ENVIRONMENTAL IMPACT OF AN INDUSTRIAL KITCHEN: A CASE STUDY

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ABSTRACT
The large number of industrial kitchens and their energy-intensive characteristics provides opportunities for pollution prevention. Life cycle assessment (LCA) is a proper tool not only for unitizing the environmental impact of the complex system of an industrial kitchen, but also for making environmental food labels for the foods produced in the same industrial kitchen. In this study, a gate-to-gate LCA of 11 types of food was conducted to evaluate the environmental impact of a typical industrial kitchen, Villanova University’s Donahue Hall. First, material and energy flow data, including cold storage, food preparation, food display, lighting, heating, ventilation, and air conditioning (HVAC), and dish washing were collected. This data, along with standard data on energy generation and transmission, were used in the LCA. The results show that global warming, fossil fuel depletion and ecotoxicity are the main environmental impact categories. Furthermore, HVAC, cold storage and cooking are the three largest contributors of environmental burden. Using the metrics developed, tuna salad, tomato soup and pasta are the most environmental friendly foods of the 11 sampled food types, while pizza and cheese quesadillas have the worst environmental performance. Energy saving measures for HVAC, cold storage and cooking are proposed.

INTRODUCTION
Food service is an essential part to human life but also is an energy-intensive process. 380,000 buildings in the US have food service as their principal activity. Another 282,000 buildings are equipped with commercial size kitchen areas [1]. Industrial kitchens, which are larger in scale and in energy consumption compared to commercial and household kitchens, are significant consumers of energy and producers of pollution. Fortunately, the implementation of energy-efficient practices in industrial kitchens is easier than in household kitchens for two reasons: (1) the range of food types in industrial kitchens is limited, which limits the variation of energy flow patterns, and therefore increases the feasibility of energy analysis; and (2) training in industrial kitchens is more rigorous than in household kitchens, so energy-efficient food preparation practices are easier to implement.

Studies on food serving has been focused on food preparation in household kitchens, which examined factors such as energy efficiency of appliances and cooking operations. Examples of recent studies include Cernela’s study on the heating performance of domestic oven-baking and pan-frying [2], Karunanithy’s study on the energy efficiency of different sauce pans on different types of cooktops [3] and Xu’s study on reducing the carbon footprint by adjusting the cooking operations [4].

Studying industrial kitchens presents a different problem: it has to be studied on a building scale since it includes dining as well as food preparation. Food preparation is still crucial, but it now must also be considered as a burden to the HVAC system. Proper raw material storage systems to guarantee food safety and lighting systems for providing a comfortable dining and working environment also play significant roles in industrial kitchens.

LCA tracks the unitized flow of mass and energy during the life cycle of a type of food and provides an inclusive view of its environmental aspects [5] [6] [7] [8]. It provides a platform to record the energy consumption, along with the associated environmental impacts, during the various stages of turning raw material into food in the kitchen (gate-to-gate), or even on a broader scale, from the agriculture stage to the waste management stage (cradle-to-grave). In this way, LCA allows us to (1) evaluate the unitized environmental performance of an industrial kitchens by quantifying the environmental impact of a meal it served; (2) compare the environmental impacts of the various stages during the “cradle-to-grave” processes of the meal and figure out the hotspots of potential energy savings.

Furthermore, by examining the food related processes in the cradle-to-grave life cycle, the environmental impact of each type of food can be obtained. This enables a new kind of environmental food labeling, as shown in Fig. 1. Food labels would then contain both nutritional facts and the environmental burden of the food. These labels can be used to promote consumer awareness, leading to changes in eating habits, similar to traditional nutrition labelling, potentially resulting in significant source pollution reduction. It should be noted that this end goal requires evaluation of processes including agriculture, transportation, and intermediate industrial facilities that transform raw products into packaged food items (e.g., pasta
sauce) that are used in the industrial kitchen. The research here focuses on the industrial kitchen since it is the most complex to evaluate among these various stages in a cradle-to-grave assessment.

Figure 1. A sample environmental food label.

As far as the authors know, no LCA research has been conducted on industrial kitchens. In this preliminary study, the environmental impact of a typical industrial kitchen, Donahue Hall in Villanova University, was evaluated using a gate-to-gate LCA. Donahue Hall is a single use building and equipped with all the elementary systems in an industrial kitchen, such as HVAC and walk-in refrigeration rooms. Reference mass and energy flows within food-type-related stages (cold storage, food preparation and food display) and non-food-type-related stages in the life cycle of a meal with 11 kinds of food were examined.

METHOD
Functional unit and system boundary
In LCA, the service(s) provided by a product system is unitized and quantified as functional unit. The amount of mass/energy inputs and outputs are calculated based on how they interact with the functional unit. For industrial kitchens, the service is to provide food to the consumers. The functional unit can be defined as a meal and interpreted as:

\[
A \text{ meal} = \frac{\text{Total amount of food produced}}{\text{Total number of consumers}}
\]

where the total amount of food produced can be obtained from the menu and the food preparation records; the total number of consumers can be obtained from the record of diners. For the dining hall under consideration in this case study, student identification card “swipes” provide the number of consumers. The dining hall is limited in menu, which repeats in a cyclical manner. It is assumed that the energy usage of the kitchen for any typical meal represents the average energy consumption for meal preparation. A cut-off has been applied for simplification based on accuracy of the data, which resulted in the selection of 11 kinds of food (as shown in Table 1) to represent the entire meal service, which actually includes more than 30 kinds of food.

This study is a gate-to-gate life cycle assessment according to the definition in the ISO standards 14040:2006 (Environmental management—Life cycle assessment—Principles and framework) and ISO 14044:2006 (Environmental management—Life cycle assessment—Requirements and guidelines). In this case, the gate is defined as when the ingredients for food preparation arrive at the kitchen. As shown in Fig. 2, stages before this gate, such as raw material production and processing and transportation are excluded from the system boundary. The construction of the kitchen, manufacturing and maintenance of the appliances and the associated human labor for this have also been excluded from the system boundary.

Table 1. Functional Unit of Life Cycle Assessment of a Meal Provided in Donahue Hall

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zucchini Onion Jam Sandwich</td>
<td>0.5 piece (~30g)</td>
</tr>
<tr>
<td>2</td>
<td>Veg Zucchini &amp; Squash &amp; Cherry Tomato</td>
<td>30 g</td>
</tr>
<tr>
<td>3</td>
<td>Tuna Salad Res Hall R</td>
<td>35 g</td>
</tr>
<tr>
<td>4</td>
<td>Soup Tomato Vegan Pouch R</td>
<td>50 ml</td>
</tr>
<tr>
<td>5</td>
<td>Portabella Mushroom with Quinoa</td>
<td>30 g</td>
</tr>
<tr>
<td>6</td>
<td>Pasta Bar</td>
<td>50 g</td>
</tr>
<tr>
<td>7</td>
<td>Chicken Noodle Soup R</td>
<td>50 ml</td>
</tr>
<tr>
<td>8</td>
<td>Cheese Quesadilla</td>
<td>30 g</td>
</tr>
<tr>
<td>9</td>
<td>Buffalo Chicken Pizza</td>
<td>0.3 slice (~25 g)</td>
</tr>
<tr>
<td>10</td>
<td>BBQ Chicken Pizza</td>
<td>0.3 slice (~25 g)</td>
</tr>
</tbody>
</table>

Life cycle inventory analysis
Material input and output
Life cycle inventory analysis is a data collection process which concerns material and energy input and output information in all stages related to the functional unit. It is the basis for life cycle impact assessment. The material flow input to the LCA is determined by the recipes. As one example, Fig. 3 is drawn based on the recipes for buffalo chicken pizza and soup tomato vegan pouch r. A recipe contains information such as required mass (or volume) of raw materials, mass (or volume) of yield, preparation method and food display method. 11 flow charts were drawn respectively for all the representative foods for analyzing the mass flow in the kitchen.
Energy consumption by food-type-related stages

Raw materials experience storage, preparation and display before they are finally located in the dish of the consumers. For different types of food, the methods used in these stages may vary. For example, as specified in the recipes, the method of storage for chicken breast is freezing storage, while the storage method for carrots is refrigeration. In this paper, we refer to raw material storage, food preparation and food display as the food-type-related stages. In contrast, stages such as lighting, HVAC, dish transportation and washing, waste shipment and waste disposal are referred to as non-food-type-related stages, since the methods used in these stages do not depend on food type. This classification allows us to compare the environmental performance of different types of food.

There are three types of walk-in cold storage rooms in Donahue Hall: fresh storage (at 9°C), refrigeration (at 4.4°C) and freezing storage (below -18°C). The surrounding temperature is assumed constant at $T_{\text{surrounding}}=20°C$. All the walls of these storage rooms are assumed to have the same overall thermal resistance $R$. The heat input is therefore

$$q_{\text{input}} = (T_{\text{surrounding}} - T_{\text{storage}})/R_{\text{overall}}$$

which indicates that the amount of heat input into the storage rooms is only affected by the storage temperature. Thus, the electricity load ratio of a fresh storage room, a refrigeration storage room and a single freezing room is equal to the heat input ratio, which can be calculated as 11:15.6:38. On days the kitchen is closed (student breaks), there is no electrical load except cold storage and HVAC. Table 2 shows electricity consumption data that has been recorded over the typical kitchen closed days, from which we can see the average electricity load is 230.6 kW. Based on [9], the energy consumption ratio for storage and HVAC is assumed to be 1:3. The electricity load for each type of room can then be calculated as the product of three quantities:

1. average electricity load for HVAC and storage
2. ratio of storage
3. ratio of storage room type

The electricity load of storage for 48 hours, the average storage time, by one fresh storage, two refrigerators and two freezers is then 257.3 kWh, 729.8 kWh and 1777.7 kWh, respectively. For each type of raw materials, the electricity load is assumed only determined by its volume, which means the electricity consumption for storage of one typical type of raw material can be calculated as the electricity load of the target storage room times the volume fraction of raw material, defined as the ratio of raw material volume to typical storage room volume. The energy consumed by food preparation is determined by the appliance power rating and cooking time. The appliances to be used and the required cooking times are specified in the recipe. Assuming appliances are working at their maximum power rating, the amount of energy can then be obtained from the nameplate on the appliances.

Before the prepared food is consumed, it is put on display trays for the students to review the food cafeteria style, which is a common practice in industrial kitchens and some commercial
For purposes of food safety and taste, three types of food displays are used in Donahue Hall: warm (above 60°C), hot (above 70°C) and chilled (under 3.3°C). Cold display is achieved by putting the display trays on customized refrigerators. Warm display and hot display are achieved by putting the display trays on hot wells, specified in the recipe, as shown in Table 3. The electricity consumption is then calculated as the power rating of the display method times the average display time.

### Energy flow through non-food-type-related life cycle stages

The energy consumption by stages such as HVAC, lighting and dish washing are not considered as part of the energy flow of food. Their energy burden contribution to the kitchen is calculated instead by the length of service time. The official lunch time is 4 hours, and during this period the HVAC system and lighting are kept at a constant load. The electricity load for the HVAC system is 173.0 kW from the previous analysis. For lighting, the overall power rating is calculated as the sum of power rating of all the lights used. The dish transportation system, equipped with a circular conveyor to collect used dishes and cups and then transport them into the dish washer room, operates for 3 hours. The dishwasher operates for 1 hour for lunch time and its power rating is 15.8 kW.

### Life cycle impact assessment

The environmental impact of a service or a product comes from the resources people have taken from nature and the waste/emission released to nature during its life cycle. These environmental impacts can be divided into several environmental categories and quantified by the appropriate units. For example, the Tool for Reduction and Assessment of Chemicals and other Environmental Impacts (TRACI), published by Environmental Impact Assessment, EPA, categorized and unitized environmental impacts (with associated units) as: Ozone depletion (kg CFC-11 eq), Smog (kg O₃ eq), Acidification (kg SO₄), Eutrophication (kg N eq), Carcinogenics (CTUh), Non-carcinogenics (CTUh), Respiratory effects (kg PM2.5 eq), Ecotoxicity (CTUe), and Fossil fuel depletion (MJ surplus) [10].

The potential environmental impact of an industrial kitchen comes from the consumption of electricity/natural gas/ raw material and production of waste along its life cycle. In the life cycle inventory analysis section, we have built a life cycle inventory for the kitchen, which contains unitized input and output information for all the stages related to the functional unit (i.e. the meal). On the other hand, the environmental impact of the life cycle of typical products, such as 1 kWh of electricity, have been quantified and the data is available from various databases, such as USLCI [11]. Based on these databases, life cycle impact assessments convert life cycle inventory data into the potential environmental impact of the functional unit, which is the meal in this study. [10].

The life cycle assessment modeling was completed using SimaPro 8.0.4.30 Multi User, which is one of the most widely used LCA modeling software packages. Secondary data (existing LCA data) was used for natural gas (US-EI 2.2, 2010), electricity (USLCI, 2008) which are included in SimaPro’s built-in databases. TRACI 2.0 was used as the method of life cycle impact assessment.

### RESULTS AND DISCUSSION

In this study, for easier evaluation, a single-score assumption was adopted for the interpretation of the LCA. With this assumption, the significance of an environmental impact category is only determined by the amount, regardless of the unit that has been used. For example, 1 MJ surplus (the unit of fossil fuel depletion) and 1 kg CO₂ equivalent (the unit for global warming) are considered having the same significance.

The overall environmental impact of a meal in Donahue Hall is shown in Fig. 4. The largest environmental impact category is global warming, which is 0.62 kg CO₂ equivalent. The second largest are fossil depletion and ecotoxicity, which are 0.41 MJ surplus and 0.36 CTUe, respectively. These results are due to the fact that the main inputs into the kitchen are natural gas and electricity. The generation of electricity and the usage of natural gas release large quantities of CO₂ into the environment. The

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**Table 2. Electricity Consumption Records During Days the Kitchen is Closed**

<table>
<thead>
<tr>
<th>Time</th>
<th>Load /kW</th>
<th>Reading /kWh</th>
<th>Accumulate consumption /kWh</th>
<th>Average load /kW</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:15 pm 11/26/2016</td>
<td>249.5</td>
<td>943814</td>
<td>--</td>
<td>215.2</td>
<td>Kitchen was off</td>
</tr>
<tr>
<td>7:12 am 11/27/2016</td>
<td>225.6</td>
<td>945955</td>
<td>3371</td>
<td>233.6</td>
<td>Kitchen was off</td>
</tr>
<tr>
<td>9:38 pm 11/27/2016</td>
<td>247.3</td>
<td>949326</td>
<td>2388</td>
<td>243.2</td>
<td>Kitchen was working</td>
</tr>
<tr>
<td>7:17 am 11/28/2016</td>
<td>315.3</td>
<td>951714</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3. Electricity Consumption by Food Display**

<table>
<thead>
<tr>
<th>Display method</th>
<th>Required Temperature/°C</th>
<th>Power Rating/W</th>
<th>Display Time/hr</th>
<th>Energy Usage/W</th>
<th>Foods Displayed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm</td>
<td>&gt;60</td>
<td>1000</td>
<td>0.15</td>
<td>150</td>
<td>Zucchini Onion Jam Sandwich R</td>
</tr>
<tr>
<td>Hot</td>
<td>&gt;70</td>
<td>9000</td>
<td>0.15</td>
<td>1350</td>
<td>Veg Zucchini &amp; Squash &amp; Cherry Tomato; Portabella Mushroom With Quinoa; Pasta Sauce; Chicken Noodle Soup R; Cheese Quesadilla; BBQ Chicken Pizza; Buffalo Chicken Pizza; Soup Tomato Vegan Pouch R</td>
</tr>
<tr>
<td>Chill</td>
<td>&lt;3.3</td>
<td>1000</td>
<td>0.15</td>
<td>150</td>
<td>Tuna Salad Res Hall R; Sauce Pizza Homemade R;</td>
</tr>
</tbody>
</table>
mining for natural gas and coal (coal accounts for 23.3% of the energy source for electricity generation in the RFC East region, where this kitchen is located [12]) is not only a process of fossil fuel depletion, but also a process with a significant ecotoxicity impact on the environment.

Fossil fuel depletion, ecotoxicity, smog and global warming are the four areas of largest significance and have been selected as the environmental impact categories to show the environmental impact for the life cycle stages and food types.

**Figure 4.** Overall environmental impact using TRACI.

Fig. 5 provides the environmental burden of each of the life cycle stages. HVAC is the largest contributor to global warming, fossil fuel depletion and ecotoxicity. This is because it is the biggest consumer of electricity in the kitchen. The space size of Donahue Hall is more than 7200 m$^3$ so that the heating demand in winter and cooling demand in summer is huge. The Donahue is a northeast facing building so there is a small amount of passive solar to make use of on winter days. There are also 7 exhaust fans equipped to remove the heat from cooking activities. In addition to the high demand levels due to size, the HVAC system is old and inefficient (equipped in 1985 and partially renovated in 1996) and is another reason for the high consumption of electricity.

Cold storage is the second largest electricity consumer, the second largest contributor to both global warming and fossil fuel depletion, and third largest contributor to ecotoxicity. Frozen raw materials are usually cooked from their frozen state in the kitchen. For example, green beans are steamed directly as they are taken out of the walk-in freezer. Chicken breasts are put directly into the oven to melt. This cooking approach results in significant energy waste. As an alternative, the frozen raw materials could be taken to the refrigerator room 12 hours before they are used. In this way, foods are taken out of the freezing storage room 12 hours earlier, which allows for a 25% savings in electricity. The melting of 1 kg frozen raw material in the refrigeration room can save 390 kJ electricity for refrigeration. An equal amount of energy is saved during cooking process.

Food preparation is the third largest environmental burden and is the largest internal demand on the HVAC system. 40.5% of electricity in the RFC East region is generated from nuclear power plants[12] and nuclear results in less ecotoxicity impact than natural gas. This is why cooking, which consumes both electricity and natural gas, has a higher impact in ecotoxicity than cold storage. A way to save energy for cooking may be to enforce new operating procedures. For example, simply putting a pot lid over a hot pot during boiling and simmering (~90 °C) rather than boiling (100 °C) can save 50-85% in energy [11].

**Figure 5.** Environmental impact by life cycle stages for major environmental impact categories.
CONCLUSION

In this study, a gate-to-gate LCA was performed for a typical industrial kitchen, Donahue Hall, to evaluate its environmental impact. The results show that the usage of natural gas and electricity by HVAC, cold storage and cooking are the main contributors to the environmental burden. Energy saving measurements such as adopting alternative cold storage strategies and new cooking operation procedures have been proposed. In the 11 kinds of food selected to represent the meal service, tuna salad, tomato soup and pasta were found to have the lowest environmental burden, while pizza and cheese quesadillas were found to have the highest burden. A new environmental performance food label is proposed to encourage consumers to choose a more environmentally sustainable diet. Further studies will examine the cradle-to-grave LCA and see how the menu and environmental food labeling will affect energy consumption in the industrial kitchen and the potential energy savings. Furthermore, the assumptions used in this study will be tested and evaluated to solidify the method used. Finally, the overall single-score approach to determining relative levels of pollution will be revisited to determine the best effective overall toxicity rating.

ACKNOWLEDGEMENTS

This material is based upon work supported by the Environmental Protection Agency under the Source Reduction Assistance grant program. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Environmental Protection Agency. Cooperation from Villanova Dining Services and Facilities Management is appreciated.

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