COVER PAGE

Title of Design: Smart Gate System for 400Hz Power Monitoring at Airports

Design Challenge Addressed: Airport Environmental Interactions

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Executive Summary

San Francisco International Airport (SFO), a world-leading airport in sustainable practices, seeks to achieve net zero energy, carbon neutrality, and reduce greenhouse gas emissions by 50% from a 1990 baseline by 2021. In order to do so, it must focus on reducing operational energy consumption. Some of the major terminal energy loads that SFO seeks to reduce include baggage handling, ground service equipment, pre-conditioned air, and 400 Hz ground power.

The utilization of 400 Hz ground power at the gates is one way SFO plans to reach its net zero goal. Before 400 Hz power was installed at SFO, aircraft had to use their auxiliary power unit (APU) to power their electrical equipment while at a gate. The APU provides electrical power for functions other than propulsion, allowing the aircraft's main engines to be turned off. APUs are powered by jet fuel, which still cause air pollution, noise pollution and increased operational costs. 400 Hz cables provide an alternative green and low-cost power directly from an airport's power grid, eliminating the need for aircraft to use APUs during the deplaning and enplaning processes.

The effectiveness of 400 Hz cables is directly dependent on the time during which they are plugged into the aircraft. In this study we address problems related to the connection of 400 Hz cables and suggest multiple solutions. Cumulatively, the study lays down the foundation for a 400Hz real-time monitoring system that would allow airports to enforce their environmental policies while helping airlines to save fuel and reduce emissions.

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1. Problem Statement and Background

In the last decade, environmental consequences of aircraft operations at airport-airside surfaces (e.g. taxiways and aprons) have not been addressed efficiently at US airports. Although many improvements have been done in reducing emissions while aircraft are in flight (such as better aircraft design and cleaner burning engines), these improvements are often reduced at US airports due to inefficient aircraft ground operations and the lack of airport control over aircraft movements in the apron/ramp areas. Recent studies have demonstrated the adverse impacts airports have on local air quality, especially due to emissions of nitrogen oxides and particulate matter from aircraft, which can cause respiratory ailments, and cardiovascular problems in exposed populations (Hudda, 2014).

Airports are making large efforts to address air pollution and to become more sustainable. Airport Sustainability Reports and Climate Action Plans are often effective means to strategically plan for sustainability and reduction in emissions. Airports with advanced "achieve zero" goals often have some of the following scopes: net zero energy, zero waste, and carbon neutrality and reduction of greenhouse gas (GHG) emissions by 50% from 1990 baseline. One of the leading airports in sustainability is San Francisco International Airport (SFO), which is planning to "achieve zero" by 2021. This means that the airport is exploring options that will reduce aircraft emissions on the ground, including emissions at a gate. We use SFO as a case study to understand current issues with managing and monitoring Auxilary Power Units (APUs) that aircraft use while being parked at a gate; and to understand how the alternative 400 Hz power, provided by an airport, can replace the use of APUs.

Before 400 Hz power was installed at SFO, aircraft had to use their APUs to power their electrical equipment while at a gate. The APU provides electrical power for functions other than propulsion, allowing the aircraft's main engines to be turned off. APUs are powered by jet fuel, which still cause air pollution, noise pollution and increased costs. 400 Hz cables provide an alternative green and low-cost power directly from an airport's power grid, eliminating the need for aircraft to use APUs during the deplaning and enplaning processes.

The effectiveness of 400 Hz cables is directly dependent on the time during which they are plugged into the aircraft. This study addresses the problems related to the connection of 400 Hz cables, and addresses them with multiple solutions and recommendations. Cumulatively, this study lays down the foundations for a 400Hz real-time monitoring system that would allow airports to enforce their environmental policies while leading airlines to save fuel and reduce emissions.

Therefore, the primary goal of this research is to develop a new method for monitoring and utilizing 400Hz (i.e., clean) energy at airports.

The objectives of this research are to:

- Review literature that relates to airport energy use, issues with emissions at airports, sustainability policies, climate action plans and models/software that reduce emissions at airports.
- Develop a model that showcases the energy consumption at gates based on the variance of aircraft type; provide an airport with an analysis tool they can use to input future data.
- Communicate with airline ground crew to understand how SFO policies work in practice.
- Verify usage of 400Hz ground power.
- Conduct an economic benefits study that uses the proposed Model as a tool for estimating, monitoring and improving clean energy use as alternative energy-saving technology into the airport environment.

2. Summary of Literature Review

Aircraft noise and local air pollution are the oldest and the biggest environmental issues faced by airports, which they have been dealing with for many decades. However, carbon emissions are, in some ways, a relatively new concern for airports. Officially, it was only in 2004 (ICAO, 2004) that the airline industry started to be concerned with carbon emissions. In addition, it was only in 2009 that the Guidance Manual on Airport Greenhouse Gas Emissions Management was released (ACI, 2009); and it was only in 2016 that ICAO issued an agreement for controling carbon emissions from international flights (ICAO, 2016).

Althoug the aviation contribution to global carbon dioxide emissions is between 2% and 2.5% (Lee et al., 2009, IATA 2017), it is expected that such emissions will increase in the future due to increases in travel demand and the continuous use of traditional fossil-fuel-based aircraft engines (Gössling et al., 2009; ICAO, 2010; IATA 2017). It is interesting to note that airports contribute about 5% of the overall aviation carbon dioxide (CO_2) equivalent emissions, which accounts for 95% of airports' greenhousegas (GHG) emissions (ACI, 2014).

2.1 APU Emissions

APU emissions (Figure 1) have been recognized as a significant source of airport pollution. Fleuti and Hofmann (2005) state that airport-handling of aircraft is usually the second largest contributor to local air pollution at an airport. It includes emissions from the non-moving aircraft, such as Auxiliary Power Units (APUs), all Ground Support Equipment (GSE) including Gtound Power Units (GPUs) for handling aircraft, but also vehicles circulating on airside premises (e.g. sweeper trucks, crew busses, catering trucks, cargo tractors, etc). In 2003, APUs contributed 18.5% to the NOx aircraft handling emissions at Zurich Airport (Fleuti and Hofmann, 2005).

Figure 1. Auxiliary Power Unit (Pratt & Witney)

Kinsey et al. (2012) conduct a study to determine the emissions from an aircraft APU during the Alternative Aviation Fuel Experiment sponsored by NASA. Their analyses results indicated that APUs can be a significant source of emissions at major airports, especially in metropolitan areas. They suggested the use of Fischer Tropsch (FT) fuel, that can substantially decrease emissions. Based on their analysis, the use of FT fuel could be a viable future control strategy for both gas- and particle-phase air pollutants.

Gwilliam (2010) discusses issues with emissions of aircraft operations at the airport airside (e.g. taxiways and aprons), which have not been reduced more aggressively. He correctly points out that most of the aviation emissions reduction has been advanced in the emissions of the aircraft in flight, both due to cleaner burning engines and more efficient aircraft design. However, once the aircraft lands, it seems that such benefits are annulled by inefficient ground operation policies and procedures. Examples of emissions and inefficiencies that reduce the benefits of these newer, cleaner more efficient aircraft are: long taxi times that keep jet engines idling, gasoline- and diesel-powered ramp equipment that could be electrified, and aircraft APUs that can be replaced by electrically powered ground equipment.

A comprehensive ACRP handbook (ACRP, 2012) provides airport practitioners with a better understanding of the existing APUs and the types of available alternative systems, including the associated emissions, energy consumption, and cost implications of implementing these alternative systems at airports.

Another APU harmful implication to human health is the noise caused by combustion of APUs that can cause cardiovascular, hearing, and psycological damages (Tubbs, 2000; Münzel, 2014). Noise from APUs is an important contributor to the overall level of ramp noise. Currently, ramp noise is regulated by international governing bodies as well as by individual airports. A significant component of APU noise is combustion noise. In the literature, suggestions have been made concerning a second combustion noise mechanism arising from the passage of hot entropy spots through the exhaust nozzle. In a stydy conducted by Tubbs (2000) no evidence has been found to indicate the existence of a second APU combustion noise component.

2.2 Energy and Sustainability Goals of Airports

According to SAGA (2019), efforts in achieving sustainability in organizations (including airports) are all unique and tailored around the specific nature of each organization. In general terms, sustainability is defined by the Triple Bottom Line (environmental stewardship, economic growth and social responsibility), while the airport industry lately has adopted the "EONS" approach to sustainability (economic vitality, operational efficiency, natural resources, social responsibility). Expanding the Triple Bottom Line by adding operational efficiency enables airports to have more influence over operating airport facilities efficiently. However, emissions of such facilites belong to Scope I, which are owned by airports (Figure 2), and therefore are managed by airports. One of US airports' pressing issues is their inability to directly influence aircraft operations on airport airside (e.g. taxiway and apron-ramp) surfaces, since aircraft emissions generated at airports belong to Scope 3 (indirect emissions, not controlled by airports). However, one of the means to reduce aircraft emissions while aircraft are at a gate is by reducing the use of APUs and utilizing clean energy (i.e. 400 Hz electricity) provided by airports. Such actions enable both airports and airlines to be more sustainable and energy efficient.

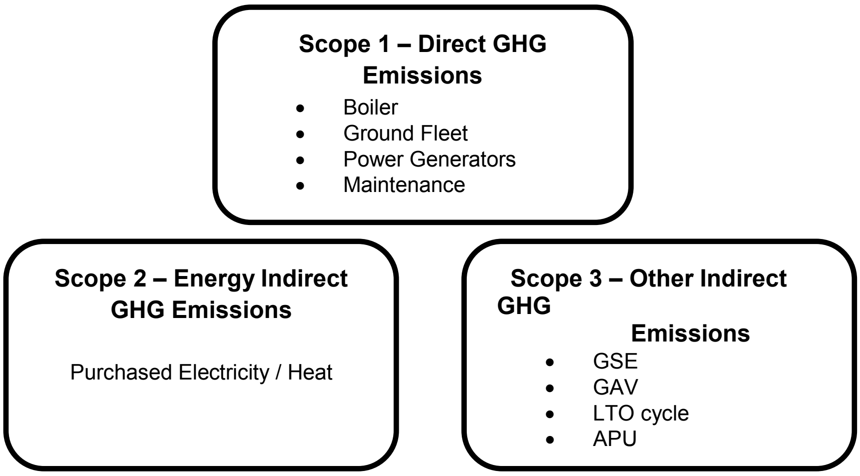

Figure 2. Airports emission sources by scope. (GSE: Ground Support Equipment; GAV: Ground Access Vehicles; LTO: Landing and Take-off; APU: Auxiliary Power Unit; collated from ACI, 2010)

Airport energy efficiency and cost reduction were well documented in ACRP (2010) but have focused only on best practices for energy efficiency in commercial buildings. To date, no airport-related studies of energy efficiency have been conducted in the area of management of airport 400 Hz power, and in APU utilization reduction at gates.

2.3 SFO Policy

SFO is a world leader in sustainability. According to SFO 2017 Climate Action Plan (SFO, 2018), the overall airport's goals are to achieve carbon neutrality by 2021 and reduce greenhouse gas emissions by 50 percent from a 1990 baseline. These goals were set by the Airport Commission in SFO's Five-Year Strategic Plan, adopted in 2016. SFO has worked toward: (a) reducing energy use in buildings and vehicles, (b) improving efficiency, (c) reducing leaks and energy losses, and (d) partnering with local businesses to find mutually beneficial emissions reduction opportunities.

In the SFO 5-year Strategic Plan 2017-2021 (SFO, 2017), one of the seven overall goals is to "achieve zero by 2021" by focusing on the following goals:

- achieve net zero energy,
- achieve zero waste,
- achieve carbon neutrality and reduce GHG emissions by 50% from 1990 baseline,
- implement a healthy buildings strategy for new and existing infrastructure, and
- maximize water conservation to achieve a 15% reduction per pax per year.

In FY17, SFO-controlled GHG emissions totaled 28,175 tonnes, which is 11% below baseline, but:

- there was 30% increase over FY 2016 GHG footprint of 21,768 tonnes, and
- GHG emissions from third-party operations, including aircraft activity, were estimated at 1,175,056 tonnes in FY 2017, an 8% increase over FY 2016 due to an increase in passenger volume and assumptions in the estimation methodology used that need to be re-tooled for SFO's current operations. Therefore, since aircraft activities belong to the third-party operations (Scope 3), emissions generated at gates can be partially reduced by utilizing airport clean energy instead of running APUs.

From the noise perspective, APUs cannot be used during certain hours: SFO regulation 11.4 (B) states that "at domestic terminals, the use of APU's is prohibited between the hours of 2200 - 0600 except 30 minutes prior to departure, when passengers are aboard, or it is needed to test other aircraft equipment. In the international terminals, aircraft scheduled to be at a gate in Boarding Areas A and G for more than 45 minutes between the hours of 0700 – 2200, are required to use 400Hz ground power and pre-conditioned air, where available. Between 2200 – 0700 hours, all aircraft are required to use 400Hz ground power and pre-conditioned air, where available, regardless of the duration at the gate. At any time of day, APU's are not authorized without prior permission from Airport Operations until 30 minutes prior to push-back." (SFO, 2012)

2.4 Summary

After reviewing relevant academic and industry literature, we did not find any literature that proposes a system for the 400 Hz power management at gates. We believe that such a system will significantly decrease fuel burn by APUs and consequently reduce apron emissions.

3. Problem Solving Approach

In response to SFO's ambitious sustainability goals our team developed a case study to understand the effectiveness of SFO's technologies and policies put in place to achieve those goals. We established a working relationship with SFO's sustainability team and obtained data on the largest operational loads for SFO's terminal buildings: baggage handling, ground service equipment, pre-conditioned air, and 400Hz ground power.

Our team decided to focus on analyzing the energy loads of the 400Hz ground power at SFO, because of the large sets of data and the large environmental impact associated with its use. A total of 55 gates have been equipped with PC air and 400Hz power. All gates in International Terminal A and G, five gates in Boarding Area C, six gates in Boarding Area F, and all twelve gates in Boarding Area E are equipped with PC air and 400Hz ground power. These 400 Hz cables are installed with an energy meter, which allowed our team to understand where and when power was being consumed. With this data, in combination with flight data about gate-in and gate-out time, our team could determine if the 400Hz cables were being used to their full potential, whenever an aircraft is parked at a gate.

Using Python code on a Jupyter Notebook, our team combined and analyzed the databases to produce power consumption probability distributions for aircraft waiting at a gate. We provided this analysis for every gate and aircraft subtype. This initial analysis provided a key insight: a significant fraction of aircraft was not consuming 400Hz power while waiting at the gate, meaning that they were running on their more expensive and more polluting APUs.

After some discussion, we understood that SFO had no system in place to monitor how effectively the 400Hz cables were used, because the meters were solely used for energy pricing.

We understood that the main value of our analysis was in being able to monitor the performance of 400Hz ground power, even if not in real time at the moment. The computer code could point out when and what aircraft didn't use 400Hz power during their turnaround time. We figured that if we could improve the accuracy of our analysis and have it run in real-time, we could have a monitoring system that would allow airports and airlines to immediately recognize and tackle issues in their use of the 400Hz ground power. That would allow the airport and the airlines to collaborate and reduce costs and emissions associated to powering aircraft waiting at the gate.

Our data analysis of a terminal's energy loads was transformed into a design to increase the effectiveness of 400Hz ground power use. This design would not simply consist of a software that processes data, but would try to improve and integrate all aspects of the 400Hz system. Our design goal was to:

- Recommend solutions to existing problems with the current hardware.
- Recommend solutions to practical and logistical challenges with 400Hz connections.
- Create a concept for a software that would collect data and analyze it in real time.
- Create a concept for a user-friendly display that airport operators could use to interpret the results of the analysis.

To accomplish these goals, our team performed on-site research at SFO, interviewed ground crews and other airport operators, and finessed the Python code to most closely resemble what the monitoring system would look like. The detailed explanation in the following technical description encapsulates the conclusions of our work.

4. Technical Description

We consider four separate elements in the proposed design, aiming to improve the performance of 400Hz ground power supply of airports. First, we discuss the 400Hz ground power cable. Second, we consider the metering hardware that collects data on power consumption through the ground power cable. Third, we conceptualize a computing software that performs a real-time data analysis of power consumption. Fourth, we present a computer display, which showcases the results of the analysis and instantly identifies problems with the 400Hz ground power system. These elements would work interdependently to allow an airport to monitor how airlines use the clean, low-cost electrical power that it supplies (Figure 3)

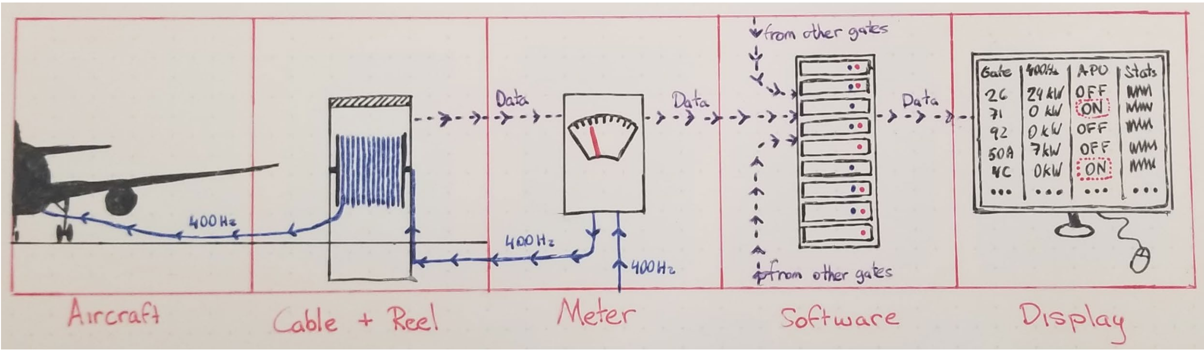

Figure 3. Proposed Diagram of Real-time Monitoring System

4.1 The 400Hz Cables

400Hz ground power cables are a field-proven technology that has helped airports and airlines around the world to lower costs and emissions. Although 400Hz cables come in different lengths and colors, their design is essentially universal throughout the world. The 400Hz outlets on the aircraft are also universal, although wide-bodied aircraft require two cables to handle the increased power demand. These cables supply power from the airport's electrical grid directly to the aircraft, allowing the captain to turn off the aircraft's APU, which would instead burn jet fuel to produce electrical power.

Because electricity from the grid is significantly and increasingly green and less costly than electricity produced by an APU, it is in everyone's interest to use the 400Hz ground power as much as possible. This means the ground crew should connect the cable as soon as they can when an aircraft arrives at a gate, and should disconnect the cable as late as possible when the aircraft is about to leave a gate. If the APU is still on when the 400Hz cable is connected, it will override the 400Hz power supplied by the cable, meaning that the captain should turn off the APU as soon as the cable is connected and should turn the APU back on as late as possible, before the 400Hz cable is detached. If the 400Hz cable is detached before the APU is turned on, the aircraft will lose its electrical power and will require around 10 minutes to restart. In the cabin, the captain has an indicator that shows whether the 400Hz cable is connected, but it is possible that it might not be noticed immediately.

There are several problems involving the 400Hz cables that prevent them from being used at all times:

- The cables are bulky, long and heavy. Portions of a cable can be slowly dragged by a single member of the ground crew. Not only does that take around a minute away from using the 400Hz cable power instead of the APU, but it also causes damages to the cable - particularly to the plug itself. According to an Alaska Airlines ground crew member at SFO, damage to the 400Hz cable plug due to dragging is the primary reason that 400Hz power may not be used. It can take up to 2 days to fix damaged 400Hz cables or plugs, during which time the aircraft have to rely upon their APUs.
- The cables often get tangled, further complicating the ground crew’s task of getting the cables into place and attaching them to the aircraft. Cable entanglements are especially common for gates equipped with 2 cables, in order to service wide-bodied aircraft.
- When an aircraft is not present, the cables are stored hanging off the side of the jet bridge. Each cable has external rings at intervals along its length that are used to attach it up to a metal bar with several hooks. This metal bar can be raised and lowered with a pulley system that can be controlled from the bottom of the jet bridge. To prevent

damage to the cable(s), SFO has programmed the systems such that it is not possible to move the jet bridge while the cable is lowered. Therefore, before the cable can be lowered from the jet bridge, dragged and connected, the aircraft needs to stop and the jet bridge needs to be moved to its final location. While this also impacts departures, pilots typically turn on APUs as part of their start-up sequences around 10 minutes (or more) before departure. For arriving aircraft, the movement of the jet bridge prevents the 400Hz cable from being plugged in for around 3 minutes. This is an unusual operational policy that is not present at many airports.

In this design, we include several recommendations to improve the 400Hz cable:

- To prevent damage to the 400Hz cable plug due to dragging, we recommend that airlines install removable plastic protective covers onto the 400Hz plugs. Because all 400Hz plugs are the same, these protective covers could be produced in bulk for a low cost. The covers could have the feature of being attached to the 400Hz cable so that they do not get misplaced or lost when they are removed from the cable. With such a protective cover, the ground crew can drag the cables without damaging the parts that are essential to their function.
- To mitigate the tangling of the 400Hz cable plug and to facilitate the work of the ground crew, we recommend revisiting the way the 400Hz cable is stored when it is not used (Figure 4). Instead of having several hooks on a pulley system, we recommend a motorized reel for each cable. Using a motorized reel will relieve some of the heavy work from the ground crew, will reduce the tangling of the cables over time and will protect the cables from environmental factors while they are not being used.
- To mitigate the lost time due to the positioning of the jet bridge, the 400Hz cable and the jet bridge should become independent of each other. A simple solution would be to

reprogram the jet bridges so that the 400Hz cable can be lowered before the jet bridge come into final position. However, that would bring forth safety and equipment concerns because the jet bridge could run over the cable or pull on the cable before it is detached from the aircraft. When this happens, the entire bridge box can be ripped from the wall of the jet bridge, resulting in weeks of unnecessary delay. To prevent this, airports should consider placing the 400Hz cables and electrical boxes on non-moving parts of the apron area, not affixed to the jet bridge. The use of a pop-up 400Hz unit installed under the surface of the apron area could be operated as soon as an aircraft arrives (Figure 5), without having to wait for the jet bridge to move. Such a system can be combined with the use of a motorized reel to alleviate the work of the ground crew and to allow the 400Hz cable to extend long distances, servicing a wide variety of aircraft.

Figure 4. 400Hz cables at SFO

Figure 5. Pop-up 400Hz cables in Hong Kong (Ref: McFadyen)

- For the purposes of a 400Hz power monitoring system, it would be useful for the airport to know when a cable is plugged into the aircraft. Currently, an aircraft's system recognizes when this occurs, but the airport does not. The plugin and plug-out time are crucial pieces of data to determine whether the 400Hz cable is being used effectively, along with the rate of power draw available in a real-time format. It would be ideal to replace current cables with "smart cables" that can understand whether they are plugged in and drawing power, but such a solution would be expensive and could negatively impact the 400Hz cables' universal nature. Another option is to have the pulley (or reel) provide data for when the cables are lowered, and to have a metering system track interval usage on a 5- or even 1-minute basis.

4.2 The Metering System

A metering system is often present wherever there is a 400Hz ground power cable (Figure 5). Because 400Hz power is generated at dedicated centralized points, metering occurs on the dedicated 400Hz cables which serve individual gates. The meters were installed with the purpose of billing airlines for their energy consumption. In the case of a gate leased by a single airline, the airline pays monthly for the energy used. In case of a shared gate, airlines pay a predetermined fraction of monthly energy usage. Most 400Hz meters record the hourly cumulative energy consumptions at SFO. With a single data point at every hour, the amount of data analysis for a flight's consumption is rather limited, as flights rarely spend more than a couple of hours at a gate. The placement and data collection of the meters for 400Hz ground power cables was driven almost exclusively for the purpose of billing, but it could be modified to serve the airport's sustainability goals.

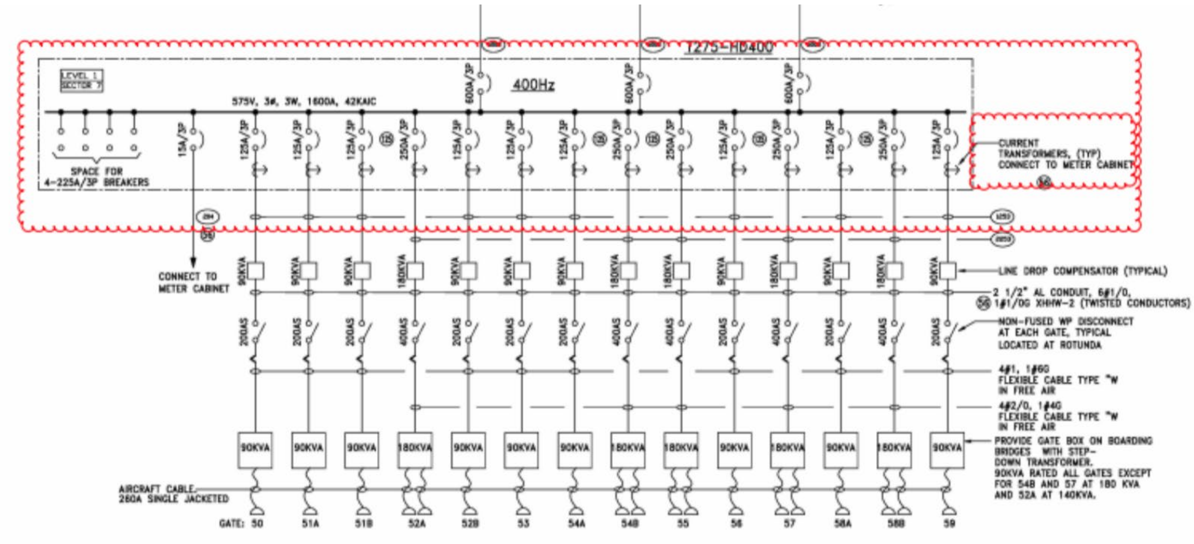

Figure 5. 400Hz Line Diagrams at SFO (Ref: SFO)

In this design, for the purposes of a 400Hz power monitoring system, we include several recommendations to improve the metering of 400Hz power:

- The accuracy and precision of the envisioned monitoring system are greatly impacted by the granularity of the data that the meters provide. The shorter the time interval between readings on each meter, the more the calculated power for that interval is accurate. With more granular data, there will be more data to be processed, but that comes at no additional cost. Therefore, we recommend that every meter be reprogrammed to collect data more frequently. Collecting energy readings every 5 minutes instead of every hour would bring dramatic improvement to the data analysis. Collecting energy readings every minute would be even better. In addition, if the 400Hz cable is able to recognize when it is connected, the meter could be programmed to take a data point for the exact moment the cable is connected or disconnected. After discussing this need for more granular data, SFO reprogrammed its meters to take data every 5 minutes instead of every hour. This happened in March 2019, which will allow for a better analysis once enough data is collected.
- Analyzing the performance of a 400Hz system at a certain gate requires a meter to be

recording down data for that gate. Unfortunately, that is not always true. Several gates might be grouped together under one meter and some gates might not have a meter at all. Without any data for a specific gate, the airport is ‘blind’ and will not be able to collect useful information or identify a problem. Therefore, we recommend that for every gate there should be a meter that is specific to its 400Hz power consumption.

- To understand how much power is consumed by an aircraft connected with a 400Hz cable, the meter must exclusively measure the energy load of the 400Hz cable. If loads from other systems are also being measured with the same meter, it becomes challenging to single out the load of the 400Hz cable. After the first iteration of our data analysis, our team observed a ‘phantom’ base power consumption of 0.5-1 kW (depending on the gate), independently of whether an aircraft is connected with a 400Hz cable. Although this base consumption is small in comparison to when an aircrft is connected (5-50kW), it is continuous through the year and ends up accounting for 10-20% of the total energy consumption measured by the meters. Despite contacting the manufacturer, neither we nor the team at SFO have been able to identify what the cause of this ‘vampire’ load is. It is important that this be determined and that either SFO or the manufacturer work to reduce or eliminate it, as appropriate.
- To be able to have a real-time monitoring system, the data produced by the meters must be made accessible in real-time. We recommend that the meters be programmed to immediately send their data to a database linked to a dynamic energy analytics tool that would then perform the data analysis in real time.

4.3 Data Analysis

The analysis of the 400Hz ground power is the main pillar of the design of this monitoring system. In an ideal design, the analysis would take readily available data from an airport and its airlines to produce useful information in real time. The workings of such an automated data analysis largely depend on the data it is supplied with and by what is considered useful information. In our interaction with the energy and sustainability teams at SFO, our team learned about what data was available and about what the desired results of such an analysis would be: (1) to provide statistics about the ground power consumption of aircraft that successfully connects the 400Hz cable(s), and (2) to identify the failed connections. As a result, we developed two separate ways to obtain the desired results, described in detail in the sections below.

4.3.1 Non-Collaborative Analysis

In the event that the airport wishes to monitor 400Hz power consumption without the assistance of airlines, they will have to use only internal airport-owned systems and data. The following sections showcase how this analysis would work.

4.3.1.1 Data

SFO provided us with data to perform the analysis for 30 gates at the airport between July 1, 2017 - June 30, 2018. Figure 6, a database interaction diagram, shows the databases that were provided and the way they were analyzed:

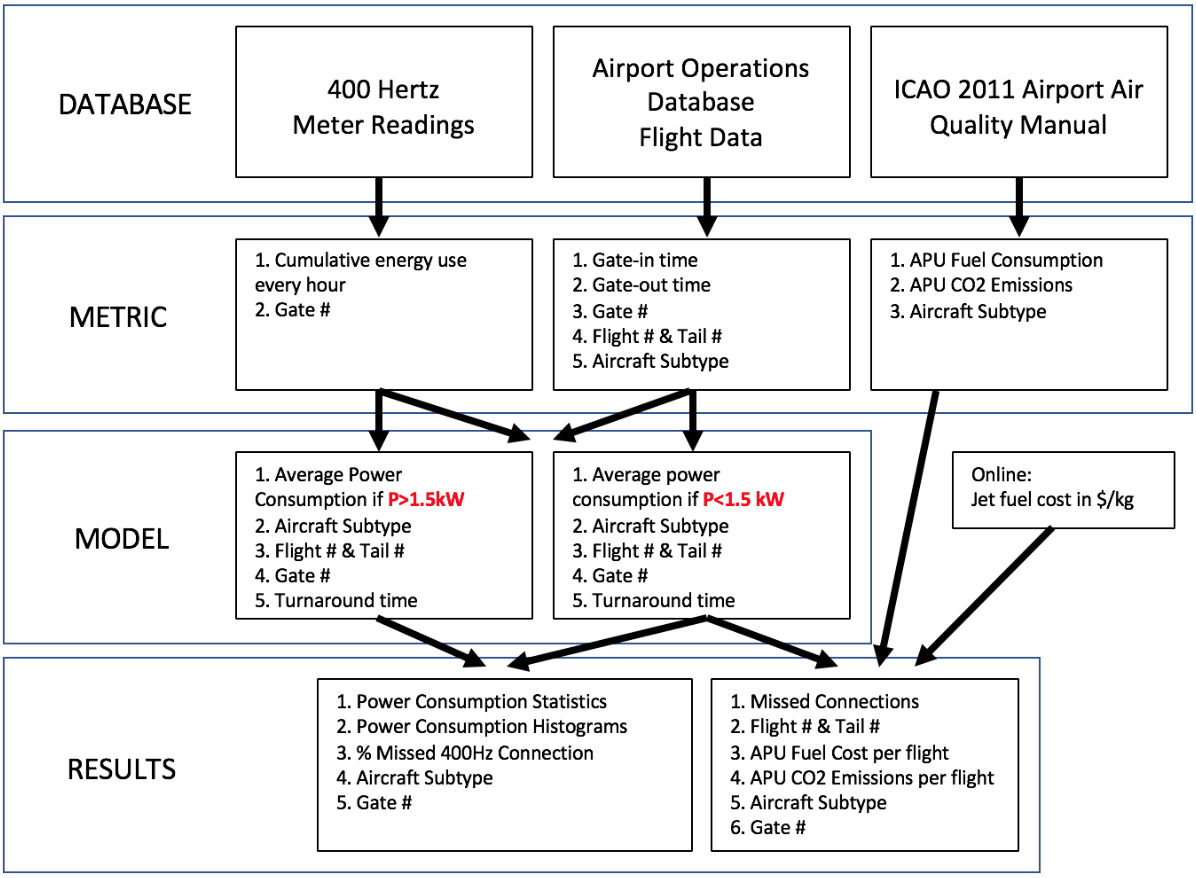

Figure 6. Database Interaction Diagram

4.3.1.2 Assumptions

- The aircraft's arrival and departure time from a gate matched the time that the 400Hz cable was connected and disconnected. We know that cables were actually connected and disconnected a few minutes after arrival and before departure, but the gate timestamps are the most accurate data available. In our envisioned design for the 400Hz monitoring system, exact timestamps for cable connection and disconnection would be used.
- Flights that stayed at the gate overnight were excluded from the analysis.
- The power consumption of the aircraft through the 400Hz cable was constant throughout every one-hour interval reading available from the meter.
- We assumed the price of aviation fuel is $2.00 / gallon. (A4A, 2019).

4.3.1.3 Code

Our team wrote the computer code to analyze the data using Python in a Jupyter Notebook.

Figure 7 depicts a small fraction of the computer code:

```
def getGates(hertzTable, gateNo):
    Gate_cleaned=hertzTable.drop('Timestamp').drop('Gate').drop('Year').drop('Month').drop('Day').drop('Hour')
    FlightDataGate=FlightData.where('GATE',are.equal_to(gateNo))
    dates = FlightDataGate.group('Date Indicator').column(0)
    FlightGate_w_Energy=FlightDataGate.join('Combined Code (Gate)',Gate_cleaned,'Combined Code (Gate)')
    tailNo = make_array()
    energyTotal = make_array()
    minDiff = make_array()
    turnAround = make_array()
    time = make_array()
    for i in np.arange(len(dates)):
        Individual_Date=FlightGate_w_Energy.where('Date Indicator', are.equal_to(dates.item(i)))
        Tail_Number_w_ARRDEP=Individual_Date.group('Tail Number').where('count',are.equal_to(2))
        FlightGate_w_Filter=Individual_Date.where('Tail Number', are.equal_to(Tail_Number_w_ARRDEP.column(0)))
        mini = FlightGate_w_Filter.column('Hour')*60 + FlightGate_w_Filter.column('Minute')
        newFG = FlightGate_w_Filter.with_column('Total', abs(mini))
        filteredFlight = newFG.group('Tail Number', np.diff)
        minDiff = np.append(minDiff, filteredFlight.column('Real Energy Total (kWh) diff')/filteredFlight.column('Total diff')*6
        tailNo = np.append(tailNo, filteredFlight.column(0))
        turnAround = np.append(turnAround, abs(filteredFlight.column('Total diff')))
        energyTotal = np.append(energyTotal, abs(filteredFlight.column('Real Energy Total (kWh) diff')))
        for z in np.arange(len(filteredFlight.column(0))):
            time_of_arrival = newFG.where('Tail Number',are.equal_to(filteredFlight.column(0).item(z))).column('ACTUAL_AOD_TIME'
            time = np.append(time, time_of_arrival)
    gated = Table().with_columns('Tail Number', tailNo,
                                 'Real Energy Total(kWh)diff', energyTotal,
                                 'Real Energy Total(kWh)diff per hour', minDiff,
                                 'Turn Around Time', turnAround,
                                 'Arrival Date and Time', time)
    gated_filtered=gated.where('Real Energy Total(kWh)diff',are.not_equal_to(0)).where('Real Energy Total(kWh)diff per hour',are
    return gated_filtered
```

Figure 7. 400Hz Monitoring System Code Snippet

The code has two inputs: a table and a gate number. The table is the raw data given by SFO and the gate number is the desired gate that the user wants to investigate. The code cleans up the raw data and extracts data needed for the analysis. For the analysis of a gate, the data extracted are the list of flights that arrive and depart from a certain gate and the energy metering data from the same gate. For the energy metering data, there are records at every hour and each hour has its own code called the "Combined Gate Code".

After extracting the raw data, they are cleaned up. We only include flights that have both an arrival time and a departure time in order to only consider aircraft which remain at the gate for the entire time. We also only consider flights that have a turnaround time of 300 minutes (5 hours) or less, because flights with a longer turnaround time typically shut down the aircraft entirely and do not use the APU and the 400Hz cable. Then, the remaining flights are matched up with the corresponding energy metering data using the “Combined Gate Code”. As most of the data are very granular, we can only assume that the energy difference between two energy metering records (between a flight’s arrival and departure) is the amount of energy used by that flight.

Then, the energy is converted into hourly power used by dividing it by turnaround time, multiplying it by 60 minutes, and dividing it by 1 hour. For each subtype of aircraft, we find the average of the hourly power used and its standard deviation, the maximum power used, and the number of flights that do not connect, where power used is below 1.5 kW. 1.5kW is the cutoff because it is the base power consumption of the 400Hz gatebox without any flights on it.

For these flights that do not connect, we calculate the fuel cost that airlines have to pay when their aircraft is not connected to the 400Hz cable, and we also calculate the amount of carbon dioxide that is produced from the APU usage. Figure 8 summarizes the coding process.

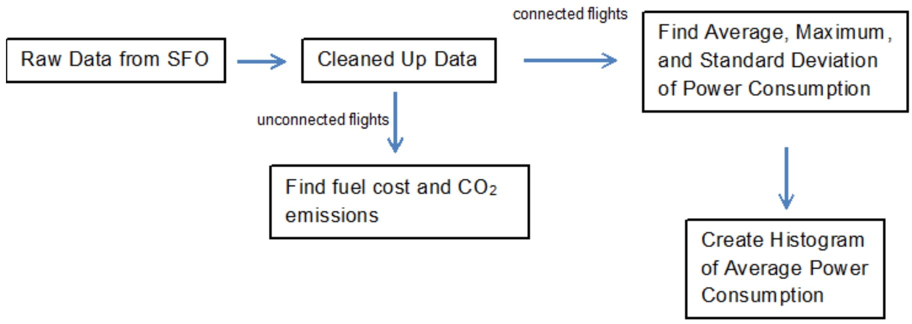

Figure 8. Summary of the Coding Process

4.3.1.4 Results

Analysis results are obtained for every aircraft subtype at every gate for which we had data for the 2017-2018 year. As an illustration, Table 1 provides results for a single domestic gate at SFO, leased by a major US-based airline.

Table 1. General Information Table

Aircraft Type	Number of Failed Connections (Below 1.5 kW Used)	Percentage of Failed Connections (Below 1.5 kW Used)	Average Power Used (kW), above 1.5 kW	Standard Deviation of Average Power Used (kW)	Max Power Consumption (kW)	Turn Around Time Averag e (min)	Count
319	0	0	18.9571	7.12496	31.5119	126	14
320	7	0.056	23.0835	6.77786	38.7667	88.072	125
321	1	0.25	23.1011	6.83877	29.4668	71.25	4
737	0	0	17.4635	5.22224	25.35	60.5	4
738	32	0.195122	17.1626	7.53448	46.7375	71.0061	164
739	61	0.165761	16.6548	7.01688	36.3655	72.8451	368

In Table 1, the first set of results for the gate is shown. For every aircraft subtype, we determine what percentage of flights consume less then 1.5kW during their turnaround time to determine how many flights unsuccessfully used the 400Hz power from the airport. In addition, for the flights that did connect, we calculate the average, the standard deviation and the maximum of the power consumption. For each aircraft type, the computer code also generates a histogram that displays the distribution in power consumption. Below are three of those histograms for the gate. Figures 9 to 12 are four histograms for average power consumption at a typical domestic and international gate. Figure 13 shows the cutoff line in a histogram that separates flights that failed to connect and flights that connected.

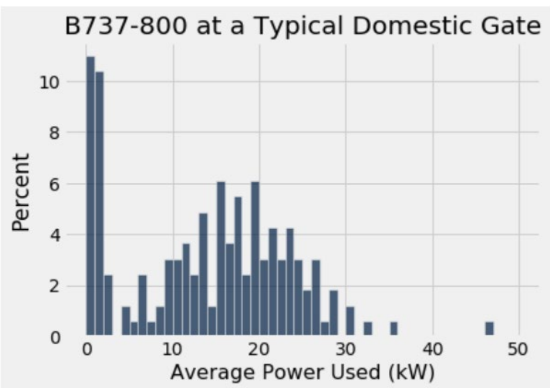

Figure 9. B737-800 at a typical domestic gate

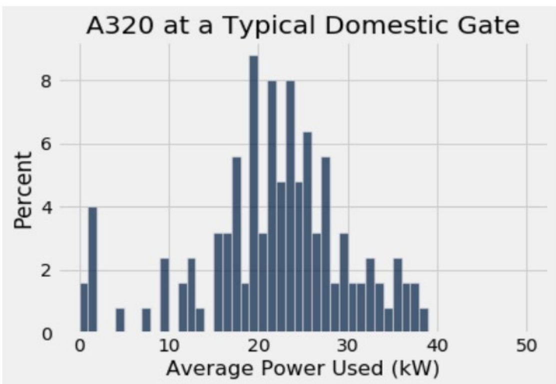

Figure 10. A320 at a typical domestic gate

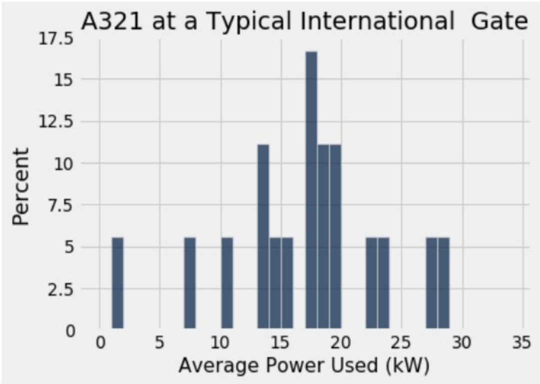

Figure 11. A321 at a typical international gate

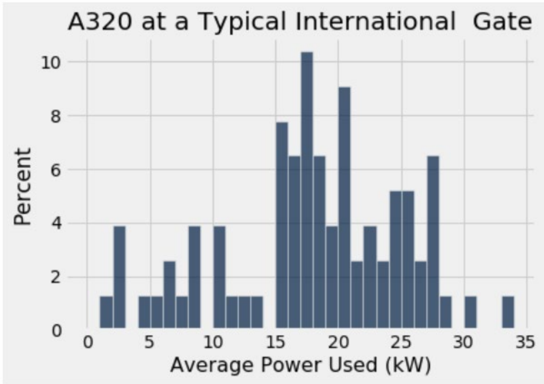

Figure 12. A320 at a typical international gate

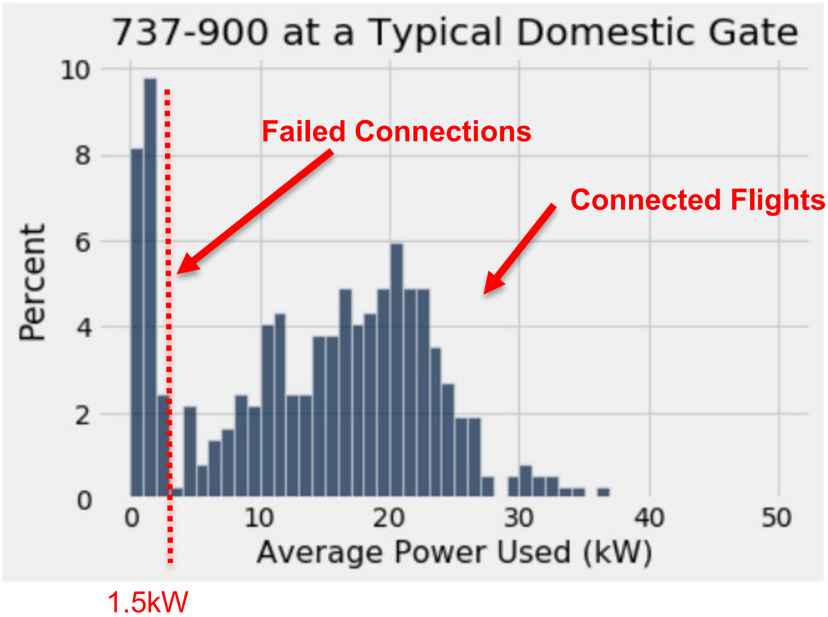

Figure 13. Average Power Used: B737-900 at a Typical Gate

Table 2 displays the flights that failed to consume more than 1.5kW, and therefore probably failed to connect the 400Hz cable. For each flight, we estimate the APU fuel emissions and cost associated with the failed connection by multiplying their turnaround time with the fuel emissions and fuel cost factor provided by ICAO.

Table 2. Failed Connection Table - Individual Flights

Tail Number	Average Power Used (kW)	Aircraft Type	Turn Around Time	Arrival Date and Time	Failed APU Connection Fuel Cost ($)	Failed APU CO2 Emission (kg CO2)
Aircraft #1	0.939677	320	62	6/18/2018 13:32	72.5185	347.2
Aircraft #2	1.07778	320	54	6/19/2018 13:19	63.1613	302.4
Aircraft #3	0.730307	320	163	5/8/2018 11:11	190.654	912.8

... (98 rows omitted)

It is evident from the results that missed connections are a common occurrence and therefore a significant problem. In the example of this gate and airline, up to 20% of the aircraft did not properly use 400Hz power. The exact reason for the failed connection cannot be determined from the data, but it could be due to a multitude of reasons. For example, the cable could be disconnected, the cable could be connected but malfunctioning, the captain might have not turned off the APU, or the aircraft might be completely shut off. By providing a flight number and a date for each failed connection, the airport might decide to inquire further into the cause for the unsuccessful connection.

4.3.2 Collaborative Data Analysis

If the airport collaborated with the airlines, and the airlines were willing to share the data collected by their aircraft, the results of such analysis would be much more accurate. An aircraft's systems directly monitor its power consumption, APU usage, and whether the 400Hz cable is being used. This data would be ideal, but it would require every airline to agree to share it, and an integrated software that can process the data from different airlines (Figure 14).

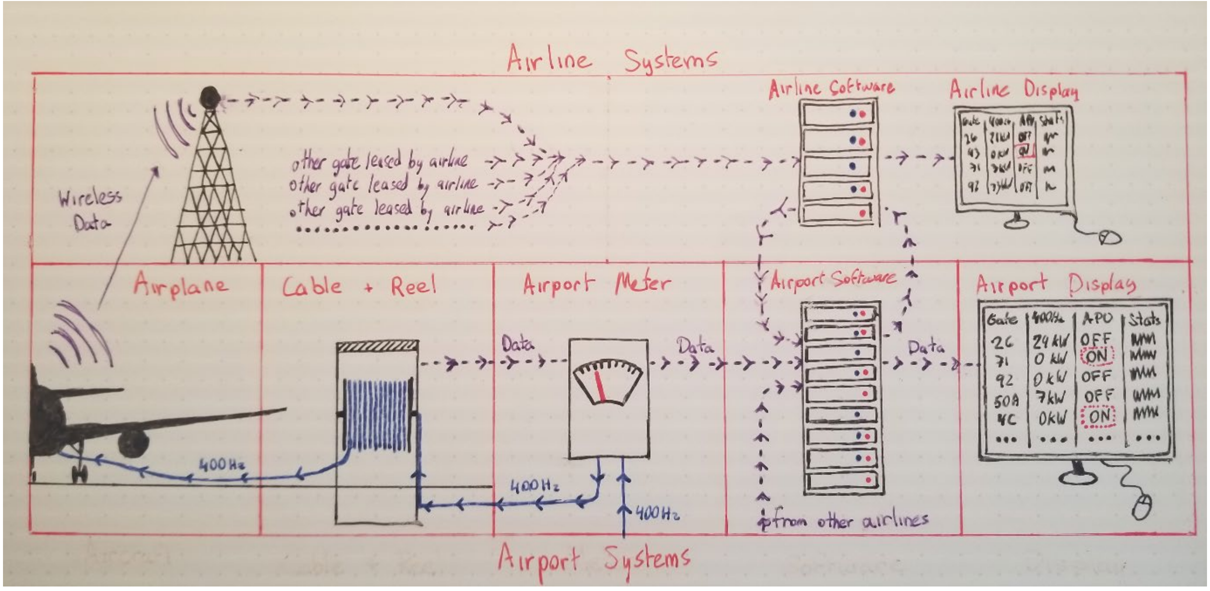

Figure 14. Proposed Collaborative System

Depending on the airline, the data is shared in real-time with systems outside the aircraft. Alaska Airlines, for example, already has a monitoring system that alerts the airline whenever the 400Hz cable has not been plugged in. If the 400Hz cable has not been connected within 5 minutes of the gate-in time, the ground crew will receive a call asking for an explanation. If the data that Alaska Airlines uses to monitor its flights was shared with the airport, the airport would be able to understand the use of its 400Hz cables in a more precise way than by using the current meters.

A real-time collaborative data collection between airlines and airport would be an ideal alternative for the data analysis, but it could not be implemented as fast and easily as a non-collaborative system.

4.4 Display of the data

The last element of the proposed monitoring system is the user interface through which an airport operator can understand how the 400Hz power is being consumed at each gate. This would be a computer software that uses the results of the data analysis to display all the information in an effective and organized manner. We recommend that the software should have the following features:

- The monitoring system should display the 400Hz connections in real time, along with information about the power consumption. For every gate, the operator should know the aircraft type, whether the 400Hz cable is plugged in and whether the APU of the aircraft has been turned off. In the event that there is an unsuccessful connection, an alert can point out where it is occurring so that immediate action can be taken to reduce costs and emissions.
- The monitoring system should also be able to provide a summary of the performance of the 400Hz ground power system for extended ranges of time. The airport should be able to understand how certain gates perform and to what degree the airlines respect the airport's policy on 400Hz power use (Figure 15).

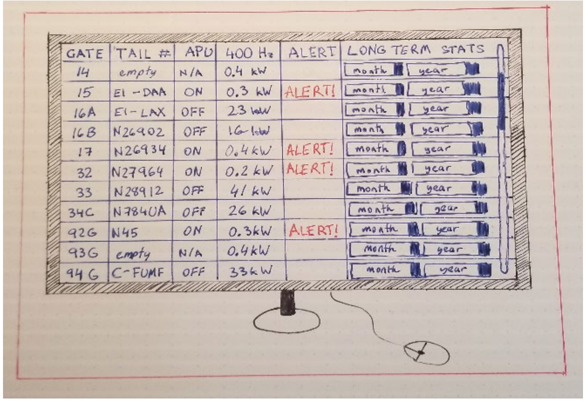

Figure 15. Smart Display

The 400Hz cables, the energy meters, the data analysis and the user interface are the 4 elements that together would allow for a detailed monitoring of the use of the 400Hz power that the airport provides. With a monitoring system, the airports have a basis for comparison and can then take steps to change their contracts, their policy and operations and observe how they will impact the performance of the 400Hz system.

5. Interaction with Airport Operators

Our team worked in close collaboration with a diverse group of experts from the airports, airlines, consulting firms, and the FAA. As UC Berkeley maintains close collaboration with SFO, our primary interaction was with employees from SFO. Phone calls, email and site visits were crucial in providing our team with the essential data for both our data analysis and practical understanding of the operations revolving around the 400Hz connections.

Benjamin Gould, Sustainability Analyst, and Jonathan Kocher, Associate Mechanical Engineer, were the two SFO employees that closely followed and contributed to the development of our data analysis and design. They provided our team the necessary data for our research, connected us to other industry experts at SFO, and guided us during a site visit in the apron area of SFO. Most importantly, their experience and expertise were fundamental in understanding the value of our analysis and to direct our efforts toward formulating a design of greatest interest for someone working within the industry. When our team would present them the results, they would provide us with further leads and contacts to deepen our understanding of the issues surrounding 400Hz connections.

Ron Cook, an Operations Manager for Alaska Airlines at SFO, has been working with ground crews in the apron area for the past three decades. Our team met with him on several occasions to understand the practical nuances related to 400Hz connections, his experiences with missed connections, and his perspective on what could be improved for the benefit of the ground crews. He explained how 400Hz connections for his airline have their own monitoring system that works using data collected directly by the aircraft, which prompted our team to consider an alternative collaborative data analysis with the airlines. He explained how ground crews tend to drag the cables on the apron floor, causing the plug to be damaged, which prompted our team to consider a solution.

Byron Thurber, Senior Airport Planner at Arup, SF office, with expertise in airport apron design, commented that our proposed improvements in the management of 400Hz cables is a good idea because it minimizes potential accidents and provides cleaner aprons. He pointed out that we should be aware of the current FAA definition of gate type categories -- there are only four gate-type categories, and the airport authorities determine the type of gate needed for the different aircraft mix based on wingspan and fuselage length as the two significant determining factors in choosing the gate size and dimension that are deemed fit for a particular aircraft. Reviewing the FAA standards for gate type categories was useful in understanding the overall apron design issues and gate sizing with respect to the cable length and power plug location.

Frank Ketchum, a pilot at Delta Airlines, thinks that the envisioned monitoring system is very useful since airlines are always interested in reducing costs of operations, i.e., consuming less fuel. He shared that airlines might not be open to sharing their 400Hz gate data with other airlines, especially if airlines utilize an exclusive gate-sharing policy. As a response to this comment, we conducted the economic analysis, which suggests that airlines will have monetary benefits if 400Hz cables are better and faster connected, and if there is a common platform for monitoring the airport-gate electricity use.

6. Impact

6.1 Impact on Policy

With the ability to monitor airlines' use of 400Hz power, SFO gains new insight into 400Hz power usage and can better set and enforce associated policies. Using a monitoring system, SFO can identify noncompliance and either alert ground crews or, if needed, levy enforcement penalties against airlines that fail to meet performance standards. In addition, because the monitoring system provides information on the failed connections, SFO's policy can be rewritten to better recognize and accommodate the uncontrollable instances of those failed connections and to help the airport gain insight as to what additional operational practices may help facilitate compliance. With better data available to airlines, they can also collaborate in these efforts to ensure proper use of 400Hz power and reduce the frequency and likelihood of failed 400Hz connections.

The monitoring system might also affect policies for airports other than SFO. It is in the best interest of both airports and airlines to reduce APU fuel consumption, and if the monitoring system at SFO is successful at enabling and driving further reductions in APU use, other airports would likely follow suit. The benefits of the monitoring system would then have much greater impact. If aircraft captains, ground crews, and airport designers were trained to maximize the use of 400Hz power in alignment with more stringent policies, better environmental practices will become ingrained in the operations of airports throughout the US and around the world.

6.2 Impact on Operation

The proposed design would mostly influence the ground crews that are responsible for the connection and disconnection of the 400Hz cable. Because moving the jet bridge and plugging in the 400Hz cable would not be sequential tasks anymore, the ground crew's operation would require less time. With a motorized reel and a protective cover for the cable, the positioning and storing of the 400Hz cable will be made quicker and the cable itself will become more durable.

The aircraft captains would also change the timeline of the tasks they have to perform once an aircraft stops at a gate. Instead of waiting several minutes to turn off the APU on arrival, the captain can do so less than 1 minute after arrival at gate, as soon as the ground crew has plugged in the 400Hz cable. That would reduce the chance that the captain fails to recognize that a 400Hz cable was connected and turn off the APU.

Because of the monitoring system, the airport will be able to identify problems and take immediate action to resolve them. In the case of a single failed connection, the airport might give a call to the airline to alert them. In case of a pattern of failed connections that is correlated to a certain terminal, gate, airline, or time, the airport can take more serious action to prevent it. In case of repeated failed connections at a gate due to malfunctioning equipment, the airport can promptly send a maintenance crew to fix it, or coordinate with the airline ground crews to ensure a timely repair.

In addition, this monitoring system collects very useful data on the power demand of aircraft at the gate. By understanding the statistics behind an aircraft's power consumption, an airport can more efficiently design future 400Hz systems and the airports electrical grid.

6.3 Safety and Risk Assessment

According to the Cambridge English dictionary, safety is defined as "a state in which, or a place, where you are safe and not in danger or at risk." Therefore, safety is the absence of risk. In this section we describe inherent risks in our proposed design and describe how these risks should be addressed to ensure safe operations.

Our proposed design is mainly algorithmic and requires changes in the airport's digital communication systems rather than physical structures. Therefore, many safety concerns with construction and physical alteration of airports do not apply here.

The following paragraphs look at risk assessment of our design from the Safety Management System (SMS) Manual -- Safety Risk Management (SRM) process, and the FAA Advisory Circular 150/5200-37 Introduction to Safety Management Systems for Airport Operations Safety Risk Assessment (SRA) points of view.

The SRM Process under the SMS Manual consists of the following steps:

A. Document proposed NAS changes regardless of their anticipated safety impact

B. Identify hazards associated with a proposed change

C. Assess and analyze the safety risk of identified hazards

D. Mitigate unacceptable safety risk and reduce the identified risks to the lowest possible level

E. Accept residual risks prior to change implementation

F. Implement the change and track hazards to resolution

G. Assess and monitor the effectiveness of the risk mitigation strategies throughout the life-cycle of the change

H. Reassess change based on the effectiveness of the mitigations

Similarly, the FAA Advisory Circular 150/5200-37 lists these steps as phases for Safety Risk Management:

Phase 1. Describe the system

Phase 2. Identify the hazards

Phase 3. Determine the risk

Phase 4. Assess and analyze the risk

Phase 5. Treat the risk (i.e., mitigate, monitor and track)

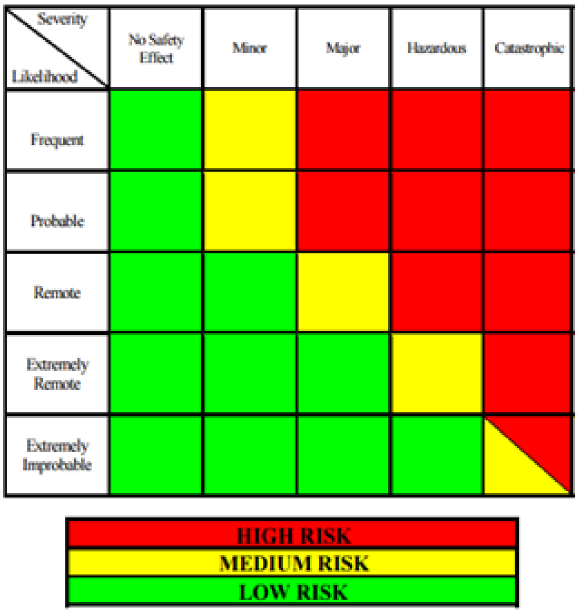

Figure 16. Safety Risk Matrix (FAA, 2007)

In addition, Figure 16 presents the safety risk matrix (FAA, 2007) that was used as a guideline for identifying the level of risk imposed by our proposed Model.

Our Model includes four elements: the cable improvement, the metering hardware, software model and software display. The proposed improvements to the cable directly improve the apron's system safety: (1) a disposable plastic protective cover for the 400Hz cable plug directly enhances cable safety by avoiding damages to the cable that can occur if the ground crew drags the cable; (2) using a motorized reel will reduce the tangling of the cables over time and will protect the cables from environmental factors while they are not being used, and will relieve some of the heavy work from the ground crew; (3) a pop-up 400Hz system with the motorized reel and 400Hz cable under the apron area will eliminate the risk of damage to the jet bridge.

The rest of the Model belongs to the software/hardware category. According to the SMS Safety Manual, "When a system includes software and/or hardware, the safety analyses consider possible design errors and the hazards they may create. Systematic design processes are an integral part of detecting and eliminating design errors." (p. 17). These design errors in software should be eliminated in the extensive testing and debugging phase that happens before integration into the larger airport communications system.

The other risk a software part of the Model might pose would be due to human error. The SMS manual states that "Human error is estimated to be the causal factor in 60 to 80 percent of aviation accidents" (p. 17). Because our designed system should be an algorithm fully integrated into existing system interfaces, there should be no additional risk involved in human error. The level of human error should remain at current rates as there are no changes in the human-to-the-system interface.

Our design should require no further safety analysis, since according the SMS manual, "if the change is not expected to introduce safety risk into the NAS, there is no need to conduct further safety analysis" (p. 23). Therefore, there is no need to perform steps D through H in the SMS Manual SRM process to follow through Phase 5 in the FAA Advisory Circular 150/5200-37 SRM process. Instead, if implemented, our design should simply require a Safety Risk

Management Decision Memoranda (SRMDM), signed when there is no additional risk introduced to the NAS.

Our proposal will actually improve safety and risk management in several ways. The Model aims to increase the amount of clean apron-gate-energy consumption at an airport. When clean apron-gate-energy consumption is increased, we minimize fuel burn of APUs. As a result, the amount of harmful gases and CO2 emitted is reduced. In the short term, this means reducing the times employees are exposed to hazardous fumes. In the long run, reduced emissions mean better air quality locally. Being more efficient and contributing less greenhouse emissions makes the airport more sustainable overall. On the other hand, due to the high noise level produced by APUs, airline ramp employees are exposed to harmful effects of noise – and with the proposed Model airline ramp employees will be exposed less to harmful effects of noise. It is known that short and long-term exposures to noise can cause severe health problems. Both the endocrine system and the autonomic nervous system have increased stimulation when exposed to environmental noise, causing changes in heart rate, increased blood pressure, and stress hormones (Münzel, 2014). And, according to EUROCONTROL (2015), aircraft noise is considered the primary environmental issue for aviation.

In accordance with the FAA Advisory Circular 150/5200-37 and the FAA Management System Manual, our proposal poses no new hazards. In an assessment of our proposal, it is clear that our proposal provides a safer way of utilizing and storing the 400Hz cables at an apron, and more efficient use of clean energy use while aircraft are gated.

6.4 Cost-Benefit Analysis

The impact of a 400Hz monitoring system depends greatly by how it is incorporated in an airport. The design of this monitoring system includes four different elements and each one carries several recommendations. Although implementing the entire design would be best, not all recommendations are critical towards the design's function. For example, the monitoring system will still work if 400Hz cables are not provided with protection. To make a cost benefit analysis of this system, we will focus strictly on the parts of this design that are critical to its function: the energy meters, the software that performs the analysis and the display. We will base our cost-benefit analysis on the 55 gates that have 400Hz power at SFO (Tables 3-6).

Table 3. Cost A. Research and Development (alpha)

Item	**Rate**	**Quantity**	**Subtotal**	**Remarks**
Labor: University Design Competition				
Student Efforts	$30/hr	200 hr	$6000	2 students
Expenses				
Travel	$20 /trip	3	$60	3 BART trips
Miscellaneous	$300	*lump sum*	$300	
Subtotal			$6,360	

Table 4. Cost B. Research and Development (beta)

Item	**Rate**	**Quantity**	**Subtotal**	**Remarks**
Labor: Academic R & D				
Student Efforts	$30/hr	400 hr	$12000	2 students
Expenses				
Travel	$20 /trip	20	$4000	20 BART trips
Miscellaneous	$2000	lump sum	$2000	
Subtotal			$18,000	

Table 5. Cost C. Production Marketing and Distribution

Item	Rate	Quantity	Subtotal	Remarks
Labor: Programming, Sales and Installation				
Programming the meters	$40 /h	25 h	$1100	performed by airport employees 55 gates; 30 min/gate
Programming the analysis	$100/h	30 h	$3000	1 program covers all 55 gates
Programming the display	$100/h	20h	$2000	1 display covers all 55 gates
Marketing			$20 000	sales representative
Expenses				
Display	$2000	1	$2000	High Quality TV Screen
Subtotal			$28,100	

According to the estimates in Tables 3-5, the total cost of implementing a 400Hz Monitoring System for SFO’s 55 gates with 400Hz power would be $52,460. This would be a one-time cost to an airport because the software requires limited maintenance.

The benefits of the proposed system are contributable to airlines and to society. To understand the benefits of a monitoring system, we will assume that every failed connection that is occurring without a monitoring system will be identified and corrected, leading to fuel savings and reduced emissions. The estimates of benefits come from the analysis of jet fuel costs and CO2 emissions from failed connections during FY17-18.

Table 6. Benefits of Reduced Fuel Consumption

Benefit	Rate	Quantity	Subtotal	Remarks
APU Jet Fuel Savings (in 1 year)				
APU Fuel Consumption Saved	$8,845 /gate	55 gates	$486,475	cost of (saved) fuel is $2/gallon (A4A, 2019)
APU Fuel CO2 Emissions Saved	43 tons/gate (~$1694 social cost)	55 gates	2329 tons (~$93,170 social cost)	$40 of social cost for every ton of CO2
Subtotal			**$579,645**	

The estimated benefit from the reduced APU fuel consumption for 55 gates is $580,000 per year (Table 6). This does not take into account many other benefits that were not quantified: reduced emissions in nitrogen oxides, hydrocarbons, carbon monoxide, particulate matter and noise pollution.

Assuming the monitoring system prevents all missed connections, the benefit of $580,000 dramatically outweighs the $52,460 costs to set it up by a ratio greater than 10 to 1. In addition, the benefit has an annual occurrence, whereas the upfront costs will be included only once. Even if the monitoring system was able to correct only 20% of failed 400Hz connections, the yearly benefits significantly outweigh the initial cost.

6.3 Additional Benefit Considerations

One of the non-critical recommendations with regards to the 400Hz cable is to separate it from the jet bridge, allowing it to be operated independently. Such a change would bring forth significant benefits in terms or reduced jet fuel consumption. As a result, we can add additional 6 minutes to the time the 400Hz cable can be plugged in. The following estimate shows how large the savings could be at SFO, assuming every gate were provided with 400Hz power:

$$Fuel\ Savings = 6\,minutes\ * 407{,}152\ \frac{flights}{year} * \frac{\$1.64}{minute} = \$\ 4{,}006{,}375\ /year$$

This yearly benefit comes with a reduction in 19,380 tons of CO2 ($775,217 in social cost) and the other air pollutants. To implement such a design, the design of the jet bridge and apron area would have to be modified, which would come at a significant cost. Therefore, this recommendation is most appropriate in the design of new terminal buildings, rather than as a replacement for current ones.

7. Conclusion

The implementation of a proposed Smart Gate System for 400Hz Power Monitoring at SFO International Airport is highly desirable from financial, operational, and especially environmental standpoints. Our case study on SFO demonstrates that there is significant room for improvement in the use of 400Hz cables. Because the 400Hz power systems are already in place and have been proven to reduce fuel waste, a monitoring system to further improve their use is a logical improvement. The system would carry minimal costs and would bring forth significant and recurring benefits. The benefits of the system would affect not only the airport and the airlines but also the people and wildlife living nearby.

Because the monitoring system is primarily algorithmic, it can be easily replicated and modified, allowing other airports that are equipped with 400Hz ground power to use it to pursue their sustainability goals. For those airports that do not have 400Hz ground power cables, the results of the SFO monitoring system will help such airports to understand and encourage their installation of 400Hz ground power systems as an alternative to APU usage and gasoline-powered ground power units.

The aviation industry is expanding and it is responsible for vast amounts of emissions and damages to the environment. The research, design, and monitoring of green technologies like 400 Hz ground power system is crucial to raising the triple bottom line of the aviation industry and a sustainable development of our global society.

Appendix A: List of Complete Contact Information

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Appendix B: Description of the University

University of California, Berkeley is the world's number 1 public university in the Academic Ranking of World Universities for 2010. It serves as a home for higher education for 36,000 students, including 25,700 undergraduates and 10,300 graduate students. UC Berkeley holds 1,455 permanent faculties and 7,059 permanent staff serving among 14 colleges and schools with 130 academic departments and more than 100 research units. More than half of all UC Berkeley seniors have assisted faculty with research or creative projects and more UC Berkeley undergraduates go on to earn Ph.D.s than any other U.S. university. The Civil and Environmental Engineering department consistently ranks at the top of the best civil engineering programs in the country by U.S. News and World Report.

The Department of Civil and Environmental Engineering has fifty full-time faculty members and twenty-two staff dedicated to the education of more than 400 undergraduate students and 360 graduate students. The education in the department prepares students for leadership in the profession of civil and environmental engineering and sends approximately one-quarter of its undergraduates into graduate education. Our CEE laboratories for teaching and research are among the best in the nation, providing opportunities for hands-on experience for all students. There is no other location with comparable resources in the San Francisco Bay Area that can provide students with ground-breaking local civil and environmental engineering projects and participate in professional activities.

UC Berkeley was chartered in 1868 as the first University of California in the multicampus UC system. The school houses a library system that contains more than 10 million volumes and is among the top 5 research libraries in North America. Throughout its full history, Berkeley has had 21 Nobel Laureates, 234 American Academy of Arts and Sciences Fellows, 213 American Association for the Advancement of Science Fellows, 363 Guggenheim Fellows, 32 MacArthur "genius" Fellows and 4 Pulitzer Prize winners. Just as important as academic excellence, UC Berkeley has held a respectable active history of public service. More than 7,000 UC Berkeley students every year do volunteer work in 240 service-oriented programs while there are more Peace Corps volunteers from UC Berkeley than from any other university. Clearly, UC Berkeley is not solely focused on academia as countless research and outreach initiatives focused on public benefits to the community, nation, and world.

Appendix C: Description of Non-University Partners

N/A

Appendix D: Sign-off Form

Appendix E: Evaluation of Educational Experience

Students

1. Did the Airport Cooperative Research Program (ACRP) University Design Competition for Addressing Airports Needs provide a meaningful learning experience for you? Why or why not?

The Airport Cooperative Research Program (ACRP) University Design Competition for Addressing Airports Needs has provided us a very meaningful learning experience. Both of us love airports very much, because we are international students and we travel through the airports very often, and it was pleasant to know that we are able to help improve SFO through this Competition, our most frequently visited airport. This project allowed us to finally apply the theory and tool we have been studying in our classes on a real world problem right next to our doorstep.

2. What challenges did you and/or your team encounter in undertaking the Competition? How did you overcome them?

The biggest challenge in undertaking this Competition was time management. Our team consisted entirely of senior students, and our schedule for the semester was hectic with design courses that were unusually time-consuming. However, thanks to consistent communication and support from faculty and industry experts, our research kept progressing. Another great challenge was knowing when to stop researching and when to start writing our results in a complete and coherent fashion. Every answer or result would lead to more questions and problems, making it hard to understand where to cut off our research. Thanks to faculty and industry experts, we were able to understand what was most valuable to the research so we decided to focus on their suggestions, without going too far down the rabbit hole that is research.

3. Describe the process you or your team used for developing your hypothesis.

Our process for developing our research was an iterative one. We would analyze data, interpret the results and come up with many more questions. After that, we would improve or modify our analysis to come up with more and better results, just to repeat the same process again and again. By observing trends in our results and modifying our analysis to focus on those trends, we came up with the greater conclusions of our project, along with the data to back them. For example, when we first started, we didn't expect missed 400Hz connections to be a significant problem, but by this iterative analysis process we understood they were, and soon after 400Hz connections became the primary focus of our research. Once we had a clear understanding of our results and of the practical issues surrounding 400Hz systems, we started coming up with numerous potential improvements, which then coalesced into our final design.

4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?

Participation by industry in the project was very helpful. Because of the supportive professionals in the industry, we were able to go to the SFO's apron area to witness the usage of 400Hz cable in real life so that we knew what we are actually dealing with. Aside from that, the professionals also provided us many feedbacks and advices regarding our project throughout the coding and writing process. Because of the industry experts, our project became more refined and credible. Without their volunteered help, our project would not have made it past our first data analysis.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

Working on this project led to a significant improvement in our researching, data science, communication and organizational skills. Because of this project, research will definitely be a big part of our future, no matter if in grad school, in the workforce or in personal projects. Aside from that, doing this project gives us a chance to be creative and innovative to manifest an idea that might actually be implemented in real life from nothing. Creativity and innovation are traits that everyone should have in order to have a successful career and we were so happy that this project allows us to be as creative and innovative as possible.

Faculty

l. Describe the value of the educational experience for your student(s) participating in this Competition submission.

My students gained tremendous educational value from this Competition. They went through the entire creative process of designing a model for the Airport Apron Energy Management from the initial stages to the end by designing a concept, applying it to a busy airport, and testing its feasibility. As some of the students are planning to attend various graduate programs, this educational experience was an ideal means for them to learn about how to start creating new concepts and new knowledge. Once they start their graduate programs, the experience gained while participating in this Competition submission process will help them make a smoother transition towards conducting more advanced research that is expected in any graduate program.

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?

The learning experience was quite appropriate for the context in which the competition was undertaken. It tested the intellectual capability of the students at the right level, and offered challenging insight into practical, real-world problems. Although the research group was relatively small, the students cooperated, organized, and designated tasks within a complex goal-oriented endeavor.

3. What challenges did the students face and overcome?

The students faced and successfully overcame many challenges. First, these are undergraduate students with no prior experience in conducting research. Furthermore, they came from a civil engineering and operations research background, and had little previous knowledge or understanding of aviation or airport systems. Many of the student-team members never took any formal aviation classes. The Airport Design class that some of the students took the previous semester was their only formal education in aviation. Hence, the beginning of the research process included a long learning process about how to conduct research and how to understand more advanced aviation concepts, such as the concept of aircraft-gate operations, apron management, aircraft and airport energy use. Another challenge the students faced was the initial resistance of their proposed concept by some airport operators and industry experts, and the industry's initial "suspicion" about the proposed design, since the proposed method suggested airline-airport data collaboration. Whenever the experts commented on their design from a more tactical, today's operational perspective, the students very professionally and patiently would explain their paradigms and strategic goals. Consequently, their communication with the airport operators and industry experts was a very positive and productive enterprise.

4. Would you use this Competition as an educational vehicle in the future? Why or why not?

I would definitely use this Competition as an educational vehicle in the future. In previous years I conducted a significant amount of undergraduate research through the UC Berkeley Undergraduate Research Opportunities (URO) program. This program was designed to assist undergraduate students in developing research skills early in their college education. On average, half of my students from the Airport Design Class would participate in aviation research projects in the following semester, and would formally be funded and sponsored by URO. Because of recent budget cuts, however, this program had to be closed. By using this Competition as an educational vehicle, I am not only continuing research with undergraduate students, but also teaching them how to structure, organize, and present their work to a large number of experts in the field.

5. Are there changes to the Competition that you would suggest for future years?

I would expand Challenge Areas by adding more emphasis on the Next Generation Air Transportation System (NextGen) requirements and expectations, as well as on aviation sustainability and climate change.

Appendix F: List of References

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