Airport Cooperative Research Program (ACRP) University Design Competition

Life-Cycle Assessment of Airport Pavement Design Alternatives for Energy and Environmental Impacts

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Executive Summary

Almost 20000 airports are located throughout the United States today. Of those, approximately 8700 feature paved runways, taxiways, and ramps/aprons need regular maintenances to ensure safety and daily operations. As one of the main infrastructure that occupied large area of the airport, the adversely environmental problem associated with construction and rehabilitation activities of the paved airport surface should not be neglected. Our team proposes an evaluating method to improve the quantification of energy and environmental impact of airport runway pavement design using life-cycle assessment approach. We also developed an Excel based LCA tool to facilitate the quantification of energy consumption and greenhouse gas emission of pavement project which is applicable to any airport runway design. In the LCA method, life-cycle inventory data were compiled from literature database and field surveys to contractors. The data variations in the material-related energy and emission rates were considered for sensitivity analysis. The impact assessment focused on the cumulative energy demand and greenhouse gas emission in the material, construction, and maintenance phases of pavement life-cycle. A methodology was developed to consider upstream components related to process fuels in the impact assessment. The results indicate that the expected pavement service life and maintenance treatments significantly affect the comparison between hot-mix asphalt and Portland cement concrete pavements. Although there are no general conclusions on pavement type selection, the research findings bring awareness to airport authorities on the impact of pavement type on energy consumption and greenhouse gas emission. The project-level analysis is suggested to be conducted for selecting the sustainable design alternatives in the airport planning process.

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1. Problem Statement and Background

Construction and rehabilitation of airfield pavements produce significant impacts on energy conservation and climate change resulting from the consumption of large amounts of construction material and the operation of construction equipment. Currently, there is no comprehensive solution to quantify environmental sustainability in airport pavement design and maintenance to support decision making process and guide the future growth with respect to economic consideration and performance requirements.

Almost 20000 airports are located throughout the United States today. Of those, approximately 8700 feature paved runways, taxiways, and ramps/aprons. With the continuous increase of air traffic volumes and the development of heavy wide-body aircraft, airfield pavements require frequent maintenance and rehabilitation activities in order to provide sufficient structure capacity and satisfactory surface characteristics. As one of the main infrastructure that occupied large area of the airport, the adversely environmental problem such as energy consumption and climate changes associated with construction and maintenance activities of the paved airport surface should not be neglected.

Specific policy and regulation related to environmental sustainability evaluation of airport pavement type selection and rehabilitation strategy are rarely seen. The factors affecting the selection of pavement type and rehabilitation strategy may include agency experience, the long-term performance of alternatives, the impact on airport operations, construction and maintenance costs, and environmental and sustainability considerations (Hallin et al.). The life-cycle cost analysis (LCCA) has been mandated by the Federal Aviation Administration (FAA) Advisory Circular to be the part of the pavement type or treatment selection process. The LCCA is mostly used to aid airport planners in identifying the most cost-effective pavement construction and rehabilitation strategies.

Although efforts have been brought into assessing and reducing GHG emission in order to alleviate the undesirable environmental burden generated by pavement construction and usage, most of the pavement environmental studies are focused on highway roads but a very few on airport runways. Life cycle assessment (LCA) is a well-developed and widely used to measure an object's environmental impact through its entire life. When it is utilized in road construction projects, it can take all the GHG emission generated from construction to end of life into consideration and quantifies the environmental impact within a defined system boundary. Traditionally, a life cycle assessment includes material, construction, usage, maintenance and rehabilitation, and end of life. Lots of research and studies have been conducted on each component. However, most of the work focuses on one or two aspects (such as material and construction, or maintenance alone) rather than building a complete framework. What's more, the previous studies only concentrate on carbon dioxide (CO_2), while the other emission factors like methane (CH_4) and nitrous (N_2O) are not addressed, which turn out to have a great impact on climate change.

Therefore, an assessment methodology and a user friendly LCA tool to properly quantify environmental sustainability in airport pavement design and rehabilitation processes is needed for airport authorities to support decision making process. The LCA tool is intended to assist decision-makers, planners and researchers to achieve a more environmentally conscious decision. The study results can be used for decision making among different runway pavement design and rehabilitation alternatives.

2. Summary of Literature Review

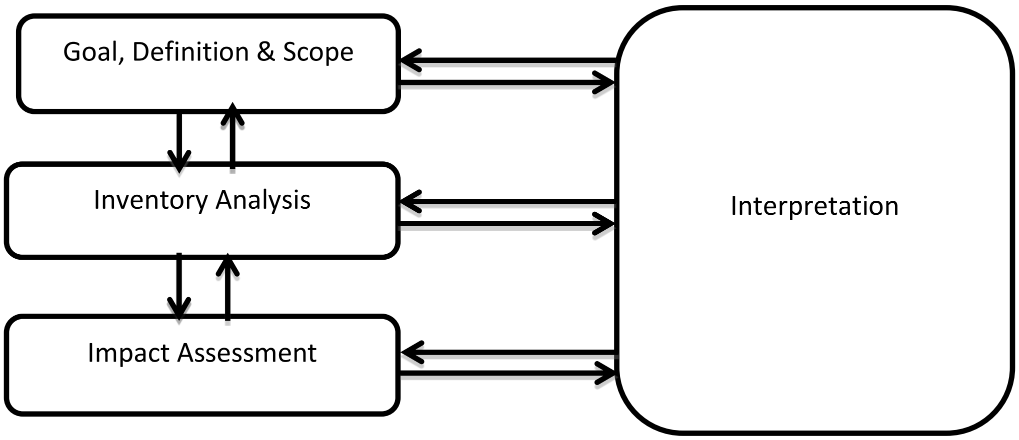
Recently, LCA studies have been widely used to evaluate environmental impacts of pavements occurred at various stages. The objective of LCA studies vary in a wide range, such as development of model for pavement construction and maintenance [3], evaluation of low-energy warm mix asphalt [4], analysis of concrete pavement with industry by-product [5], quantification of environmental benefits of in-place recycling [6], and analysis of pavement rolling resistance on GHG emission [7]. The process-based, economic input-output-based, and hybrid approaches have been used for conducting pavement LCA.

The review here focused on the LCA studies that focused on comparing the environmental impacts of different types of pavements (flexible vs. rigid). Previous researches reported mixed findings between asphalt and concrete pavement design strategies and a lack of consistency was found among the study results. For example, Hakkinen and Makela (1996) performed a study based on pavement structures in Finland and found that concrete pavement produced 40-60% more CO2 emission as compared to asphalt pavement [8]. Horvath and Hendrickson (1998) performed a study using EIO-LCA (Economic Input- Output Life Cycle Assessment) model and concluded that the asphalt pavement consumes 40% more energy than the concrete pavement [9]. Treloar et al. (2004) performed a hybrid LCA analysis and concluded that the un-doweled JPCP had the lowest energy input, while the full depth asphalt had the highest energy input [10]. Zapata and Gambatese (2005) concluded that the CRCP consumed more energy in comparison to asphalt pavement [11]. Weiland and Muench (2010) analyzed three different pavement rehabilitation alternatives and found that energy consumption is highest in the HMA option while the global warming impact is highest in the PCC option [12].

There are many factors that may affect the LCA results, such as system boundaries, the quality and source of inventory data, inconsistent pavement designs, and geographic locations. The type of concrete pavement (Jointed Plain Concrete Pavement [JPCP], Jointed Reinforced Concrete Pavement [JRCP], and Continuously Reinforce Concrete Pavement [CRCP]) was found having significant effects on the environment impact due to the existence of steel. The comparison was complicated by the assumption of pavement service life and maintenance history used in the analysis. Few previous studies on pavement LCA considered maintenance treatments along with the initial construction. The definition of analysis period varied from the pavement service life for the initial construction to the specific design life with scheduled maintenance treatments. Therefore, general conclusions derived from literature studies may not be applicable for specific pavement projects.

3. Problem Solving Approach

3.1 LCA Method



Life-Cycle Assessment (LCA) is used in this study, which a technique to assess environmental effects associated with a product's life cycle with flexibility and comprehensiveness [13]. The process-based LCA method is usually used for construction projects since the methodology can disaggregate the projects into individual processes or activities independently [14]. The life-cycle of pavement can be divided into different stages including raw material extraction, material processing and manufacturing, transportation, construction, maintenance, and end-of-life.

This study follows the basic steps of life cycle assessment: goal definition and scope, inventory analysis, impact assessment and interpretation as defined by International Organization for Standardization (ISO) 14044 (3). The goal is to quantify energy consumption and environmental impacts of airport pavement design alternatives. The study scope includes design alternatives for both new pavement design and pavement overlays on existing runway pavements. The pavement structures considered include the surface layer constructed with Portland cement concrete or asphalt concrete over base layers or existing pavement layers. The function unit is defined as one-mile runway with 200-ft width that is designed to carry the aircraft traffic mix in the analysis period at the major hub airport. The system boundary covers the material, construction and maintenance stages of the pavement life cycle. The end-of-life stage was not considered here due to the complexity involved between different pavement types. Concrete runway pavements are usually left in place as base layer for new overlays; while asphalt runway pavements are removed and used as base or sub-base material at other areas of airfield.

The inventory analysis is limited to energy consumption and greenhouse gas emissions (GHG); as a result, the impact assessment determines the cumulative energy demand (CED) and global warming scores of the GHG emissions. The greenhouse gases considered in this study include Carbon Dioxide (CO2), Methane (CH4) and Nitrous Oxide (N2O). The global warming potential (GWP) of a greenhouse gas is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas [15]. The CO2 was used as reference gas in this study, and the GWP weighted emissions were measured in CO2 equivalent (CO2 Eq.) using the GWP equivalency factors.

The unit inventory data for material-related energy consumption and GHG emission were extracted from up-to-dated articles and research papers and the uncertainty of data sources were analyzed. Contractor survey and field observations were conducted to obtain the operation efficiency of construction equipment for runway construction. Direct energy consumptions and GHG Emissions were obtained from fuel combustion and electricity consumption for various material acquisition and process operations in the system boundary. Consideration of energy and emissions associated with the production of process fuels and electricity in the upstream process was included to account for the indirect energy consumption and GHG emission.

3.2 Development of LCA Tool

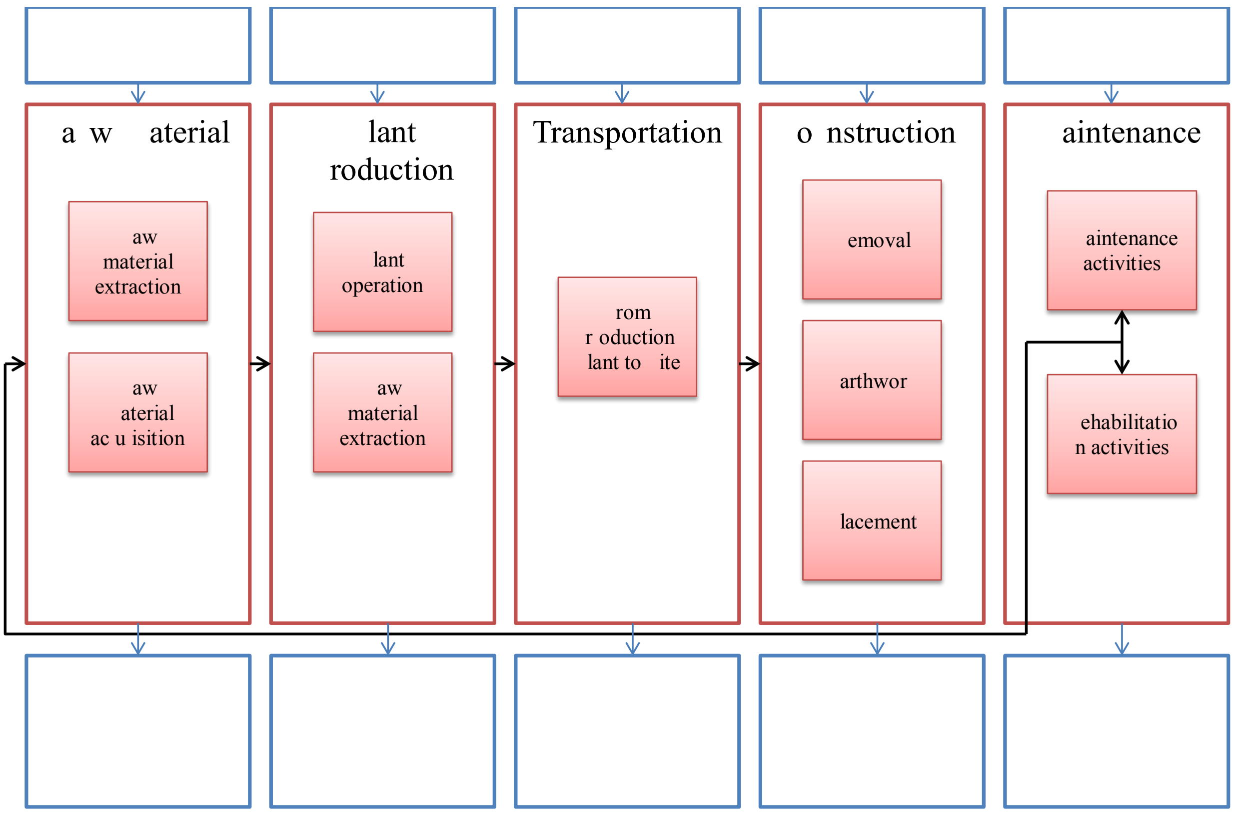
The goal of developing the LCA tool is to carry out quantitative assessment of environmental impacts for the LCA stages in the pavement life cycle- raw material extraction, plant production, construction and maintenance. An excel based tool, Pavement Project Energy and Emission Calculator (PPEEC) has been developed to facilitate the quantification of energy consumption and GHG emission of pavement project life cycle based on the user input. Furthermore, the tool reports a database of life cycle inventory values from pertinent studies.

The tool is intended to give airport agencies a highly customizable tool to assist them in quantitatively assessing the total environmental footprint of their procedures, strategies and decisions regarding the construction and maintenance airfield pavements at project level. The tool enables the user to assess the environmental impacts and resources consumption of alternative solutions for pavement design and maintenance throughout the different phases of life cycle.

The system boundaries of the proposed pavement LCA model entails six pavement life cycle phases, modeled through individual but interconnected modules. The LCA phases included are: (1) extraction of materials and production, consisting of the acquisition and processing of raw materials and the mixing process of HMA mixtures in plants; (2) construction and M&R, including all construction and M&R procedures and related construction equipment usage; (3) transportation of materials, accounting for the transportation of materials to and from the construction site and between intermediate facilities (e.g. transportation of aggregates from the quarries to HMA mixing plants).

The pavement system considers the pavement structure including the subbase, base, wearing course and surface course. The pavement system does not consider draining, lighting, and tack coats. The pavement system evaluated included upstream (indirect) processes along with combustion (direct) processes.

Figure 1 summarizes the system boundaries for the study.



4. Description of the Technical Aspects

4.1 Life-Cycle Stages

In order to quantify energy consumption and emission of pavement, the first step is to determine the material components and manufacturing processes for each material or process in the pavement life-cycle. Materials are obtained in raw forms and then manufactured to the final form as required by the construction demand. For the asphalt concrete (AC) pavement and jointed plain concrete pavement (JPCP) considered in this study, raw materials contain asphalt, cement, aggregate, slag cement, polymer additive, and steel (dowel bar in JPCP). Manufacturing of material includes handling, drying, mixing and preparation of materials for placement, such as production of hot-mix asphalt (HMA) and cement concrete.

In this study, life inventory data of raw material and manufacturing process were collected from published reports from literature. Although multiple data sources are available for life-cycle inventory data of typical construction materials and processes for pavements, discrepancies may exit due to different geographic locations, technologies, and system boundaries. To address this, baseline analysis was conducted using the inventory data identified as the most appropriate for this analysis. The inventory data used in the baseline analysis were selected from the previous studies conducted in U.S. as compared to a relatively larger set of inventory data reported by European researchers. The extreme ranges of inventory data (minimum and maximum values) reported in the literature were also used in the analysis to investigate the sensitivity of analysis results to the variation of inventory data. Table 1 lists the material-related life-cycle inventory data with references from various data sources including the baseline values based on the studies conducted in U.S., respectively, for energy consumption and GHG emission values. It is noted that the documented LCI data for raw materials are selected without considering upstream components, which will be calculated separately using a uniform approach in this study.

There are three transport stages in the pavement life-cycle: 1) transportation of raw materials from the extraction site to the processing facility, such as transport of crude oil to refinery; 2) transportation of processed materials to manufacturing plants, such as transport of asphalt from refinery to the hot-mix asphalt plant or transport of aggregate products from quarry to the mixing plant, 3) transportation of manufactured materials from the production site to the construction job site. The first transport stage was included in the life-cycle inventory of raw material in most studies. Although it is ideal to consider the specific transport distance of processed materials to manufacturing plants, these were not considered in this study due to lack of data availability. This assumption was considered not affecting the comparison results because previous studies have concluded that the contribution of transportation stage is usually small as compared to other stages if no extreme transport distance was observed [28, 29]. However, the transportation of hot-mix asphalt or cement concrete from the plant to the job site was considered. The one-way transport distance from the asphalt plant to the job site is about 20 miles, while the transport distance is only 2 miles for the on-site concrete batch plant. The transportation of milled material from the existing asphalt pavement was negligible because the project allowed for reuse of the removed pavement as subbase materials for new taxiways instead of trucking it off site for recycling or disposal.

Table 1 Material-Related Life-Cycle Inventory for Asphalt and Concrete Pavements

Material / Process	Baseline Value		Other LCI Data from Literature	
	Energy Consumption (MJ/t)	Emissions CO_2 eq. (kg/t)	Energy Consumption (MJ/t)	Emissions CO_2 eq. (kg/t)
Asphalt Binder	5810 [16]	480 [16]	6000 [8], 3634 [17], 5812 [18], 3980 [19]	330 [8], 173 [17], 377 [18], 244 [19]
Portland Cement	4340 [20]	928 [20]	5350 [8], 4776 [17], 5232 [21]	799 [8] ,806 [17], 670 [21]
Sand or Gravel	21 [20]	0.0728 [20]	24 [8], 6 [17], 68.6 [21]	1.74 [8], 0.07 [17], 6.1 [21]
Crushed Stone	32 [20]	1.42 [20]	52 [8], 38 [17]	2.0 [8], 6 [21]
Steel	21520 [22]	1578 [22]	21800 [17], 11300 [21]	241 [17], 232 [21]
Polymer Additive	76742 [19]	3715 [19]	N/A	
Slag Cement	644 [23]	7.42 [23]	N/A	
HMA Manufacturing	266 [24]	16.4 [24]	485 [8], 432 [17]	34.8 [8], 21.9 [17], 15.1 [25]
PCC Manufacturing	18 [26]	0.72 [26]	40 [17], 110 [21], 56 [27]	1.67 [17], 7.70 [21], 9.54 [27]

The manufactured material will then be transported to the construction site for placement. Placement of materials depends on types of construction requirement on the project site and it is accomplished using different types of equipment. In the construction phase, the environmental burdens are due to the combustion-related emissions from construction equipment usage. The NONROAD (nonroad engines, equipment, and vehicles) 2008 model developed by Environment Protection Agency (EPA) was used to calculate CO_2 emission (in g/hour) for off-road equipment by its function, horsepower, and fuel type [30]. Since NONROAD cannot directly provide energy consumption, the energy consumption was calculated based on the heating value of diesel fuel and the emission factors for CO_2, as shown in Equation 1 [31, 32]. After the energy consumption rate is known, the emission rates for CH_4 and N_2O can be obtained in as similar way using Equation 1.

$$r_{energy} = r_{emission} \times \frac{HV}{f(emission)} \quad (1)$$

Where, r_{energy} is energy rate in MJ/hour;

$r_{emission}$ is emission rate in g/hour (obtained from NONROAD for CO_2, but solved for CH_4 and N_2O after energy rate is known);

HV is heating value, 138.451 MJ/gallon for diesel fuel; and

f(emission) is fuel-specific emission factor for CO_2, CH_4, or N_2O in g/gallon.

In order to calculate the energy consumption and emissions generated in the construction process, contractor surveys and field observations were conducted to determine the productivity for each type of equipment and operation hours of equipment can be calculated based on the total tonnage or volume of material that is needed to construct one-mile runway with 200-ft width. Table 2 summarizes the construction activities with the equipment used, horsepower rating, and operation efficiency.

Table 2 Construction Equipment and Operation Efficiency for Pavement Construction

Construction activity		Equipment	Horsepower (hp) rating	Productivity
HMA	Paving	Vogele Super 2100-2	250	1,500-2,000 tons/12 hours
	Rolling compaction	HAMM HD+140	155	Same as paving (5-10 passes)
PCC	Front Paver (Placer/Spreader)	GOMACO PS-2600	275	275 yards/hour
	Middle Paver (Slip Form Paver)	GOMACO GP-4000	440	275 yards/hour
	Back Finishing Paver (Texture/Cure)	GOMACO TC-600	60	275 yards/hour
	Concrete Saw cutting	Edco SS-26 31D	31	8000 linear feet/10 hours
	Drilling Dowel Bar	EZ Drill 210B-4	20	800 bars/10 hours
	Joint Sealant		10	8000 linear ft./10 hours
General	Milling	Wirtgen 250i	990	1000 cubic yards/12 hours shift
	Grooving	Lincon Electric 10,000 Plus	23	10,000 square yards/ 12 hours
	Articulated Dump Truck	Caterpillar 740	445	40-ton capacity

4.2 Consideration of Upstream Components

The overall environmental impact of a process depends on both the combustion (direct) energy and emissions for operating equipment and vehicles, and the upstream energy requirements for producing and delivering the energy source. The upstream (indirect) emissions are generated from processing fuel consumed during various processes from material extraction to construction. Energy is required to produce fuels and electricity used in the downstream processes. Therefore, in addition to the energy use and emission of direct use of fuels and electricity, the energy and emissions associated with the production of these fuels and electricity were considered in the analysis.

To incorporate the upstream (indirect) values, the GREET 2013 model developed by Argonne National Laboratory was used. The GREET model is a life-cycle modeling tool to evaluate the impact of fuel use including all fuel production processes from oil exploration to fuel use (from well to wheels) [33] For process fuels such as coal, natural gas, gasoline, fuel oil, liquefied petroleum gases (LPG), etc., upstream values can be extracted for each specific fuel type. The mix of energy source for production of electricity was obtained for the northeast states of U.S. from the fuel cycle model in GREET and used to calculate the upstream values for electricity. Table 3 lists the energy usage profile for production of raw materials and manufacturing processes of PCC and HMA as reported by different literature sources. The process fuel used for transportation and construction can be directly determined from the fuel type used by the specific transport vehicle and construction equipment.

The calculation of upstream energy consumption and emission for a particular material or process can be shown in Equation 2, where the unit upstream energy consumption and GHG emission extracted from the GREET 2013 model are then multiplied with the energy usage profile of process fuels and electricity.

$$\mathrm{UEE} = \sum_{i=1}^{n} \mathrm{CE} \cdot \mathrm{PE_i} \cdot \mathrm{UEE_i} \quad (2)$$

Where,
UEE = Upstream energy consumption (BTU/ton) or emission (g/ton);
CE = Combustion energy (MMBTU/ton);
$\mathrm{PE_i}$ = Percent of the ith type of energy in the energy matrix;
$\mathrm{UEE_i}$ = Upstream energy consumption (BTU/MMBTU) or emission (g/MMBTU) for the ith type of energy (calculated from GREET);
i = Type of energy including coal, diesel, gasoline, liquefied petroleum gas, natural gas, distillate oil, petroleum coke, residual oil, and electricity; and
n = Total number of energy type.

Table 3 Energy Usage Profiles for Production of Raw Materials and Manufacturing Processes of PCC and HMA

Process fuels (Reference)	Asphalt [34]	Cement [20]	Sand [20]	Crushed Stone [20]	Steel [35]	Slag Cement [23]	Polymer [19]	HMA plant [24]	PCC plant [20]
Coal	0.04%	56.58%	0	1.89%	1.42%	0	9.75%	0	0
Diesel	0	0	0	0	0	0	0	0	0
Gasoline	1.05%	0.04%	3.41%	3.85%	0.25%	0	0	0	0
LPG	0.51%	0.02%	0	0	0	0	0	0	0
Natural Gas	72.54%	0.85%	6.87%	11.63%	33.2%	77.56%	53.9%	80%	39.3%
Distillate Fuel Oil	0.15%	3.45%	39.1%	42.40%	0	0.09%	36.35%	20%	26.2%
Petroleum Coke	18.39%	18.12%	0	0	18.4%	0	0	0	0
Residual Oil	0.47%	0.09%	9.46%	7.11%	2.23%	0	0	0	0
Nuclear Power	0	9.26%	0	0	0	0	0	0	0
Electricity	4.25%	11.58%	41.2%	33.1%	17.8%	22.35%	0	0	34.5%

4.3 JFK Case Study Result and Discussion

4.3 Comparison between Different Pavement Materials

The analysis was conducted using the standard mixture designs that were used at airfield pavements and the baseline values in the life-cycle inventory database. The material-related energy consumption and GHG emission were shown in Table 4, respectively, for combustion and upstream components of each raw material and manufacturing process (plant operation for producing mixtures). The relative energy consumption and GHG emission values (shown in the parentheses in Table 4) were calculated as the energy or emission resulted from each material component with respect to the total energy or emission of HMA or PCC. The combustion (direct) values are generated in the processes for raw material acquisition and manufacturing process; while the upstream values are related to the type and quantify of process fuel that is consumed in the combustion process. The results show that the upstream components play significantly to the total environmental burdens, although the exact values of upstream components vary depending on the percentage of process fuel and electricity.

Table 4 Material-Related Energy Consumption and GHG Emssion (One Ton of HMA and PCC)

Raw material		Energy consumption (MJ)		GHG emission (CO_2 eq. ton)	
Material	Mass percentage	Combustion	Upstream	Combustion	Upstream
Asphalt	4.93%	286.4 *(48%)**	87.7 *(50%)*	23.7 *(62%)*	6.1 *(51%)*
Aggregate	94.7%	25.3 *(4%)*	26.1 *(15%)*	0.59 *(2%)*	1.1 *(9%)*
Polymer	0.37%	283.9 *(48%)*	63.1 *(36%)*	13.7 *(36%)*	4.8 *(40%)*
Total	100%	595.7	176.9	38	12
HMA Manuracturing		266	58.9	16.4	4.7
Portland	6.1%	265	93	56.7	8.2

cement		*(87%)*	*(75%)*	*(99%)*	*(85%)*
Slag cement	3.5%	22 *(7%)*	15 *(12%)*	0.3 *(0.5%)*	0.7 *(8%)*
Aggregate	58.6%	17 *(6%)*	17 *(13%)*	0.6 *(1%)*	0.7 *(8%)*
Water	31.8%	0	0	0	0
Toal	100%	304	125	58	10
PCC Manufacturing		18	18	17	0.7

*Numbers in the parentheses indicate percentages.

For both hot-mix asphalt and Portland cement concrete, the binding agent (asphalt binder or Portland cement) with small mass percentages has the most significant component in the energy consumption and GHG emission for raw material. The typical process of producing asphalt binder is divided into four stages: crude oil extraction, transport, production in refinery, and storage (DOE). The manufacturing process of Portland cement mainly includes quarry and crush, raw meal preparation, pyroprocess, and finishing grind. It is noted that Portland cement has roughly the same energy consumption but twice the GHG emission due to the clinker process in cement kilns. Although the polymer content is small in HMA, its impact is significant due to the energy-demanding process in polymer production process. The use of slag cement as partial replacement of Portland cement significantly reduces energy consumption and GHG emission. Slag cement is produced when the molten slag (by-product produced during iron production) is rapidly quenched with water in a controlled process and then ground into fine powder.

On the other hand, aggregates contribute to the total energy consumption and GHG emission in a much less degree as compared to asphalt binder or Portland cement. Aggregates contribute to the total energy consumption in a more significant role as compared to the GHG emission. Crushed aggregate requires mechanical breaking after acquisition or quarrying; while natural aggregates (sand or gravel) are obtained by dredging.

As expected, the manufacturing of HMA consumes much more energy and generates more GHG emission than the production of PCC. Asphalt production includes mixing of asphalt binder, aggregate and other additives at the required temperature, where energy consumption and emission are mainly generated from heating and mixing. The exact amount of heat energy varies depending on the moisture content in the aggregate and the discharge temperature of HMA. On other hand, concrete is produced by mixing cement with fine aggregate (sand), coarse aggregate (crushed stone), and water without heating requirements. This causes much less energy consumption in the concrete plant as compared to the HMA plant.

It is noted that energy consumption and GHG emission for steel production are counted separately for concrete pavement. Dowel bars were used to improve load transfer efficiency between concrete slabs. Totally there are 24,000 dowel bars are needed for concrete pavements of the whole runway. The steel production process includes ore recovery, ore pelletizing & sintering, coke production, blast furnace, basic oxygen processing, electric arc furnace, sheet production, and rolling and stamping, which causes significant amount of environmental burdens that cannot be neglected.

4.4 Comparison between Runway Rehabilitation Strategies

Since differences in properties of asphalt concrete and cement concrete can have strong influences on pavement structure design and quantities of material usage, it is critical to conduct LCA of different pavement types with the same performance standard. In an early study conducted by FAA, field data collected from 30 airports in U.S. concluded that flexible and rigid pavements designed based on FAA standards have structure condition index (SCI) values at or above 80 after 20 years. While the structural performance of flexible and rigid pavements was found comparable, differences in functional performance was noted [36].

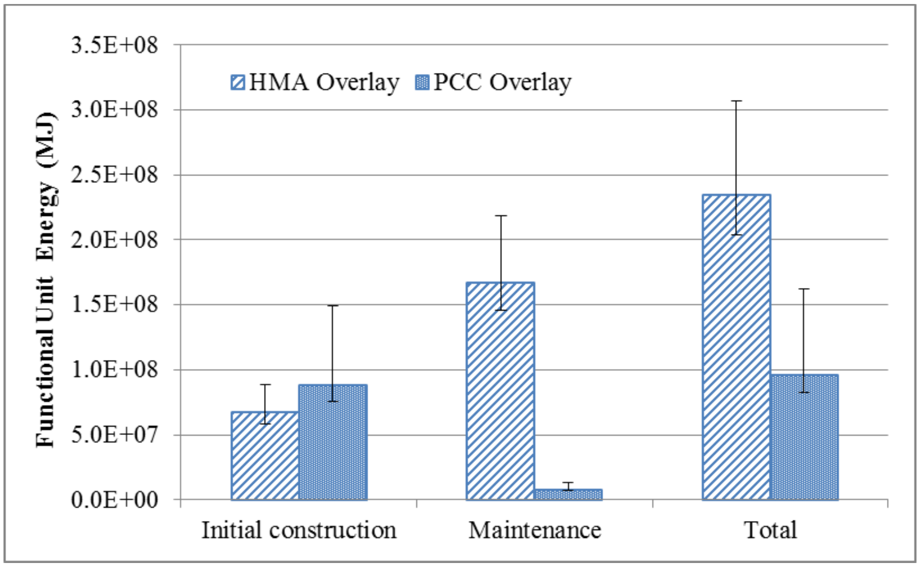
In this study, the two design alternatives for resurfacing runway 13R-31L at the JFK airport were based on the analysis of existing pavement condition data and the past experience, as shown in Table 5. Each design alternative is expected to sustain the desired performance level over the runway's life cycle although they varied significantly due to consideration of pavement life and rehabilitation needs. The experience at JFK airport with asphalt surfaced runway was no longer lasting over 10 years before rehabilitation was required. Hence, the asphalt pavement was designed to require significant overlay treatments every eight years in the 40-year design life. On the other hand, only concrete repair was required for concrete pavements every eight years. The concrete repair treatments mainly include patching and partial-depth repair.Based on the experience in the PANY&NJ, the concrete repair usually takes2% of initial construction cost. The same percentage was used for calculation of energy consumption and environmental impact. This is considered as the best approximation since it is difficult to predict the exact number of occurrences for repair treatments.

Table 5 Design Alternatives for Resurfacing Runway Pavement

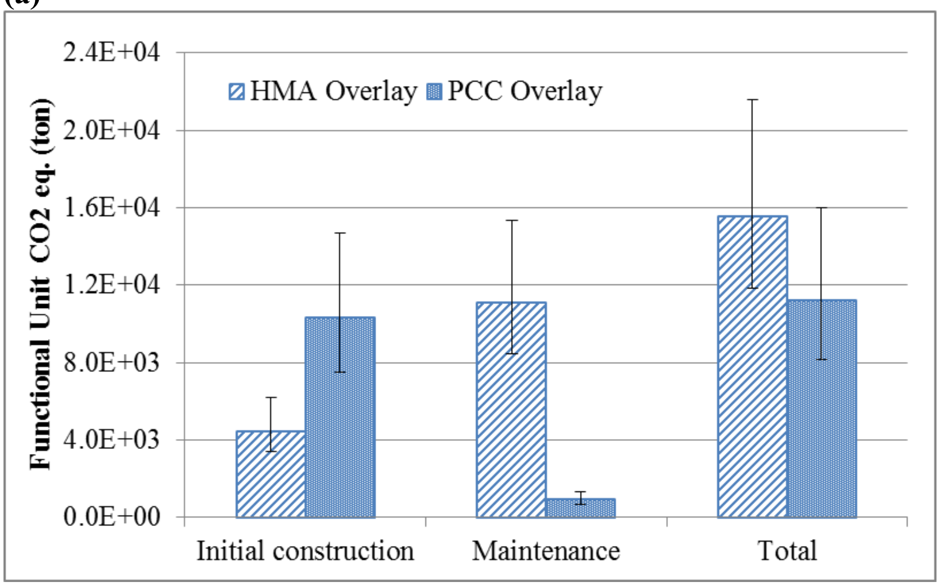
Stage	Year	Rigid Overlay	Flexible Overlay
Initial Construction	0	Milling 6-inch asphalt + overlay 2-inch asphalt	Milling 3-inch asphalt
	0	18-inch Concrete Overlay	9-inch Asphalt Overlay
Maintenance	8	Concrete Repair	Milling 3-inch + overlay 4-inch asphalt
	16	Concrete Repair	Milling 6-inch + overlay 7-inch asphalt
	24	Concrete Repair	Milling 3-inch + overlay 4-inch asphalt
	32	Concrete Repair	Milling 6-inch + overlay 7-inch asphalt

Figures 1 (a) and (b) compare the environmental impacts of two rehabilitation strategies with HMA and PCC overlays, respectively, for energy consumption and GHG emission. The impact assessment results using the baseline values in the life-cycle inventory database are show in the column values and the variation of results are displayed in error bars representing the minimum and maximum values.

The results show that the HMA overlay causes greater energy consumption and GHG emission, as compared to the PCC overlay. The similar trend can be observed considering the variations in the inventory data. The maintenance stage constitutes the major component in the life-cycle energy consumption and GHG emission for the HMA overlay, although the HMA overlay has less impact during the initial construction stage compared to the PCC overlay. It is noted that this comparison was performed for two rehabilitation strategies in a 40-year analysis period that is different from the pure comparison between HMA and PCC materials. For example, the PCC overlay design includes two-inch asphalt overlay after 6-inch milling of existing asphalt layer in addition the 18-inch concrete overlay.



(a)



(b)

Figure 2 Environmental impacts of pavement rehabilitation strategies for (a) energy consumption and (b) GHG emission

Figure 2 shows the percentage distributions of energy consumption and GHG emission at different stages of initial construction. For both HMA and PCC overlays, the material-related environment impacts play the most significant role in the total energy consumption and GHG emission regardless of variations in the inventory data. For the analysis using baseline values, the percentages of energy consumption and GHG emission caused by material-related components are 88-89% of for HMA overlay and 94-96% for PCC overlay. The acquisition and production of raw materials consume 85% of total energy and generates 92% of total GHG emission for PCC overlay; while only 63% of total energy and 62% of total GHG emission for HMA overlay.

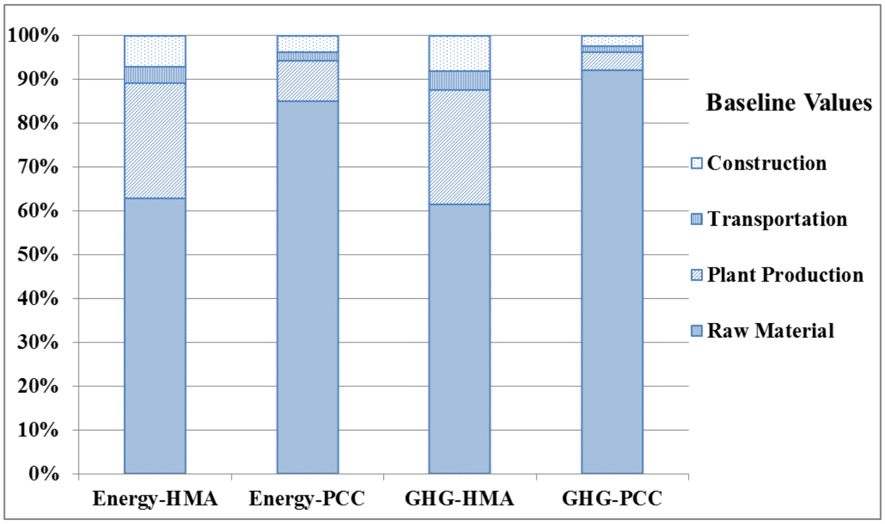


Figure 3 Percentage distributon of energy consumption and GHG emission at different stages of initial construction using (a) baseline (b) minimun and (c) maximum values

The on-site transportation component is minor due to the short transport distance to the HMA plant and the on-site concrete batch plant. The construction equipment causes 7% energy consumption for HMA overlay but only 4% for PCC overlay. This is because significant amount of milling and paving operation for multi-lifts of HMA overlay as compared to the one-lift slip-form paving process for PCC overlay. These findings clearly illustrate that LCA can identify the material and process with high impact in the pavement life-cycle and help develop action plans for impact mitigation.

4.5 LCA Tool Development

The proposed Pavement Project Energy and Emission Calculator (PPEEC) was developed on Microsoft Excel platform consisting of multiple excel worksheets following the LCA framework. The worksheets have an allocated input area for the user to create an easy to use interactive interface primarily designed for agency decision-makers to benchmark and estimate the energy consumption and emissions. The PPEEC tool also reports all relevant material production energy consumption and emission values as inventory database and its variation. The following section describes the overall framework and architecture of the PPEEC.

The framework for PPEEC tool follows three main life cycle stages relevant to pavements: materials, construction and maintenance. The PPEEC Tool is a collection of spreadsheets and allows for different inputs at a project level, including geometry of the pavement, frequency of maintenance activities, mix design for material, equipment operating rate for construction tasks.

The user first inputs basic geometric information (length, width and thickness) and general life cycle characteristics (construction year, structure, maintenance activities) of the pavement project in the General Project Information worksheet. These geometries and characteristics are used throughout the PPEEC to calculate the volume related quantities. The series of worksheets guide the user through the stages of LCA. Each pavement life cycle phase has its own inputs and outputs.

The inputs for PPEEC tool are split into Primary Inputs and Secondary Inputs that the user can specify; however, they are interrelated. The Primary Inputs is the desired inputs at a project level, including geometry of the pavement, frequency of maintenance activities, mix design for material, equipment operating rate for construction tasks. The Secondary Input is the advanced input for analyzing the energy consumption and emission value variation among the inventory database from relevant publication sources. It also provides an alternative for the input of user defined unit energy consumption and emission values.

The combustion (direct) and upstream (indirect) CED and GWP results of the pavement LCA are displayed in the Results worksheet and Summary Report worksheet which has numerical and graphical representation.

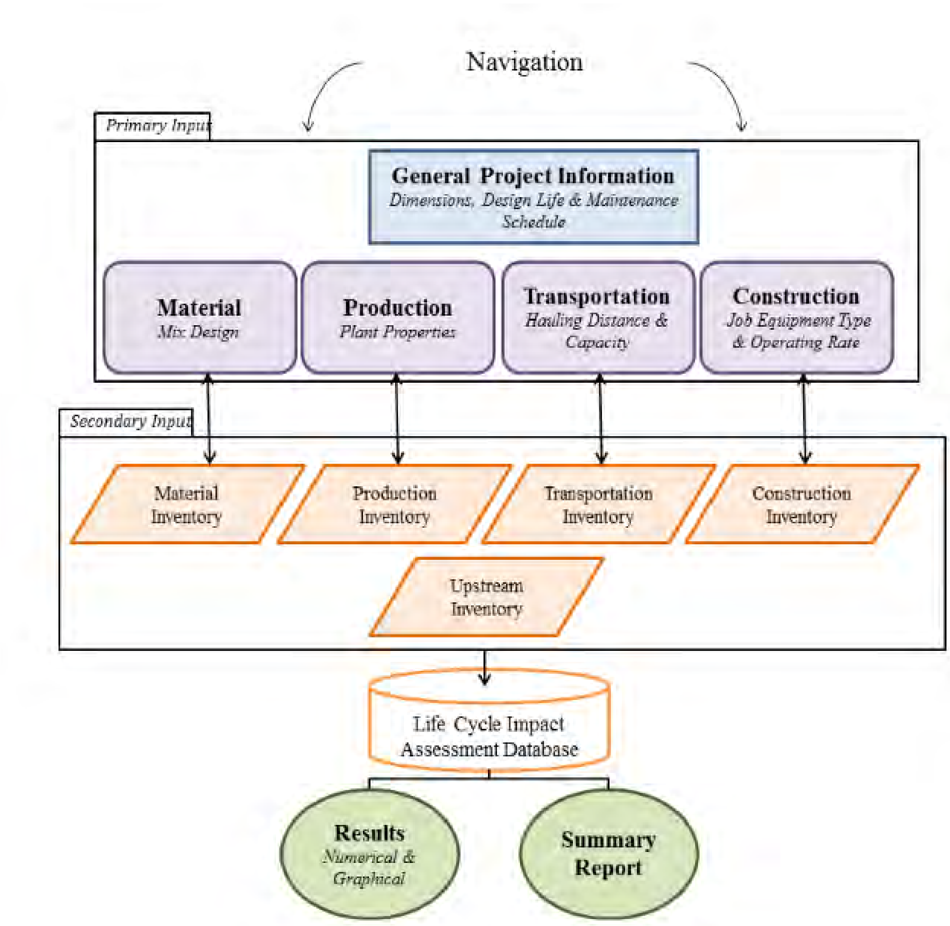


Figure 4 System Architecture

4.51 Worksheet Categories

The PPEEC consist of thirteen worksheets as shown in Table 4.1. The input parts of the worksheets are interactive to the user, and other supporting parts of the worksheet are ready-only for the user.

Table 6 Worksheet categories for the PPEEC tool

Worksheet	**Primary Input**	**Secondary Input**
General Project Information	Project Title, Location, Project Type, Design Life, Pavement Structure Dimensions, Maintenance Schedule and Activity	
Material	Mix Design	
Production	Plant Production Type	Plant Properties: Ambient Temperature, Heating Temperature, % Moisture Content
Transportation	Capacity of Truck, Distance to & From site, Operating Speed of Truck	
Construction	Equipment type based on HP, Operating Quantity, Operating Rate	
Results	-	-
Reports	-	-
Material Inventory		Select Relevant Publication Source from Inventory Database, User Defined unit energy consumption and emission values
Production Inventory		Select Relevant Publication Source from Inventory Database, User Defined unit energy consumption and emission values
Transportation Inventory	-	-
Construction Inventory	-	-
Upstream Inventory		Energy Matrix for Materials and Plant Production

The PPEEC Tool desires inputs at a project level, including geometry of the pavement, frequency of maintenance activities, mix design for material, equipment operating rate for construction tasks etc. which are termed as *Primary Inputs.* These Primary Inputs correspond to the following worksheets:

General Info Worksheet

The *General Project Information* worksheet (Figure) functions as the main input for the tool and the user can enter basic geometric information and general life cycle characteristics of the pavement project. These inputs include the title and location, project type, pavement dimensions, layer type and thickness, maintenance schedule and activities. The maintenance activities only consider flexible overlay, rigid Overlay and unplanned maintenance (% impact of initial construction). These geometries and characteristics are used throughout the tool to calculate the volume-related quantities.

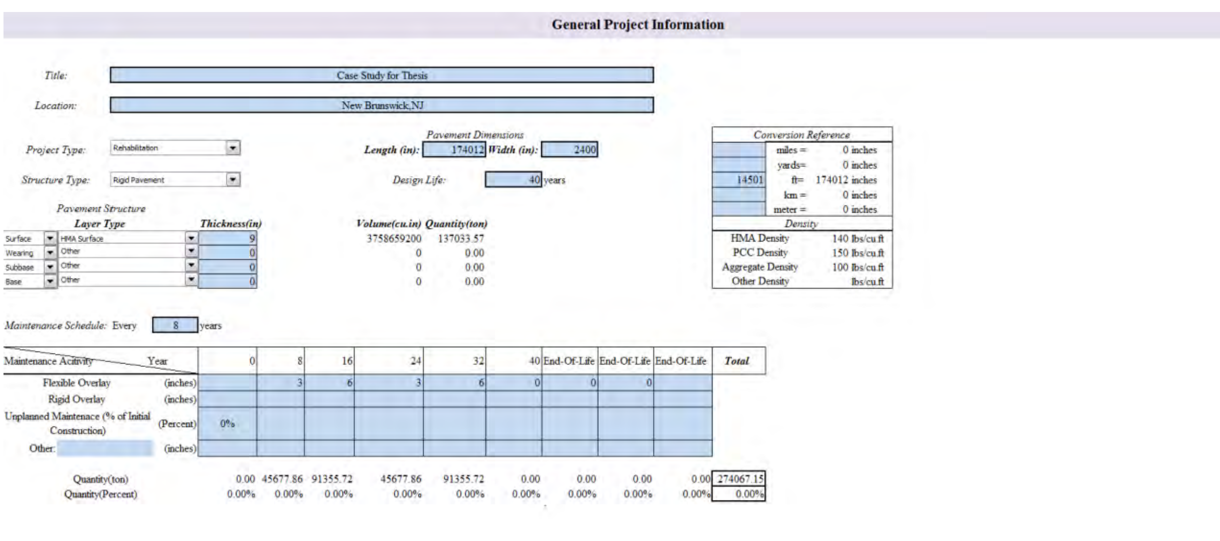
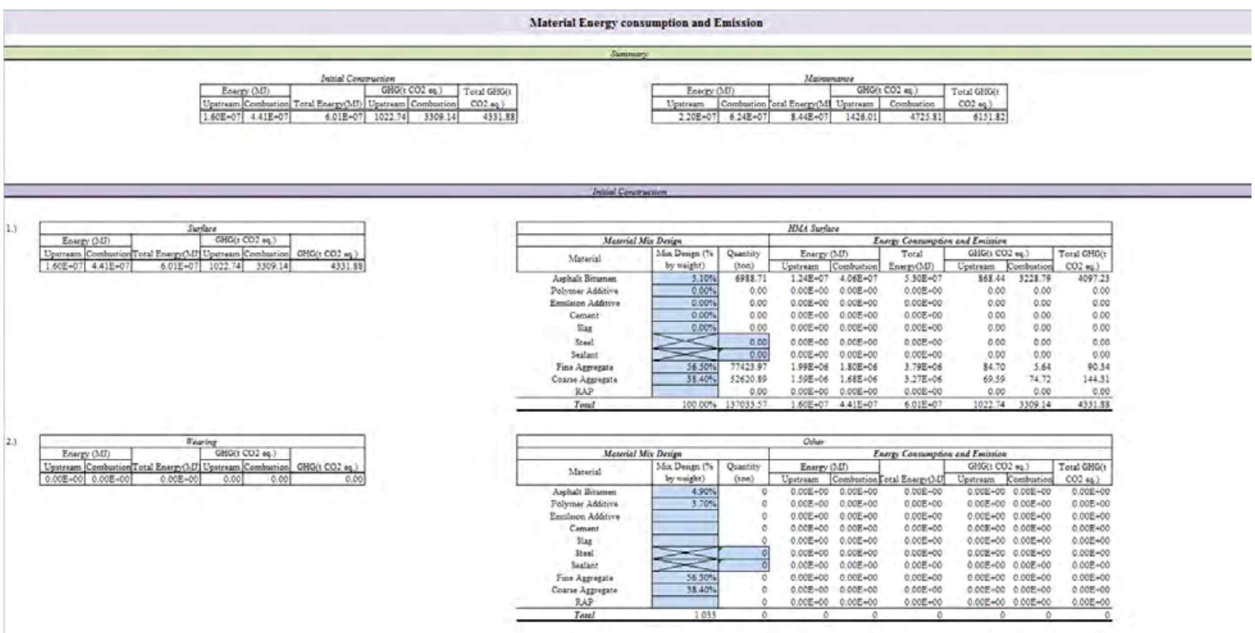


Figure 5 General Info Worksheet

Materials Worksheet

The *Materials* worksheet (Figure) is associated with raw material extraction phase. For each layer in the pavement structure, the user can specify the mix design (percentage by weight or tonnage) for the respective material type. Raw materials included in the worksheet are asphalt bitumen, polymer additive, emulsion additive, cement, slag, steel, sealant, fine aggregate, coarse aggregate and recycled asphalt pavement (RAP). The user defined input helps analyze the effect of using different mix designs for material selection in projects. This allows users to quantify the impacts of sustainable practices like using RAP and slag cement. The *Materials* worksheet has separate mix design inputs for initial construction and maintenance.



Material Energy consumption and Emission

Summary

Initial Construction

Energy (MJ) Upstream	Energy (MJ) Combustion	Total Energy(MJ)	GHG(t CO2 eq.) Upstream	GHG(t CO2 eq.) Combustion	Total GHG(t CO2 eq.)
1.60E+07	4.41E+07	6.01E+07	1022.74	3309.14	4331.88

Maintenance

Energy (MJ) Upstream	Energy (MJ) Combustion	Total Energy(MJ)	GHG(t CO2 eq.) Upstream	GHG(t CO2 eq.) Combustion	Total GHG(t CO2 eq.)
2.20E+07	6.24E+07	8.44E+07	1426.01	4725.81	6151.82

Initial Construction

1.) Surface

Energy (MJ) Upstream	Energy (MJ) Combustion	Total Energy(MJ)	GHG(t CO2 eq.) Upstream	GHG(t CO2 eq.) Combustion	GHG(t CO2 eq.)
1.60E+07	4.41E+07	6.01E+07	1022.74	3309.14	4331.88

HMA Surface

Material	Mix Design (% by weight)	Quantity (ton)	Energy (MJ) Upstream	Energy (MJ) Combustion	Total Energy(MJ)	GHG(t CO2 eq.) Upstream	GHG(t CO2 eq.) Combustion	Total GHG(t CO2 eq.)
Asphalt Bitumen	5.10%	6988.71	1.24E+07	4.06E+07	5.30E+07	868.44	3228.79	4097.23
Polymer Additive	0.00%	0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Emulsion Additive	0.00%	0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Cement	0.00%	0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Slag	0.00%	0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Steel		0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Sealant		0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Fine Aggregate	56.50%	77423.97	1.99E+06	1.80E+06	3.79E+06	84.70	5.64	90.34
Coarse Aggregate	38.40%	52620.89	1.59E+06	1.68E+06	3.27E+06	69.59	74.72	144.31
RAP		0.00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00
Total	100.00%	137033.57	1.60E+07	4.41E+07	6.01E+07	1022.74	3309.14	4331.88

2.) Wearing

Energy (MJ) Upstream	Energy (MJ) Combustion	Total Energy(MJ)	GHG(t CO2 eq.) Upstream	GHG(t CO2 eq.) Combustion	GHG(t CO2 eq.)
0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00

Other

Material	Mix Design (% by weight)	Quantity (ton)	Energy (MJ) Upstream	Energy (MJ) Combustion	Total Energy(MJ)	GHG(t CO2 eq.) Upstream	GHG(t CO2 eq.) Combustion	Total GHG(t CO2 eq.)
Asphalt Bitumen	4.90%	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Polymer Additive	3.70%	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Emulsion Additive		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cement		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Slag		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Steel		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sealant		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fine Aggregate	56.30%	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Coarse Aggregate	38.40%	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
RAP		0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	1.033	0	0	0	0	0	0	0

Figure 6 Materials Worksheet

Production Worksheet

The *Production worksheet* (Figure) lets the user select plant production operations like hot-mix asphalt, cement concrete, user defined HMA/WMA, and user defined HMA with RAP. If the user-defined alternatives are chosen, the user has to input plant parameters like ambient temperature, heating temperature, and moisture content. The *Production* worksheet is also split into initial construction and maintenance.

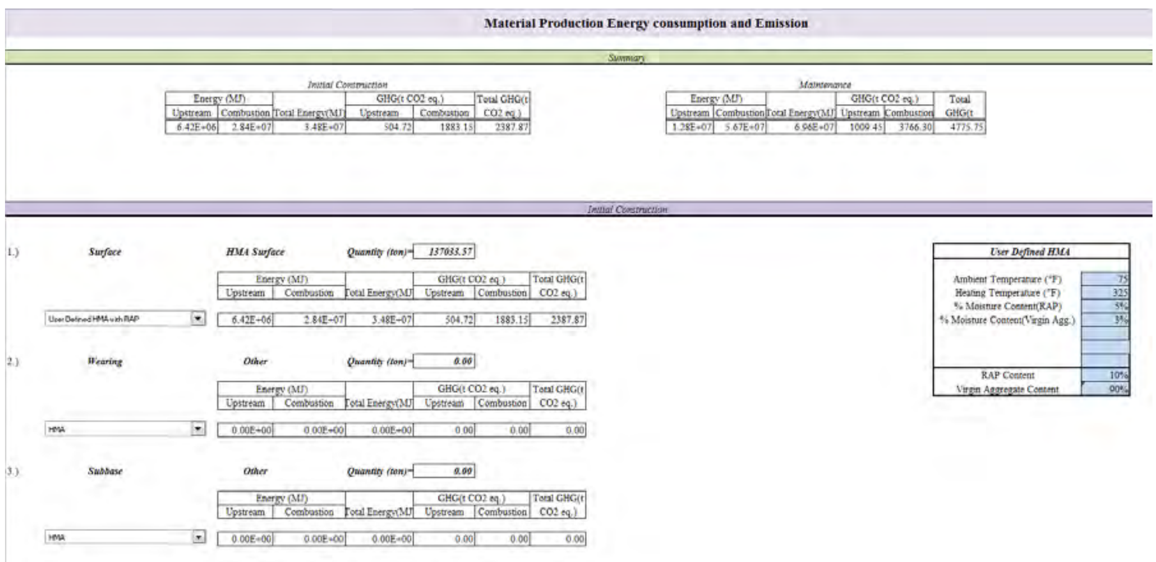
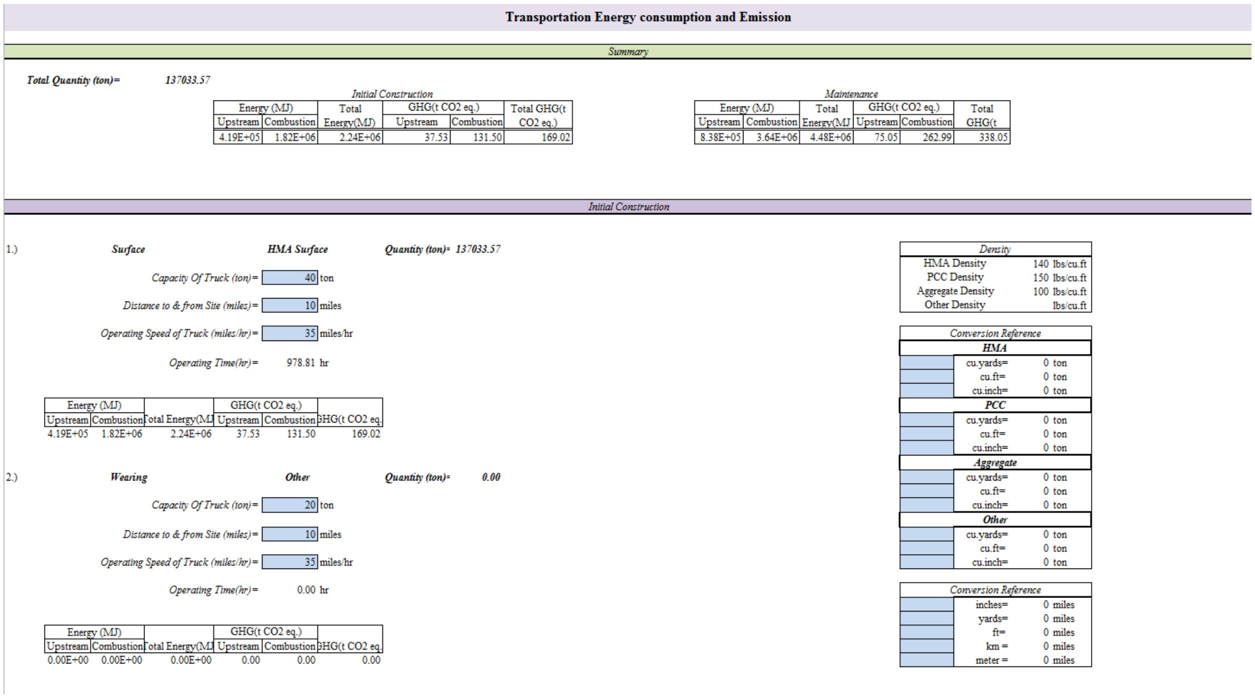


Figure 7 Production Worksheet

Transportation Worksheet

The Transportation Worksheet (Figure) relates to the transportation of paving material from the plant to the job site. For each layer, the user has to input properties like capacity of truck, distance to and from site and operating speed of truck.



Transportation Energy consumption and Emission

Summary

Total Quantity (ton)= 137033.57

Initial Construction

Energy (MJ)		Total	GHG(t CO2 eq.)		Total GHG(t
Upstream	Combustion	Energy(MJ)	Upstream	Combustion	CO2 eq.)
4.19E+05	1.82E+06	2.24E+06	37.53	131.50	169.02

Maintenance

Energy (MJ)		Total	GHG(t CO2 eq.)		Total
Upstream	Combustion	Energy(MJ	Upstream	Combustion	GHG(t
8.38E+05	3.64E+06	4.48E+06	75.05	262.99	338.05

Initial Construction

1.) **Surface** **HMA Surface** **Quantity (ton)=** 137033.57

Capacity Of Truck (ton)= 40 ton

Distance to & from Site (miles)= 10 miles

Operating Speed of Truck (miles/hr)= 35 miles/hr

Operating Time(hr)= 978.81 hr

Energy (MJ)			GHG(t CO2 eq.)		
Upstream	Combustion	Total Energy(MJ	Upstream	Combustion	GHG(t CO2 eq.
4.19E+05	1.82E+06	2.24E+06	37.53	131.50	169.02

2.) **Wearing** **Other** **Quantity (ton)=** 0.00

Capacity Of Truck (ton)= 20 ton

Distance to & from Site (miles)= 10 miles

Operating Speed of Truck (miles/hr)= 35 miles/hr

Operating Time(hr)= 0.00 hr

Energy (MJ)			GHG(t CO2 eq.)		
Upstream	Combustion	Total Energy(MJ	Upstream	Combustion	GHG(t CO2 eq.
0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00

Density		
HMA Density	140	lbs/cu.ft
PCC Density	150	lbs/cu.ft
Aggregate Density	100	lbs/cu.ft
Other Density		lbs/cu.ft

Conversion Reference		
HMA		
cu.yards=	0	ton
cu.ft=	0	ton
cu.inch=	0	ton
PCC		
cu.yards=	0	ton
cu.ft=	0	ton
cu.inch=	0	ton
Aggregate		
cu.yards=	0	ton
cu.ft=	0	ton
cu.inch=	0	ton
Other		
cu.yards=	0	ton
cu.ft=	0	ton
cu.inch=	0	ton

Conversion Reference		
inches=	0	miles
yards=	0	miles
ft=	0	miles
km =	0	miles
meter =	0	miles

Figure 8 Transportation Worksheet

Construction Worksheet

The *Construction Worksheet* (Figure) corresponds to the construction activity for initial construction and maintenance. For each construction activity (e.g. paving, milling, rolling, grooving etc.), the user has to select the equipment type based on horse power (HP), specify the operating quantity for a selected unit (e.g. ton, sq. ft, cu. ft etc.) and the operating rate for the selected unit per hour (e.g. ton/hr, sq. ft/hr, cu. ft/hr etc.).

Material Inventory Worksheet

The *material inventory* worksheet reports inventory database for energy consumption and emission values collected from relevant published sources. Raw materials included are asphalt bitumen, polymer additive, emulsion additive, cement, slag, steel, joint sealant, fine aggregate, and coarse aggregate. By default setting the recommended values (sources with an asterisk (*) mark) are selected. However, the user is allowed to choose any energy consumption and emission value from the inventory database source for any corresponding material. The user can also enter 'user defined' unit energy consumption and emission values from any relevant source outside the database.

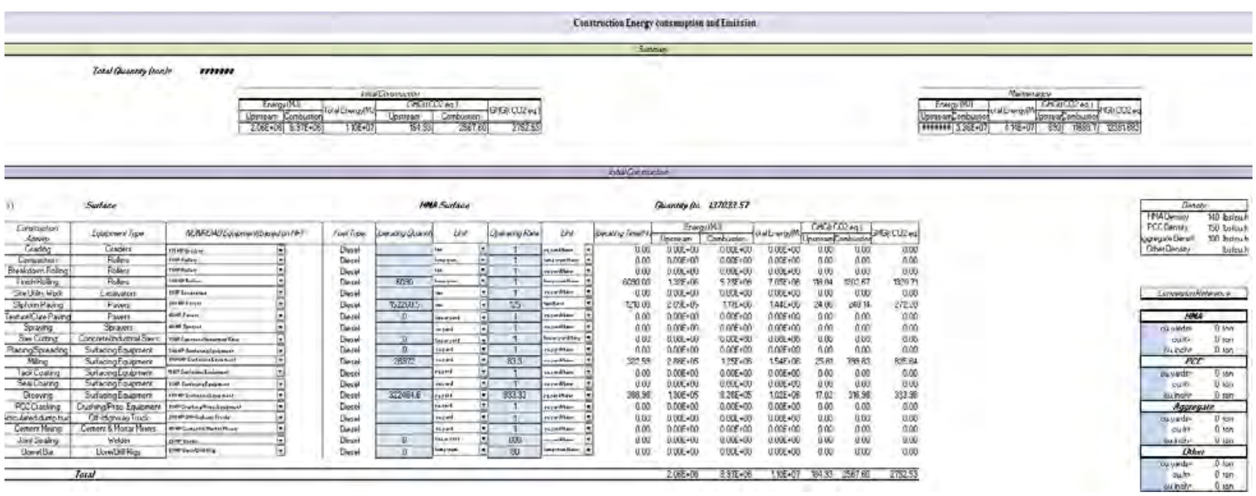


Figure 9 Construction Worksheet

Production Inventory Worksheet

The *production inventory* worksheet reports inventory database for energy consumption values and emission values collected from relevant published sources. Production plant includes HMA plant and cement concrete plant. By default setting the recommended values (sources with an asterisk (*) mark) are selected. However, the user is allowed to choose any energy consumption and emission value from the inventory database source for any corresponding production plant. The user can also enter 'user defined' unit energy consumption and emission values from any relevant source outside the database.

Transportation Inventory Worksheet

The *transportation inventory* worksheet reports inventory database for energy consumption values and emission values for truck transportation based on NONROAD model as discussed in section 5.3.2

Construction Inventory Worksheet

The *construction inventory* worksheet reports inventory database for energy consumption values and emission values for seventeen different construction equipments (Table 3.16) obtained from NONROAD model based on equipment type and horse power as discussed in section 5.3.2

Upstream Worksheet

The *upstream inventory* worksheet reports inventory database for energy consumption values and emission values for all phases of material, production transportation and construction. The upstream energy and emissions of process fuel and electricity (Table 3.19, 3.20) are extracted from GREET. The energy usage profile for raw material and plant production process of PCC and HMA (Table 5.3) from various sources are listed, which can be changed by the user.

Results Worksheet

Calculations are performed in hidden formulas across the tool but the Results worksheet summarizes the energy consumption and GHG emissions across the life cycle phases. Furthermore, it also variation among different inventory database values for the material and production stages. Based on the user input the impacts are linked to the unit process from the inventory database and then, using the tool, the impacts are consequently summed at different phases and levels.

Reports Worksheet

The reports worksheet provides the user with a printable format of the results. This worksheet is intended for agencies and decision makers to summarize the results at various phases of LCA at the pavement project level. The benefits of report worksheet are that it provides an overview of the LCA for the pavement projects; the generated reports for different structures, materials, and construction and maintenance options can be easily compared and benchmarked.

4.52 Inventory Values and Impact Assessment

Available literature includes various sets of data sources for the various materials, representing different geographic conditions, procedures, technologies and system boundaries. Ideally, these data should be checked for representativeness (technological, geographical and time related), completeness (regarding impact category coverage in the inventory), precision/uncertainty (of the collected remodeled inventory data), and methodological appropriateness and consistency. However, the literature sources do not always describe all the processes accounted for in the cradle-to-gate LCI of some materials. This introduces difficulties in assessing whether the system boundaries associated with available data fully match the goal and scope.

The environmental indicators are used in the tool: energy consumption and GHG emissions (GWP from greenhouse gases: Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O)). Most of the data are from existing up-to-dated studies, and certain indicators are calculated according to proper methodology. One advantage of this tool is the use of different environmental indicators for various relevant sources. The LCI data available from various relevant sources helps the user access the variation in environmental impact of pavement projects for the phases of material production and plant processing. Because of the highly customizable nature throughout the various modules of the tool, the user is not constrained to predefined conditions and assumptions. The tool allows the user to choose from different materials, structures, construction techniques and maintenance plans. Further, the user has an option to input 'user defined' inventory values or choose from the listed inventory data sources, which makes the life cycle analysis more relevant to the goal and scope of the respective pavement project.

5. Safety Risk Assessment

The proposed Life Cycle Assessment approach to quantify energy and environmental impact of airport runway pavement design. The excel-based tool - Pavement Project Energy and Emission Calculator (PPEEC) is intended to give airport agencies a highly customizable tool to assist them in quantitatively assessing the total environmental footprint of their procedures, strategies and decisions regarding the construction and maintenance airfield pavements.

According to FAA Safety Management System Manual, the work itself does not contain any inherent risks, but rather helps to mitigate indirect risk from environmental impact. Since more natural resources and energy consumption makes significant contribution to greenhouse gas emission which directly related to climate change such as more extreme weather conditions and natural disasters. By exactly quantifying the total environmental footprint, more environmental friendly pavement design and maintenance strategy will be highlighted.

6. Projected Impacts

The design and tool we developed assessed the cumulative energy demand (CED) and greenhouse gas (GHG) emission of different airport pavement design alternatives using a LCA approach. The results indicate that the expected pavement service life and maintenance treatments significantly affect the comparison between HMA and PCC pavements. The consideration of energy and emissions associated with the production of process fuels and electricity in the upstream process cannot be neglected. *The implementation of LCA approach enables decision makers to quantify energy consumption and GHG emissions among alternative pavement designs.*

We found out that the environmental impact among different pavement design alternatives significantly depend upon pavement type, design assumptions, and maintenance strategies. Although there are no general conclusions on pavement type selection, the comparison of energy consumption and GHG emission due to upstream, construction, and maintenance stages brings awareness to the airport authorities on the impact of pavement type selection. The project-level analysis need be conducted for selecting the sustainable design alternative in the airport planning process considering performance, economic cost, and environment impacts.

Since our design is LCA method used to quantify environmental impact of airport pavement and an excel-based tool, the cost of this product might be the resources for method and tool improvement including personal salary and advertisement. However, benefit can be quantified as time saving for airport related organization to develop their own environmental impact quantification methods and tools.

7. Interactions with airport operators and industry experts

The Interaction with airport operators and industry experts is through a technical survey distributed on line and with regular meetings with our project partner of Port Authority of NY & NJ. There valid responses to the questionnaire were received and analyzed.

Non university advisors:

Guy Zummo

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JFK Airport reconstruction

http://www.georgetownclimate.org/resources/jfk-airport-runway-13r-31l-rehabilitation-john-f-kennedy-international-airport-new-york-ci

Survey Questions	Lee County Port Authority dabyers@gmail.com	Lee County Port Authority bcbratton@flylcpa.com	FAA steven.debban@faa.gov
In your observation, what kind of pavements is mostly used in the airport and on which part?	Asphalt pavements on Taxiways and Runways. Concrete pavement on aprons.	Asphalt concrete for all surfaces except helicopter pads.	Currently ~ 80% surface HMA, 20% PCC
What is the typical maintenance schedule of airport runway at your airport?	It depends on the type of "maintenance". For striping, rubber removal, cleaning; is at least once a year. For major pavement rehabilitation or replacement, is every 15-20 years.	Annual crack sealing and pavement sealer as required.	Maintenance Locally funded not controlled by FAA
Is reclaimed asphalt pavement (RAP) being used in the current airport runway pavement or will be used in the future?	Not currently being used. Don't have any future plans for its use.	Yes, wherever economically feasible.	RAP is not allowed on surface currently
Is sustainability issues involved in the decision making process related to airport management and operation at your airport/ company/ organization?	Yes; to the extent possible without interfering with FAA requirements for materials/processes.	Yes	small factor
Is sustainability issues involved in the airport pavement design and maintenance at your airport/ company/ organization?	Yes.	Yes	not currently
Has Life cycle cost analysis (LCCA) been used for pavement type selection and rehabilitation strategy?		No	It is used however the reality of funds currently available to fund construction always must be considered.
What sustainable practices have been used in your airport infrastructure?	LED lighting.	LED lighting, solar power generation.	You need to check the economics of heated aprons, not necessarily cost effective.
Are you interested in a user-friendly tool to quantify environmental	Yes.	Sure	no

impact related to airport runway pavement?			

Figure 10 Regular Meeting with Experts of Port Authority of NY&NJ on April 12, 2016

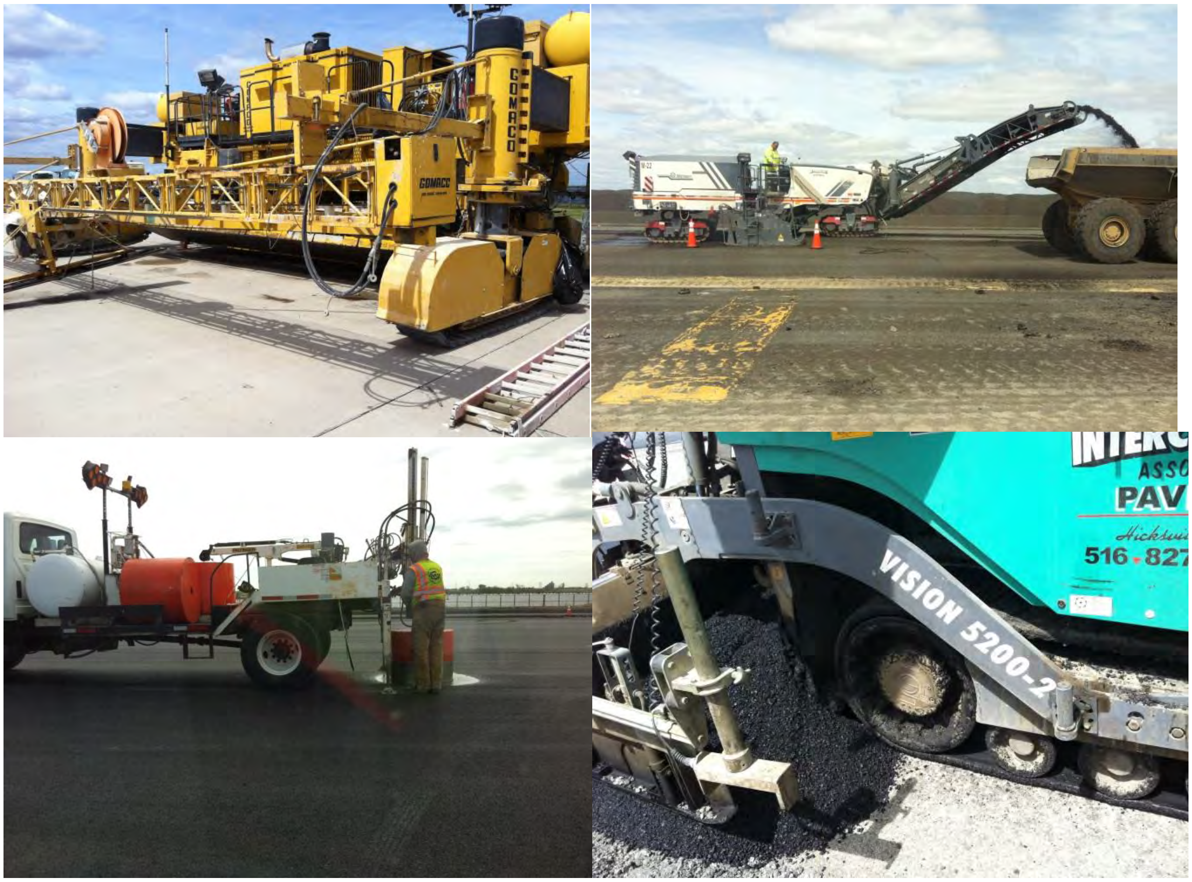

Figure 11 Field Visit to JFK International Airport and Data Collection

Appendix A. List of Complete Contact Information

1. Advisor

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2. Student 1

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2. Student 1

Name: Chinmay Thakkar

Affiliates: Graduate Research Assistant

Email: crt55@scarletmail.rutgers.edu

Appendix B. Description of the University

Rutgers, The State University of New Jersey, is a leading national research university and the state of New Jersey's preeminent, comprehensive public institution of higher education. Established in 1766 and celebrating a milestone 250th anniversary in 2016, the university is the eighth oldest higher education institution in the United States. More than 67,000 students and 22,000 faculty and staff learn, work, and serve the public at Rutgers locations across New Jersey and around the world.

University Mission

As the premier comprehensive public research university in the state's system of higher education, Rutgers, The State University of New Jersey, has the threefold mission of

- providing for the instructional needs of New Jersey's citizens through its undergraduate, graduate, and continuing education programs;
- conducting the cutting-edge research that contributes to the medical, environmental, social, and cultural well-being of the state, as well as aiding the economy and the state's businesses and industries; and
- performing public service in support of the needs of the citizens of the state and its local, county, and state governments.

a ch component of the university's mission reinforces and supports the other two.

Rutgers is dedicated to teaching that meets the highest standards of excellence, to conducting research that breaks new ground, and to providing services, solutions, and clinical care that help individuals and the local, national, and global communities where they live.

Appendix C. Description of Non-University Partners

The Port Authority of New York and New Jersey (PANYNJ) is a joint venture between the U.S. states of New York and New Jersey, established in 1921 through an interstate compact authorized by the United States Congress. The Port Authority oversees much of the regional transportation infrastructure, including bridges, tunnels, airports, and seaports, within the geographical jurisdiction of the Port of New York and New Jersey. This 1,500-square-mile (3,900 km^2) port district is generally encompassed within a 25-mile (40 km) radius of the Statue of Liberty National Monument. The Port Authority is headquartered at 4 World Trade Center.

Appendix E. Evaluation of the Educational Experience Provided by the Project

Faculty Evaluation

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

The students were able to conduct life-cycle assessment analysis and develop a useful tool for decision making through the design competition. This is invaluable experience for them in addition to what they learned in the classroom. They applied the knowledge into the real case scenarios through data collection and analysis. I believe the experience from this design competition will polish their analysis skills but also engage their career interests into aviation field.

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

Yes. The learning experience matches the level of graduate course that I am currently teaching at Rutgers University, such as the new graduate course on Sustainable Transportation Infrastructure. The students learned the life-cycle assessment and life-cycle cost analysis method, collected data from literature and field survey, conducted impact assessment analysis with different scenarios, and developed an EXCEL-based user-friendly tool.

3. What challenges did the students face and overcome?

There are several challenges faced by the student, such as the learning curve of life-cycle assessment, the collection of accurate life-inventory data for material and construction, and the development of tool in a short-time period. The students were able to conquer the problems *through the close communication with the project partners (PANY&NJ) and the faculty advisor. Several meetings were held jointly to discuss the analysis plan, check the project progress, and provide feedback. In addition, the students devoted a lot of time to this project and this made a lot of difference for the project outcome.*

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

Yes, I will definitely incorporate the design competition into the graduate and undergraduate course I am currently teaching. It seems that the best way is to encourage the students to select the relevant topics is through the class project, which will make the students engaged to the design competition and also get them excited. Another way is to enhance education experience is to engage more aviation industry partners working with the design competition.

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

The competition provides an excellent opportunity for students getting to know aviation industry and developing certain experience through the project process. I will definitely support the continuation of the design competition in future years.

Student Evaluation (Chinmay & Xiaodan Chen)

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?

Airport Cooperative Research Program (ACRP) University Design Competition provided an excellent opportunity for us to learn Life Cycle Assessemnt method applied in airport pavement to quantify the environmental impact. We also learn team work spirit to complete a design project while overcoming a lot of difficulties.

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

We both have many course works and the time management became a big challenge for us. After talking with our advisor, we try to learn a better time management skills such as setting goals once a week, being organized with all profiles, and deconstruct complex problem into small objects.

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

The resources on Airport Cooperative Research Program (ACRP) University Design Competition website are very inspiring and helpful to setup our design outline. After discussing with our advisor, doing literature review and consulting with our project partner, we had a very clear hypothesis.

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

We get most of our feedback from the regular meeting with Port Authority of NY &NJ. For example, the tool is not that user friendly at the very beginning, but after numeral revision, the tool can be understand and use by non-technical person.

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?

The competition extremely broadened our knowledge on environmental impact study. Furthermore, we learned something more important than knowledge is to be an responsible team member and how to interact with professionals efficiently and maturely.

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