Multi-objective optimization of process design using process-based sustainable impact analysis

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Abstract

Process design in material supply systems requires careful analysis from the process manager in order to optimize important variables, such as the number of assembly areas and their locations. Decisions on these critical variables can have significant impacts on multiple objectives, including minimizing project cost and adverse environmental impacts. The objective of this paper is to present the development of a robust methodology to optimize process design in logistics of material supply systems. This methodology incorporates (1) cost and environmental impact assessment models that utilize process-based assessment (Activity-Based Costing and Process-Based Life-Cycle Analysis); and (2) a multi-objective optimization model that utilizes Non-Dominated Sorting Genetic Algorithms II (NSGA2). The presented models in this paper focuses on optimizing decisions related to the process design of prefabricated rebar supply systems for construction projects with space constraints. The developed models are capable of minimizing (1) the logistics costs; and (2) the associated environmental impacts. The paper also presents a case study in order to illustrate the use of the model and its unique capabilities in optimizing material supply systems.

Keywords: activity-based costing, process-based life-cycle analysis, optimization, genetic algorithm

1 Introduction

The tradition of the construction industry has long been to deliver standard-sized rebar from a rebar supplier to the construction site in large batches, fabricate (i.e., cut and bend) rebar on-site, and position it for assembly. The traditional rebar supply system requires large on-site yard and holding costs. On the other hand, prefabrication uses off-site cut & bend, which reduces on-site yard requirements and improves productivity. Accordingly, many building contractors in the United States adopt prefabrication for their projects located in urban areas, where space is constrained. However, contractors and process managers still need to develop process design of rebar supply chain even in the case where prefabrication is employed.

Process design in material supply systems requires careful analysis from the process manager in order to optimize important variables, such as the number of distribution centers and their locations. Decisions on these critical variables can have significant impacts on multiple and conflicting objectives, including minimizing project costs as well as adverse environmental impacts. While most relevant research regarding supply systems focused on how lead time can be reduced using either process improvements or external integration with suppliers (Kim et al. 2007; Arbulu et al. 2003; Akel et al. 2004), few
research studies have investigated optimizing process design of supply systems taking into account costs and environmental impacts.

The objective of this paper is to present the development of a robust methodology to optimize process design in logistics of material supply systems. This methodology incorporates the development of (1) cost and environmental impact assessment models that utilize process-based assessment (Activity-Based Costing and Process-Based Life-Cycle Analysis); and (2) a multi-objective optimization model that utilizes Non-Dominated Sorting Genetic Algorithms II (NSGA2). The paper then presents a case study in order to illustrate the use of the model and its unique capabilities in optimizing material supply systems. The presented case study focuses on optimizing the rebar supply system using data obtained from a high-rise residential building project in Seattle, Washington, USA.

2 Cost model

Activity-Based Costing (ABC) is a method of assigning the organization's resource costs through activities to the products and services (Cokins, 1996). Time-based ABC can be used to trace (1) direct labor costs; and (2) overhead costs which include procurement costs, transportation costs, rent for assembly yards, and other miscellaneous costs (Cooper, 1990). The time-based ABC system for the process design of the prefabricated rebar supply system is developed using three steps, including (1) estimating the cost per time for each resource, (2) estimating durations and resource consumption of activities, and (3) deriving activity costs.

The overhead costs were first analyzed; including salaries, rent, and energy costs as well as direct labor and rebar material costs associated with rebar supply from the supplier to the construction site. Second, the weekly cost of each activity and the total rebar supply chain cost are formulated for any project k. The total cost may be expressed using Eq. 1.

\[
C_k = LELC_k + DM_k = \sum_{j=1}^{J} \left( \frac{d_{jk}}{D_j} \times C_j \right) + DM_k = \sum_{j=1}^{J} (d_{jk} \times c_j) + DM_k
\]

\[
= \sum_{j=1}^{J} \left( d_{jk} \times \sum_{r=1}^{R} (c_r \times r_{jr}) \right) + DM_k = \sum_{r=1}^{R} \sum_{j=1}^{J} (d_{jk} \times c_r \times r_{jr}) + DM_k
\]

Where, \(C_k\) is the weekly total cost for project \(k\); \(LELC_k\) is the weekly labor, energy, and land leasing costs for project \(k\); \(DM_k\) is the direct material cost for project \(k\); \(J\) is the number of activities for project \(k\); \(d_{jk}\) is the volume of cost driver on activity \(j\) for project \(k\); \(D_j\) is the total volume of cost driver of activity \(j\); \(C_j\) is the total cost of activity \(j\); \(c_j\) is the unit cost of activity \(j\) (cost of activity \(j\) per cost driver); \(r_{jr}\) is the rate of consumption of resource \(r\) for activity \(j\); \(R\) is the number of resources for activity \(j\); and \(c_r\) is the unit cost of resource \(r\).

3 Environmental model

Life-Cycle Analysis (LCA) is a model-based approach for assessing where, and in what form, energy and materials are used (and wasted) throughout a life cycle (Cooper 2003; Cooper and Godwin 2008). The life cycle of a building spans the acquisition and processing of building materials and fuels, building construction, building operation and maintenance, and demolition and materials recovery activities.

The core LCA model on which this analysis is based is as outlined in Heijungs and Suh (2002) and consists of two main steps; namely (1) process mapping; and (2) inventory analysis. First, process mapping is used to identify the system boundaries and what functional units should be used for comparative analysis. The inventory analysis then arranges the collected data into matrices that can then be solved to give the emissions and energy results for each scenario, including (1) the technology matrix.
(A), which consists of the economic flows for each of the processes; (2) the intervention matrix (B), which consists of the environmental flows for each of these processes; and (3) the demand vector (f), which contains the quantities for each economic flow that are required to fulfil the desired scope. Once all of these inputs are acquired, the final inventory vector (g) can be computed, as shown in Eq. 2. The inventory vector is the final output of the system for the functional unit. The inventory results are then manipulated to give the total environmental impacts of each system in the impact assessment section.

\[ g = B A^{-1} f \]  

(2)

Energy consumptions, air emissions, and material loss rates of the traditional and prefabrication delivery systems were measured during the fabrication, transportation, and installation of rebar. The energy types in the investigated project include electricity, diesel, and propane. Air emissions include CO, NOx, SOx, VOCs, PM10, and greenhouse gases, such as CO2, CH4, and N2O. The focus of this paper is on quantifying and minimizing the global warming emissions (E) measured as CO2-e (CO2 equivalent) driven by CO2, CH4, and N2O (US EPA). For this research, a two-step process LCA was developed, including (1) inventory analysis based on sub-processes resulting from process mapping; and (2) impact analysis and interpretation.

4 Optimization model

The objective of the optimization model is to identify the optimal logistics planning decisions in order to minimize their associated costs and adverse environmental impacts, simultaneously. The presented model in this paper focuses on optimizing decisions related to the process design of prefabricated rebar supply systems for construction projects with space constraints (which require assembling the rebar off-site). Accordingly, the model is designed to optimize the following important set of decisions: (1) should the rebar be assembled at the fabrication plant or at a logistics center? (2) How many logistics centers would be needed for a set of construction projects? (3) Which logistics centers should serve which projects? The following sections briefly describe the model design, which includes (1) decision variables identification; (2) optimization objectives formulation; and (3) model implementation.

4.1 Decision variables identification

The decision variables are designed to represent the aforementioned set of decisions. As shown in Figure 1, the assembly area selected for each project is represented using one decision variable \( p_i \), which can have the values of 0,1,2 … L (where L is the number of candidate locations for the logistics centers). For example, if \( p_1 = 2 \), then the rebar needed for project #1 should be assembled at the logistics center #2. However, if \( p_4 = 0 \), then the rebar needed for project #4 should be assembled at the fabrication plant. Accordingly, the number of decision variables is equal to the number of projects.

4.2 Optimization objectives formulation

The model is designed to optimize two main objectives: (1) minimizing the total costs associated with the prefabricated rebar supply systems; and (2) minimizing the corresponding adverse environmental impacts. First, to minimize the total costs, the model computes all the costs that can have different values
based on the selected supply system (i.e. assembly at fabrication plant, logistics center #1, logistics center #2, etc.) for each project using Eq. 1. These costs include costs of transportation, loading/unloading, assembly, and renting the assembly area. The model then computes the total costs for the supply systems selected for all the projects, as shown in Eq. 3.

\[ C = \sum_{i=1}^{I} (C_i \times R_i) \]  

Where, \( C \) is the weekly total cost associated with the considered logistics plan, which consists of all the costs that will have different values based on the selected prefabricated rebar supply systems in that logistics plan; \( I \) is the number of projects; \( C_i \) is the weekly total costs associated with the selected prefabricated rebar supply system for project \( i \); and \( R_i \) is the amount of assembled rebar required weekly by project \( i \).

Second, to minimize the adverse environmental impacts associated with the adoption of the proposed supply systems for each project, the model utilizes Eq. 2. The model then computes the total environmental impacts for all the projects using Eq. 4. As previously mentioned, the focus of this paper is on the emissions that contribute to global warming as an example of the adverse environmental impacts. The research is being expanded to consider other impacts as well.

\[ E = \sum_{i=1}^{I} (E_i \times R_i) \]  

Where, \( E \) is the weekly total contribution to global warming from all the projects as a result of adopting the considered logistics plan, which consists of all the emissions levels that will have different values based on the selected prefabricated rebar supply systems in that logistics plan; \( I \) is the number of projects; \( E_i \) is the weekly contribution to global warming from project \( i \) as a result of adopting the selected prefabricated rebar supply system; and \( R_i \) is the amount of assembled rebar required weekly by project \( i \).

4.3 Model implementation

The model is implemented using multi-objective genetic algorithms in order to account for the multi-objective nature of the problem. Non-Dominated Sorting Genetic Algorithm II (NSGA2) is used to implement the proposed model because of its superior performance compared to other multi-objective genetic algorithms (D’Souza and Simpson 2002; Deb et al. 2001; Weile et al. 1996). This superior performance is attributed to important characteristics of NSGA2, such as fast non-dominated sorting, constrained-domination principle, elitism, and crowding (Deb et al., 2001).

The model is implemented in four main phases using NSGA2: (1) initialization phase, in which a population of random logistics plans is generated, where each plan represents a possible solution; (2) plans evaluation phase, where each candidate logistics plan is evaluated based on its performance in the two optimization objectives (i.e. the computed total cost and environmental impact) as well as its compliance with the capacity constraints of the assembly areas; (3) ranking phase, in which all the candidate logistics plans are ranked using the constrained-domination principle, and (4) population generation, where a new improved population of logistics plans is generated using selection, crossover, and mutation operations. Phases (2) to (4) are then repeated for a predetermined number of generations, as shown in Figure 2.
5 Case Study

The rebar supply chain of a condominium construction project in downtown Seattle was selected to provide the needed data for the case study. The project consists of a 19-story residential tower, 16-story office building, and several commercial stores. It is a GC/CM (CM at risk) project with a guaranteed maximum price contract. Major stakeholders involved in rebar supply chain include a general contractor (construction manager), a subcontractor (assembling and installing), and a rebar fabricator (shop drawing and fabrication). However, to illustrate the use of the model and its capabilities in identifying the optimal logistics planning decisions for larger-scale problems, the data obtained from the aforementioned project was used to develop reasonable values of data for 10 hypothetical construction projects in need of prefabricated rebar.

Figure 2, Model implementation phases

The input data for the model was categorized in the following six main categories: (1) projects data, including the amount of rebar required weekly; (2) potential assembly area locations, which included five logistics centers locations in addition to an assembly yard next to the fabrication plant; (3) equipment data, including consumption rates and costs; (4) assembly activity data obtained from the cost model using ABC; (5) environmental data obtained from the environmental model using LCA; and (6) travel distances between projects, fabrication plant, and potential locations of the logistics centers. Accordingly, there are ten decision variables in this optimization problem, where each variable represents the assembly area for each construction project. Each decision variable can take one of six values representing the assembly at each of the five logistics centers or at the assembly area next to the fabrication plant. Therefore, the search space for this problem is equal to $6^{10} = 60,466,176$.

The model was then used to identify the optimal logistics plans that would minimize costs as well as environmental impact. The optimization parameters for this problem included a population size of 50, crossover probability of 0.9, and mutation probability of 0.0333. Figure 3 shows the improvement in the performance of the logistics plans generated by the model until it reached the optimal plans in less than 300 generations. Figure 3(a) shows the costs savings of improved logistics plans compared to the plans identified after 10 generations, while Figure 3(b) shows the reduction in global warming emissions measured in CO₂ equivalent for improved plans compared to the plans identified after 10 generations.

6 Conclusions

This paper presented the development of a robust methodology to optimize process design in logistics of material supply systems in order to (1) minimize the logistics costs; and (2) minimize the associated
environmental impacts. This methodology incorporates the following three models: (1) cost model that utilizes Activity-Based Costing; (2) environmental impact assessment model that utilizes Process-Based Life-Cycle Analysis; and (3) a multi-objective optimization model that utilizes Non-Dominated Sorting Genetic Algorithms II.

The paper also presented a case study in order to illustrate the use of the model and its unique capabilities in optimizing material supply systems. In this case study the model was used to identify the optimal configuration of assembly areas to provide prefabricated rebar to 10 construction projects. The model was capable of minimizing the associated costs as well as the global warming emissions (measured in CO₂ equivalent).

Figure 3, Optimization results

References


