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Logistics optimisation in road construction project

Introduction

Cost escalation and time delays are widely accepted performance indicators of a project as stated in the project management literature. Many researchers have tried systematically investigating and classifying various causes and effects of cost and time overrun in this context. These studies have either encompassed a project in general (Mansfield *et al*., 1994; Assaf and Al-Hejji, 2006; Magnussen and Olsson, 2006; Cheng, 2014; Shehu *et al*., 2014) or focused on a specific sector, e.g., road (Manavazhi and Adhikari; 2002; Kaliba *et al*., 2009; Mahamid, 2013). They also recommended the ways to meet the desired project performance by mitigating identified causes. Many of these recommendations are in the form of appropriate project management practises, tools and frameworks. In many instances, the researchers have used optimisation models in specific domains of project and construction management. For example, Salem *et al*. (2007) proposed the optimisation model for minimising the cutting-waste of reinforcement steel bars used in the construction projects and showed significant cost savings. The application of model showed the reduction in the amount of cutting-waste by 29% in the actual plan prepared by team. It has been observed that the implicit objective of many of these studies was to gain adequate benefits by improving project performance. Hazir (2014) advocated that there is enough scope for using optimisation models for solving complex and real life problems in different domains of project management. Moreover, in order to make them concrete and applicable to the need of the project industry, this study suggested making it more practitioner orientated while helping them in decision making processes. The current research is an effort to exhibit the use of optimisation model in another distinct area of project management. In particular, the study focused on optimising the supply chain of raw material (i.e. aggregate), that is expected to be consumed in various segments and different layers of a road project.

A large number of road projects are being planned and executed in developing and developed countries for last many decades. The performance measures, such as quality, cost and time of road project are governed by various factors. The researchers have identified many causes that impact the performance of a road project. Lack of material planning was observed to be one of the prominent causes for cost and time overruns in road projects (Wong and Norman, 1997; Mahamid, 2013; Manavazhi and Adhikari; 2002; Cheng, 2014). An enormous amount of materials are moved and relocated in the road construction. Further, the consumption point of materials moves along the entire length of a road, making it geographically dispersed. It is also required to move the material through various stages of the supply chain, such as sourcing, processing and distribution. This requires careful material procurement and logistics planning by the project team. Sobotka *et al*. (2012) argued that the managerial skills and knowledge along with the use of best project management practises can influence the project performance. They also suggested that the selection of a right supply chain model and optimisation of logistics decisions can indeed improve the financial benefit to the project specially due to considerable saving in logistics cost. The systematic supply chain model for raw material logistics is likely to have a direct impact on cost efficiency, and hence, overall cost of the project.

This paper presented the optimisation model for sourcing, processing and distribution of raw material for road construction to minimise the total logistics cost. The raw material for a road project includes materials such as aggregate, cement etc. This paper considered material named 'aggregate', one of the important raw material constituents of the road construction work. The output of the model provided an optimal distribution of the aggregate from the available supply locations to the final demand locations of road construction segments via intermediate processing facilities. The research optimised the aggregate raw material supply chain for a road project.

The main objective of the research is to demonstrate the ability of optimisation to provide cost efficiency in managing the logistics of raw material supply chain in the road project. The key contributions of the paper are as follows: This research on the optimisation applications in a road construction project considered three stages of raw material supply chain unlike previous work which included only two stages. The optimisation model of handling three stages of the supply chain grows in complexity with increasing number of decision variables and constraints. This work shows that the real life construction and project management problems are really complex to reach a cost efficient solution without the use of the proposed optimisation model. It presents the direct relationship between the potential of saving in logistic cost and dealing with complexity of real project applications. Additionally, the paper contributes to the literature, a new promising area in road construction project for efficient logistics planning by optimisation applications.

Optimisation in Construction

The advances and applications of optimisation models have received widespread attention in general management literature. Although, not predominantly used, it is observed that some scholars (kindly see, Zayed and Minkarah, 2004; LeBlanc *et al*., 2000; Zhang and Fan, 2014; De Athayde *et al*., 2015; Qiu, 1997; Tam *et al*., 2001; Al-Hussein, 2005; Hossain and Chua, 2014; Shafahi and Haghani, 2014) of project management demonstrated the usefulness of optimisation tools in specific areas of construction management. These studies attempted to identify and apply optimisations in distinct areas of a project ranging from project manager's assignment, concrete batch plant's operation to selecting appropriate project risk, etc. The familiar optimisation tools exercised in these studied includes models such as linear programming (LP), mixed integer linear programming (MILP), genetic algorithm (GA). MILP is extension of LP and includes zero-one decision variables such as choice of setting plant or any other facility.

Logistics optimisation in construction and project

Logistics optimisation and its variations have found numerous applications in business. Some researchers (See, Table 1) in construction and project areas have used logistics optimisation in a specific context of project planning. The logistics planning in construction and project involves movement of various materials and equipment from multiple identified sources to multiple consumption points in cost effective manner. In logistics literature, these kind of optimizations are called transportation model when model includes only two stages i.e. supply and demand points. Likewise, these are called transhipment model when model includes more than two stages i.e. supply, demand and intermediate processing points. However, both the types of models are mathematically formulated and solved simply by linear programming (LP) technique.

Insert Table 1 here

The use of linear programming (LP) optimization model was first developed by Mayer and Stark (1981, as cited in Easa, 1998; Jayawardane and Harris, 1990; De Lima *et al.,* 2013) for minimising logistics cost of earthwork. These kind of models typically use decision variables to formulate mathematical model to meet the required objective by satisfying many practical constraints. For example, the objective could be minimise the total cost while satisfying the material demand at multiple consumption points from the available supply at multiple sources. Latter, Easa (1998) extended it as MILP model to minimise earthwork cost for movement among cut, fill, existing borrow and existing land fill areas by additionally incorporating the cost of setting up new borrow and land fill areas. In order to complete the earthwork within the planned project duration, Jayawardane and Harris (1990) introduced the variables of choosing the right equipment fleets in MILP model to minimise cost. The model also showed the sensitivity of total cost (i.e. reduces cost) for varying completion time (i.e. by extending the project time). However, these studies worked on representative data with more focus on model and did not probably include real cases due to lack of sophisticated computer software/computing power.

Son *et al*. (2005) presented a linear programming model and procedure to determine the accurate shortest transport distances among locations of cut and fill areas to move soil in earthmoving. The model was used for minimising the cost of earthwork at golf construction site. Sobotka *et al*. (2012) proposed transportation model in road construction work by optimising movement of aggregate from suppliers to destinations based on two criteria: minimise cost and time. This linear programming model included supply and demand nodes and finally provided a tradeoff view based on weightages given to both the criteria. De Lima *et al*. (2013) considered the optimisation model in making earthwork planning for road construction at a minimal cost. The work proposed mixed integer linear programming (MILP) model by considering earthmoving, decision on plant locations and material blending at the same time. The well planned construction-site facility layout is considered to have significant impact on productivity, costs and duration of construction (Wong *et al*., 2010). Wong *et al*. (2010) formulated MILP model for planning construction facility layout which simultaneously considered the decision on location of various facilities and movement of resources (e.g. sand, aggregate, cement, precast yard, formwork etc.) on the site to minimize the site logistics cost.

Some researchers (Hegazy and Kassab, 2003; Moselhi and Alshibani, 2009; Said and EI-Raye, 2011; Koo and Park, 2012) have proposed GA especially in optimizing logistics planning activities of earthmoving operations by adding more number of variable such as truck sizes, budgets, decision of setting new facilities etc. The exact algorithm available to solve such complex formulation are computationally inefficient and are unable to solve real big size problem. In such cases, researchers use metaheuristic (refer, Liao *et al*., 2011) based solution approach such as genetic algorithm (GA) etc. These (Hegazy and Kassab, 2003; Moselhi and Alshibani, 2009) models considered inputs such as resources, budget, equipment characteristics etc. to determine the optimum number of resource quantities, workload and assignment strategies in order to improve overall construction site productivity. Said and EI-Rayes (2011) presented the construction logistics planning model simultaneously integrating and optimising the decisions of material procurement, storage and movement on construction sites. The model utilised GA to minimise construction logistics costs that cover material ordering, finance, stock-out and layout management cost. However, in the proposed model, logistics planning was restricted to procurement policy and site layout. Koo and Park (2012) used GA for identifying the optimum plan for delivering construction materials among the various possible combination of truck types, routes and suppliers with the objective of minimising the fuel consumption. However, the movement of material in model included multiple supply points and one demand point while illustrating the case study using representative data.

The literature review related to logistics planning in project and construction demonstrated the possible modelling approach in logistics planning. These models mostly considered linear programming (LP) for formulating the movement of material from supply points to demand points by incorporating various costs of transfer. Further, the objective of all these models confirmed the improvement in the logistics planning leading to considerable cost savings. Nonetheless, the intentions of these models were to capture different practical variations in construction planning in the form of decision variables.

The modelling approaches (Easa, 1998; Jayawardane and Harris, 1990; Sobotka *et al*., 2012; De Lima et al., 2013) in general used in logistics of road project consider the two stages of supply chain that includes only supply and demand points. Typically, these studies in road project tried to handle the single product and are limited to earthwork. The pavement road is made up of various layers. Explicitly considering each product of different layers in the same model is very essential in real life and seemed to be not addressed by previous studies. The objective of two studies (Easa, 1998; Jayawardane and Harris, 1990) were to demonstrate the use of LP model in handling earthwork but lacked in demonstrating real case studies. De Lima et al. (2013) use the model in road earthwork logistics showing the potential of saving using real cases while Sobotka *et al.* (2012) use two stage model for movement of material for single layer of road project. However, materials procured from various sources need additional processing and mixing at intermediate locations (Vidalakis *et al*., 2011) before final consumption. The material which can directly be consumed in construction comprises of two stages i.e. supply sources and final demand points. However, material which needs some intermediate processing before final consumption requires additional stage i.e. processing/ mixing facility. The optimisation involving three or more stages is termed as transhipment problem and is more complex to formulate and solve given the large number of feasible options. For example, aggregate procured from quarries needs to be processed and mixed into required size, composition before its final consumption. The proposed model in this paper considered additional processing stage and five different products for material movement in order to map real life scenario. In addition to this novelty, paper also considered other variables of interest such as quality of material, different variety of products used in road construction.

Research Methodology

Logistics planning in project generally includes materials procurement, materials distribution/transportation and materials storage (Ng *et* al., 2008; Fang and Ng, 2011; Said and El-Rayes, 2011; Vidalakis *et al*., 2011; Koo and Park, 2012). Deficiency in material delivery planning is understood to be one of the causes for cost overrun in many construction projects (Manavazhi and Adhikari, 2003). Logistics optimisation has received a lot of attention for last few decades in the supply chain and logistics management literature (Ballou, 1995; He *et al.*, 2006, Ma and Suo, 2006; Meepetchdee and Shah, 2007; Steinrücke and Jahr, 2012). In general, logistics network optimisation consists of moving a variety of products from a number of sources to different end customers via various available intermediates facilities (Winston, 2003; Ma and Suo, 2006). These kinds of studies and associated models consider multi-echelon production and/or transportation planning and distribution systems (Ma and Suo, 2006).

The network of supply chain that incurs the lowest total cost of distribution is regarded as an optimal solution to the distribution problem. The problem that consider three and more stages are termed as transhipment model in the optimisation literature. The generalised schematic diagram of three stages along with potential costs are represented in Figure 1. The relevant costs which may impact the optimum plan should always be included in the model. For example, when the unit cost of procurement among the available sources varies, the optimum plan of the model will be sensitive to these costs and certainly be included. On the other hand, there is no compulsion to include this cost in the model as the final optimum plan of the model won't get affected when the unit cost of procurement among all sources are same. The optimum plan means the quantity of material to be procured from each source, quantity of material to be transported on various links of three stages, how the quantity of material to be consumed at various demand points. The logistics manager needs to ensure that optimum plan of quantity of procurement and transportation is operationalised in reality to meet the objective of minimising total cost. This paper considers the costs which were found be more relevant in proposed optimisation model and described latter with appropriate justification.

Insert Figure 1 here

These class of problems can be formulated simply by linear programming technique or mixed integer linear programing (He *et al.*, 2006, Winston, 2003; Ma and Suo, 2006; Steinrücke and Jahr, 2012). The equations of objective function (i.e. total cost) and constrains listed in the formulation are in linear relationship with decision variables (i.e. quantity of material). Accordingly, linear programming means the planning of activities represented by mathematical model of a linear relationships (Hillier and Hillier, 2009). In short, linear programming is a technique for the optimization of a linear objective function, subject to linear equality and linear inequality constraints. A linear programming algorithm finds a point where the function has the smallest (largest) value if objective function is minimisation (maximisation).

Considering the above discussion, the following generalised linear programming formulation is proposed in this paper to map three stages of the supply chain that includes *i* raw material sources, *j* intermediate raw material processing facilities and *k* final demand consumption points.

$$Min\ Cost \sum_{i=1}^{I}\sum_{j=1}^{J} Cij * Qij + \sum_{j=1}^{J}\sum_{k=1}^{K} Tjk * Ajk \qquad (1)$$

$$Subject\ to$$

$$\sum_{j=1}^{J} Qij \leq Si \qquad for\ i = 1, \ldots\ldots I \qquad (2)$$

$$\sum_{i=1}^{I} Qij = \sum_{k=1}^{K} Ajk \qquad for\ j = 1, \ldots\ldots J \qquad (3)$$

$$\sum_{j=1}^{J} Ajk \geq Dk \qquad for\ k = 1, \ldots\ldots K \qquad (4)$$

$$Qij \geq 0, \qquad Ajk \geq 0 \qquad (5)$$

Insert Table 2 here

All symbols used in the model formulation are described in the notation list of the paper. Expression (1) represents the objective function while expressions (2)-(5) represent various constraints. In the model, objective function (1) minimises total supply chain cost from sources to final demand locations for shipping the total quantity of raw material for a complete project. The supply chain cost for shipping of raw material, includes purchasing cost at sources, primary transportation cost from sources to intermediate locations, processing cost at intermediate processing locations and secondary transportation cost from intermediate locations to demand locations. Expression (2) imposes that the total sum of raw materials shipped from a source cannot exceed the maximum available supply quantity of the raw material. Expression (3) states the raw material flow constraint at each intermediate location. Accordingly, the total sum of raw material shipped out of an intermediate processing location cannot exceed the total amount of raw material received from the sources. Expression (4) ensures that total sum of raw material shipped to a demand location must meet specified quantity of raw material at each location. Expression (5) enforces that all the decision variables can either take positive or zero values.

Road Project Case Study

This part first describes the research problem being studied in the road project and conceptualises it as a logistics raw material optimisation problem. Next, it uses a proposed generalised optimisation model for raw material expected to be consumed in the construction work. Finally, it defines various input and output variables applicable in aggregate raw material supply chain decisions and operationalizing procedure for the proposed model.

Problem description

The research considered the road construction project between two major cities. This stretch of the road forms an important link as the part of national highways. The work of the project was awarded to construction company on BOT (Built operate transfer) basis. The construction time for completion of project was estimated to be three years. The construction company created and deployed project team to look after the entire construction of this stretch. The project scope included the widening of the existing four-lane road to six-lane flexible pavement road for the stretch of 84 kilometres (km). One of the important raw materials required for road construction and widening work is 'aggregate' (this is a category of coarse particulate material of different size/ grades used in construction). A large percentage of material cost in the road project is attributed to aggregate. The project team had selected three sources (called quarries) for procurement of aggregate and identified four plant locations for aggregate processing along the road. The project team was expected to plan the procurement and movement of aggregate from quarries to road construction site through one of these processing plant locations. The intermediate processing plants (Vidalakis *et al*., 2011) job was to mix and convert raw aggregate into some usable form before final consumption in road construction.

The entire road widening stretch was divided into 84 segments of 1 km each by project team for the convenience of entire logistics and project planning. The required data was also sought and arranged for each road segment. This paper also considered the 84 segments for the sake of benchmarking this research's optimal plan with original reference plan. Aggregate was expected to be consumed in various layers and parts of road segments such as WMM (Wet Mix Macadam), DBM (Dense Bituminous Macadam), BC (Bituminous Concrete), concrete and precast. The WMM, DBM, BC are the various layers of bituminous road from bottom to top respectively. The concrete was supposed to be used for making median, kerb, footpath (used at specific segments only), underpasses, bridges and various minor concrete construction work on road. The median separates opposing lanes of traffic on divided roadways while kerb is the elevated edge at both the sides of road surface. The precast was for specific requirement in some part of road construction segments. The precast was expected to be required in the form of objects in construction of pedestrian underpasses, minor bridges and flyovers that fall within the road construction stretch. This paper referred them as five different products constituting the entire road construction work. According to estimate, the approximate quantity (in tonnes) of aggregate that was likely to be consumed for these products were determined. These five products required different processing facilities such as wet mixing plant (WMM), hot mixing plant (DBM, BC), batching plant (concrete) and precast yard (precast members). The details of these specific information are provided in Table 3.

Insert Table 3 here

These products in general change in compositions in terms of composition of various raw materials and also need different grades and quality of aggregate. There are quality and compatibility issue like oversizing, flakiness, low density making aggregate from specific quarry unsuitable for some products (Jayawardane and Harris, 1990). This compatibility of aggregate from second quarry (Q2) made them unsuitable for DBM and BC products. The project team planned to set up the aggregate intermediate processing plant facilities for all the five products at four identified locations. However, it was not necessitated to set up such processing facilities for all the five products at each of the four identified plant locations due to economic consideration. The decision of setting up the facility was taken on the total demand of the aggregate for each product (see, Table 3). Considering this aspect, project team decided to locate four facilities for WMM, three facilities for DBM, BC, concrete and only one facility for precast. The details of the same are also provided in Table 3. For example, location of processing plant 3 (P3) did not have facility of hot mixing plant to process the aggregate requirement of DBM.

The entire supply chain of aggregate from quarries to each road segment was expected to incur several costs. These costs included various components such as cost of aggregate at each quarry, primary transportation cost from quarries to processing plants and secondary transportation cost from processing plants to road segments. Based on experience and judgment, project team prepared the feasible logistics plan and determined the expected total logistics cost using MS Excel for shipping aggregate from quarries to all road segments via processing plants. Although, literature refers the use of optimisation model in the earthwork planning, project team was not aware and did not use any such model.

One can observe a large number of feasible choices and routes to procure, process and transport the aggregate from identified sources to the road segments via processing facilities. It makes complex task for human to search best possibility which get multiplied by number of options at three stages. These complexity of routing can be captured by decision variables. The number decision variables required for each product are determined in Table 3. Therefore, it is not easy to work out the optimal solution for the discussed situation without the use of an optimisation model. This paper conceptualised it as a logistic optimisation problem. The Figure 2 depicted the pictorial representation of the problem. The purpose of the study was to optimise the supply chain of aggregate from three quarry locations to road segments via processing plants with the objective of minimising the total logistics cost of aggregate required for the entire road project.

Some steps to be performed to achieve this goal were: (1) conceptualise sourcing, processing and distribution of raw material (i.e. aggregate) for road construction as logistics optimisation problem; (2) formulate the linear programming (LP) model for a given problem statement and implied resource constraints; (3) solve the LP formulation by an optimisation solver (4) interpret the final output of the solver to determine the quantity to be procured from each source locations, quantity to be processed at each processing location and quantity to be distributed through various nodes that connect different stages of a material supply chain.

Insert Figure 2 here

Operationalising the proposed model

The project team was required to handle aggregate in three stages of supply chain i.e. supply sources, processing facilities and final demand destinations. Accordingly, the aggregate was to be procured from various quarries, shipped to intermediate processing plant locations, processed by processing plants and finally shipped from processing plants to different road segments. These activities of aggregate supply chain were estimated to incur different costs.

The objective of the study was not to get into technicality and design of road work. With reference to work of De Lima *et al*. (2013), this study also made assumption that the following information is available for proposed model: volume of deposit of materials (in tonnes) required in different layers (e.g. WMM) of road segments; compatibility of aggregate for each product; locations of quarries; locations of plants; cost of aggregate ($/km/tonne), cost of transportation; distances among quarries, plants and road segments (kilometres). In fact, project team sought these information from concerned stakeholders of the project and used these information for preparing the original logistics plan. This study collected the same data as inputs to the proposed optimisation model. Total 84 kilometres road was divided into 84 road segments with each segment covering 1 kilometre distance. The data comprised the information related to three stages of aggregate supply chain: three quarries, four intermediate processing plant locations and 84 road segments. The data related to quarries included quality and cost of aggregate at each quarry. Further, it considered the decision of the project team to locate the processing plant facilities to process the five products (refer, Table 3). The data for 84 road segments determined the total demand of an aggregate at all road segments for each product with the desired quality of an aggregate. The additional data comprised the transportation cost from each quarry to each processing plant, from each processing plant to each road segment which was determined based on the distance between two locations. The proposed formulation and corresponding variables stated in notation were determined based on problem being studied and defined as follows. Parameters: I = total number of quarries = 3; J = aggregate processing plants locations for the various products = 4; K = total number road segments = 84; unit of quantity of aggregate to be procured, processed and transported is tonnes.

The proposed generalised model formulation used the cost matrix as an input and provide decision variables as an output using excel spreadsheet. Figure 3 illustrates the representation of input and output data in the MS Excel spreadsheet (refer, Bartolacci *et al*., 2012). The following data were set at appropriate cells in the excel spreadsheet.

Insert Figure 3 here

- Cost of shipping from quarries to processing plants (Cij): This included cost of aggregate at each quarry ($ per tonne) and unit transportation cost from each quarry to each processing plant. The cost of aggregate which differs from one quarry to another was sought originally from quarry operators by project team. The cost of transportation was determined by multiplying distance between a quarry and a processing plant by quote ($ per tonne per kilometre) provided by transporter.

- Cost of shipping from processing plants to road segments (Tjk): It comprised transportation cost from each processing plant to each road segment. The cost of transportation was calculated by multiplying distance between a processing plant and a road segment by quote ($ per tonne per kilometre) provided by transporter. The flow from the identified location for aggregate processing plant was assumed to be zero when the processing facility to process the particular product (refer, Table 3) was not available. For example, the flow from plant location (P3) was assumed to be zero (see, Figure 3) by making X3 (Cell, E10) = 0 in the spreadsheet while using the proposed model for product 'concrete'. This changes provide input to optimisation model that no processing facility is available at this location and make sure that no flow of aggregate takes place through this location. The unit cost of processing of aggregate was expected to be same at all potential locations and was not included in original plan prepared by project team. Hence, this paper also did not consider the same in order to benchmark optimal plan of model with project team plan and to compare the saving. It is to be noted that inclusion of this cost in the model is not sensitive to optimal plan. It means optimal plan would remain same in both the circumstances. Further, the storage cost was not considered as entire stretch of land including the four plant locations were handed over to project team without any cost during the entire project span. The aggregate was stored and used for different products in open space making it difficult to determine to appropriate storage cost. The project team found that any overhead used to determine the storage cost would not change at all the four plants locations. This assumption make the optimal plan of model insensitive to the storage cost. Hence, this research did not include the storage cost also to benchmark project team plan. However, the supply chain network and respective formulation for various stages (ref, Figure 1) are precisely equipped to represent and include all the kind of costs that incur from sources to consumption points.

- Total demand of aggregate at road segments (Dk): Total requirement of aggregate (in tonnes) at each road segment was based on the plan and profile of the road alignment across all segments. The demand of road sections (WMM, DBM etc.) are generally estimated using methods such as Simpson's rule, using road design and quantity calculation software. This methods give the quantity in cubic metre. The quantity of aggregate is usually calculated by multiplying with density and percentages of aggregate as per mix design. Similarly, concrete and precast member sections quantity in cubic meter is normally estimated by methods such as center line method and using software like Autocad. Latter, the quantity of aggregate is derived using mix design. However, the paper makes explicit assumption that these information generally available as discussed in De Lima *et al*., 2013 (pp. 1048). This was determined for all five products such as WMM (Wet Mix Macadam), DBM (Dense Bituminous Macadam), BC (Bituminous Concrete), concrete and precast.

- Maximum supply capacity of aggregate at quarry (Si): There was sufficient quantity (in tonnes) of aggregate available at each quarry to meet complete aggregate requirement of an entire road project. Hence, the model assumed that the total demand of aggregate for all segments is maximum and can also be supplied from one quarry if cost effective. However, the quality of aggregate suitable for respective product was noted while using the model (refer, Table 3). As discussed earlier, aggregate from quarry Q2 (source 2) was understood to be not appropriate (see, pp. 26, Jayawardane and Harris, 1990) for product DBM. In such case, the maximum available aggregate quantity from quarry 2 was assumed to be zero (S2=0, Cell, I8) in the spreadsheet.

The three supply sources, four intermediate processing plants and 84 demand constraints in the spreadsheet model comprised total 348 decision variables. The Excel spreadsheet has Built-In academic solver. Excel Built-In Solver supports just 200 decision variables while the Premium Solver supports up to 800 decision variables. This made us to use Excel Premium Solver which solve the problem within the second. Fylstra *et al*. (1998) presented additional information about the use of Excel solver tool. Fortunately, Excel provides platform for solving LP and MILP problems by incorporating the proposed formulation discussed in the paper. The Solver window has the option of either minimising or maximising the objective of model and adding the constraints of the formulation. The output of the solver provided the plan of aggregate procurement, processing and distribution for the corresponding optimum solution. This paper used, copied produced and solved the same spreadsheet as five different scenarios for each of the five products (i.e. WMM, DBM, BC, concrete and precast) by making appropriate changes in MS Excel spreadsheet data. The cells where the changes are required are shown in bold fonts in Figure 3. For example, the demand of aggregate in 84 road segments for each scenario was changed in appropriate demand cells (Cells M12:R12). Similarly, the supply from three quarries were changed to the total demand of aggregate (Cells, I7:I9). The aggregate from quarry Q2 was not compatible for DBM and BC. This was reflected by entering S2 value zero (Cell, I8). The processing facility was not located at P3 for DBM and BC. This was reflected by entering X3 value zero (Cell, E10). The Solver output of the each scenario was interpreted for decision on aggregate procurement, processing and shipment from quarries to road segments for the optimum solution.

Results and Discussion

The optimal solutions provided the detailed procurement, processing and distribution plan of aggregate from quarries to processing plant and to road segments for all the five scenarios.

The results of the optimal plan for each scenario was found using proposed model were compared with the original logistics plan which was prepared by the project team using excel spreadsheet. As discussed earlier, project team had prepared logistics plan and computed corresponding logistics cost for moving aggregate from quarries to all road segments via processing plants for all the scenarios. It is to be noted that project team used their experience, judgement and attempted to identify the best plan for the aggregate procurement, processing and distribution in the supply chain. The detailed comparison of both optimal and original project team plans along with potential cost saving is provided in the Table 4 for each scenario. It is to be noted that optimal plan is the best distribution plan which cannot be improved further within the given constrains. It was expected to save 0.536 million dollars ($535864) in case the optimal plan was used instead of original plan prepared by the project team. This indicated approximately 3.33 percent saving over the original logistics cost estimate of the project team. De Lima *et al.* (2013) have shown on an average 3.47 to 3.92 percent saving in logistics optimization when used for earthwork planning.

Insert Table 4 here

The cost of procurement and transportation from quarries to road segments via available processing facilities showed considerable saving in the optimal plan when compared with the project team plan for all the scenarios. However, there were three exceptions in the table where cost of the project team plan was lower than the optimal plan (see, Table 4). The cost of aggregate procurement happened to be lower in the project team plan when compared to the optimal plan for DBM and BC. It was discussed earlier that quarries 1 and 3 was only suitable to meet the requirement of DBM and BC (See, Table 3). As the cost of aggregate varied among all quarries, the lower cost in the aggregate procurement was due to the project team procuring more quantity from quarry which charges less price as compared to other quarry but spending more cost on transportation. Similarly, the cost of transporting aggregate from quarries to plant observed to be lower for concrete. Nonetheless, the total cost of aggregate supply chain for DBM, BC and concrete was found to be lower in the optimal plan than the project team plan. The objective of any project manager will be to identify the most cost effective logistics plan. Hence, it should not matter as long as the total cost of entire supply chain is lower with considerable saving as the proposed linear programming (LP) formulation searches global optimal solution. As the optimal plan is the best plan, it is reasonable to procure more quantity of aggregate from quarry which charges more price than other but save significant cost on transportation of aggregate. Hence, the project team need not bother much about these situations as the Solver always takes care of final optimal solution.

Another interesting results from Table 4 is the quantum of saving realized in the optimal plans of the five scenarios. The results showed that that the percentage saving in logistics cost for various scenarios are different while comparing the optimal and the project team plan. The percentage saving is higher for the WMM followed by the concrete while it is somewhat lower for the DBM and the BC. In fact, there was no saving for the precast as the optimal plan matches the project team plan. The findings and observations can be interpreted and linked with the data provided in Table 3. The number of feasible options that are available for the movement of aggregate depend upon the elements such as number of sources, available processing facilities and road segments. These elements can be captured by defining appropriate number of decision variables. Surprisingly, the quantum of saving realized in the optimal plan for various products correlates with total number of possible routes (see, Table 3, column e) available to products (i.e. WMM, DBM etc.). The large number of decision variables make problem complex to solve without use of any optimisation method. Hence, more (less) complexity leads to enormous (few) number of feasible alternative solutions. The project team found it easy with judgement to identify the better feasible option (though not best) amongst the few available while it found it challenging to develop even the good plan amongst enormous number of feasible alternative solutions. It should be noted that it is difficult to find optimal solution for a more complex model without using optimisation model. Hence, the feasible solution obtained only by means of experience, judgement may be far from optimal solution and hence inefficient (Sobotka *et al.*, 2012). For example, consider the movement of aggregate for precast scenario from quarries to road segments. The processing facility for the aggregate was available only at one intermediate location leading to 96 possible routes (refer, Table 3) and can be termed as less complex. This has resulted into the ability of project team to identify best plan which fortunately matches with the optimal plan.

The project team can use the following two expressions derived from the constraints (2) and (3) of the proposed formulation and interpret respective results from the spreadsheet for the given optimum solution. The project team plan and optimal plan solutions produced in the spreadsheets are not provided in the paper because of space limitation but is available from the authors upon request. However, summary of percentage of aggregate procured from three quarries and percentage of aggregate processed at different processing plants are shown in Table 5 for both optimal and project team plan.

Insert Table 5 here

$$\sum_{j=1}^{J} Qij \quad for\ i = 1\ to\ 3 \quad where\ \ J = 4 \qquad (6)$$

$$\sum_{k=1}^{K} Ajk \quad for\ j = 1\ to\ 4 \quad where\ \ K = 84 \qquad (7)$$

Constraint (6) estimates the optimal quantity (in tonnes) of aggregate that would be procured from each quarry for each scenario/ product. The percentages of these quantity differ for four products (i.e. WMM, DBM, BC and concrete) for the project team plan and the optimal plan while it is same for precast as both the plans match. The results reported that the quantity of aggregate to be procured for WMM from quarry 1 (Q1) is 0.2504 X 1294441 tonnes in the optimal plan but it was 0.4401*1294441 in the project team plan. The addition of all the five scenarios provides the total quantity of aggregate that will be consumed from each quarry for entire road construction. This output can be useful to procurement team for planning contract with each quarry operators in advance.

Expression (7) beforehand determines in advance the quantity of total aggregate that needs to be processed for each product at all the four intermediate locations. The percentages of these quantity to be processed at different processing locations differ for four products except precast. It is observed that the amount of aggregate to be processed for concrete at P3 location is 0.6611*261061 tonnes in the optimal plan as compared to 0.4976*261061 tonnes in the project team plan. This output of the model provides project team the perspective of capacity required at any location without explicit capacity analysis. The project manager therefore can assess the appropriate capacity scheduling decision of a processing plant required while setting up the intermediate processing plant facilities at all four locations.

The spreadsheet's optimum solution also provides the information regarding the quantity of aggregate to be transported on each link (decision variables, Qij and Ajk) connecting quarries to intermediate processing facilities and processing facilities to road segments. These output details are useful to logistics team in preparing the transportation plan while executing the actual project schedule of the aggregate movement.

Conclusions

This research demonstrates the use of optimisation model and systematic approach for procuring, processing and distribution of aggregate for the road construction project to obtain cost efficient logistics plans. The output of the proposed optimisation model indicates substantial savings in logistics cost over some feasible solution obtained by any other common sense method. As the spreadsheet has become more commonly used tool among the managers, the research shows the ability of optimisation combined with Excel Solver to help the project managers in decision-making and planning logistics of the project. The important contribution of the paper in the project and construction management literature is the development and capability of user friendly optimisation model for planning movement of material in three stages of project supply chain.

The limitation of the model is the assumption of input data and the structure of project supply chain. The model considers that various data required as an inputs are readily available without any uncertainty. Given that data are available, the model provides guarantee to produce the optimal plan irrespective of it uses across any project. Further, the use of model is applicable and relevant to construction supply chain structure which includes different number of stages with many options at each stage.

The model can serve as a platform for future research. The authors are currently working on them. The total number of intermediate processing plants and its potential locations is generally the decision that project team needs to consider. By adding the binary (0-1) variables, the model can also incorporate the optimal locations of the processing plants. The project generally consumes different type of raw materials. The proposed model can be expanded to formulate the integrated supply chain model for optimizing the movement of all the materials together from sourcing to processing plants and processing plants to consumption locations.

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Table 1: Optimization models use in logistics application in construction and project

Authors	Area of application	Optimization model	Contributions	Remarks
Easa, 1988	Earthwork allocations to minimise cost for road construction	Mixed Integer linear programming (MILP)	Considered the movement of earthwork among cut, fill, borrow and land fill areas with decision of adding new borrow areas and associated costs to minimise total cost.	Used representative case and data, use two stages i.e. multiple supply points and multiple demand points for material movement.
Jayawardane, and Harris, 1990	Earthwork allocations to minimise cost within the given project duration for road construction	Mixed Integer linear programming (MILP)	Considered the movement of earthwork among cut, fill, borrow and land fill areas, decision of adding new borrow areas and equipment fleets for meeting given project duration while minimising the total cost.	Used representative case and data, use two stages i.e. multiple supply points and multiple demand points for material movement.
Hegazy and Kassab, 2003	Planning resources for earthmoving operations on construction site	Genetic algorithm (GA)	Considered decision of selecting trucks types, loaders, truck repair time to complete required work with minimum cost.	Used a case study with real data, use two stages, Ignore the distances between supply and demand point and hence transportation cost.
Son *et al.*, 2005	Earthwork allocations to minimise cost on golf construction site	Linear programming (LP)	Considered the movement of earthwork among cut, fill, borrow, land fill areas and procedure to calculate accurate haul distances to minimise total cost.	Used a case study with real data, use two stages i.e. multiple supply points and multiple demand points for material movement.
Moselhi and Alshibani, 2009	Planning resources for earthmoving operations on multiple construction site	Linear programming (LP) + Genetic algorithm (GA)	Considered decision of selecting optimum combinations of equipment (e.g. trucks, loaders, grader, compactor), time for equipment and material movement	Used a case study with real data, use two stages i.e. multiple supply points and multiple demand points for material movement.

			to minimum total cost and project time	
Wong *et al*., 2010	Planning facility layout to minimise transportation cost on construction site	Mixed Integer linear programming (MILP)	Considered the potential locations for resources (e.g. sand, aggregate, cement, precast yard, formwork etc.), and its flow on site to minimise the total site logistics cost.	Used a case study with real data, use two stages i.e. multiple supply points and multiple demand points for material movement.
Said and El-Rayes, 2011	Planning material procurement and material storage on construction site	Genetic algorithm (GA)	Considered project schedule, material ordering, finance including quantity discount, stock-out and only layout logistics for onsite handling cost for total cost.	Used representative case and data, use two stages i.e. one supply point and one demand point at a time for each material type.
Koo and Park, 2012	Construction materials distribution among the various possible combinations of truck types, routes and suppliers to construction site	Genetic algorithm (GA)	Consider truck types, suppliers, routes for meeting global cost objective i.e. reduce carbon emission.	Used representative case and data, use two stages i.e. multiple supply points and one demand point for material movement.
Sobotka *et al.,* 2012	Movement of aggregate from sources to segments to plan road construction	Linear programming (LP)	Considered aggregate transportation cost, delivery time for meeting total cost objective and minimise time of delivery.	Used a case study with real data, use two stages i.e. multiple supply points and multiple demand points for material movement.
De Lima *et al*., 2013	Earthwork and paving optimization to plan road construction	Mixed Integer linear programming (MILP)	Considered earthmoving and paving, decision on plant location and material blending at the same time for total cost. Model shows the saving of 3 to 4%.	Used three case studies with real data, use two stages i.e. multiple supply points and multiple demand points for material movement.

Table 2: Description on the notations used in the model formulation

Notations		Description
Index		
	i	Source index (from 1 to I);
	j	Intermediate point index (from 1 to J);
	k	Demand index (from 1 to K);
Decision variables		
	$\mathrm{A}ij$	Unit quantity of raw material shipped from intermediate point j to demand location k;
	$\mathrm{Q}jk$	Unit quantity of raw material shipped from source i to intermediate point j;
Parameters		
	I	Total number of sources;
	J	Total number of Intermediate facilities processing points;
	K	Total number of demand points /locations;
	Cij	Cost of purchasing and transporting unit quantity of raw material from source i to intermediate point j;
	$\mathrm{D}k$	Total demand of raw material at demand location k in units;
	$\mathrm{S}i$	Maximum supply capacity of raw material at source i in units quantity;
	$\mathrm{T}jk$	Cost of transporting unit quantity of raw material from intermediate point j to demand location k;

Table 3: Compatibility and complexity matrix for different products

Type of processing plant, compatibility of aggregate and processing plant availability for the product

Products	Type of processing plant	Sources (Quarries)			Processing availability (processing plants)			
		Q1	Q2	Q3	P1	P2	P3	P4
WMM	Wet mix plant	√	√	√	√	√	√	√
DBM	Hot mix plant	√		√	√	√		√
BC	Hot mix plant	√		√	√	√		√
Concrete	Batching plant	√	√	√	√		√	√
Precast	Precast yard	√	√	√			√	

Tick (√) indicates that aggregate quality is appropriate for meeting particular product requirement from respective quarry.

Tick (√) indicates that processing plant has facility to process respective product.

Quantity and complexity of aggregate supply chain based on no. of sources, processing plant and road segments

Products	Quantity of aggregate to be consumed (in tonnes)	Number of			Decision variables (quarries to plants to road segments)	No of routes /path combinations
		Sources (Quarries)	Processing locations	Road segments		
		a	b	c	d = a*b + b*c	e = a*b *c
WMM	1294441	3	4	84	348	1008
DBM	708859	2	3	84	258	504
BC	254022	2	3	84	258	504
Concrete	261061	3	3	84	261	756
Precast	59528	3	1	32	35	96

Table 4: Cost comparison of optimal and project team logistics plan

Scenario	1. WMM (Cost , million $)			2. DBM (Cost , million $)			3. BC (Cost , million $)			4. Concrete (Cost , million $)		
	Optimal	Project	Saving	Optimal	Project	Saving	Optimal	Project	Saving	Optimal	Project	Saving
A	4.248	4.693	0.446	2.638	2.620	-0.018	0.945	0.939	-0.006	0.843	0.882	0.039
T1	2.562	2.572	0.010	1.471	1.489	0.018	0.525	0.532	0.007	0.495	0.489	-0.006
T2	0.639	0.662	0.023	0.484	0.489	0.005	0.173	0.175	0.002	0.145	0.161	0.016
Total Cost	7.449	7.928	**0.479**	4.593	4.598	**0.005**	1.643	1.645	**0.002**	1.483	1.533	**0.050**

	5. Precast (Cost , million $)		
	Optimal	Project	Saving
A	0.179	0.179	0.000
T1	0.120	0.120	0.000
T2	0.108	0.108	0.000
Total Cost	0.407	0.407	**0.000**

Optimal: Optimal plan
Project: Project team plan

Notation:
A: Cost of aggregate to be procured from all quarries

T1: Cost of transporting aggregate from quarries to plants

T2: Cost of transporting aggregate from plants to 84 road segments

Scenario	Products	Total logistics cost in million dollars ($)			Percent age saving
		Optimal	Project	Saving	
1	WMM	7.449	7.928	0.479	6.04
2	DBM	4.593	4.598	0.005	0.12
3	BC	1.643	1.645	0.002	0.12
4	Concrete	1.483	1.533	0.050	3.23
5	Precast	0.407	0.407	0.000	0.00
	Total Saving			**0.536**	**3.33**

Table 5: Quantity of aggregate to be procured from quarries and to be processed at processing plants for optimal and project team logistics plans

Percentages of aggregate quantity to be procured from quarries										
Products	1. WMM		2. DBM		3. BC		4. Concrete		5. Precast	
Quarries	Optimal	Project	Optimal	Project	Optimal	Project	Optimal	Project	Optimal	Project
Q1	25.03	44.01	60.58	64.92	60.76	65.06	23.23	27.64	0.00	0.00
Q2	60.25	17.96	NA	NA	NA	NA	66.11	49.76	100.00	100.00
Q3	14.73	38.03	39.42	35.08	39.24	34.94	10.66	22.60	0.00	0.00
Total %	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Total (tonnes)	1294441		708859		254022		261061		59528	
Percentages of aggregate quantity to be processed at different plant locations										
Products	1. WMM		2. DBM		3. BC		4. Concrete		5. Precast	
Processing plants	Optimal	Project	Optimal	Project	Optimal	Project	Optimal	Project	Optimal	Project
P1	25.03	28.50	27.19	27.18	28.00	27.98	23.23	27.64	NA	NA
P2	11.23	15.76	33.38	37.74	32.76	37.08	NA	NA	NA	NA
P3	49.02	19.32	NA	NA	NA	NA	66.11	49.76	100.00	100.00
P4	14.73	36.42	39.42	35.08	39.24	34.94	10.66	22.60	NA	NA
Total %	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Total (tonnes)	1294441		708859		254022		261061		59528	

NA: Not applicable due to quality or plant availability constraints (see Table 3, compatibility matrix)
Optimal: Optimal plan, Project: Project team plan

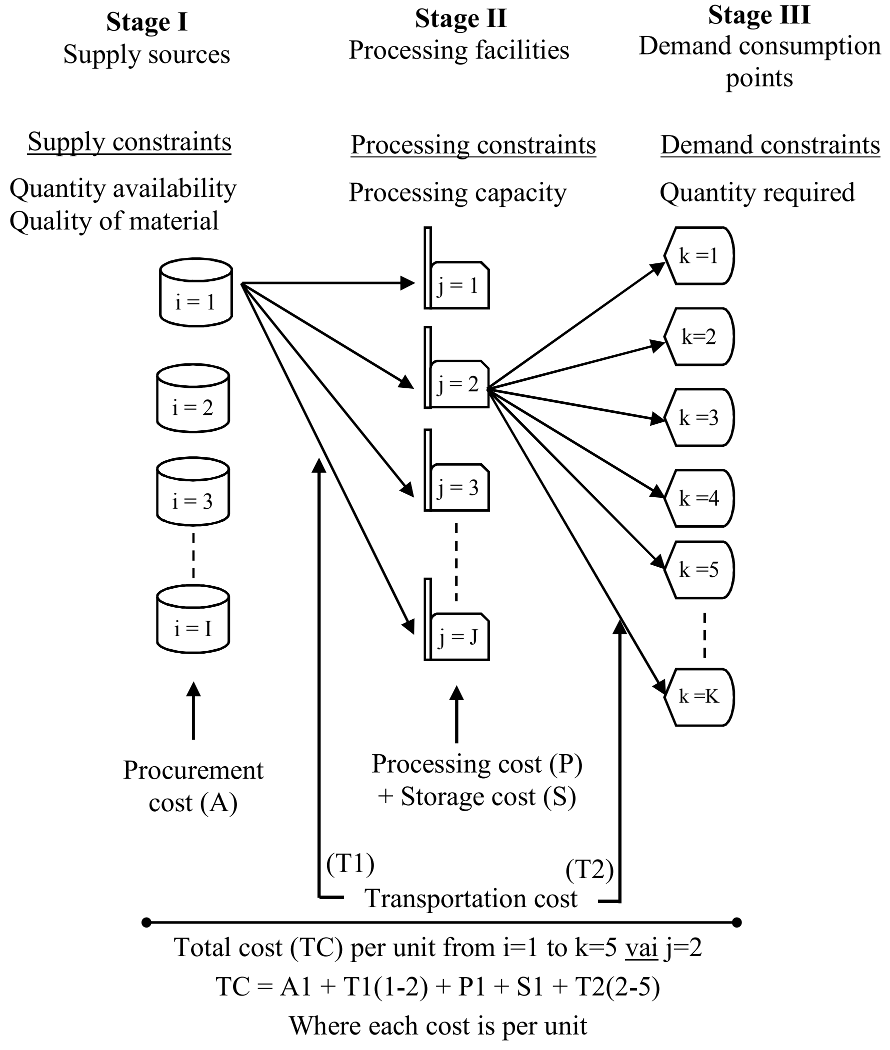


Figure 1: A Schematic network diagram for three stages of supply chain

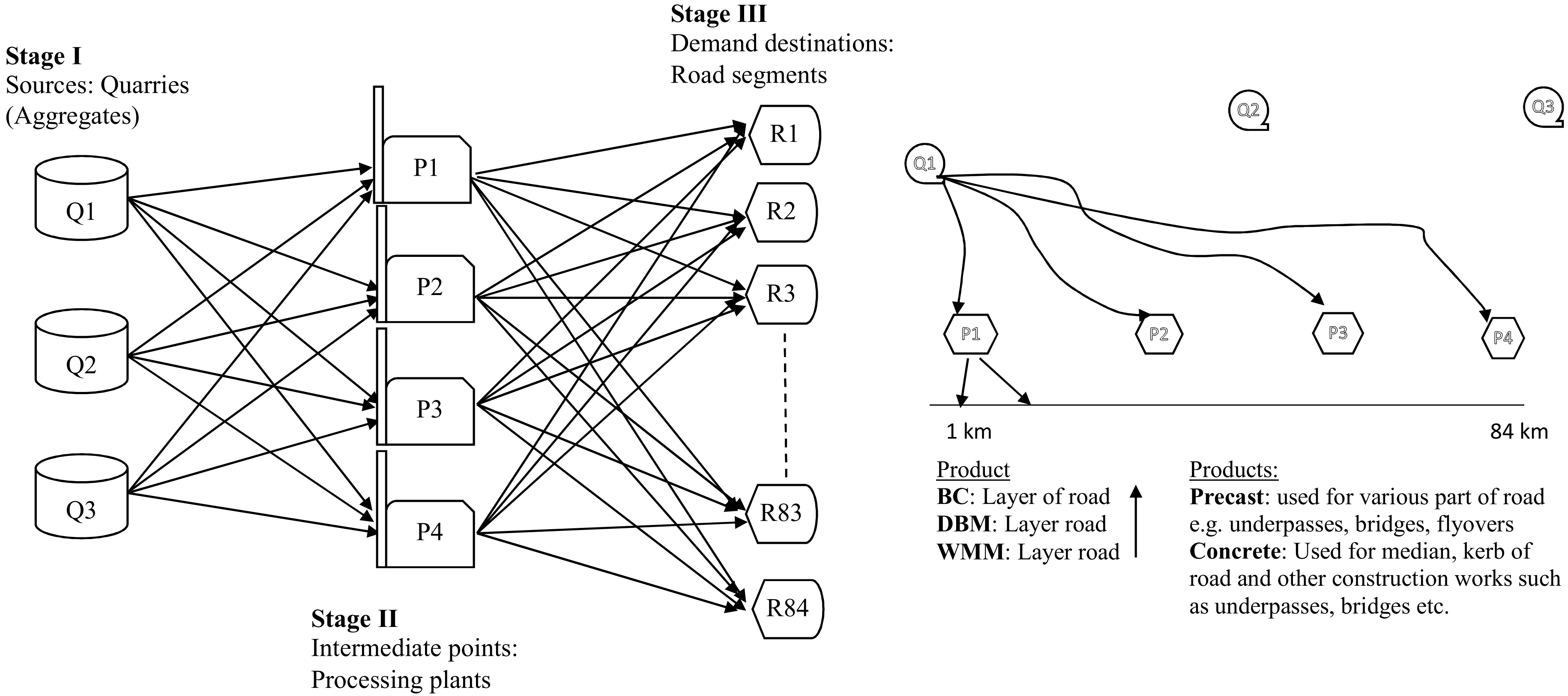
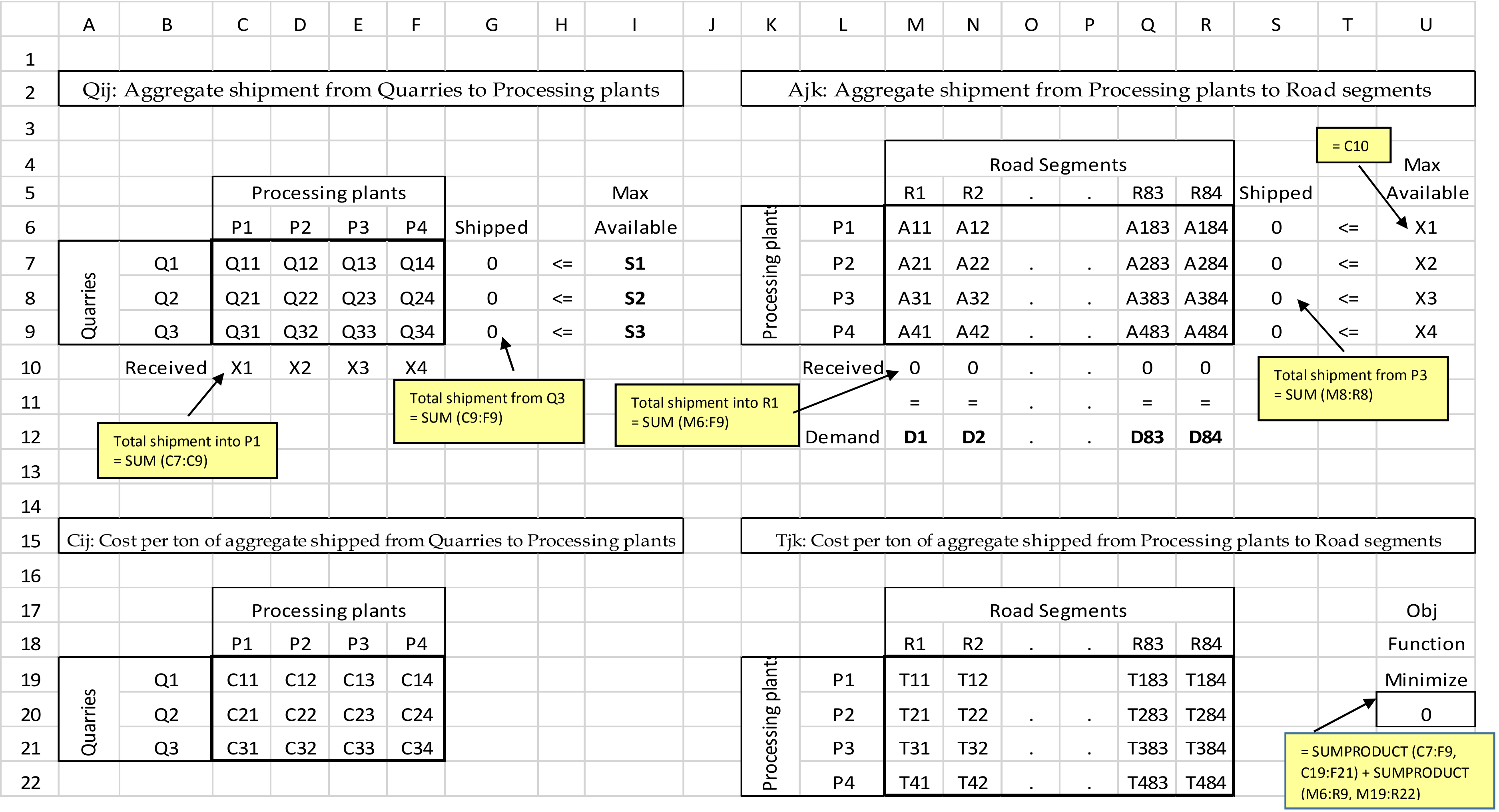


Figure 2: Conceptual supply chain model for procurement, processing and distribution of aggregate



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1																					
2	Qij: Aggregate shipment from Quarries to Processing plants										Ajk: Aggregate shipment from Processing plants to Road segments										
3																					
4													Road Segments								Max
5			Processing plants						Max				R1	R2	.	.	R83	R84	Shipped		Available
6			P1	P2	P3	P4	Shipped		Available		Processing plants	P1	A11	A12			A183	A184	0	<=	X1
7	Quarries	Q1	Q11	Q12	Q13	Q14	0	<=	**S1**			P2	A21	A22	.	.	A283	A284	0	<=	X2
8		Q2	Q21	Q22	Q23	Q24	0	<=	**S2**			P3	A31	A32	.	.	A383	A384	0	<=	X3
9		Q3	Q31	Q32	Q33	Q34	0	<=	**S3**			P4	A41	A42	.	.	A483	A484	0	<=	X4
10		Received	X1	X2	X3	X4						Received	0	0	.	.	0	0			
11													=	=	.	.	=	=			
12												Demand	**D1**	**D2**	.	.	**D83**	**D84**			
13																					
14																					
15	Cij: Cost per ton of aggregate shipped from Quarries to Processing plants										Tjk: Cost per ton of aggregate shipped from Processing plants to Road segments										
16																					
17			Processing plants										Road Segments								Obj
18			P1	P2	P3	P4							R1	R2	.	.	R83	R84			Function
19	Quarries	Q1	C11	C12	C13	C14					Processing plants	P1	T11	T12			T183	T184			Minimize
20		Q2	C21	C22	C23	C24						P2	T21	T22	.	.	T283	T284			0
21		Q3	C31	C32	C33	C34						P3	T31	T32	.	.	T383	T384			
22												P4	T41	T42	.	.	T483	T484			

= C10

Total shipment into P1
= SUM (C7:C9)

Total shipment from Q3
= SUM (C9:F9)

Total shipment into R1
= SUM (M6:F9)

Total shipment from P3
= SUM (M8:R8)

= SUMPRODUCT (C7:F9, C19:F21) + SUMPRODUCT (M6:R9, M19:R22)

Figure 3: Supply chain spreadsheet showing quarries shipping to processing plants and processing plants shipping to road segments.

About the authors

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