Proceedings of the 34th European Modeling & Simulation Symposium, 034
19th International Multidisciplinary Modeling & Simulation Multiconference

2724-0029 © 2022 The Authors.
doi: 10.46354/i3m.2022.emss.034

Structural comparison between two alternatives for a hydroelectric power plant building

J.Los-Santos Ortega[1]*, G. Anoz Varea[1], C. Gonzalez-Gonzalez, J. Ferreiro-Cabello[1] , E. Jimenez Macias[1]

[1]University of La Rioja, Luis de Ulloa 4, Logroño (La Rioja), 26004, Spain

*Corresponding author. Email address: jorge.los-santos@alum.unirioja.es

Abstract

This paper deals with the design and modelling of a hydroelectric power plant building, considering the most general characteristics that this type of building should include, such as bridge cranes, space for the repair of a turbogenerator set, etc.,. Once its dimensions are determined, this problem is solved by means of two structures that use different structural materials. The main contribution of this paper is to obtain a detailed comparison between both alternatives as well as the methodology to apply this simulation to any other hydroelectric power plant. The first one is a model building with a metal structure. The second alternative would be to design the plant with a reinforced concrete structure. In both alternatives, strength and safety calculations are justified in the face of environmental actions such as those identified by other elements, thus ensuring the structural integrity of the power plant. Subsequently, an analysis is carried out of the results obtained in terms of both economic and environmental criteria, the latter by means of a Life Cycle Analysis (LCA). The implementation of one alternative over the other represents a difference of 10.65% of the budget. In the life cycle analysis comparison, there are greater differences in terms of impacts, with values ranging from 17.47% in some indicators to 35.15% in others.

Keywords: Modelling structures, Reinforced concrete, Structural steel, Economic analysis, Global warming potential, Non-renewable primary energy use.

1. Introduction

Spain's national energy scenario shows that renewable energies are booming in terms of the creation of energy production facilities. As a result of this, a need is observed to create infrastructures that increase the national installed power, hence the work "Calculation and design of a hydraulic turbine for the Enciso dam (La Rioja)", which is a detailed study of the hydroelectric use of a recently built civil infrastructure such as the Enciso dam (La Rioja). This work responds to the need to create and model an industrial building that allows for the correct operation of the hydroelectric power plant. The calculation and design of the turbine building of Enciso Dam is modelled through two alternatives using two different structural materials, steel and concrete. This research aims to provide a comparison of the two alternatives, not only economically but also environmentally through a life cycle analysis. The assessment of their impacts should not be neglected, as they are becoming increasingly relevant (MTMAU, 2021) and may, in the future, become an equally important factor as the economic one.

After this introduction section 2 presents a state of the art, section 3 analyzes the materials and methods used in this case-study and the associated methodology, section 4 includes the Results and Discussion, and section 5 shows the conclusions.

2. State of the art

Today's construction sector is a major consumer of energy and resources. Linked to this is the fact that it is an activity that generates major impacts on the environment, such as the consumption of raw materials, the generation of waste, the consumption of drinking water and the emission of greenhouse gases (Filho et al., 2022) (Fraile-Garcia et al., 2015, 2016a, 2016b, 2018). For all these reasons, efforts are being made to ensure that new projects adhere to the concept of sustainable construction, which seeks efficiency in the use of natural resources through their management and reuse, thus achieving more sustainable buildings.

An increasing number of studies apply life cycle assessment methodology to assess the impact of a new building or to prioritise between different building renovation strategies. Among the different assumptions to be considered during the application of this methodology, the selection of the impact indicator is crucial, as this choice will change the interpretation of the results entirely (Oregi et al., 2020). The application of economic and sustainable concepts is common in infrastructure projects, such as wastewater treatment plants (Zhang & Ma, 2020) (Pryce et al., 2021)(Cabello et al., 2015) and railway installations (de Bortoli et al., 2020). The Life Cycle Assessment (LCA) method has been used to quantify and compare the cradle-to-gate environmental impact of different systems for the retrofitting of building floors. (Demertzi et al., 2020). The same methodology has been used to assess steel structures using cold-formed steel (CFS). Highlighting as representative the indicators of global warming potential (GWP) and primary and non-renewable energy consumption (EP) in the production stage (Abouhamad & Abu-Hamd, 2020).

3. Materials and Methods

A preliminary summary of the most relevant features of modelling is given. The definition of both alternatives for the hydroelectric power plant building responds to common basic needs. These needs determine the space required for the building (Table 1) in order to obtain approximate floor plan dimensions for the subsequent design of these alternatives.

Table 1. Spaces and surfaces necessary for the building

Area/Space	Surface (m^2)
Machinery room	180
Maintenance room	9
Toilet/Changing room	9
Control room	18

In the end, the floor plan dimensions were 21m long by 10m wide, which represents a surface area of 210 m2. Another fundamental need in industrial buildings of this type is the installation of an overhead crane that allows for the lifting and movement of the generator sets during maintenance work, repairs, etc. It has been estimated that a type of overhead crane with a capacity of 10 tonnes is necessary, and within the topology of existing overhead cranes on the market, the one that best adapts to these spans between pillars is a monorail overhead crane. It should be noted that this structural element is not included in the comparisons that have been made.

Alternative 1: Metal Structure

In this alternative, the hydroelectric power plant building is determined by means of a series of portal frames made of S275 steel sections. These proposed porticoes are gabled with a slope inclination of 22º. A bowstring truss with eight intermediate spans was chosen for the roof. The modelling of the portal frame can be seen in Figure 1.

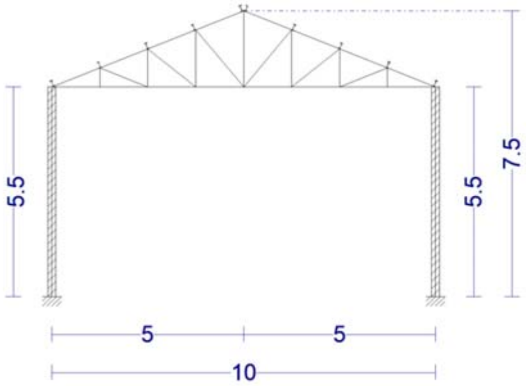

Figure 1. Generic porch of the hydroelectric power plant (measured in metres)

For the structural analysis, the loads were calculated according to the regulations of the Technical Building Code in its Basic Document on Structural Safety - Actions in Building (CTE-DB-SE-AE) and were introduced into the CYPE 3D structural calculation programme to delimit the rest of the remaining elements (purlins, columns, slabs, rail beam, etc.). The profiles used for each element are shown in Table 2.

Table 2. Employee profiles 1st Alternative

Structural Element	Profile Type
Lintels	IPE 180
Truss	IPE 100
Purlins	IPE 160
Portal Pillars 1,2,5	IPE 240
Portal Pillars 3,4 overhead crane	IPE 300
Control room structure	IPE 160

The foundation design is based on square insulated footings connected by tie beams. The material used, as well as its characteristics and the definition of the type of environment, is as follows: HA-25/P/30/IIa with B500S steel reinforcing bars. Figure 2 shows a 3D rendering of the 1st Alternative designed.

Figure 2. 3D Representation of the 1st Alternative

Alternative 2: Reinforced concrete structure

We start with the same floor plan dimensions, as well as the same needs that the building must meet. Here, the material used for the modelling of this alternative consists of reinforced concrete instead of the use of metal sections. The CYPECAD programme is used for its calculation and modelling. The material used is HA-25/P/15/IIa reinforced concrete for both structural elements and foundations. The reinforcement is made with B500S steel bars. The building has a total of 18 columns. The defined column cross-section is quadrangular and there are two different types of columns: 30cm x 30cm and 40cm x 40cm.

As for the beams that connect the columns to each other, there are different types. In the case of the first floor, a flat square beam of 30cm x 30cm is used. And for the rest of the beams that make up the building (beams that join the overhead crane pillars and the roof beams), they are executed using the 30cm x 45cm and 40cm x 70cm rectangular beams. The next modelling element will be the slabs of the first floor (control room) and the roof. The former has been defined by means of a reinforced concrete joist slab, see table 3 for design parameters. In the case of the roof slab, it is designed using hollow core slabs (Table 4).

Table 3. Floor dimensions of concrete joists

Concrete joist slab	
Polystyrene Edge Vault	25cm
Compression layer	5cm
Interaxis distance	72cm
Rib width	12cm

Table 4. Roof slab dimensions

Hollow core slab	
Total slab edge	45cm
Width of slab	120cm
Thickness of compression layer	5cm

Once the building structure has been defined, the foundations must be built. Like alternative 1, it is made of reinforced concrete defined as HA-25/P/15/IIa and reinforced with B500S steel bars. The solution consists of square insulated footings connected by 40cm x 40cm tie beams. Table 5 shows some of the footing dimensions of the foundation.

Table 5. Dimensions of the foundation slab

Dimensions
285x285x60cm
240x240x55cm
225x225x50cm

A 3D representation of the modelling of the second alternative can be seen in Figure 3.

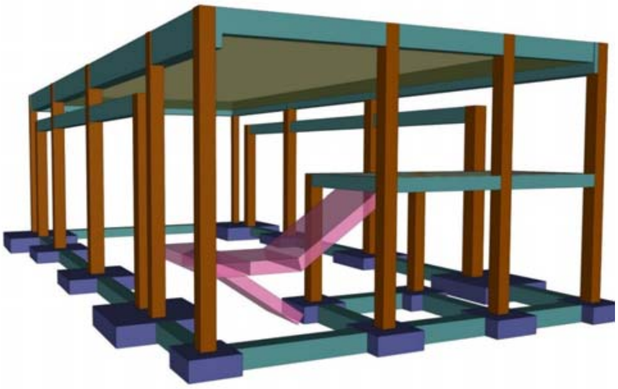

Figure 3. 3D Representation of the 2nd Alternative

Once both alternatives have been defined, the methodology of the comparative study is explained. The first of these deals with methodology at the economic level. In this case, a budget was drawn up for each alternative using the Archimedes software with the items referring to the foundations, slabs, pillars, roof, etc. These were obtained from the structural calculation programmes CYPE3D and CYPECAD. In addition to this, the stationary values of percentages influencing the budget, such as overheads, industrial profit and VAT, were fixed. Finally, the contract execution budgets for each alternative were determined in order to compare them in absolute terms as to how much one increases or decreases with respect to the other.

The budget has been divided into chapters. The names of these chapters are foundations, structure, façades and partitions, and installations. Only the foundation and structure chapters have been used for the comparative analysis. The remaining chapters are common to both alternatives.

The following comparison, as indicated above, is to determine the environmental impact that may arise from the implementation of one alternative or the other. For this purpose, the Life Cycle Assessment (LCA) methodology is used, which is a tool that studies the evaluation of the environmental impact of a product or service during its life cycle. In this research, of all the stages that make up the LCA according to the UNE-EN ISO 14040 standard, only those referring to the production process of the product and its construction process will be studied, as they are considered to be the most relevant for this type of building. Because it is at these stages that the greatest impacts may occur. Table 6 shows the defined nomenclature and the activities that fall under each stage.

Table 6. Definition of the processes of each stage

LCA Stage	Process/Activity
Product Stage (A1-A3)	Extraction of Raw Materials (A1)
	Transport to Factory (A2)
	Manufacturing (A3)
Construction Process Stage (A4-A5)	Product Transport (A4)
	Product installation and construction process (A5)

Defined the scope of the stages of the LCA process. The environmental impact and resource use indicators to be assessed must be determined. Table 7 shows the usual indicators used in the LCA and the selected proxy indicators.

As shown in Table 7, the analysis has focused on the GWP showing the greenhouse gases produced by the various elements involved in the structure in their selected phases of the LCA. It is expressed in kg CO_2 equivalents. On the other hand, the indicator of total use of non-renewable primary energy (PERNRT) is selected. It evaluates the amount of energy from sources that are found in nature in limited quantities, such as coal, natural gas, oil etc. Its unit of measurement is the MJ.

Table 7. Environmental impact indicators and resource use

Environmental Impact Indicators	Indicator Assessed
Global Warming Potential (GWP)	✓
Stratospheric Ozone Depletion Potential (ODP)	✗
Acidification potential of soil and water resources (AP)	✗
Eutrophication Potential (EP)	✗
Tropospheric ozone formation potential (POCP)	✗
Abiotic Depletion Potential for Non-Fossil Resources (ADPE)	✗
Abiotic Depletion Potential for Fossil Resources (ADFP)	✗
Use of Resources	**Indicator Assessed**
Primary Energy Renewable Total (PERT)	✗
Primary Energy Non-Renewable Total (PERNRT)	✓
Net use of flowing water resources (FW)	✗

Once the methodology used in this research has been explained, we proceed to the interpretation and discussion of the results obtained.

4. Results and Discussion

The first results shown correspond to the first comparison. Table 8 shows the values obtained for the foundation and structure chapters.

Table 8. Economic comparison of modelled alternatives

Alternative	Contract Execution Budget
First Alternative	€182,252.46
Second Alternative	€162,842.70

As can be seen, the difference between the two budgets amounts to a total of 19,409.76€, an increase of 10.65%. In a real case of choice by the developer, alternative 2 would be selected due to reduced costs, however, in this research, we want to detail more indicative choices that can influence the decision making process.

The results of the environmental benchmarking are therefore interpreted. Table 9 shows the kg of CO_2 equivalents produced in each alternative, as well as their numerical values for each of the chapters studied and in the different LCA processes studied.

Table 9. Results of the GWP Environmental indicator (measured in kg of CO_2 equivalent)

Alternative	Chapter	Product (A1-A2-A3)	Transport (A4)	Construction (A5)
1^{a}	Foundations	11,335.96	191.1	2,300.92
	Structure	39,660.34	29.33	0.83
2^{a}	Foundations	8,519.85	150.56	2,267.03
	Structure	48,810.73	1,240.55	3,855.53

From Table 9, it can be noted that in both alternatives, higher values of kilograms of CO_2 equivalent emissions are being produced in the product forming processes or activities (A1-A2-A3), with much lower values of CO₂ emissions corresponding to the construction stage (A5) and transport (A4) respectively. This is because the activities involved in the product production stage require high amounts of energy in their processes, and this usually comes from non-renewable primary energy, which raises the CO₂ equivalent emission values, as shown in Table 9. This is reflected visually in Figure 4, where each vertical bar represents an alternative and where the kg CO₂ equivalent value representation of each of the activities that make up the LCA is shown.

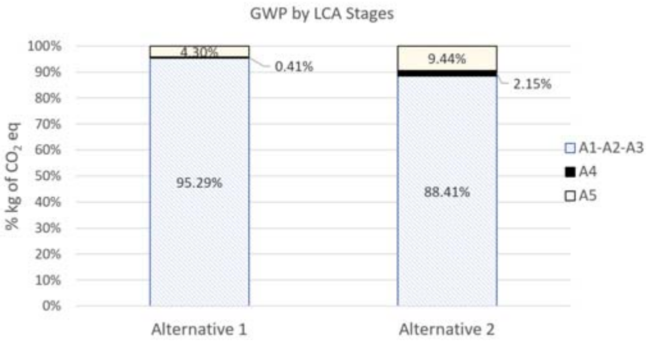

Figure 4. GWP comparative chart by stages of the LCA

The emissions produced globally for each chapter of each alternative are presented in the following graph (Figure 5). This provides an overall comparison of the two alternatives.

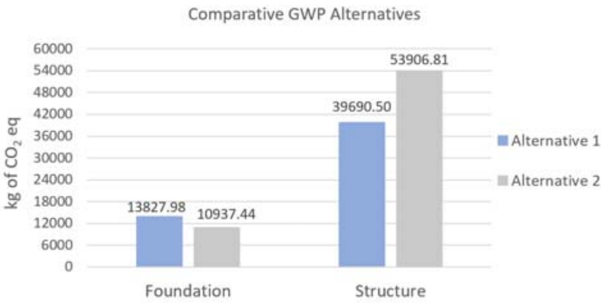

Figure 5. GWP comparative chart

If analysed first at the foundation level, Alternative 1 (Metal structure) indicates that it emits more kg CO₂ equivalents. This is due to the fact that when metal structures are generally used, the foundations are usually dimensionally larger than when a concrete structure is used. This means a higher requirement for concrete and steel to be used. Therefore, more kg of CO₂ equivalent emitted. However, on the other hand, the situation is reversed in the chapter on structures, with alternative 2 (reinforced concrete structure) emitting the most kg CO₂ equivalents. Justified by the use of metallic structures, in which the steel used is made of recycled steel in the manufacturing process. Therefore, the emissions released may be reduced. In total or absolute terms, Alternative 2 represents an emission of 64,844.25 kg of CO₂ equivalent compared to Alternative 1 of 53,518.48 kg of CO₂ equivalent. In percentage terms, this represents a significant increase of 17.47%.

The next indicator is the total non-renewable primary energy use. Table 10, as before, shows a breakdown of the values for each chapter and its stage of the LCA process.

Table 10. Results of the PERNRT resource usage indicator (measured in MJ)

Alternative	Chapter	Product (A1-A2-A3)	Transport (A4)	Construction (A5)
1[a]	Foundations	65,074.21	2,582.41	31,091.17
	Structure	295,992.35	13,909.82	5.73
2[a]	Foundations	51,453.99	2,034.63	30,634.53
	Structure	477,160.72	16,764.24	52,094.68

The use of non-renewable primary energy is directly linked to CO₂ emissions. The use of this type of energy is directly responsible for the creation of greenhouse gases. Consequently, the results obtained for PERNRT are consistent with the above values. Again, it can be seen that activity A1-A2-A3 involves a higher energy expenditure. In alternative 1, this type of activities, A1-A2-A3, accounts for 88.35% of the total energy use for the assessed stages, leaving 4.04% of the energy use for transport activities (A4) and 7.61% of the energy use for the construction process (A5).

In the case of alternative 2, its distribution in percentage of non-renewable energy use is 83.89% for product activities (A1-A2-A3), 2.98% for transport activities (A4) and finally 13.13% for construction (A5). Therefore, it is justified that the highest energy consumptions occur regardless of each alternative for the product forming stage, as shown in figure 6.

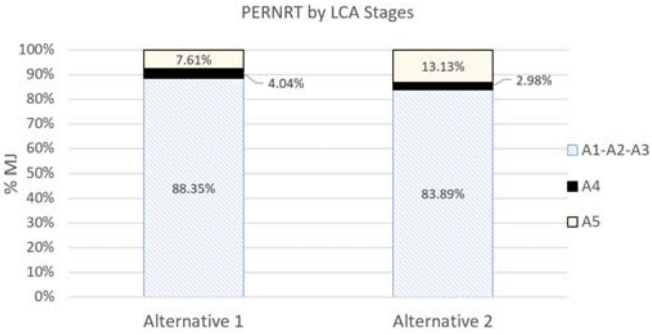

Figure 6. PERNRT percentages chart

In Figure 7, the non-renewable primary energy consumptions are shown for each chapter, irrespective of the LCA stages. n this way, both alternatives can be compared.

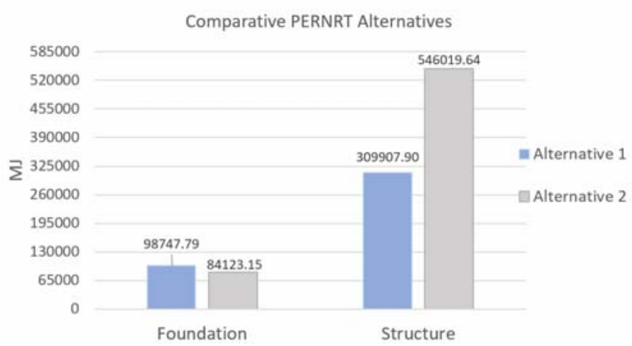

Figure 7. PERNRT comparative chart

It can be observed that the use of non-renewable primary energy for the foundation chapter is very similar in both alternatives due to the fact that the dimensions of the foundations, and consequently the amount of concrete and steel used, do not vary too much. A value of 14.81% non-renewable primary energy use is obtained with respect to alternative 2. On the other hand, in the structures chapter, we can once more observe an increase of 43.24% in the use of non-renewable primary energy in alternative 2 compared to alternative 1. Finally, the implementation in global terms of Alternative 2 would mean an increase of 35.15% in the indicator of non-renewable primary energy use with respect to the implementation of Alternative 1.

5. Conclusions

Once the results have been interpreted, it can be affirmed that the choice of implementation of one alternative to another for this type of infrastructure no longer depends solely on economic criteria, as is normal when choosing between different proposals. This is confirmed by this study, which shows a 10.65% difference between budgets. Furthermore, with the application of the life cycle analysis (LCA) methodology for the quantification of environmental impacts, it is found that the implementation of alternative 2 generates 17.47% kg CO_2 equivalents compared to alternative 1. In addition, the non-renewable primary energy use indicator increases by 35.15% for Alternative 2, compared to Alternative 1.

Furthermore, this research can be justified due to the current subject matter of the various European structural regulations that not only demand the compliance of the structure with resistance and deformation criteria but also the need to incorporate an analysis of the structure at an environmental level. This is reflected in the new Spanish structural code regulations, where chapter two of its general bases already indicates the contribution of the structure to sustainability, although this aspect is currently of a voluntary nature for the developer.

As a result, this research has shown that, although there are several alternatives for the execution of a project, it is not only necessary to stick to the budgetary level to select one, but that there are various environmental parameters which, in the future and with new construction legislation, may become even more important than economic factors. This will bring building projects closer to the concept of sustainable construction.

References

Abouhamad, M., & Abu-Hamd, M. (2020). Life Cycle Environmental Assessment of Light Steel Framed Buildings with Cement-Based Walls and Floors. Sustainability, 12(24), 10686. https://doi.org/10.3390/su122410686

Cabello, J. F., García, E. F., Cámara, E. M., & Macías, E. J. (2015). Analysis of thermal and acoustic performance in residential buildings with one way slab depending on the rib width and compression layer. Paper presented at the 3rd International Workshop on Simulation for Energy, Sustainable Development and Environment, SESDE 2015, P160-P165.

de Bortoli, A., Bouhaya, L., & Feraille, A. (2020). A life cycle model for high-speed rail infrastructure: environmental inventories and assessment of the Tours-Bordeaux railway in France. The International Journal of Life Cycle Assessment, 25(4), 814–830. https://doi.org/10.1007/s11367-019-01727-2

Demertzi, M., Silvestre, J., Garrido, M., Correia, J. R., Durão, V., & Proença, M. (2020). Life cycle assessment of alternative building floor rehabilitation systems. Structures, 26, 237–246. https://doi.org/10.1016/j.istruc.2020.03.060

Filho, M. V. A. P. M., da Costa, B. B. F., Najjar, M., Figueiredo, K. V., de Mendonça, M. B., & Haddad, A. N. (2022). Sustainability Assessment of a Low-Income Building: A BIM-LCSA-FAHP-Based Analysis. Buildings, 12(2), 181. https://doi.org/10.3390/buildings12020181

Fraile-Garcia, E., Ferreiro-Cabello, J., & Jimenez, E. (2018). Modeling and environmental assessment of structural solutions for a single-family home. Paper presented at the 30th European Modeling and Simulation Symposium, EMSS 2018, 331-335.

Fraile-García, E., Ferreiro-Cabello, J., Marrodán-Esparza, F. J., & Jiménez-Macías, E. (2016b). Building structure models. impact on cumulative energy demand and carbon footprint. Paper presented at the 4th International Workshop on Simulation for Energy, Sustainable Development and Environment, SESDE 2016, 63-68.

Fraile-Garcia, E., Ferreiro-Cabello, J., Martinez-Camara, E., & Jimenez-Macias, E. (2016). Optimization based on life cycle analysis for reinforced concrete structures with one-way slabs. Engineering Structures, 109, 126–138. https://doi.org/10.1016/j.engstruct.2015.12.001

Fraile-Garcia, E., Ferreiro-Cabello, J., Martinez-Camara, E., & Jimenez-Macias, E. (2015). Adaptation of methodology to select structural alternatives of one-way slab in residential building to the guidelines of the european committee for standardization (CEN/TC 350). Environmental Impact Assessment Review, 55, 144-155. doi:10.1016/j.eiar.2015.08.004

MTMAU *Ministerio de Transportes Movilidad y Agenda Urbana. (2021). Código Estructural. In Boletín Oficial del Estado*; Translated as Ministry of Transport, Mobility and Urban Agenda. (2021). Structural Code. In Official State Gazette (Issue 190, pp. 97664–99452).

Oregi, X., Hernández, R. J., & Hernandez, P. (2020). Environmental and Economic Prioritization of Building Energy Refurbishment Strategies with Life-Cycle Approach. Sustainability, 12(9), 3914. https://doi.org/10.3390/su12093914

Pryce, D., Memon, F. A., & Kapelan, Z. (2021). Life cycle analysis approach to comparing environmental impacts of alternative materials used in the construction of small wastewater treatment plants. Environmental Advances, 4, 100065. https://doi.org/10.1016/j.envadv.2021.100065

Zhang, J., & Ma, L. (2020). Environmental sustainability assessment of a new sewage treatment plant in china based on infrastructure construction and operation phases emergy analysis. Water (Switzerland), 12(2), 484. https://doi.org/10.3390/w12020484