Development of an Environmental Life-Cycle Assessment (LCA) Protocol for Flexible Pavements that Integrates Life-Cycle Components to a Proprietary Software

F. Osmani, M. Hettiwatte, S. Kshirsagar, S. Senadheera & HC. Zhang
Texas Tech University, Lubbock, TX, USA

ABSTRACT: Significant progress has been made in research on environmental life-cycle assessment (LCA) of pavements. Use of this new knowledge has been slowed by a lack of standardized datasets and analysis protocols. Several software packages have been developed to address this by providing datasets with broader coverage and better quality, but practitioners need application-specific data input interfaces for easy use. The authors report work on developing a protocol for environmental LCA of flexible pavements that uses a proprietary software system with data input interface plug-ins they developed for each of the five flexible pavement life-cycle phases. This protocol allows designers to integrate environmental LCA with life-cycle cost analysis (LCCA) to select the optimum design from several alternatives. With looming transformative changes in pavement materials and technology landscapes, this protocol also has the potential to allow a more effectively holistic assessment of such novel systems.

1 INTRODUCTION

1.1 *Background*

Environmental LCA of products and processes has been a topic of interest for the last couple of decades, particularly since the introduction of the International Organization for Standardization (ISO) 14001 in 2004 (ISO14001, 2004). Many agencies have adopted this framework since then. In 2006, the ISO 14001 was replaced with ISO 14040 and ISO 14044 (ISO14040, 2006; ISO14044, 2006), and both government agencies and private sector began assessing sustainability impacts of their products and services. More and more agencies are now moving towards incorporating holistic sustainability concepts to make decisions based not only on LCCA but also on impacts to their organization, surrounding community and the society in general.

1.2 *Literature review*

The following literature review takes a broader look at LCA combined with some focused studies that relate to flexible pavements. The review showed a wide variation in approaches and results that are sometimes contradictory. However, many of these variations are the result of a diverse array of goals and objectives in these studies.

1.2.1 *Environmental LCA*

The concepts of environmental LCA were first introduced in the 1960s to monitor and estimate impacts due to solid waste as well as emissions to air, land and water (Harvey et al., 2016). Later it was broadened to include emissions from chemicals, energy production and use of resources. The first international standard was introduced in 2004, when ISO 14001 provided a framework to estimate these impacts in order to make important decisions on products and services

(ISO14001, 2004). The life-cycle of a product comprises of consecutive and interlinked phases from raw material acquisition or generation to product end-of-life and disposal. LCA for a product is the compilation and evaluation of inputs, outputs and their potential environmental impacts throughout its life-cycle. This systematic approach will ensure accurate assignment of a potential environmental burden to the appropriate life-cycle phase or individual process (ISO14040, 2006).

The ISO 14040 LCA has the following four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. According to ISO 14040, the system boundary for an LCA must be framed to highlight key phases of the product life-cycle. This typically includes unit process for raw materials, inputs and outputs of the primary production/manufacturing/processing sequence, distribution, product use and maintenance, disposal of process wastes and used products, recovery of used products (including reuse, recycling and energy recovery), production and use of fuels, electricity and heat, manufacture of ancillary materials, manufacture, maintenance and decommissioning of capital equipment, lighting and heating (ISO14040:2006).

1.2.2 *Flexible pavement life-cycle*

In general, a pavement life-cycle consists of six phases, all of which have significant impacts on the environment: material production, pavement design, construction, service period, maintenance/rehabilitation, and end-of-life (Harvey et al., 2016). It can be considered as a closed loop for a particular project depending on the system boundaries for which the LCA is to be conducted. Design is not identified as a separate phase in most instances, and its impact is considered to be included among the other five phases.

1.2.3 *Pavement LCA*

Pavement LCA is an area of active interest among both researchers and practitioners, and both groups generally follow the ISO 14040 guidelines (AzariJafari et al., 2016). However, efforts of these groups are constrained by the lack of reliable data with appropriate levels of accuracy. Most sustainability studies focus on quantifying the environmental impacts and only a few address other important aspects such as design, material selection, constructability, maintenance and development of policies that promote achieving sustainability goals (Santero et al., 2011a). This situation can be addressed by standardizing the way functional units and system boundaries are established, thus paving the way for unification of LCA protocols around the world. LCA is still at its infancy in areas such as pavements, and many gaps in data and methodologies that still exist need to be addressed in order to accurately quantify their environmental impacts (Santero et al., 2011b). These gaps include misinterpretation of data due to lack of standardization and differences in analysis methods. If a common set of guidelines for data collection and analysis are agreed upon, these gaps can be further reduced and the data made more valuable to the pavement engineering community.

1.2.4 *Pavement LCA with Commercial Databases*

A number of pavement sustainability LCA studies have used commercial software platforms primarily to get access to accurate data. However, literature suggest that the user should recognize the strengths and limitations before using them. One such limitation for US users is that many of the leading LCA software have been developed in Europe and their data and methodologies cater to conditions there (Kang et al., 2014). In other instances, some software and databases have been reported to have double counting of sustainability impacts among unit process components (Vidal et al., 2013). Furthermore, the proprietary nature of commercial LCA software makes it very difficult to automate sustainability evaluations for clients' unique requirements (Gopalakrishnan et al., 2014).

1.2.5 *Introduction of paper*

A review of technical literature suggests a strong need for standardized protocols to conduct LCA of pavements. The purpose of this paper is to present a software-based framework for flexible pavements in which all five phases of a pavement life-cycle (excluding the design phase) are incorporated. These phases are materials processing, construction, pavement in service, maintenance/rehabilitation, and end-of-life. Unit process flow charts were developed for each life-cycle phase and a software plug-in was developed to seamlessly integrate customer design data with the proprietary LCA software and the database to allow the calculation of sustainability metrics. This method will allow the user to easily identify key process components in each phase that show high sustainability impacts and focus on ways to minimize those impacts to make the product (i.e. the pavement) more sustainable. The software-based plug-in interfaces for the five life-cycle phases have been developed in such a way that the pavement designer can evaluate each alternative using both the LCCA and environmental LCA at the time of design, so both criteria can be used to select the optimum design.

2 LCA FRAMEWORK FOR FLEXIBLE PAVEMENTS

The LCA approach is gaining ground as a viable concept to make pavements more sustainable (Huang et al., 2009). For this study, a process-based modeling approach was selected since it facilitates the assessment of every minute detail of the pavement life-cycle to assess sustainability impacts so remediation measures can be identified. The five phases of the pavement life-cycle considered here are material production, construction, pavement in service, maintenance/rehabilitation, and end-of-life. Performing all inventory analyses manually can be very time-consuming, so modeling for individual life-cycles phases was done using the commercial software platform GaBi^{TM} (thinkstep, 2016). Many software platforms are available for inventory analysis, including GaBi^{TM}, open LCA, Simapro, Umberto, and PaLATE. A free pavement LCA software tool, Athena Pavement LCA (Athena, 2016) is also currently available with limited data availability. Athena Pavement LCA includes data specific to Canada and selected US regions; data includes materials manufacturing, roadway construction, and maintenance life-cycle stages. Data does not include demolition and disposal of the pavement. This tool calculates environmental impacts in accordance with the US Environmental Protection Agency's (EPA) methodology for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI).

This paper is the result of a broader research study to develop and assess novel material systems for flexible pavements. The commercial software platform GaBi^{TM} was found to offer capabilities convenient to developing process flow charts, and it also provides extensive datasets for United States to go with its robust European database. GaBi^{TM} offers twenty-three vendor-developed databases for a wide array of industries, materials and continents, and a number of these databases are relevant for flexible pavements. The databases include Professional, Energy, End-of-Life, Manufacturing Processes, Renewable Raw Materials, Construction Materials, National Renewable Energy Laboratory (NREL) US Life-Cycle Inventory (LCI) Integrated, and Full US databases. The Full US Database allowed this research team to conduct LCA of flexible pavement systems by entering candidate pavement designs shortlisted from LCCA. The schematic in Figure 1 illustrates this analysis framework. The GaBi^{TM} software can also identify process hotspots for more detailed analysis and conduct what-if analyses for situations such as materials and process replacement candidates. The LCA for this study used a number of sustainability metrics (balances) available in GaBi^{TM} including climate change, ozone layer depletion, acidification, eutrophication, formation of photochemical oxidants, depletion of fossil and mineral resources, and hazardous/nonhazardous waste.

The effects of these metrics can be assessed by using Institute of Environmental Sciences (CML) 2001 and TRACI methodologies commonly used for characterization of environmental impact assessment. In this study, the whole life-cycle of the pavement was considered, from material production to end-of-life scenarios, processes such as production of asphalt cement, asphalt concrete and base materials, fuel and electricity, construction and rehabilitation, pavement in service, and recycling. The Full US database in GaBi^{TM} software (thinkstep, 2016) was used in this study because it has many complete US life-cycle inventory data sets. The GaBi^{TM} software and the database allow the quantification of inputs (material, fuel, and electricity) required, and outputs (air, water, and soil emissions) released during the pavement life-cycle. Figure 2 illustrates the components of the flexible pavement life-cycle and its components, along with the system boundary used for LCA.

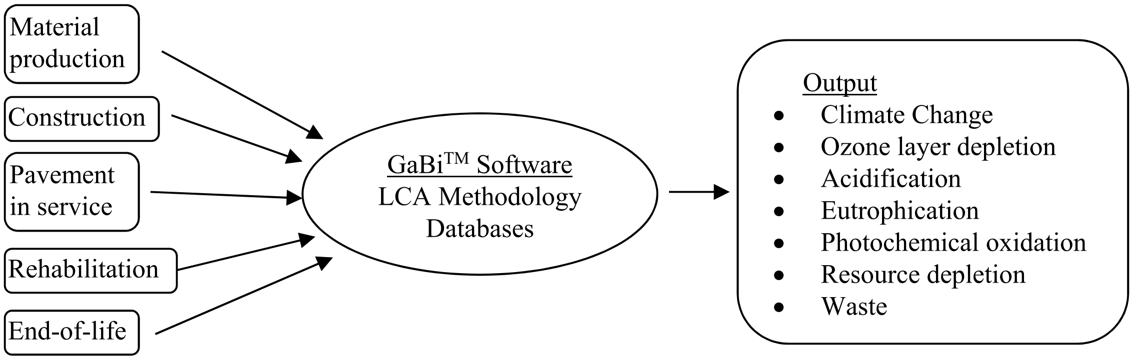

Figure 1. Illustration of LCA method

To conduct this study, we defined a functional unit (a comparative medium with all the properties of a system) and reference flows supporting the information for the establishment of functional units. Functional unit represents the system's function and provides an equivalent level of function or service for comparison. The functional unit of the conventional pavement system for this study is listed in Table 1. It was defined for a principle arterial highway located in Lubbock County, Texas. The LCA software and the data entry plug-in allows the use of the corresponding electricity grid mix from the Southwest Power Pool (SPP) (US EIA, 2016).

Table 1 Functional Unit

Parameters	*Values*
AADT	9,146
Truck %	35%
Traffic growth rate	2%
Design Life	25 years
Surface Area	1 yard × 1 yard

A reference flow is a quantified amount of product(s), including product parts, necessary for a specific product system to deliver the performance described by the functional unit. For this study the reference flow quantities according to the life-cycle phases are: *Structural design of the pavement* (number of layers and their composition): *Construction* (activity type): *Rehabilitation of the pavement* (when-after construction, expected design life-how many years will pass before the activity needs to happen again, percentage of element affected by activity, material types and quantities).

3 INTEGRATION OF LIFE-CYCLE COMPONENTS

The life-cycle impact assessment (LCIA) phase of an LCA is the estimation of potential human health and environmental impacts of the environmental resources and emissions during the life-cycle of a process or product (US EPA, 2006). Impact assessment should include ecological and human health effects; it also includes the resource depletion. An LCIA attempts to establish a connection between the product or process and its impacts on the environment. In this study, three layered configurations were used as shown in Table 2. These configurations were obtained for the same functional units as mentioned in Table 1, using the Flexible Pavement Design System (FPS-21) software used by Texas Department of Transportation (TxDOT) to design flexible pavements. All three configurations have four layers with the same material composition, but with different layer thickness values.

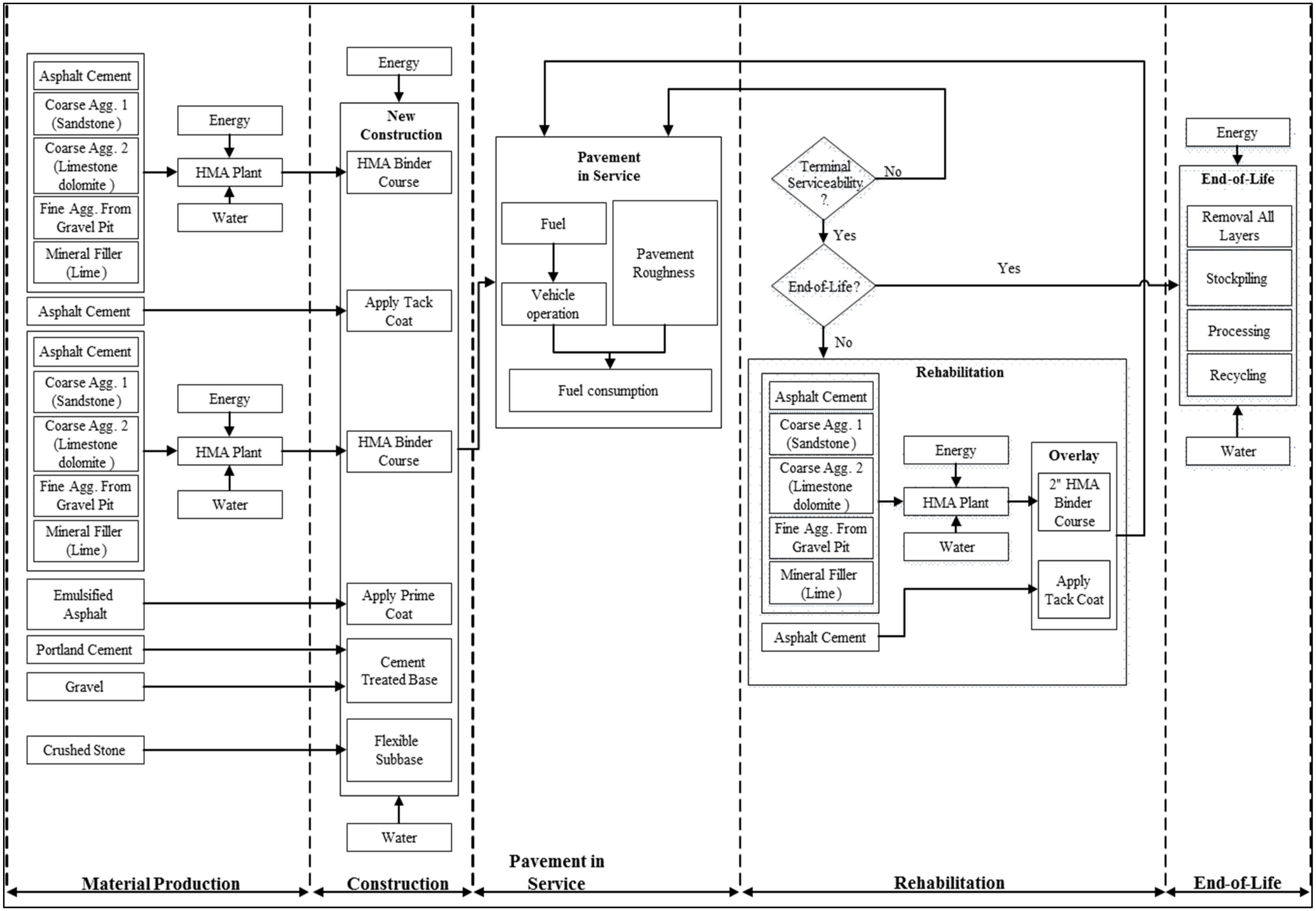

Figure 2. Pavement Life-Cycle and System Boundary used for LCA

Table 2: Flexible Pavement Layer Configurations

Design	Layer 1	Layer 2	Layer 3	Layer 4	Rehabilitations	Total Cost/SY
Design 1	HMA 4.5”	HMA 2”	CTB 7”	FB 8”	8 and 16	$ 23.73
Design 2	HMA 2”	HMA 5”	CTB 7”	FB 8”	8 and 17	$ 24.36
Design 3	HMA 6”	HMA 2”	CTB 5”	FB 8”	8 and 16	$ 24.46

Note: HMA = Hot mix asphalt; CTB = Cement stabilized base; FB = Flexible base; SY = Square yard

3.1 *Material production*

Material production consists of the processes involved to produce pavement materials. This process includes the entire upstream of the supply chain required to produce each material and mixing at the asphalt plant (FHWA, 2014). Traffic level and the soil characteristics at a particular location are the most important variables regarding pavement structural design and material composition. Using the functional units indicated in Table 1, a layered configuration was designed using FPS-21 software for one square yard of pavement surface. Based on the design output from FPS-21, the Hot-Mix Asphalt (HMA) layers consist of 40.1% sandstone, 34.7% limestone-dolomite, 9.4% aggregate from a gravel pit, 9.4% mineral filler (lime) and 6.3% asphalt cement. The Cement-Treated Base (CTB) consists of 5% Portland cement treated limestone-dolomite compacted to 120 lb./ft^3. The Flexible Base (FB) also consists of limestone-dolomite compacted to 115 lb./ft^3. These layer material compositions are unique for this study, and using the software plug-in interface for the material production phase, designers have the flexibility of changing these materials and compositions to suit their pavement design.

3.2 *Construction*

As shown in Figure 2, the environmental impacts of the construction phase involve the impacts from the diesel fuel combusted in the project equipment and the production of the fuel. Information like the daily output of each activity and the horse power (HP) of every piece of equipment was used, and an eight-hour workday was assumed. The construction phase includes a series of paving processes. In this model, the system boundary of the asphalt pavement construction phase is defined in generic form for any situation. This system boundary includes stabilized subgrade, unbound granular base, bound granular base tack coat/prime coat application and HMA/ Warm Mix Asphalt (WMA) placement/compaction. The environmental burdens associated with the construction phase mainly come from the energy consumption, emissions from equipment used in these activities and from diesel fuel production, which is a function of the thickness of different layers and their material compositions.

3.3 *Pavement in service*

Figure 2 illustrates the system boundary of the pavement in service phase consisting of the vehicles using the pavement, fuel production, and combustion. In this study, the environmental impact inventory covers both gasoline and diesel impacts for the vehicle mix on the roadway. Vehicles operating on diesel fuel include all types of vehicles from medium car to articulated truck, while vehicles operating on gasoline cover only the smaller vehicles such as medium car, van and SUV. The pavement in service phase is mainly composed of vehicular operation on the pavement. For the vehicle to stay in movement, it has to overcome many forces, such as inertia, gravity, internal friction, aerodynamic drag, and rolling resistance. All these factors, with the exception of rolling resistance, are vehicle-related. Rolling resistance is affected primarily by pavement texture, roughness, and the pavement type. These properties may significantly increase energy consumed by the vehicles, thus increasing the fuel consumption (Willis et al., 2015). The widely accepted International Roughness Index (IRI) standard was introduced by the World Bank in 1982. The IRI is a scale for roughness based on the simulated response of a generic motor vehicle to the roughness in a single wheel path of the road surface (NCHRP, 1978). IRI values are measured in inches/mile or m/km (Al-Rousan et al, 2010). As pavement roughness increases with time, it increases the vehicle fuel consumption rate. Authors have used results from previous research by Chatti & Zaabar (2012) for the base fuel consumption and how it changes based on travel speed and pavement roughness.

The effect of maintenance activities, such as patching and crack sealing, on the pavement IRI is not clear (Yang, 2014). Because of that, this study only considered the effect of rehabilitation (overlays) on the pavement IRI. It is assumed that the rehabilitation of a pavement restores its condition, but not to the point when the pavement was initially constructed. Rehabilitation will be done after a fixed number of years and will be repeated again, until it reaches its end-of-life.

The pavement in service phase is the most complex section when analyzing the environmental impact of a pavement system (Yang, 2014). The interaction between vehicles and the pavement surface has a significant effect on vehicle fuel consumption (Santero et al., 2011b). The vehicle fuel consumption is influenced by the load and pavement roughness. In this study, the flexible pavement roughness is represented using one of two parameters: pavement serviceability expressed by present serviceability index (PSI) and pavement roughness expressed by IRI. The IRI is incorporated into the sustainability assessment using the model provided in equation 1, 2 and 3 (Hall & Muñoz, 1999). The IRI values will change during the life-cycle of the pavement depending on its performance cycle, and it can be calculated for a certain year using equations 4 and 5. All these processes are incorporated in the GaBi$^{\text{TM}}$ plug-in to calculate the vehicle emissions.

$$PSI = 5 - 0.2937x^4 + 1.1771x^3 - 1.4045x^2 - 1.5803x \tag{1}$$

$$x = \log(1 + SV) \tag{2}$$

$$SV = 2.2704 * IRI^2 \tag{3}$$

$$IRI_n = IRI_{Initial} e^{bn} \tag{4}$$

$$b = \frac{\ln\left(\dfrac{IRI_{Ter\min al}}{IRI_{Initial}}\right)}{Timebetweenrehabilitation} \tag{5}$$

Where, *PSI* = present serviceability index; *SV* = slope variance used to characterize the pavement roughness; *IRI* = International Roughness Index; n = number of year; b = site constant for IRI.

The authors used this approach to obtain the IRI value for a certain year of the life-cycle, using the initial PSI, final PSI, and time between rehabilitations calculated during the pavement design process. Hence, we calculated the varying fuel consumption depending on the IRI for a given time of the life-cycle. For this study, a traffic mix of 10% medium cars (gasoline), 20% vans (gasoline), 30% SUVs (gasoline), 20% light trucks (diesel) and 20% articulated trucks (diesel) was considered. The impacts were calculated based on the extra fuel consumption due to increasing IRI for an average speed of 55 mph. The traffic mix used in this study is unique for the selected design, but using the software plug-in interface for the pavement in service phase, designers can change the traffic mix and average speed to suit their pavement design.

3.4 *Rehabilitation*

As shown in Figure 2, the rehabilitation process considered in this study is the overlay of the 2” HMA surface course. In this study, it is assumed that the overlay uses the same type of materials as the new construction. The environmental impacts considered in the rehabilitation process include the impacts released by the production of asphalt cement, aggregates, asphalt concrete, diesel fuel combusted by the equipment during the rehabilitation process, and the production of the diesel fuel used to run the equipment during the rehabilitation process. In order to calculate the amount of emission released, the model used for the material production phase was applied.

The data input plug-in interface for the rehabilitation phase provides flexibility to the pavement design engineer to enter the timing and overlay material information for each rehabilitation operation conducted during its life-cycle. The number of rehabilitation operations for a design life-cycle is limited to a maximum of four. The rehabilitation and preventive maintenance phase will generally include three alternatives: overlay, seal coat, slurry seal. But for this study we only looked at a 2” overlay alternative.

3.5 *End-of-life*

A pavement is expected to provide satisfactory service over its design life. It is rehabilitated a number of times before it is demolished and a new pavement is built at the same location. Figure 2 shows the system boundaries followed in the study for end-of-life of a pavement. As seen, it was assumed that at the end of its design life, the asphalt cement layer is removed completely from the road by milling machines. The other layers are reused and function as salvaged materials. For calculating the environmental impacts from the milling machine, the impacts from the diesel fuel combusted in the equipment and the production of the fuel are considered. The milled asphalt concrete is transported back to the HMA plant, where it is reintroduced with the raw materials as reclaimed asphalt pavement (RAP). The process included after transporting the reclaimed asphalt is stockpiling, which involves the use of an excavating machine and loader, and crushing, a procedure that involves the use of a dozer machine (Yang et al., 2014). When calculating the environmental impacts for this equipment, the impacts from the diesel fuel combusted in the equipment and the production of the fuel are considered. For this study, it was assumed that all the waste material was transported by trucks 100 miles away from the pavement location. The authors have assumed that all material are either landfilled or transported to a recycling/processing facility, and the materials will be reused in another pavement system. The effect of landfilling is captured in this study, but to capture the effect of recycled materials this system has to be connected with another pavement system which is out of the system boundary of this study.

4 RESULTS AND DISCUSSION

The results for different impact categories determined by GaBi^{TM} Software for the three design alternatives are listed in Table 3. The results for each impact category for a particular design alternative is the sum of impact categories for each of the five phases of the pavement life-cycle. As expected, for each impact category, the values are dominated by the 'pavement in service' phase of the life-cycle. The next high impact life-cycle phase is material production. Due to the high material intensity of pavement structures, the material depletion and waste impact categories show up significantly as expected. The important thing about this analysis is that it provides detailed data by impact category and by life-cycle phase of the pavement system for each design alternative. This form of LCA, which integrates both conventional life-cycle economics and environmental sustainability, will lay the groundwork to create a unified assessment of design alternatives.

As shown in Table 2, FPS-21 calculated different life-cycle cost values for the three designs being considered in this illustration. If a designer was to select the best design based only on the LCCA criteria, design 1 would be selected because it has the lowest cost ($23.73/SY) of the three designs. But if we considered the LCA criteria, according to the values in Table 3, the best design would have been design 2, which has the lowest footprint values for the overall pavement life-cycle. Therefore, this clearly indicates that considering only the LCCA criteria will overlook the sustainability aspect of a design, and end up in giving a less sustainable design. Hence, we must consider both LCA and LCCA methods to achieve the best viable sustainable design. The software-based data entry plug-in interfaces for the five life-cycle phases developed here will allow the designers to achieve the best design with minimum effort, since the data required for the interfaces are typical pavement design parameters that are already known by the designers at the design stage.

5 CONCLUSIONS AND RECOMMENDATIONS

Pavement structures are highly material and energy intensive and as a result, their sustainability impacts are substantial. By making pavements more sustainable and environmentally friendly, a significant positive impact will benefit the society as a whole. There is a strong need to develop tools that will facilitate more accurate and practical assessment such that pavement designers can conduct LCA of pavement design alternatives and combine LCA results with results from conventional LCCA to select the optimum design alternative by considering both criteria. This paper presents software-based data entry plug-in interfaces for the five life-cycle phases of LCA of flexible pavements that were developed around a proprietary LCA software platform. The detailed unit process flow charts developed for each of the five phases of the flexible pavement life-cycle will allow the designers to assess the sustainability impacts of each component in each phase in the pavement life-cycle. This method will also allow the designers to change their designs to get the best-balanced design in terms of both LCA and LCCA criteria, where it will help the sustainable development of the future flexible pavement systems. The results of this study are encouraging and further work is currently underway in looking at incorporating novel material flexible pavement systems to this protocol.

Table 3. LCA results for three design alternatives, for one square yard of pavement surface area

Design alternative	Life-cycle phase	Impact Category						
		Climate change	Ozone layer depletion	Acidification	Eutrophication	Photo-chemical oxidation	Material depletion	Waste
Design 1	MP	1.70e2	1.62e-7	4.60e-1	1.14e0	3.50e-1	2.91e4	2.93e4
	C	4.02e0	2.59e-11	5.00e-2	3.63e-3	6.90e-2	1.68e2	1.76e2
	PIS	2.09e5	3.77e-6	1.91e3	1.43e4	3.62e3	6.17e6	6.53e6
	R	2.27e1	3.43e-8	1.50e-1	8.44e-3	1.53e-1	4.65e3	4.79e3
	EOL	1.64e1	1.82e-10	5.00e-2	4.19e-3	5.50e-2	3.51e3	3.85e3
Design 2	MP	1.17e2	1.94e-7	4.18e-1	9.5e-1	3.12e-1	2.14e4	2.14e4
	C	4.46e0	2.87e-11	5.50e-2	4.03e-3	7.70e-2	1.86e2	1.96e2
	PIS	2.00e5	3.60e-6	1.83e3	1.37e4	3.47e3	5.92e6	6.27e6
	R	2.27e1	3.43e-8	1.50e-1	8.44e-3	1.53e-1	4.65e3	4.79e3
	EOL	1.78e1	1.97e-10	5.00e-2	4.63e-3	6.20e-2	3.79e3	4.15e3
Design 3	MP	2.08e2	1.58e-7	5.22e-1	1.32e0	4.07e-1	3.68e4	3.72e4
	C	3.54e0	2.28e-11	4.40e-2	3.19e-3	6.10e-2	1.48e2	1.55e2
	PIS	2.09e5	3.77e-6	1.91e3	1.43e4	3.62e3	6.17e6	6.53e6
	R	2.27e1	3.43e-8	1.50e-1	8.44e-3	1.53e-1	4.65e3	4.79e3
	EOL	1.99e1	2.22e-10	6.00e-2	4.88e-3	6.30e-2	4.31e3	4.73e3

Note: MP = Material production, C = Construction, PIS = Pavement in service, R = Rehabilitation, EOL = End-of-life, Climate change (Global warming potential) using kg of CO_2 -eq.; Ozone layer depletion using kg of CFE 11-eq.; Acidification using kg of SO_2^- -eq.; Eutrophication using kg of N-eq.; Photochemical oxidation using kg NMVOC Equiv.; Material depletion in kg; Waste in kg (Emissions to air, water, soil and deposited goods); SY = Square yard

6 ACKNOWLEDGEMENT

Authors would like to acknowledge the Texas Department of Transportation (TxDOT) for their support as sponsor of this research. Authors would also like to acknowledge the technical support received by Dr. Feri Afrinaldi and Mrs. Shahrima Maharubin during this study.

7 REFERENCE

Al-Rousan, T., Asi, I., & Baker, A. A. 2010. *Roughness evaluation of Jordan highway network*. In 24th ARRB Conference, Melbourne, Australia 41.

Athena. 2016. Athena Sustainable Materials Institute. http://www.athenasmi.org/our-software-data/pavement-lca/; visited: 11/26/2016

AzariJafari, H., Yahia, A., & Amor, A. B. 2016. *Life cycle assessment of pavements: reviewing research challenges and opportunities*. Journal of Cleaner Production, 112, 2187-2197.

Chatti, K., & Zaabar, I. 2012. *Estimating the effects of pavement condition on vehicle operating costs* 720. Transportation Research Board.

Federal Highway Administration. 2014. *Life Cycle Assessment of Pavements*. Retrieved from http://www.fhwa.dot.gov/pavement/sustainability

Gopalakrishnan, K., Steyn, W. J., & Harvey, J. 2014. *Climate Change, Energy, Sustainability and Pavements*. Green Energy and Technology. Springer. Heidelberg.

Hall, K., & Muñoz, C. 1999. *Estimation of present serviceability index from international roughness index*. Transportation Research Record: Journal of the Transportation Research Board, (1655), 93-99.

Harvey, J. T., Meijer, J., Ozer, H., Al-Qadi, I. L., Sabori, A. and Kendall, A. 2016. *Pavement Life Cycle Assessment Framework.* FHWA-HIF-16-014

Huang, Y., Bird, R., & Heidrich, O. 2009. *Development of a life cycle assessment tool for construction and maintenance of asphalt pavements*. Journal of Cleaner Production, 17(2), 283-296.

ISO 14001:2004(E). *Environmental management systems-requirements with guidance for use*

ISO 14040:2006(E). *Environmental management -life cycle assessment-principles and framework*

ISO 14044:2006(E). *Environmental management -life cycle assessment-requirements and guidelines*

Kang, S., Yang, R., Ozer, H., & Al-Qadi, I.L. 2014. *Life-Cycle Greenhouse Gases and Energy Consumption for Material and Construction Phases of Pavement with Traffic Delay*. Transportation Research Record: Journal of the Transportation Research Board, (2428), 27-34.

NCHRP. 1978. *Calibration of Response Type Road Roughness Measuring System.* D.C, U.S.A: Trans-portational Research Board.

Santero, N. J., Masanet, E., & Horvath, A. 2011a. *Life-cycle assessment of pavements Part I: Critical Review*, 55(9), 801-809.

Santero, N. J., Masanet, E., & Horvath, A. 2011b. *Life-cycle assessment of pavements Part II: Filling the research gaps.* Resources, Conservation and Recycling, 55(9), 810-818.

thinkstep. 2016. *GaBi Software*, v7.3 Leinfelden-Echterdingen, www.gabi-software.com

US EIA. 2016. United States Energy Information Administration. https://www.eia.gov/electricity/; visited: 06/25/2016

US EPA. 2006. *Life Cycle Assessment: Principle and Practice. Cincinnati*, OH: National Risk Man-agement Research Laboratory and EPA. United States Environmental Protection Agency.

Vidal, R., Moliner, E., Martinez, G., & Rubio, M. C. 2013. *Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement*. Resources, Conservation and Recycling, 74, 101-114.

Willis, J. R., Robbins, M. M., & Thompson, M. 2015. *Effects of Pavement Properties on Vehicular Rolling Resistanc*e: A Literature Review.

Yang, R. Y. 2014. *Development of a Pavement Life Cycle Assessment Tool Utilizing Regional Data and Introducing an Asphalt Binder Model* (Doctoral dissertation, University of Illinois at Urbana-Champaign).

Yang, R., Ozer, H., Kang, S., & Al-Qadi, I.L. 2014. *Environmental Impacts of Producing Asphalt Mix-tures with Varying Degrees of Recycled Asphalt Materials*. International Symposium on Pavement LCA 2014, Davis, CA, October 14-16 2014.