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Project Title

Optimal Selection of Upgrade and Maintenance Interventions to Minimize Life-Cycle-Cost

University

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Research Needs

Operation and maintenance costs are reported to be the longest and most costly phase of buildings and infrastructure systems where it exceeds cost of design and construction (Grussing and Marrano 2007). It is recently reported that lack of efficient maintenance plans, lack of knowledge on maintenance and deterioration models, and low maintenance quality significantly affect operational costs (Islam et al. 2019). Periodic maintenance cost is the largest contributor of life-cycle-cost of bridges (Barker 2016). Similarly, energy consumption is the largest contributor to the operation and maintenance costs of buildings (Energy Star 2013). Despite the fact that buildings and infrastructure systems are regularly maintained and upgraded, the upgrade and maintenance investments are often not optimal due to a number of challenges such as lack of capital, inefficient inspection schedule, unreliable deterioration models, uncertainty of expected savings and payback period, and unavailability of efficient and practical decision support tools (Austin 2012; Bertone et al. 2018). Technological advancements in building system components and infrastructure systems provide unique opportunities to reduce operation and maintenance costs (Sofos et al. 2020). For example, upgrading building fixtures, equipment and envelop components can achieve savings more than 45% in energy and water consumption (PNNL 2011). Due to complexity of buildings and infrastructure systems, decision makers are always faced with a challenging task to identify optimal maintenance and upgrade interventions to minimize operational costs while complying with available budgets. This highlights the importance of developing innovative models that can support decision makers in efficiently upgrading and maintaining their assets.

Several optimization models were developed to identify optimal maintenance interventions for bridges to minimize life-cycle-cost or equivalent annual cost while maintaining or maximizing service life. For example, Ghodosi et. al. (2018) developed an optimization model that can compare different maintenance intervention scenarios and select the most cost-effective one to minimize life-cycle-cost. This study used a database that contains asset inventory and maintenance actions along with reliability-based deterioration model and intervention-effect model to identify bridge condition throughout its life based on various maintenance interventions. The study showed that undertaking minor cost repair actions can achieve significant savings in bride life-cycle-cost as a result of reducing costly major interventions, showing up to 4.5 times cost savings. Han et al. (2010) developed multi-objective optimization model that is capable of identifying maintenance plan of concrete bridge structures to minimize life-cycle-cost and deterioration rate while maximizing service life. This study considered external environment, load and structure material, and deterioration process of bridge structure in identifying optimal maintenance plan. The study found out that the developed model can perform cost analysis and optimization for effective use of public funds (Han et al. 2010). Similarly, other optimization models were developed that can identify optimal maintenance interventions to minimize life-cycle-cost (Hadji 2020; Hadjidemetriou et al. 2020; Huang et al. 2004; Lounis 2005; Miyamoto et al. 2006). Despite the contribution of these studies, there is still need to advance the existing models to improve quality of the generated solutions and efficiency of the computations.

Deterioration models are essential to predict conditions of buildings and infrastructure systems throughout their service life. Therefore, a number of deterioration models were developed in the literature for bridges, including deterministic, stochastic, Markov chain-based, time-based, mechanistic, and artificial intelligence models (Srikanth and Arockiasamy 2020). Srikanth and Arockiasamy (2020) performed comparative analysis of bridge deterioration models to identify most accurate models. While Markov chain-based model is the most widely used model, deterministic model can provide higher accuracy in the predicted conditions. Similarly, Chyad (2018) compared a number deterioration models for bridge assessment and found out that probability distribution functions, such as Lognormal and Weibull, can provide better prediction of concrete bridge decks under certain condition ratings. Other studies focused on the use of various deterioration models for predicting bridge conditions (Bush et al. 2017; Huang 2010; Huang et al. 2004; Stipanovic et al. 2020). On the other hand, Markov chain process and Weibull probability method were used widely in the literature for building component maintenance planning (Fan and Xia 2017; Grussing and Liu 2014a; Paulo et al. 2016). Agrawal et al. (2010) compared Markov chain and Weibull deterioration models and showed that Weibull-based approach has a more realistic probabilistic performance approach due to inclusion of duration dependencies between maintenance interventions.

Optimization models were developed for buildings to minimize energy and water consumption, operational cost, and life-cycle cost. These models used linear programming, non-linear programming; genetic algorithms; harmony search, and particle swarm optimization (Hashempour et al. 2020). For example, Abdallah et al. developed several optimization models that are capable of selecting building upgrade measures to minimizing life-cycle costs, operational costs, and negative environmental impacts of existing buildings within limited upgrade budgets. In similar studies, genetic algorithms were used to minimize energy-demands, energy-costs, and investment costs (Asadi et al. 2014; Rosso et al. 2020; Sharif and Hammad 2019). Other similar studies used harmony search (Mostavi et al. 2017), particle swarm optimization (Delgarm et al. 2016; Karaguzel et al. 2014; Rabani et al. 2020), and differential evolution algorithms (Wang et al. 2014) to minimize life-cycle-cost of existing buildings. Despite the contribution of these studies, they are incapable of modeling comprehensive set of building upgrade measures (i.e. building fixtures, equipment, envelope components, and renewable energy systems simultaneously). Moreover, these models only focused on identifying optimal upgrades for buildings and did not consider maintenance plans for a predefined study period with respect to available budgets to generate practical solutions.

Budgeting methods for building maintenance were developed to support decision makers in planning and prioritizing maintenance and renovation activities. For example, Shohet (2010) presented a building evaluation framework for scoring maintenance priorities. The framework is developed to (1) monitor the condition of building components based on systematic performance scales; (2) identify key performance indicator that ensures clear detection of building elements that are in failing conditions; and (3) generate performance scores for to compare performance of different buildings. In a similar study, Moretti and Re Cecconi (2019) developed a decision support system to optimize the allocation of economic resources for maintenance activities. This study used Maintenance Priority Index (MPI) to determine budget allocation for maintenance activities. According to this study, MPI can be calculated based on four indexes including facility condition index, service life, preference of the owner, and criticality of each component. Although these models facilitate maintenance decision making by prioritizing maintenance activities based on building components condition, they did not consider practical constraints such as limitation of operational budgets and did not model upgrade and maintenance simultaneously to generate practical solutions.

Several other studies focused on developing building upgrade and maintenance optimization models while considering budget constraints. For example, Grussing and Liu (2014b) presented a genetic algorithm optimization model for selection of maintenance, repair, and renovation activities to minimize life cycle cost or maximize performance levels of existing buildings while complying with specified annual budgets. In a similar study, Farahani et al. (2020) presented an optimization model that is capable of identifying optimal maintenance and renovation schedule to minimize buildings service life-cycle-cost while complying with specified annual budgets. The results of the model in a case study projected up to 12.8% potential savings in annual costs compared to conventional maintenance methods. Several other models were developed to identify optimal selection of building maintenance and upgrade plans (Fan and Xia 2017; Farahani et al. 2020; Grussing and Liu 2014a; Ikuzwe et al. 2020; Paulo et al. 2016; Sharif and Hammad 2019; Taillandier et al. 2017; Wang and Xia 2015; Wu et al. 2021). Although the above studies were able to schedule maintenance interventions while considering annual budgets, they are incapable of using energy simulation to estimate energy consumption and generate practical results, and modeling a wide range of building upgrade measures.

Despite the contribution of the aforementioned studies in identifying optimal maintenance and upgrade plans for existing buildings and bridges, there is a pressing need to develop innovative models that are capable of (1) integrating reactive, preventive, and predictive maintenance strategies in maintaining buildings and infrastructure systems; (2) using simulation-based maintenance and upgrade approach to generate accurate and practical results for buildings; (3) modeling wide range of upgrade measures supported by updateable and expandable databases of upgrade and maintenance alternatives; and (4) executing model computations efficiently to identify high quality and global optimal solution of maintenance and upgrades simultaneously. This research proposal will focus on addressing these needs.

Research Objectives

The objective of this research work is to develop an innovation optimization model that can identify optimal selection of upgrade and maintenance interventions to minimize life-cycle-cost or equivalent annual cost of buildings and bridges. The model will be designed to maximize economic benefits by identifying optimal schedule of interventions with respect to available annual budgets and service life to reduce operational and maintenance costs. This model is expected to provide much needed support to asset management teams in state DOTs to identify optimal schedule of upgrades and maintenance interventions. To this end, the sub-objectives of this research work are designed to:

(1) Identify upgrade and maintenance interventions for state DOT buildings and Bridges
(2) Achieve significant savings in life-cycle cost of bridges and buildings by developing a new model that can identifying optimal selection of upgrade and maintenance interventions.
(3) Document life-cycle-cost savings of the model using case studies of a state DOT building and a bridge
(4) Study the feasibility of expanding the model to analyze multiple assets, such as building portfolio

Research Methods

The goal of this research work is to identify optimal selection of upgrade and maintenance interventions to minimize annual operation and maintenance cost while complying with specified annual budgets and operational performance. The model will be developed in three main steps (1) formulation step where decision variables, objective function and constraints are identified and formulated; (2) implementation step where an optimization algorithm is selected to execute the model computations efficiently; and (3) evaluation step where the performance of the optimization model is verified using case studies. The research team will study two applications of the proposed model, including upgrade and maintenance of buildings and bridges.

The mode is expected to represent wide range of feasible alternatives for repairing, replacing, or upgrading asset components for a predefined period of study. To this end, several maintenance strategies for asset components will be modeled, including reactive maintenance, preventive maintenance, predictive maintenance, and reliability centered maintenance. Deterioration models will be investigated and selected to predict asset conditions over its service life. Furthermore, wide range of upgrade measures will be modeled. For example, buildings will require modeling of lighting fixtures, motion sensors, hand dryers, water faucets, urinals, toilets, water heaters, cooling and heating equipment, window glazing and films, wall insulation, roof insulation, and photovoltaic (PV) systems to minimize operational cost. The objective function of the optimization model will be designed to calculate and minimize equivalent annual cost based on the selection of upgrade and maintenance interventions in a predefined study period, such as 20 years. To ensure practicality of the generated results, the model will integrate constraints such as available budget and performance requirements. For example, buildings require specified loads for heat ventilation and air condition to maintain comfortable indoor environment for occupants during building operation. The model will use energy simulation software packages for buildings, such as OpenStudio, to estimate energy consumption of various upgrade measures. To enable the simultaneous optimization of the upgrade and maintenance interventions, the research team will explore direct search methods such as linear programming and non-linear programming; evolutionary algorithms such as genetic algorithms; and meta-heuristic algorithms such as harmony search and particle swarm optimization to execute the model computations. The PI has extensive expertise and have successfully developed numerous optimization models that utilized linear and integer programming as well as evolutionary algorithms to support decision makers (Abdallah 2014; Abdallah et al. 2013, 2014, 2016b; a; Abdallah and El-Rayes 2015, 2016). The model will depend on available alternatives of upgrade and maintenance interventions to generate its results. Accordingly, an expandable database of building upgrades and maintenance interventions will be developed to collect and store data from supplier and vendors on available upgrade alternatives in the market. The components of the present model and its data flow ae depicted for bridges and buildings in Figure 1 and customized for buildings in Figure 2.

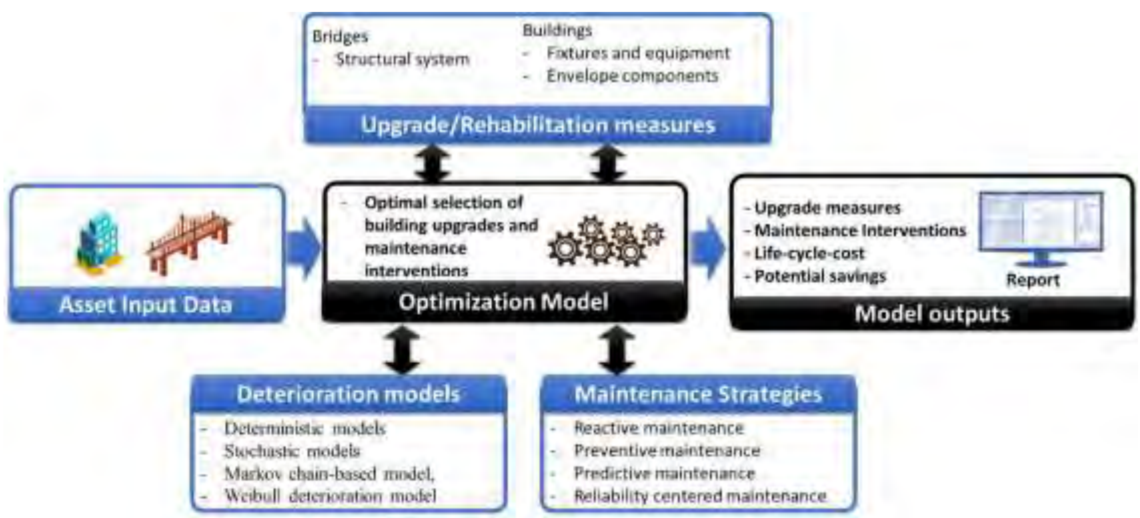

Figure 1. Components and data flow of the present model for buildings and bridges

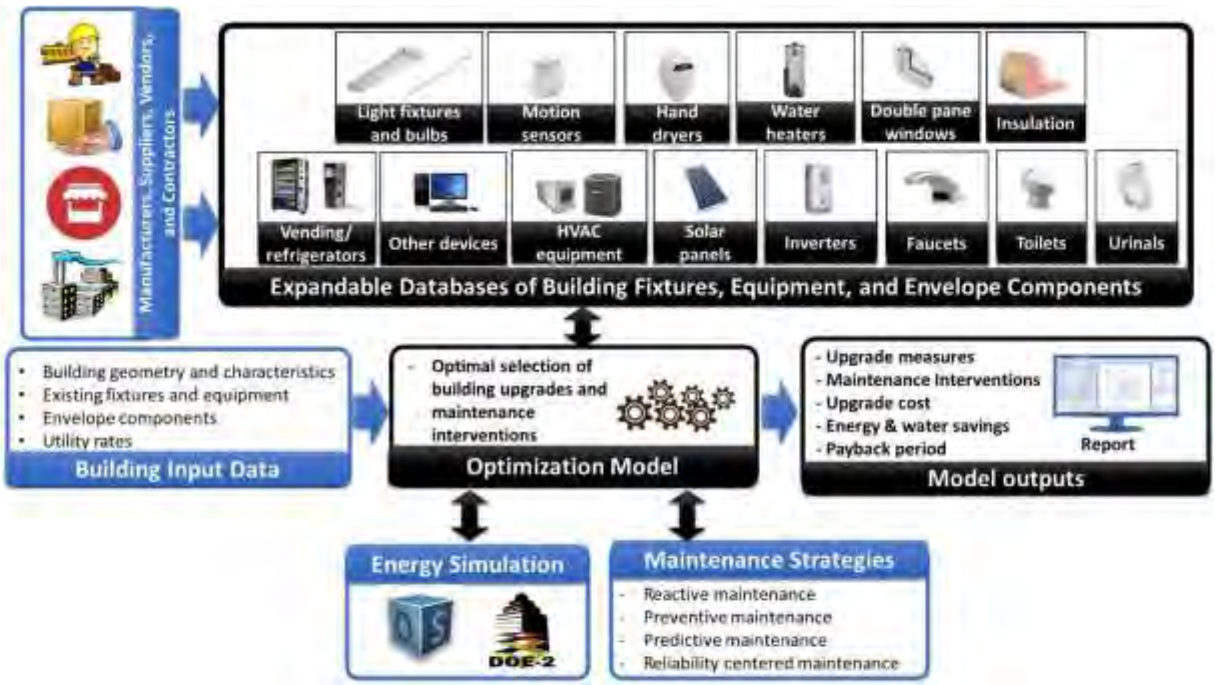

Figure 2. Components of the present model for Buildings

Expected Outcomes

This research work will present new approach for modeling and optimizing upgrade and maintenance interventions simultaneously to minimize life-cycle-cost. The present model will be capable of generating detailed plan for upgrading and maintaining state DOT buildings and bridges for a predefined period of study, such as 20 years, and within available budgets. The detailed plan will support decision makers to identify intervention strategy (i.e., repair, replace, or upgrade) for each asset component and in which year based on available budgets. Furthermore, the proposed model will integrate databases of upgrade and maintenance alternatives that can be updated frequently from manufactures, supplier, and vendors to generate up-to-date and practical recommendations. The proposed model will enable maintenance teams of state DOTs to identify best use of their budgets in upgrading and maintaining their assets. The wide application of the proposed model is expected to reduce energy demand, operational cost, and greenhouse gas emissions of state DOT buildings. The research team will explore commercializing the proposed model to facilitate its use by state DOTs.

Relevance to Strategic Goals

The findings of this research work are expected to contribute primary to the “Economic Competitiveness” strategic goal as the proposed model will allow maintenance teams in state DOTs to identify optimal selection of upgrade and maintenance interventions to minimize life-cycle-cost. These optimal selections will enable maintenance teams to efficiently manage their assets and generate savings in their operational cost which can be used to further upgrade these assets to generate additional savings or used for other purposes. The secondary strategic goal that this research contributes to is “Environmental Sustainability”. The proposed model will be designed to minimize operational cost which will reduce energy and water demand in buildings. Reduction in energy and water demands will directly reduce greenhouse gas emissions.

Educational Benefits

One graduate student will be trained to develop the proposed optimization model and demonstrate its new capabilities using case studies. Over the past years, the PI advised and mentored tens of graduate students to complete several research projects. These students are currently active and advancing in various industries today, including transportation, planning, construction, engineering, and consulting. The outcomes of the proposed research work will generate new educational modules and materials to be integrated into graduate courses. Modules will be carefully designed and implemented to enable students to (1) understand modeling of upgrade and maintenance interventions to minimize operational cost, and (2) develop optimization model to select upgrade and maintenance interventions under limited budgets.

Technology Transfer

The research team will disseminate and transfer the knowledge generated from the proposed research using publications in scientific journals and/or presentations in national and international conferences. Additionally, the research team will explore opportunities to facilitate the transfer of new technologies to the industry by reaching out to agencies that can directly benefit from the outcomes of this research work such as CDOT. Finally, the research team will explore commercializing the proposed model to serve state DOTS on upgrading and maintaining their assets.

Work Plan

In order to accomplish the objectives of this research work, the following research tasks will be conducted:

Task 1: Review of existing studies on optimal selection of upgrade measures for buildings and bridges

Task 2: Review existing studies on deterioration models and maintenance interventions for buildings and bridges

Task 3: Develop an optimization model to identify optimal selection of upgrade and maintenance interventions to minimize life-cycle-cost

Task 4: Evaluate the model performance using a case study of state DOT building

Task 5: Evaluate the model performance using a case study of a bridge

Task 6: Explore expanding the capabilities of the model to analyze multiple assets such as building portfolio

Task 7: Prepare and submit final report

The primary focus of this research work is to develop new model that can identify optimal selection of upgrade and maintenance interventions to minimize life-cycle-cost or equivalent annual cost while complying with specified budgets and performance levels. The research team will start this project by reviewing existing research studies to document the capabilities of existing models and identify existing gaps, as shown in Tasks 1 and 2 in Figure 3. The team will then develop the proposed optimization model following three steps as discussed in the Research Methods section and shown in Task 3 - Figure 3. Two case studies will be used as applications of the proposed model, include state DOT building and bridge, as shown in Tasks 4 and 5 - Figure 3. After that, the team will explore expanding the capabilities of the model to analyze multiple assets such as buildings, as shown in Task 6 – Figure 3. Finally, the team will prepare and submit final report that summarizes the findings of the conducted research work. The schedule of the project tasks is shown in Figure 3.

Project Tasks	Start (M)	Dur. (M)	Year 1												Year 2											
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Optimal Selection of Upgrade and Maintenance Interventions to Minimize Life-cycle-cost																										
Task 1: Review of existing studies on optimal selection of upgrade measures	1	3																								
Task 2: Review existing studies on deterioration models and maintenance interventions	1	3																								
Task 3: Develop an optimization model	4	6																								
Task 4: Evaluate the model performance using a case study of state DOT building	10	3																								
Task 5: Evaluate the model performance using a case study of a bridge	10	3																								
Task 6: Explore expanding the capabilities of the model	13	3																								
Task 7: Prepare and submit final report	16	3																								

Figure 3. Schedule of the Project Tasks

Project Cost

Total Project Costs:	$112,958
MPC Funds Requested:	$ 54,949
Matching Funds:	$ 58,009
Source of Matching Funds:	University of Colorado Denver, $40,009
	Colorado State University, $18,000

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