CHEMICAL ENGINEERING TRANSACTIONS

VOL. 70, 2018

A publication of AIDIC

The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš

ISBN 978-88-95608-67-9; **ISSN** 2283-9216

DOI: 10.3303/CET1870099

A Source-Sink Model for Assigning Construction Firms to Projects During Urban Rebuilding

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Urban rebuilding efforts in the aftermath of destructive events such as natural hazards or war invariably require allocation of scarce resources to multiple projects that run concurrently. In such scenarios, the construction firms available in a geographic locality may have insufficient capability to cope with the scale of all the rebuilding projects. In such cases, construction firms from outside of the immediate region, but with the required capabilities, may be needed to supplement local capacity. Use of such external capacity incurs additional financial and environmental penalties (e.g., carbon footprint) due to the need to transport heavy equipment, supplies and labor over greater distances. As such, it is necessary to maximize the use of locally available firms, and hence to minimize the need for external ones. The problem is conceptually similar to the optimization of Resource Conservation Networks (RCNs), and lends itself to being solved via Process Integration (PI) approaches. In this work, a source-sink model is developed to optimize the assignment of construction firms to multiple concurrent projects taking place during a concerted urban rebuilding campaign. The model is formulated as a Mixed Integer Linear Program (MILP) whose objective function is to minimize total carbon footprint during urban rebuilding. This carbon footprint is proportional to the project cost and the distance of the construction firm's headquarters to the city where urban rebuilding is needed. A semi-hypothetical case study on urban rebuilding in the southern Philippines is used to illustrate the application of the model.

1. Introduction

Process Integration (PI) was originally developed as a systematic framework for optimizing the use of heat in industrial plants (Linnhoff and Flower, 1978). The field of PI has grown and diversified since the 1970s, in terms of both methodology and applications (Klemeš, 2013). The PI methodology is based on either Pinch Analysis (PA) or Mathematical Programming (MP), with an increasing recognition of their complementary rather than competing roles (Klemeš and Kravanja, 2013). The application of PI to various non-conventional problem domains has also been noted in a recent paper (Tan et al., 2015). In particular, the generic source-sink model, which allocates streams based on both quantity and quality characteristics, has proven to be a versatile framework for the development of new PI applications. In this work, this framework is further extended to a problem involving the allocation of reconstruction projects to different firms, using carbon footprint (CF) as the quality index. Such footprint metrics are generally used nowadays to measure various sustainability dimensions (Čuček et al, 2012). The carbon footprint in this case will consider only those in the general requirements such as mobilization, logistics of materials and equipment, and others. It does not include operational carbon footprint (i.e. use of equipment during construction phase) and embodied carbon footprint (i.e. life cycle assessment of the materials from cradle to gate). It is assumed that all contractors will produce the same amount of operational and embodied carbon footprint on the urban rebuilding projects once resources are available on site.
The study deals with urban rebuilding after destructive events which are is necessary for the economic growth of countries. These destructions may come from natural hazards such as earthquakes, volcanic eruptions,

Please cite this article as: Ongpeng J.M.C., Dungca J.R., Aviso K.B., Tan R.R., 2018, A source-sink model for assigning construction firms to projects during urban rebuilding , Chemical Engineering Transactions, 70, 589-594 DOI:10.3303/CET1870099

typhoons, and others. Use of smart city approach in the reconstruction of Christchurch, New Zealand, after the earthquake was implemented by having sensor tools to measure air quality (Marek et al., 2017). In Japan, prior to a disaster, environmental and economic waste management was considered such as the processes of transportation and storage (Tabata et al., 2017). In addition, destructions can also come from war. In Beirut, the political economy of violence increases profit making from transnational capital for construction and reconstruction activities (Sakr-Tierney, 2017).

In the construction industry, few or limited papers focused on tools in resource allocation. In a supply chain of ready mixed concrete batching plant operation, linear programming was used to optimize the supply of ready mixed concrete to projects (Zayed and Minkarah 2004). In addition, a decision support model was developed for allocating resources among various projects for rehabilitation, renovation, and upgrading of existing buildings (Shohet and Perelstein, 2004). This paper focuses on resource allocation following the framework of Resource Conservation Networks (RCNs) where construction firms are assigned to projects for urban rebuilding.

Another important factor for the urban rebuilding is the environmental impact it can cause. The environmental impact of construction activities has been evaluated using the life cycle assessment framework to compare various options for construction (Moretti et al., 2018) and to analyse the environmental impact of the different phases of construction (Sandanayake et al., 2018). A multi-attribute evaluation index was also proposed by del Mar Casanovas-Rubio and Ramos (2017) for the selection of construction processes while Zolfani et al. (2017) used a hybrid multi-criteria decision-making approach for the evaluation of hotel buildings in terms of their environmental impact. In this paper, a Mixed Integer Linear Program (MILP) model was developed where the objective function is to minimize carbon footprint for allocating construction firms in urban rebuilding.

The rest of the paper is organized as follows. Section 2 provides the formal problem statement while Section 3 discusses the development of the model. Section 4 then considers a case study in order to demonstrate the capabilities of the model. Conclusions and recommendations for future work are then given in Section 5.

2. Problem statement

The formal problem statement can be stated as follows:

Given that there is M number of contractors (both local and external) that are classified into K different categories depending on their capability to fund construction projects with a given maximum total available funds for project construction. Given N number of projects of varying costs in a given region that need to be completed such that the projects require construction firms to meet a minimum level of class category. Given that there is an associated carbon footprint to complete the projects which are dependent on the distance (between the contractor's head office and project location) and the general requirements of the construction (mobilization/demobilization and others). The problem then is to determine the best allocation of construction firms to projects in order to minimize the carbon footprint.

3. Model formulation

The problem is modelled similarly to a source-sink model which is illustrated in Figure1. The contractors are considered as the sources, since they provide funds and resources while the projects are considered as the sinks. The objective function is to minimize the carbon footprint as given in Eq(1) where z_{ij} is a binary variable which indicates if project firm i supports project j (z_{ij} = 1) or not (z_{ij} = 0), and CF_{ij} is the associated carbon footprint for construction firm i to accomplish project j. The carbon footprint is evaluated using Eq(2) where Q_j is the total project cost, r is a factor which accounts for the proportion of material and equipment requirement of the project, d_{ij} is the distance between firm i and project j while k (in kg CO_2/km-t) is the typical carbon footprint generated for material and equipment logistics.

$$\min = \sum_{j=1}^{N}\sum_{i=1}^{M} z_{ij}CF_{ij} \tag{1}$$

Each construction firm can only support projects which will have a total capital cost value which is less than its total capital available (C_i) as indicated in Eq(3) where x_{ij} is the capital provided by firm i to project j. Similarly, any project j should have sufficient funds to complete its total project cost Q_j as indicated in Eq(4). Eq(5) ensures that the required minimum class category of a construction firm as defined by project j is met. F_i refers to the class category of the construction firm i while P_j refers to the minimum class category required by project j. Eq(6) assigns variable z_{ij} to be binary. Furthermore, all variables are non-negative.

$$CF_{ij} = rQ_jd_{ij}k \tag{2}$$

$$\sum_{j=1}^{M} x_{ij} \leq C_i \quad (3)$$

$$\sum_{i=1}^{N} x_{ij} = Q_j \quad (4)$$

$$x_{ij} \leq 1000\, z_{ij} \left(F_i - P_j + 1\right) \quad (5)$$

$$z_{ij} = \{0,1\} \quad (6)$$

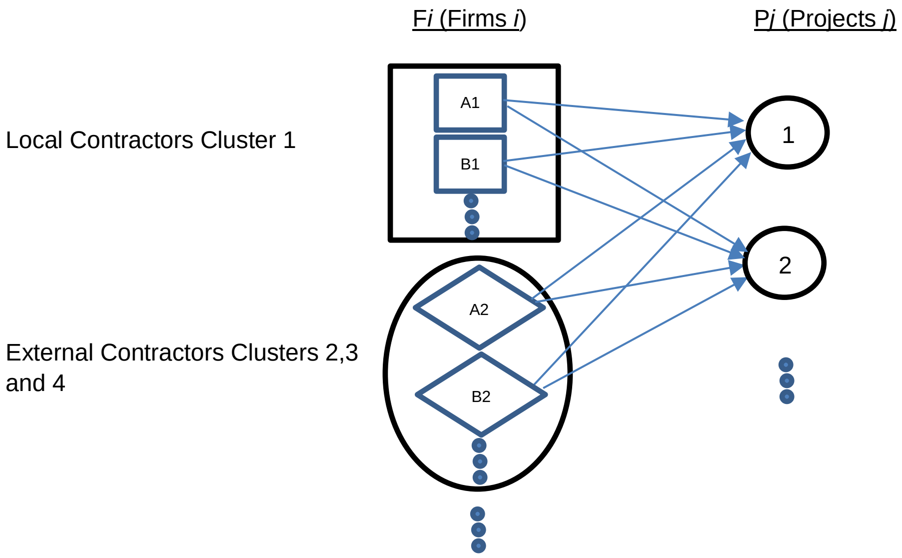

Figure 1: Source-sink model having four classifications of contractors assigned to construction projects

4. Case study

Marawi city, a city in the southern region of the Philippines, was destroyed in the longest urban war experienced in the country. The war started in the month of May and lasted until October 2017 having a five-month duration for the Armed Forces of the Philippines to be liberated from terrorist influence. In nearly five months, residents were displaced and establishments and infrastructures were destroyed. After the war, the National Disaster Risk Reduction and Management (NDRRM) Council together with multi-agency teams assessed the damage in Marawi City. In total, 24 barangays of the 96 in Marawi City were assessed. Barangay is the smallest administrative office in the Philippines. Cities and municipalities consist of several barangays. It was announced by NDRRM that the fund needed for the city's quick recovery, reconstruction, and rehabilitation will amount to PhP 10 billion.

The construction industry in the Philippines thus plays an important role in the rebuilding efforts. However, the Philippines is an archipelago and the available contractors are spread out across the country in 17 regions. Different regions and island groups are shown in Table 1. This scenario will result in enormous construction energy usage from the mobilization of engineers, crews and equipment for material supply and logistics. This is with the assumption that the recovery, reconstruction, and rehabilitation is done altogether with time limitation using all resources such as manpower, materials, and equipment across the country while optimizing locally available resources.

The official list of licensed contractors in the country as of November 2017 can be obtained from the Philippine Contractor's Accreditation Board (PCAB). There are 9,361 licensed contracting firms which are classified into six categories based on the maximum project cost a firm can handle. Five of the 7 categories are considered capable of conducting regional works outside of their head office based on their registered location in the contractor's license. These are contractors categorized as AAAA, AAA, AA, A, and B with their corresponding Allowable Range of Contract Cost (ARCC) indicated in Table 2. This resulted in a total number of contractors equal to 3,655 out of the total available 9,361 contractors. The 3,655 contractors are then subdivided into four clusters. The first cluster is the region where Marawi City is situated and the remaining clusters are the three island groups where the contractor belongs in (e.g. Luzon, Visayas, and Mindanao). The stretch or length of the Philippines is approximately 1,850 km. The number of contractors according to their project cost capability is shown in Table 1.

Table 1: Number of contractors and their respective head office location

Region	Name of Region	Category of Contractor					Island Group	Cluster
		AAAA	AAA	AA	A	B		
I	Ilocos Region	0	5	5	21	70	Luzon	1
II	Cagayan Valley	0	4	5	32	66	Luzon	1
III	Central Luzon	0	50	15	140	245	Luzon	1
IV – A	Calabarzon	0	31	16	136	274	Luzon	1
IV – B	Mimaropa	0	3	1	16	55	Luzon	1
V	Bicol Region	0	15	6	37	116	Luzon	1
NCR	National Capital Region	13	189	69	423	529	Luzon	1
CAR	Cordillera Administrative Region	0	2	3	30	80	Luzon	1
VI	Western Visayas	0	7	2	37	82	Visayas	2
VII	Central Visayas	0	20	9	43	93	Visayas	2
VIII	Eastern Visayas	0	8	4	30	76	Visayas	2
IX	Zamboanga Peninsula	0	5	5	28	57	Mindanao	3
X	Northern Mindanao	0	8	1	16	57	Mindanao	3
XI	Davao Region	0	11	5	43	87	Mindanao	3
XII	Soccsksargen	0	2	4	25	57	Mindanao	3
Caraga	Caraga	0	5	4	22	37	Mindanao	3
ARMM	Autonomous Region of Muslim Mindanao (where Marawi City is located)	0	2	1	21	39	Mindanao	4
SUBTOTAL		13	367	155	1,100	2020		
TOTAL		3,655						

Table 2: Different classes of contractors based on an allowable range of contract cost

Class	Allowable range of contract cost (ARCC)
AAAA	> PhP 1 billion
AAA	PhP 500 million < ARCC ≤ PhP 1 billion
AA	PhP 300 million < ARCC ≤ PhP 500 million
A	PhP 150 million <ARCC ≤ PhP 300 million
B	ARCC ≤ PhP 150 million

Table 3: Limiting data for the case study

Construction firm	Region	Distance (in km) (d_{ij})	Class category of firm (F_i)	Capacity In billion PhP (C_i)	Project	Required Category for construction firm (P_j)	Cost In billion PhP (Q_j)
A	VI	638	3	2	1	1	0.3
B	VIII	970	1	1	2	3	0.8
C	NCR	1,503	4	10	3	2	0.5
D	ARMM	196	3	0.5			
E	ARMM	196	1	0.5			
F	I	1,699	1	0.6			

The case study considers 3 different projects and there are 6 different construction firms. The category classification of the construction firms and their total funding capacity are shown in Table 3. The cost of the projects and the minimum required firm to construct the project are also shown in Table 3.

In addition, the carbon footprint is directly proportion to the distance (between the project location site and the main office of a construction firm by virtue of the need to transport equipment and services) and the general requirements of the construction project (mobilization, demobilization, and others which is approximately 10 % of the total construction cost). For this case study, the associated carbon footprint was determined using Eq.2 and the source and sink pair is as shown in Table 4. The distance from the construction firm's head office to Marawi City in km is d_{ij} while the value for k is taken as 0.09 kg CO_2/km-t (EEA, 2003).

Table 4: Carbon footprint for each source-sink pair (in tons of CO_2) (CFij)

Construction firm (i)	Project 1	Project 2	Project 3
A	1.72	4.59	2.87
B	2.62	6.98	4.37
C	4.06	10.82	6.76
D	0.53	1.41	0.88
E	0.53	1.41	0.88
F	4.59	12.23	7.65

Solving Eqs(1) to (6) result in the resource allocation indicated in Table 5. As a result, firm E in ARMM, A in Region I, and D in ARMM funded the projects 1, 2, and 3, respectively. Maximizing local construction firms to minimize carbon footprint was observed since both projects 1 and 3 were funded by local construction firms in ARMM. Project 2 on the other hand needed higher capacity of funding where minimal carbon footprint occurred which is from the next closest construction firm that is situated in Region VI 638 km away from Marawi city. Furthermore, this assignment resulted in a minimum carbon footprint of 6.00 tons of CO_2.

Table 5. Optimal solution to case study

Construction firm (*i*)	Project 1 (in tons of CO_2)	Project 2 (in tons of CO_2)	Project 3 (in tons of CO_2)	Total (in tons of CO_2)
A	0.0	0.8	0.0	0.8
B	0.0	0.0	0.0	0.0
C	0.0	0.0	0.0	0.0
D	0.0	0.0	0.5	0.5
E	0.3	0.0	0.0	0.3
F	0.0	0.0	0.0	0.0
Total	0.3	0.8	0.5	

5. Conclusions

This work developed a source-sink model for the assignment of existing construction firms to available projects. It takes into consideration carbon footprint which is associated as environmental implications taken from the general requirements of construction company specifically on the line item mobilization, logistics of materials and manpower, demobilization, and the distance from head office to the urban rebuilding location.

It was found out that during urban rebuilding in an archipelago like the Philippines is a challenge. The challenges were present when most of the contractors are spread out across regions and few contractors were available in the local area where rebuilding is needed. The model on how to allocate contractors focused on with the limitations and constraints of constructions firms like classifications and capacity of funds. It had objective function that is to minimize total carbon footprint. The sample case study gave good results where distance from the head office to the urban rebuilding location is an important factor to be considered.

Nomenclature

RCN – Resource Conservation Networks
PI – Process Integration
MILP – Mixed Integer Linear Program
PA – Pinch Analysis
MP – Mathematical Programming
CF – Carbon Footprint
NDRRM – National Disaster Risk Reduction and Management
PCAB – Philippine Contractor's Accreditation Board

PhP – Philippine Pesos
ARCC – Allowable Range of Contract Cost (in PhP)
NCR – National Capital Region
CAR – Cordillera Administrative Region
ARMM – Autonomous Region in Muslim Mindanao
M – number of contractors (both local and external)
K – categories of contractor depending on their funding capacity
N – number of projects in a given region
z_{ij} – binary variable which indicates if project firm i supports project j (z_{ij} = 1) or not (z_{ij} = 0)
CF_{ij} – associated carbon footprint for construction firm *i* to accomplish project *j* (in tons of CO_2)
Q_j – total project cost (in PhP)
r – factor which accounts for the proportion of material and equipment requirement of the project
d_{ij} – distance between firm *i* and project *j* (in km)
k – typical carbon footprint generated for material and equipment logistics (in kg CO_2/km-t)
C_i – total capital available (in PhP)
x_{ij} – is the capital provided by firm *i* to project *j* (in PhP)
F_i – refers to the class category of the construction firm *i*
P_j – refers to the minimum class category required by project *j*

Acknowledgments

This research was done through the efforts of interdisciplinary work in the Gokongwei College of Engineering of De La Salle University, Manila, Philippines.

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