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Research article

The environmental impacts of face-to-face and remote university classes during the COVID-19 pandemic

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A R T I C L E  I N F O

Article history:
Received 18 February 2021
Revised 4 May 2021
Accepted 4 May 2021
Available online 9 May 2021

Editor: Dr. Raymond Tan

Keywords:
Life cycle management
Comparative LCA
Digital impacts

A B S T R A C T

The face-to-face university classes were abruptly transferred to virtual environments during the pandemic of COVID-19, which generated changes in teaching routine and environmental impacts associated with them. Considering this reality, studies comparing the environmental impacts of face-to-face and remote classes can be of great value. In this sense, this study performed a Life Cycle Assessment (LCA) of face-to-face and remote university classes in a Higher Education institution in the context of COVID-19. Inputs of energy and materials (food, office materials), outputs (air and water emissions, and solid waste) were gathered in situ for the functional unit of 2 hours of face-to-face or virtual class per week for 60 engineering students. Thirteen midpoint impact categories were selected by using the recent Impact World+ midpoint method for Continental Latin America, version 1.251. In the literature, most papers about the environmental management of educational activities focus on the energy efficiency of buildings and electronic equipment during their use. But this study revealed other environmental hotspots primarily associated with meal consumption followed by ethanol fuel use. Meal consumption patterns can be explained by the fact that people usually eat more often during home-office activities. Otherwise, the transportation impacts due to ethanol use are related mainly to face-to-face classes, as much transport is required such as for food supply and student transportation. Finally, an uncertainty and a sensitivity analysis were designed for the LCA conclusions. We concluded that remote classes during the COVID-19 pandemic tend to minimize the overall evaluated impacts to ten of the thirteen impact categories. An optimal scenario was also proposed showing an overall minimization of the impacts by up to 57%, if a hybrid class model were to be adopted.

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1. Introduction

The year of 2020 was an atypical time in people's lives due to the consequences of the COVID-19 pandemic. At first, this moment was marked by human uncertainty about dealing with an unknown threat, over which it was not possible to have a reasonable level of control (Rubbini, 2020). Due to the high infection rates, social distancing of people was a measure applied worldwide. With this action, it was possible for countries to manage contamination rates and to avoid overloading health systems (Chadee et al., 2021; D'Angelo et al., 2021). Social distancing generated considerable and abrupt changes in the dynamics of people's lives (D'Angelo et al., 2021). In relation to the job market, some companies stopped their operations while others adopted Work From Home (WFH) (Kramer and Kramer, 2020). In the education sector, face-to-face classes were abruptly transferred to virtual environments, despite uncertainties regarding strategic, pedagogical and operational aspects during this transition (Moser et al., 2020).

Moser et al. (2020) and Sepulveda-Escobar and Morrison (2020) recognize the right decision taken by High Educational Institutions to safeguard the lives of professors, support staff and students, but they highlight that remote education during the pandemic should be considered a transitional phase, in which some correct and some misguided actions were taken. These misguided actions should be debated to improve the educational process. Re-
garding the challenges of educational transition, several difficulties were observed by students and professors (Mishra et al., 2020). Among these difficulties, students highlight that paying attention to the classes is harder in remote modality (Aristovnik et al., 2020), while professors complain about the lack of interaction with students (Mishra et al., 2020).

Focusing on the environment of large universities, there was a considerable change in their daily lives (Filimonau et al., 2020). In many universities tens of thousands of people circulated in their facilities every day, hundreds of classes were taught each period, several laboratories operated simultaneously, in addition to a basic structure of administrative services, cafeterias, bathrooms, cleaning services, transport services, and others, which supported educational operations. Especially with the issue of transport, it is worth remembering that many students traveled many kilometers from their homes to the colleges where they attended their classes daily. Such a displacement, whether by collective or individual transport, also carried an associated environmental impact which most of the time is unknown. Thus, even though many campuses adopted sustainable operating strategies, impacts on the environment could still be noticed in their daily operations. With the transition to remote initiatives, many of these activities have stopped occurring, such as the transportation of students to campus and supplying stock (office materials) and support services (building and IT maintenance). Other activities have been fragmented. For example, students’ meals have started to be consumed in their homes.

In this context, it is interesting to perform a comparative analysis between the environmental impacts caused by universities’ activities before the COVID-19 pandemic and the activities that are being performed remotely today. Of course, these impacts should be analyzed case by case, since the contextual specificities need to be considered, such as campus location, developed activities, students socio-economic profiles, etc. Interesting research was conducted by Filimonau et al. (2020), who studied the carbon footprint of a medium-sized English university before and after the lockdown caused by the COVID-19 pandemic. The carbon footprint reduced by almost 30% when comparing the periods before and during the lockdown. However, the authors highlighted the substantial increase in teaching activities, which have become remote, in the composition of the carbon footprint results.

Life Cycle Assessment (LCA) is a holistic approach to investigate the environmental impacts and trade-offs existing, for example, in a university campus operation (Sangwan et al., 2018; Shields, 2019). However, for Shields (2019), there is still little research in this field and more studies on the real environmental impacts provided by higher education operationalization are required. It is worth remembering that the guidelines for conducting the LCA are defined by ISO 14040 and 14044 (ISO, 2006a,2006b).

According to Oyedeo et al. (2020), every operation in a university campus generates considerable environmental impacts and they need to be measured in order to subsidize the search towards sustainability solutions. In their study, the authors also highlight the relevant environmental impact generated by university campuses due to their high level of energy consumption and that reducing this consumption generates environmental and financial gains. For Teshnizi et al. (2018), the understanding of the environmental impacts existing on a university campus can better subsidize projects of different types, such as administrative, research or educational projects. Mendoza et al. (2019), for example, debate in their study, possibilities of a circular economy project applied to the University of Manchester.

An interesting example of the use of LCA to verify the carbon footprint of a university campus was performed by Clabeaux et al. (2020). They analyzed Clemson University campus and generated useful information for the campus to become more sustainable. Another example of LCA applied in universities can be found in the study of Barros et al. (2020), in which authors analyzed sustainability practices implemented in a group of university campuses in Brazil through LCA. More specifically, the authors verified the impact of plastic cups substitution by reusable ones and confirmed via LCA that the change was positive for the environment. Focusing on administrative activities of a university, it is worth highlighting the study of Marques et al. (2019), that analyzed the impacts of information technology to better define plans towards sustainability.

Although the literature presents interesting studies about LCA of educational activities (Silva et al., 2015). In Silva et al. (2015), the authors conducted an LCA and material flow analysis of an university campus located in Barcelona, Spain, offering face-to-face classes. The results also highlighted the need to improve buildings’ energy efficiency to reduce the overall carbon footprint.

Shields (2019) assessed the environmental impacts of student mobility in higher education and found that emissions from this mobility have been increasing more than global emissions in general; however, when student emissions are analyzed, they are decreasing compared to past data. Evidently, the authors remember that these environmental impacts must be evaluated together with the benefits resulting from the student mobility process.

In the line of assessing the impacts on students’ training, it is worth mentioning the study by Parsons (2009) which, despite having been published in 2009, still presents results that can motivate interesting debates. In this study, the author assessed the environmental impacts on the training of graduate students from the University of Southern Queensland’s Faculty of Engineering and Surveying. It was found that energy inputs, employee travel and impacts embedded in buildings were the hotspots. It is also interesting to highlight that the author emphasizes the complexity of carrying out an analysis of this type.

However, most of the studies are focused on energy efficiency and materials consumption evaluations; other environmental aspects (e.g., food supply, office and cleaning consumables) and their impacts are less studied. According to Lo-Iacono-Ferreira et al. (2016), LCA on the activities of Higher Education institutions will only provide real results if data about their environmental management systems are reliable and available to be used.

The number of publications is lower when remote/online classes are involved. Also, there are still important gaps to be addressed by new research in this area. For example, most of the papers focus only on the energy consumption and efficiency of buildings (Ting et al., 2012; Fonseca et al. 2018, Gorgulu and Kokabey, 2020), not including the whole life cycle perspective of goods required. Considering this context, this article aims to carry out a comparative LCA between face-to-face and remote university classes located at the Sorocabá campus of the Federal University of São Carlos, São Paulo State, Brazil. That is, this research considers a product lifecycle perspective, providing a broader analysis of the compared contexts during the COVID-19 context. The evaluated product systems included energy demand as well as infrastructure and support activities and flows involved (transport for shopping and food supplying, water consumption and waste and emissions generations and management), as described in section 2.

2. Methodology

The LCA methodology was used in this paper and it can be divided into four stages (ISO 2006a,b): Goal and scope definition; Life cycle inventory analysis (LCI); Life cycle impact assessment (LCIA); and LCA interpretation, as detailed in the next paragraphs.

2.1. Unit of analysis and definition of goal and scope

The Federal University of São Carlos (UFSCar) has four campuses located in the following cities in São Paulo state, Brazil: São Car-

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los, Araras, Sorocaba, and Lagoa do Sino. This study assesses the life cycle of the classroom and virtual classes at the UFSCar, Sorocaba campus (Fig. 1). The selected university campus currently offers 14 undergraduate and 12 graduate programs, with a circulating population of 4,292 people/day (students, professors, and technical staff).

The goal was to evaluate and compare the environmental performance of face-to-face and remote classes. To this end, the unit of analysis was focused on the Production Engineering degree program offered by UFSCar Sorocaba campus before and during the pandemic COVID-19 period. This limitation to the Production Engineering course evaluation occurred due to the remote classes’ information and data required for the LCA study, provided only by the students and professors of this graduation course. The other courses of UFSCar did not participate in this research.

This research covers the cradle-to-grave life cycle of face-to-face and remote classes using an attributional LCA approach. All the inputs and outputs of materials, energy, waste and emissions required for a Production Engineering remote/face-to-face class, as well as the input and output flows of the background and end-of-life treatment processes, are shown in the system boundaries from Fig. 2. The system boundaries for the virtual (A) and face-to-face classes (B).

It is important to note that the Functional Unit (FU) was defined as 02 hours of classes/week for 60 students because this is the lowest teaching scheme adopted by the Production Engineering course at UFSCar, Sorocaba campus. In other words, the chosen FU is the minimum requirement of a class for the case studied.

The face-to-face class system was designed for a pre-COVID-19 context. Face-to-face classes take place at the campus, where the lecturer and students move to the class meetings. Usually, the sessions are given in conventional rooms that have as part of their infrastructure types of equipment that consume electrical energy, such as fans, projectors, notebook/computers, and LED lamps. Therefore, the consumption of storeroom materials also occurs. Generally, students stay at the campus for 5 hours a day and tend to have at least one meal at the university restaurant, besides consuming water at the location. Regarding solid waste management, they are sent to a municipal landfill at Sorocaba city (35.7 km), while recyclable waste follows a recycling local cooperative (18.6 km). Besides, liquid effluents are treated in a municipal sewage treatment station.

Remote system classes occurred through the 2020 period. Virtual class sessions were asynchronous and synchronous. For asynchronous classes, the professors recorded the content of the lesson and made them available to students on the VLE (Virtual Learning Environment) platform. On the other hand, synchronous sessions were live on the Google Meet® platform with both the Production Engineering students and teachers online using their personal computers. Assignments were made available and delivered to the VLE platform for academic evaluations and grading. As the students attended the classes at their homes, the solid and recyclable wastes were intended to their respective municipal landfills and recycling cooperatives, transported by vehicles of city halls. Also, the liquid effluents were treated in municipal sewage treatment stations in their cities and to 16% of the students in septic tank systems.

2.2. Life cycle inventory, data quality and assumptions

Table 1 summarizes the gate-to-gate inventory life cycle flows with quantities and standard deviations (SD) for both the systems. The Pedigree Matrix (Weidema et al., 2013) was adopted to complement the inventory in Table 2. This choice was made to allow an uncertainty analysis along section 3 for the LCA results. It is important to mention that the ecoinvent database also uses the Pedigree Matrix for the background and end-of-life processes adopted for this study.

Fig. 3 shows the selected processes used to represent the background and end-of-life processes of the face-to-face and remote classes. The openLCA version 1.10 was the software tool used to develop the LCA product systems under investigation, and the ecoinvent 3.7 was the selected database, which considers cut-off processes to deal with multifunctionality issues and provides regionalized processes whenever possible. Approximately 26% of the background processes were found for the Brazilian geopolitical condi-
Table 1
Gate-to-gate inventory data per FU for remote and face-to-face classes (including fuel consumption and its transport emissions)

| Flow                  | Unit        | Remote class                      | Face-to-face class                      | Pedigree code |
|-----------------------|-------------|-----------------------------------|----------------------------------------|---------------|
|                       |             | Mean | S.D | Pedigree code | Mean | S.D | Pedigree code |
| **INPUTS**            |             |      |     |               |      |     |               |
| Paper                 | kg          | 5.60×10⁻² | 4.20×10⁻² | (2;2;1;1;1) | 2.60×10⁻² | 1.05×10⁰ | (2;2;1;1;1) |
| Ink (whiteboard pen)  | kg          | -    | -   | (2;2;1;1;1) | 2.60×10⁻² | 1.02×10⁰ | (1;2;1;1;1) |
| Plastic (whiteboard pen) | kg        | -    | -   | (2;2;1;1;1) | 2.60×10⁻² | 1.02×10⁰ | (1;2;1;1;1) |
| Water                 | kg          | 7.22×10⁻⁶ | 2.50×10⁻⁶ | (1;1;1;1;1) | 1.37×10⁻¹ | 3.00×10⁰ | (1;1;1;1;1) |
| Electricity, medium voltage | kWh      | 1.12×10⁰ | 2.57×10⁰ | (1;1;1;1;1) | 2.68×10⁰ | 7.40×10⁻³ | (1;1;1;1;1) |
| Diesel                | kg          | -    | -   | (1;1;1;1;1) | 1.77×10⁰ | 1.00×10⁰ | (1;1;1;1;1) |
| Ethanol               | kg          | 3.80×10⁻⁶ | 6.20×10⁻⁶ | (2;2;1;1;1) | 8.49×10⁰ | 1.05×10⁰ | (2;2;1;1;1) |
| Gasoline              | kg          | 2.90×10⁻⁶ | 7.00×10⁻⁶ | (2;2;1;1;1) | 1.49×10⁰ | 1.05×10⁰ | (2;2;1;1;1) |
| Meat                  | kg          | 8.80×10⁻⁶ | 8.42×10⁻⁶ | (2;2;1;1;1) | 3.71×10⁻¹ | 4.22×10⁰ | (2;2;1;1;1) |
| Grains and vegetables | kg          | 9.60×10⁻⁶ | 9.20×10⁻⁶ | (2;2;1;1;1) | 4.37×10⁻¹ | 7.38×10⁰ | (2;2;1;1;1) |
| Fruits                | kg          | 3.50×10⁻⁶ | 3.50×10⁻⁶ | (2;2;1;1;1) | 2.04×10⁻¹ | 4.22×10⁰ | (2;2;1;1;1) |
| Animal derived        | kg          | 3.30×10⁻⁶ | 2.60×10⁻⁶ | (2;2;1;1;1) | 8.00×10⁻² | 2.11×10⁰ | (2;2;1;1;1) |
| Pasta                 | kg          | 8.80×10⁻² | 7.20×10⁻² | (2;2;1;1;1) | 3.9×10⁻² | 1.05×10⁰ | (2;2;1;1;1) |
| Total                 | kg          | 7.46×10⁰ | 2.56×10⁰ | - | 1.53×10⁵ | 2.62×10⁰ | - |

**OUTPUTS**
- Hours of class for 60 students
- Carbon dioxide, biogenic
- Carbon dioxide, fossil
- Dinitrogen monoxide
- Methane
- Waste, organic
- Metal
- Plastic
- Paper
- Liquid effluent
- Total

*main product** from fossil fuel use*** from packaging

- Including bovine, chicken, fish, and swine meat
- Including potato, pea, rice, soybean, sugar beet, carrot, chickpea, fava bean, and maize grain
- Including apple, mandarin, orange, and tomato
- Including cow milk and egg

S.D. 1978
tions, while 74% represent Rest-of-the-World (RoW) countries or global approaches.

The student’s food diet profile was established for each system based on the flowchart data described in Fig. 4.

In the first step in Fig. 4, the university restaurant menu showed a food list of 20 different items. The amount of food consumed for face-to-face classes was estimated from the Annual per capita Household Food in Brazil (IBGE, 2019). The IBGE (2019) food database provides the average quantity of food ingredients consumed in São Paulo state per person and per year. For the remote classes, the data was collected based on Biró et al. (2002). According to the authors, one of the feasible methods for measuring food intake data is through the Food Frequency Questionnaire application, which consists of a list of human diet ingredients which the respondent provides the food intake data. The last step in Fig. 4 was to convert and validate the raw food data in the LCI (Table 1). SD values per FU were calculated to be used in the LCA uncertainty analysis.

The inventory data details for remote and face-to-face classes was obtained separately, as detailed in the next sections. The GHG Protocol tool version 2020 1.2 assisted in the calculation of the transport’s GHG emissions, considering the type of fuel and the consumption per FU.

**Table 2**

| Transport activity | Fuel       | Distance (km/FU) |
|--------------------|------------|------------------|
| Truck 7.5 t payload (food transport) | Diesel     | $8.65 \times 10^{-3}$ |
| Small/medium Car, 5 passengers (students transport) | Gasoline   | $5.28 \times 10^1$ |
| Urban bus (students transport) | Ethanol    | $8.39 \times 10^1$ |
| Small/medium car, 5 passengers (Institutional fleet) | Diesel     | $1.17 \times 10^1$ |
| Pickup car, 2 passengers (Institutional fleet) | Gasoline   | $4.50 \times 10^{-2}$ |
| Minivan, 5 passengers (Institutional fleet) | Ethanol    | $1.37 \times 10^{-2}$ |
| Van 3.5t payload (Institutional fleet) | Gasoline   | $1.65 \times 10^{-2}$ |
| Truck 9t payload (solid waste transport) | Ethanol    | $2.64 \times 10^{-2}$ |
| Truck 4t payload (recyclable waste transport) | Diesel     | $3.56 \times 10^{-2}$ |
| Pickup car, 2 passengers (organic waste transport) | Gasoline   | $6.19 \times 10^{-3}$ |

**Fig. 3.** Secondary data sources used from ecoinvent 3.7 database
To consolidate the LCI step, the university administration provided the primary data required for the foreground processes, as well as the supporting information to calculate the amounts of inputs and outputs per FU.

The university population, solid waste generation and management activities at the university restaurant, and consumption of electricity, water, fuel, and storeroom materials are examples of the main input/output flows collected during this step. The university population before the COVID-19 pandemic was 4,292 people, of whom 371 were employees (professors, technical staff, and out-sourced employees) and 3,921 were students (graduate and postgraduate).

Regarding the storeroom materials, a Pareto chart identified the main materials to be included: brown envelopes (25.4%), paper towels (19.7%), whiteboard pens (14.4%), toilet paper (8.1%), and A4 paper (6.7%). According to Fig. 3, a dataset of graphic paper production from the ecoinvent database was selected to represent the production of paper in the two product systems, while ink and plastic datasets were chosen to represent the whiteboard pens. The ISO 216 (ISO, 2007) provided the guidelines to convert paper items into the main unit reference, and the whiteboard pens were weighed “in situ” to express an average mass input per FU.

The face-to-face classes system had four transport activities: student’s transportation to the university, institutional fleet activities, food transportation to the university restaurant, and solid waste transportation. The inventory of these activities considered different quantification techniques. Concerning the student’s transportation, the distance and fuel consumption were informed by the survey respondents, as shown in appendix I (Supplementary Material). To the institutional fleet, the university administration provided the distances and fuel consumption. Regarding food transportation, the prepared meals come daily from Itapetininga, a city 67.8 km away from the university campus, and are transported to UFSCar Sorocaba campus twice daily; the diesel consumption for food transport is considered 271.2 km traveled per day considering a diesel efficiency of 7 km/l. Lastly, regarding waste transportation, fuel consumption was inventoried considering the transported load and the traveled distances. It was considered 0.42 liters of diesel/t.km for general waste transportation (truck 9t payload) and 0.51 liters of diesel/t.km for recyclable waste transportation (truck 4t payload) (Guzdek et al., 2020). Gasoline consumption referring to organic waste transportation (pickup car) considered an efficiency of 10.8 km/L. A detailed list of the transportation distances and vehicles can be seen in Table 2.

After classes, the liquid effluents and solid residues must be treated. The measurement of liquid effluents considered the generation of 50 liters of effluent per person per day in school environments (ABNT, 1993). The CH₄ and CO₂ equivalent emissions from this treatment process were calculated using the GHG Protocol version 2020.1.2 tools. The Methane Conversion Factor was equal to 0.2 (representing the conversion to the facultative, mixed, or maturing lagoon systems) and a load of BOD (Biochemical Oxygen Demand) of 54 g/person/day, according to the primary data collected in the Master Planning of Sorocaba city.

The CH₄ and CO₂ equivalent emissions from landfills were also obtained in the GHG Protocol tool considering a landfill without specifications, predominantly food as waste type, and without CH₄ burning. The recycling of waste considered the processes available from the ecoinvent 3.7 cut-off database (see Fig. 3 again).

a) Main assumptions for the LCI data: remote class

To build the LCI of the remote class, a survey with Production Engineering students during the COVID-19 pandemic, was used to provide the primary data. The survey was approved by the Research Ethics Committee at the university level, as required in Brazil (Certificate of Ethical Appreciation Presentation CAAE - 37973420.8.0000.5504).

An electronic spreadsheet was used for data collection in the remote class system. A detailed version of the spreadsheet can be downloaded in Appendix I as Supplementary Material.

The students provided the data for consumption of electricity, water, fuel and food. Also, they informed the generation of organic residues, recyclable residues and liquid effluents in their homes. All data required by the spreadsheet were informed per home per month and then converted to the FU.

The outliers were deleted from the measurements to ensure an adequate statistical data structure. The outlier’s identification considered the calculation of SD and the average amounts for each input/output flow, following the recommendation of Pestana and Gageiro (2014). Thus, the inventory values higher/lower than the average plus SD were disregarded. After the exclusion procedure for the outliers, the final inventory flows were obtained and adapted for 60 students and for 2 hours.

It is important to mention that virtual classes also require a lot of infrastructure to make them feasible (Filimonau et al., 2020), such as transport activities for shopping and food supply. Thus, it may not make sense to perform an LCA for digital services only focused on the direct energy consumption itself, limited only to the impacts of electronic gadgets use. A more holistic approach is required to effectively compare the environmental burdens of face-to-face vs. remote services, and a detailed list with the transportation distances and vehicles used by the students and to dispose of the solid residues in remote classes follows in Table 3. To remote classes, the solid waste’ transportation considered the distance from students’ centers city to the sanitary landfill and to the municipal recycling cooperative.

The treatment of organic and recyclable solid waste emissions was carried out using the same procedure used in the face-to-face classroom system. To estimate the generation of liquid effluents in their homes, the students considered the Brazilian standard NBR 7229 (ABNT, 1993). Emissions for the effluent’s treatment were calculated on municipal sewage treatment stations. However, for 16% of the students, the treatment processes are undergoing by septic tanks, and the Methane Conversion Factor was changed to 0.5, because it represents the informed treatment system, as indicated in the GHG Protocol tool.

2.3. Life cycle impact assessment and interpretation

The selected LCIA method was the Impact World+ (IW+) for Continental Latin America, version 1.251, recently developed by Bulle et al. (2019), which allows access to regionalized impacts in the LCIA step. In total, 13 midpoint categories were adopted for the study, and these categories represent relevant environmental concerns for service polygons, as suggested by Silva et al. (2015).
The analyzed impact categories were climate change long term (kg CO₂ eq.), water scarcity (m³ eq.), fossil and nuclear energy use (MJ), fresh water acidification (kg SO₂ eq.), terrestrial acidification (kg SO₂ eq.), fresh water eutrophication (kg Pₐeq. Plim. eq.), ozone layer depletion (kg CFC - 11 eq.), human toxicity cancer (CfUh), human toxicity non-cancer (CfUh), freshwater ecotoxicity (CTUe), particulate matter formation (kg PM₁₀₂ eq.), and photochemical oxidant formation (kg NMVOC eq.). The categories of fresh water eutrophication, ozone layer depletion, human toxicity cancer, and non-cancer are more associated with the background processes of food supply, which make them relevant to this research. The remaining impact categories were also studied by previous publications on the topic, such as Barros et al. (2020), Lo-Jacobo-Ferreira et al. (2017), and Silva et al. (2015).

Besides the IW+ midpoint method, the Cumulative Energy Demand (CED) was also used to analyze in more detail the energy consumptions per FU of this comparative LCA. The CED method was proposed by Frischknecht et al. (2015), and evaluates the impact of renewable (biomass, geothermal, solar, water, and wind) and non-renewable (fossil, nuclear, primary forest) energy consumption.

Therefore, the environmental impacts before and during the COVID-19 pandemic were calculated based on these two LCA methods, as well as for the hotspot’s analysis. Finally, a sensitivity analysis was performed to better understand and minimize the hotspots for each of the 13 impact categories. For this, different scenarios were designed and the uncertainties for this comparative LCA were measured and critically evaluated as described in section 2.4.

2.4. Sensitivity and uncertainty analysis

To facilitate understanding of the comparative LCA results, a Monte Carlo Simulation was applied to simulate intervals of impacts through the openLCA software used. After that, a sensitivity analysis was performed based on the scenarios described in the next paragraphs to investigate possible improvement suggestions for each of the two compared systems.

The Monte Carlo Simulation is a stochastic method in which each parameter in question (input and/or output flows) should be specified according to an uncertainty probabilistic distribution and SD value (Sonnemann et al., 2018). The simulation occurs through the selection of aleatory values for the investigated parameters variation to provide a specific number of diverse iterations. For each iteration, a new result scenario is obtained for a specific environmental impact category.

The face-to-face and remote classes considered the basic uncertainties provided in Table 1 as the SD for each inventory flow. Some flows assumed a normal distribution (GHG emissions and fuel consumptions), while the log-normal distribution was adopted for the remaining inventory flows. Also, the ecoinvent’s Pedigree Matrix provided the background processes uncertainty values based on reliability, completeness, temporal correlation, geographical correlation, further technological correlation, sample size, and basic uncertainty (Weidema et al., 2013). The Monte Carlo Simulation considered 1,000 iterations, and results were analyzed in a box-plot diagram for the two compared systems.

After investigating the confidence intervals of impacts, a sensitivity analysis was performed based on the one-at-time approach, as discussed by Igos et al., 2019. It represents the most basic approach for local LCA sensitivity analysis that can be assumed to be a screening approach to measuring for an input/output variation and/or new scenarios proposals for the product systems. In Fig. 5, we describe the scenarios chosen for this study due to the environmental hotspots results that will be presented in section 3.

3. Results and discussion

3.1. Primary energy demand

Table 4 shows the CED results for calculating the amount of primary energy (in MJeq) demanded by each system per FU.

According to Table 4, the total energy demand (renewable and non-renewable) was 3.16 × 10² and 1.64 × 10² MJeq, respectively, for the face-to-face and the remote class systems. The renewable energy corresponded to 60.6% of this total value for the face-to-face classes, with emphasis on primary biomass and hydropower consumptions in the cradle-to-grave LCA. This was mainly due to the consumption of ethanol used for transportation activities to/from the UFSCar campus. For the remote classes, the renewable energy corresponds to 44.2% of the total energy consumption, the main hotspot also being the ethanol required for the daily transportation activities (e.g. purchase of groceries and hygiene products for housing supply). Regarding the non-renewable energy, fossil fuels (diesel, gasoline) were the main hotspots for both evaluated systems as a result of the already mentioned transportation activities for these two systems as well as due to the food and feed activities needed for the production of fruits, vegetables, and meat. It is important to mention that 39.4% of the total energy was from non-renewable sources for the face-to-face classes system, while 55.8% represents the non-renewable energy participation in the total CED results for the remote classes. Therefore, the face-to-face classes tend to require more than twice the total energy per FU than the remote classes. However, the remote classes showed a relative higher participation of the non-renewable resources in its total energy consumptions.

3.2. Environmental impacts potential

Table 5 shows the overall results of the LCIA of the service provision of 02 hours of class per week for 60 Production Engineering students. Also, Fig. 6 illustrates the contribution analysis per unit process for the two comparative systems.

According to Fig. 6, most of these impacts are attributed to food and water supplies, representing more than 49% of the impacts and up to 97% of the impacts in each category by IW+ method for the remote classes. In face-to-face classes, on the other hand, the effect of fuel consumption was so relevant as the food and water consumptions for the LCA results. Food and water supplies showed
the highest impacts for four of the impact categories under investigation, while the fuel consumption represented the highest impacts for five of the evaluated categories.

Impacts for the waste management in the face-to-face system were up to 32% of the whole life cycle impacts (climate change category), mainly due to the GHG releases during the solid waste decomposition in landfills (23%) and the liquid effluent treatment process (6%). Also, 15% of the cradle-to-grave impacts were accounted for in the freshwater eutrophication category because of the recycling of waste (mainly paper recycling). In the remote classes system, these end-of-life strategies showed impacts up to 21% to climate change followed by 20% freshwater eutrophication. Waste transportation showed irrelevant impacts for both the comparative product systems.

Regarding food consumption, beef meat, followed by rice, cow milk, and chicken were the main food diet that affected the evaluated impacts in Fig. 7. Ethanol and electricity consumptions were also the main hotspots, and Fig. 7 summarizes the main hotspots (> 40% impactful) in the cradle-to-grave assessment of the two systems per impact category.

Most hotspots are related to the cow meat followed by ethanol appearing fifteen and eight times, respectively. Food items (cow meat, cow milk, chicken meat, rice, etc.) were more relevant for the remote class system than compared with the face-to-face system. This can be explained by the fact that people usually eat more often during home-office activities and due to the COVID-19 pandemic as discussed by Eftimov et al. (2020), Ruiz-Rozo et al. (2020), and Scarmozzino and Vissoli (2020). Therefore, a clear improvement opportunity for the cradle-to-grave remote class system should focus on promoting personal assistance and social campaigns to reduce anxiety and better control the amount of food and the frequency of times we eat when doing online/virtual activities.

| Table 4 |
|---------|
| CED results for the two comparative studies |
| Indicator | Face-to-face class (MJ/FU) | Remote class (MJ/FU) |
| Non-renewable | Fossil | $1.04 \times 10^7$ | $5.01 \times 10^7$ |
| | nuclear | $5.71 \times 10^6$ | $6.44 \times 10^6$ |
| | primary | $1.52 \times 10^4$ | $3.01 \times 10^4$ |
| TOTAL NON-RENEWABLE | biomass | $1.83 \times 10^4$ | $6.60 \times 10^4$ |
| Renewable | kinetic (wind) | $4.50 \times 10^{-1}$ | $4.00 \times 10^{-1}$ |
| | Solar | $4.30 \times 10^{-4}$ | $5.70 \times 10^{-2}$ |
| | geothermal | $3.20 \times 10^{-2}$ | $3.90 \times 10^{-2}$ |
| | Water | $8.06 \times 10^{-5}$ | $6.00 \times 10^{-5}$ |
| TOTAL RENEWABLE | $1.91 \times 10^{-2}$ | $7.25 \times 10^{-2}$ |
The transportation impacts are due to ethanol as the main hotspot, followed by gasoline and diesel. This is related mainly to the face-to-face classes, as a lot of transport infrastructure is needed (e.g., food supply and student transportation). Most of the impacts are related to climate change, acidification, eutrophication, particulate formation and photochemical oxidation categories, because of the direct and indirect air releases of CO$_2$, NMVOC, particulate matter and others. As a result, another important suggestion should be made to reduce transportation distances and/or fuel consumptions, as pointed out by Bauer et al. (2015), de Souza et al. (2018), and Patouillard et al. (2020).

Electricity consumption was a less common hotspot mainly highlighted for the water scarcity, as a result of the Brazilian electricity mix focused on hydropower and biomass as primary energy sources (see details in Table 4 again). This result is interesting because most of the digital services’ impacts in literature
Fig. 8. Uncertainty analysis: relative contribution (%) of face-to-face and remote classes. Variation of the results were grouped as part A) -40 to 120%, part B) -200 to 300% and part C) -100 to 200%.
highlight the need for improving energy efficiency of equipment and electric devices. According to Schien et al. (2013), the overall energy footprint in digital services is dependent on the choice of service type, user device, and access to network speed. Also, in recent years, there is an encouraging move to develop more energy efficient smartphones and tablets, for example. On the other hand, when looking at the whole product’s life cycle perspective, a more holistic approach can be found for the environmental performance analysis, and this paper points out other primary aspects followed by energy consumption as a hotspot over the service life cycle for the two comparative systems. If only energy is analyzed, Table 1 showed much more need for electricity demand for the remote system. In other words, the remote system has a greater impact in terms of the overall life cycle energy consumption. In section 3.3, a sensitivity analysis is provided to gather more relevant information on the energy consumption issues.

Based on these hotspots, an analysis of the LCA uncertainties and scenarios analysis was made to identify more sustainable alternatives to improve the teaching classes’ format.

### 3.3. Sensitivity and uncertainty analysis

In sequence, the uncertainty analysis was performed based on the Monte Carlo stochastic simulation. Fig. 8 shows box-plots for the set of impact categories expressed as a % of the impact.

Results in Fig. 8 point out that climate change, mineral resource use, freshwater eutrophication and ozone layer depletion impacts, are higher in the face-to-face classes compared to the remote classes in most cases. However, a relevant part of the data from the remote classes system, for the second and third quartiles, is equivalent to the first quartile results of the face-to-face classes system’s impacts. Therefore, it can be affirmed that there is a tendency to have more impacts on face-to-face classes in these impact categories. A clearer conclusion about the lowest impacts of the remote classes system can be found for the fossil and nuclear energy use, water scarcity, freshwater and terrestrial acidifications, photochemical oxidant formation and particulate matter formation, where the confidence intervals were different at 95% confidence level.

However, equivalent impacts can be found for the toxicological impacts at under 95% confidence intervals, such as the results for freshwater ecotoxicity, human toxicity cancer and non-cancer effects. Most of these box-plots have shared the same interquartile ranges and similar maximum/minimum control limits. Therefore, we cannot conclude about the higher/lower impacts of the comparative LCA systems under investigation in these impact categories.

Only three of the thirteen investigated impact categories were virtually equivalent to each other for this comparative LCA. The non-toxicological impacts seem to differ significantly in the uncertainty analysis and they were chosen as the impact categories to be included in the sensitivity analysis.

After discussing the uncertainties of the LCA results, the scenarios designed in section 2.4 were tested to investigate the influence of the main hotspots discussed for this comparative LCA study. A more detailed discussion was given for those impacts that seemed to be statistically different according to the box-plots in Fig. 8.

Scenario 1 evaluated the ethanol and electricity consumption variations to simulate energy consumption effects under the current environmental impacts. To do this, energy consumption (ethanol and electricity) was assumed as the lower consumption profile according to the comparative LCI data in Table 1. Thus, face-to-face and remote classes considered both the electricity consumption as equal to 2.68 kWh and 0.38 kg of ethanol per FU. Fig. 9 shows the results in terms of the changes as percentages relative to the baseline scenario of face-to-face teaching (impacts fixed as 100%).

It can be observed that the remote classes contributed most with the impact categories varying from 38% (particulate matter formation) to 75% (climate change). In Table 5, the face-to-face classes are shown to have a greater impact as baseline scenario. However, when the energy demand is optimized to Scenario 1, the face-to-face classes remain the best system. Reductions in the transportation distances should be the main process parameter to be studied in further research to achieve these environmental LCA performance results. For example, the use of part of the UFSCar campus (see Fig. 1) to expand the local restaurant capacity to produce more food, could be studied, thereby avoiding the activities of meal preparation and transportation from Itapetininga city everyday (271.2 km/day).

Scenario 2 looked at the food diet adopted by the surveyed students during the remote vs. face-to-face classes. It focused on the consumption variations of beef, rice, milk and chicken meat.
inputs, because they represented the most relevant hotspots. The face-to-face classes profile was assumed to be a reference for the two compared systems since it represented the lower consumption profile in Table 1. Results (see Fig. 10) indicated that the face-to-face system stayed as the major contributor, and the relative impacts of remote classes could be minimized up to 24% (water scarcity). In this case, it was clear that the food diet is an important issue to the remote classes system because it can drastically reduce the impacts compared to the baseline scenario, as will be further discussed in Fig. 11. More sustainable lifestyles focused on a better food diet being required for the remote classes system in order to reduce the life cycle environmental impacts.

Finally, Scenario 3 was a combination of Scenarios 1 and 2 to investigate the total minimization of impacts that could be possibly achieved by assuming the best scenarios for energy and food consumptions. According to the results in Fig. 11, the face-to-face system had more impact for almost all categories. It can be affirmed that the remote classes during the COVID-19 pandemic tend to minimize the overall evaluated impacts by up to 81% (fossil and nuclear energy use).

A combination of reductions to the transportation and food impacts in Scenario 3 showed an average minimization of the impacts by 65% relative to the baseline scenario. Perhaps, this reduction of the life cycle impacts by each impact category does not motivate the Higher Educational institution to promote a change in the current classroom system, but it is important to remember that such a difference in impacts was considered statistically relevant. Besides, an alternative path could be a hybrid approach combining face-to-face and remote classes throughout the classroom week, which could provide intermediate values in reducing these impacts. For example, if 50% of weekly classes were in person and 50% remote, the impacts showed in Table 5 would be reduced by 57%, on average, for all impact categories, respectively. Such a reduction, according to the Monte Carlo Simulation, would continue to be significant for most of the impact categories.
4. Conclusions

In literature most papers about the environmental management of educational activities fail because they give attention only to the energy consumption and efficiency of equipment and their devices. The kind of equipment used by students in remote learning is an important issue, but this paper moved forward and gave depth to the current research content by performing a LCA of face-to-face and remote university classes in a Brazilian Higher Education institution. Besides energy, materials (food, office materials) and emissions (GHG emission, liquid and solid waste generations) were gathered in situ and supported by LCA software and databases to build two cradle-to-grave systems.

Considering this gap, the present research performed a LCA of face-to-face and remote classes in a Higher Education institution during the context of COVID-19. The results showed that electricity consumption was a less common hotspot. This result confirms that when looking at the entire product’s life cycle other primary aspects can be found for the two comparative LCA systems.

Most environmental hotspots for each of the thirteen impact categories were due to cow meat followed by ethanol fuel consumptions. Food items (cow meat, cow milk, chicken meat, rice) were more relevant for the remote class system when compared with the face-to-face system. This can be explained by the fact that people usually eat more often during home-office activities and due to the COVID-19 pandemic. Otherwise, the transportation impact due to ethanol is related mainly to the face-to-face classes, as much transport is required such as food supply and student transportation.

From the hotspots analysis, uncertainty followed by sensitivity analysis was performed based on scenario variations. We conclude that the university remote classes during the COVID-19 pandemic tend to minimize the overall evaluated impacts to the following impact categories: climate change, mineral resources use, freshwater eutrophication, ozone layer depletion, fossil and nuclear energy use, water scarcity, freshwater and terrestrial acidifications, photochemical oxidant formation and particulate matter formation. The impact to freshwater ecotoxicity, human toxicity cancer and non-cancer effects were considered equivalent in the comparison of face-to-face and remote classes.

It is important to note that if Scenario 3 is to become feasible it will require a clear improvement for the cradle-to-grave remote class system, because it should focus on promoting personal assistance and social campaigns to reduce student’s anxiety and better control the amount of food they eat daily towards a more sustainable virtual classes system. The current food diet described in Table 1 should be approximately the same as the face-to-face and remote classes.

It should be highlighted that the broad analysis presented in this study contributes to the literature regarding LCA, especially in the field of university courses and classes. This study showed that the reduce of transports use in remote classes presents environmental gains, however, there are also disadvantages related to this change. This finding is relevant to guide public policies and Higher Education Institutions changes related to classes modalities definition. When considering environment impacts, several perspectives must be considered, in order to optimize changes impacts. Among these perspectives, it can be mentioned the kind of diet students have, the kind of transport used by them, and even if there are significant differences between waste treatment in campuses and at people’s home.

Regarding changes on actions taken by students, considering that during the pandemic the remote classes are inevitable, they can rethink their diet, eating less cow meat, for example. When performing face-to-face classes, the use of public transports or non-polluting mode of transport, such as bicycle should be considered.

The study limitations should also be mentioned, as we identified a major need for more LCI background datasets for the Brazilian conditions, since most of the ecoinvent datasets used were taken from RoW geographical contexts. Also, a small group of students was surveyed to build the remote classes’ model. Therefore, more people should have been included in the research.

Despite the study limitations, relevant practical and theoretical implications can be mentioned from the presented findings. For practice, it is possible to verify the most relevant environmental impacts in face-to-face and remote classes, as previously presented. These findings can be used in future analysis for mitigating environmental negative impacts of educational systems. In addition, the comparative analysis allowed a deeper understanding about differences between the two teaching modalities. Regarding the theoretical implications, this study presents a methodology and a line of reasoning that can be used by other researchers to analyze different teaching realities and compare the findings.

For future research, we highlight the need of studies to investigate how students can minimize the environmental negative impacts they generate both in face-to-face and remote classes, that is, how students can be focus of changes. Besides the great proportion of people circulating at campuses, students will be professionals that can play a relevant role in society, when starting to change their mind during their graduate/undergraduate programs.

Ethical Statement, Interest Statement, Financial Support

As a measure of best practices for research and publication, we state that this material has not been published in whole or in part elsewhere, the manuscript is not currently being considered for publication in another journal, and all authors have been personally and actively involved in substantive work leading to the manuscript, and will hold themselves jointly and individually responsible for its content.

This work was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under grants 302722/2019–0, and 307536/2018–1; Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), under grant 2019/03287–5; and by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001, under process 88887.464433/2019-00.

Declaration of Competing Interest

None.

Acknowledgments

This work was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under grants 302722/2019–0, and 307536/2018–1; Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), under grant 2019/03287–5; and by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001, under process 88887.464433/2019-00.

Supplementary materials

Supplementary materials associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.05.002.

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