+ 08 | 6.16E+ 06 | 4.99E+ 06 | 1.62E+ 07 | 1.30E+ 05 | 6.41E+ 05 | 2.96E+ 05 | 3.71E+ 05 |
| Legumes | kg/yr | 1.14E+ 07 | 3.20E+ 08 | 4.21E+ 06 | 3.41E+ 06 | 1.10E+ 07 | 8.87E+ 04 | 4.38E+ 05 | 2.02E+ 05 | 2.53E+ 05 |
| Roots and tubers | kg/yr | 1.08E+ 07 | 3.05E+ 08 | 4.01E+ 06 | 3.25E+ 06 | 1.05E+ 07 | 8.45E+ 04 | 4.17E+ 05 | 1.92E+ 05 | 2.41E+ 05 |
| Sugars | kg/yr | 2.66E+ 07 | 7.48E+ 08 | 9.84E+ 06 | 7.97E+ 06 | 2.59E+ 07 | 2.08E+ 05 | 1.02E+ 06 | 4.72E+ 05 | 5.92E+ 05 |
| Vegetable oils | kg/yr | 3.12E+ 06 | 8.76E+ 07 | 1.15E+ 06 | 9.34E+ 05 | 3.03E+ 06 | 2.43E+ 04 | 1.20E+ 05 | 5.53E+ 04 | 6.94E+ 04 |
| Energy | | | | | | | | | | |
| Electricity (BR) | MWh/yr | 1.39E+ 06 | 2.72E+ 07 | 7.75E+ 05 | 2.35E+ 06 | 1.07E+ 06 | 1.52E+ 04 | 1.64E+ 04 | 6.53E+ 03 | 2.40E+ 04 |
| Electricity (GLO) | MWh/yr | | | | | | | | | |
| Natural gas | $m^3$ /yr | 1.40E+ 07 | 1.04E+ 09 | 2.97E+ 07 | 3.80E+ 08 | 2.67E+ 07 | | | | |
| Ethanol | L/yr | 5.81E+ 07 | 2.20E+ 09 | 4.32E+ 07 | 5.53E+ 06 | 6.90E+ 07 | 4.31E+ 06 | 1.45E+ 06 | 1.17E+ 06 | 2.50E+ 04 |
| Oil derivates | toe[1]/yr | 1.74E+ 05 | 3.82E+ 06 | 5.52E+ 04 | 1.81E+ 05 | 1.05E+ 05 | 6.02E+ 03 | 5.46E+ 03 | 1.20E+ 04 | 5.18E+ 03 |
| Coal | kg/yr | | | | | | | | | |
| Water | | | | | | | | | | |
| Water | L/yr | 7.22E+ 10 | 1.45E+ 12 | 1.79E+ 10 | 1.84E+ 10 | 4.05E+ 10 | 5.68E+ 08 | 1.01E+ 09 | 2.21E+ 08 | 3.15E+ 08 |
| Population (2018) | Inhab. | 4.33E+ 05 | 1.22E+ 07 | 1.60E+ 05 | 1.30E+ 05 | 4.21E+ 05 | 3.38E+ 03 | 1.67E+ 04 | 7.69E+ 03 | 9.65E+ 03 |
| Food | kcal/ person day | 2836.01 | 2836.01 | 2836.01 | 2836.01 | 2836.01 | 2836.01 | 2836.01 | 2836.01 | 2836.01 |

Source: Food consumption: IBGE (2020); Energy consumption: Government of São Paulo (2020); Water consumption: ANA (2015); Population: IBGE (2018).
Note: [1]tonne of oil equivalent.

## Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.06.013.

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