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# Multi-objective optimization of greenhouse gas emissions in highway construction projects

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ABSTRACT

With the increasing interest in relationships between built environments and ecosystems, the environmental impacts of the construction industry have been a subject of many studies. Based on the results of previous studies using construction systems modeling and life cycle assessment, the authors treated greenhouse gas (GHG) emissions as an additional project objective to time and cost, and applied multi-objective optimization to derive optimal solutions for transportation projects. Two highway construction case studies were analyzed for relationships between time, cost and environmental impacts. The results showed strong positive correlation between time and cost, moderate positive correlation between cost and GHG emissions, and weak positive correlation between time and GHG emissions. The results suggest that it is less likely that time and GHG emissions may affect each other. It is more so to time and GHG emissions. In addition, it is unlikely that there are common factors that can simultaneously affect cost and GHG emissions, or time and GHG emissions. Future studies are needed to include other types of environmental impacts and further understand the advantages and disadvantages of the lack of dependency between time and GHG emissions, as well as cost and GHG emissions in order to enhance sustainable construction.



## 1. Introduction

The construction sector plays a significant role in the increase of environmental impacts nationally and globally. In the U.S., buildings were accounted for 39% of primary energy use, 40% of raw material use, and 38% of $CO_2$ emissions (USGBC, 2008). EPA reported that 1.7% of total U.S. greenhouse gas (GHG) emissions and 6% of total industrial-related emissions in the U.S. were produced by the construction industry, which placed this industry to the list of top emitting sectors (EPA, 2009). According to previous research, the construction sector ranked the third in producing GHG emissions, following the oil/gas and chemical industries (Truitt, 2009). Additionally, 13.4% of the total industrial GHG emissions in the U.S. were produced by highway, street, and bridge construction (Kibert, 2002). Regarding raw material use, the U.S. Geological Survey (USGS) reported that 1.5 billion metric tons (Gt) of natural aggregates, 48 million metric tons (Mt) of concrete, 35 Mt of asphalt, and 6 Mt of steel were used by interstate highway construction in total. The estimates were based on a 42,500-mile (73,000-km) interstate highway system with four 12-foot (3.7-m) wide lanes (USGS, 2006). Due to such a considerable amount of environmental impacts, increasing interest has been paid to highway construction projects in adopting sustainability practice such as the application of green rating systems.

Over the past years, literature on sustainability has focused on defining and assessing environmental performance indicators and environmental scoring systems (e.g. Yao, Shen, & Yam, 2007). The significant contribution of the construction industry to GHG emissions has triggered extensive research attention for environmental impact mitigation technologies in both building and highway construction. For example, systems thinking, life cycle thinking, and integrated design process (USGBC, 2012) were adopted in sustainable construction. The Leadership in Environmental and Energy Design (LEED) was introduced by the U.S. Green Building Council (USGBC) to assess buildings in terms of environmental performance. Meanwhile, the Department of Transportation (DOT) in various states also implemented sustainable practices such as reusing materials at the site (Gambatese, 2005). In addition, assessment methods of environmental performance of highway construction have also been developed. For example, the New York State DOT introduced GreenLITES to measure sustainability

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performance of highway projects. Only recently, the Envision rating was introduced by the Institute for Sustainable Infrastructure (ISI) as a national scoring tool for highway projects. Envision is a green rating system to assess the sustainability of all types and sizes of infrastructure projects including roads and bridges. It has 60 credit points in five main categories, Quality of Life, Leadership, Resource Allocation, Natural World, and Climate and Risk (ISI, 2016).

Even though the concept of sustainable construction is not new in both building and highway projects, improving the application of environmentally conscious construction in a timely and feasible manner to construction projects is still in its early stage. Principles of sustainable infrastructure have evolved with the advancement in designs, materials, and construction technologies. Increasing interest in effectively reducing environmental impacts, highway construction practitioners led to the search for delivering projects in a resource-efficient, cost-effective, and environmentally friendly manner (Jha, Shariat, Abdullah, & Devkota, 2012). As an example, Carpenter, Gardner, Fopiano, Benson, and Edil, 2007 quantified cost and environmental impact benefits of highway projects by using a life cycle assessment (LCA) approach.

Environmentally conscious construction was defined as the encouragement of ecological, economic, and social-cultural sustainability in buildings (Kua & Lee, 2002). Therefore, the concept includes environmental as well as other objectives. Although previous researchers clearly summarized the significance of environmental impacts during the construction phase (e.g. Bilec, Ries, Matthews, & Sharrard, 2006), there are still gaps between the ultimate goal of environmentally conscious construction and contributions of those studies. This is mainly because most of the studies have been directed to understanding and analyzing solely the relationship between environmental impacts and construction processes, and have overlooked the multi-objective nature of construction projects, even though there are a couple of exceptions (e.g. Marzouk, Madany, Abou-Zied, & El-Said, 2008).

In this study, time, cost and environmental impact (TCEI) objectives are analyzed to understand the interdependency between them. There are external factors in the construction system, which produce an impact on the relationship between TCEI. They are referred to as project conditions in this study, and affect the flow of construction projects through its life cycle by influencing the selection of construction methods. The details regarding this process have been covered in previous publications (Ozcan-Deniz & Zhu, 2016). Using the construction method selection mechanism in the previous study, this paper will focus on the correlation between TCEI. Being an effective tool in optimizing multiple parameters, multi-objective optimization is used in this study to optimize these three potentially conflicting objectives in construction projects. Two highway construction cases are used in this study. The first part of this paper contains background information about LCA, highway construction, and multi-objective optimization. Second part is focused on the details of the multi-objective optimization process. Then, the relationship between time, cost and environmental impacts is discussed using the two cases. Finally, conclusions and future directions regarding this study are summarized.

## 2. Background

### 2.1. Life cycle assessment (LCA)

LCA was considered as an important tool to analyze and calculate resource consumption and environmental impacts of products and services from a "cradle-to-grave" perspective (Bengtsson, 2001). The life cycle of building was divided into four stages as raw material extraction, manufacturing, use, and end-of-life (Bilec et al., 2006). Construction literature is rich in LCA studies focusing on especially greenhouse gas (GHG) emissions, energy consumption, and sustainable resource utilization. For example, Sharma, Shree, and Nautiyal (2012) performed LCA to find out the energy consumption and GHG emissions of an example building. Sartori and Hestnes (2007) used LCA to compare the energy utilization of conventional and low-energy buildings through their lives, and showed a linear relationship between the operating and total energy demand of these buildings. To enhance the integration of sustainability and construction operations, Li, Zhu, and Zhang (2010) proposed a work breakdown structure to identify materials and equipment used in a construction activity, and LCA was applied to the materials and equipment for environmental analysis. In the scope of this study, the calculation of environmental impacts is only focused on evaluating GHG emissions by using the LCA approach.

### 2.2. Highway resurfacing construction methods

Highway resurfacing projects consist of core activities such as milling existing asphalt, placing asphaltic concrete, and putting the concrete friction course. A typical resurfacing operation is often performed lane by lane. Normally, existing asphalt is first milled and hauled away by dump trucks to be recycled. Then virgin or recycled asphaltic concrete is placed. An asphalt composition can be different in terms of recycled concrete amount and its temperature of mixing, which results in different environmental performance.

There are research studies analyzing different ways to perform resurfacing of roads. Uhlman (2009) compared eco-efficiency of chip seal resurfacing, hot mix asphalt (HMA) overlays, and micro-surfacing as being alternative types of resurfacing operations. Hot chip seal resurfacing was reported to have higher global warming potential compared to colder substitutes. Similarly, Chehovits and Galehouse (2010) compared energy usage and GHG emissions of resurfacing operations. They analyzed HMA, Hot-in-place (HIP) recycling, chip seal resurfacing, and micro-surfacing in their list of pavement preservation treatments. The results showed that different types of resurfacing operations required differing amounts of energy per year of pavement life.

Fuel selection, equipment idling, electricity use, equipment maintenance, equipment selection, and materials recycling were also reported to affect GHG emissions (EPA, 2009). Material recycling techniques such as using Reclaimed Asphalt Pavement "RAP" reduced demand for new materials, saved energy, and reduced carbon output (Huddleston, 2008). Warm mix asphalt (WMA) was another technique decreasing fuel/energy consumption, GHG emissions, and dust production (Chowdhury & Button, 2008). Overall, WMA provided 15% reduction on the environment impacts of HMA (Hassan, 2009). As an emerging technology, HIP recycling also significantly reduced overall energy and resource use (CCE, 2005). When HMA and HIP technologies were compared, HIP consumed less energy than HMA (Terrel & Hicks, 2008).

In the scope of this study, existing methods and new technologies for highway construction were used to generate several construction alternatives for resurfacing projects. Possible construction methods were defined for core activities, i.e., milling, resurfacing, and placing friction course. Various construction methods in terms of material, equipment and technology selection were considered for the three activities so that their TCEI values were calculated and analyzed.

### 2.3. Applications of multi-objective optimization in construction

Existing construction literature is rich in studies that concentrate on optimizing multiple project objectives. Traditionally, two most common objectives to be optimized simultaneously are time and cost of construction. In recent years, quality or environmental concerns are often incorporated as another dimension in