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# Land-use optimization based on Transit Oriented Development with Linear Programming

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**Abstract.** The large-scale and continuous increase in the number of urbanization make the daily needs in urban areas more diverse and significantly following to increase. The basic needs become the main thing to make the stability and survival of the city area that must get support from the surrounding environment. The concept of transitoriented development (TOD) is present to help the direction of the urban development program. The main problem is how to determine the priority function or designation of an urban area effectively. This research tends to attempt the function optimization in the urban area so that the infrastructure development can support urban progress effectively. Research began with qualitative methods which validation is the analysis rule in the city development variables as a result of literature studies. The results of the validation are input to the Linear Programming analysis process which it is a quantitative method. There are five types of property that become the main property development priority to support the ridership effectiveness of infrastructure development with the TOD concept. The study took a case study in a developing country region that recommended office, residential, and retail functions which are the three functions having the greatest influence on the development of the TOD region that is in line with the region's potential. The number of ridership improvement in the case study reached 55% which the model recommended in this study.

**Keywords:** Transit-Oriented Development (TOD), Land-Use, Transit Ridership, Optimization Process.

## 1 Introduction

Traveling using private vehicles is commonly found in developing countries such as Indonesia to reach their targeted destination. The increasing trips using automobiles will increase the use of fuel, pollutant emission, and traffic congestion. In longer term, it may affect the people's quality of life [1]. Provision of rail rapid transit system has been identified as a solution to overcome those consequences by partially shifting auto trips to transit usage, and reducing their dependency on private vehicles [2, 3], as well as reducing carbon emission, raising economic growth through accessibility improvement, and decreasing road-related accidental risks [4]. Therefore, many cities worldwide have started to establish rail-based transit system including Indonesia. LRT system is one of the transit projects recently executed by Government of Indonesia to alleviate the traffic problem in greater Jakarta.

On the otherhand, rail transit development consumes as one of the biggest investment among the other transit modes and requires high return to attract private sectors [5]. The main typical problem is about the ridership. Although incapable to cover the overall investment, the revenue merely from fare box is significant. Railway and its related operations contribute 34% to the total net income of Hong Kong's MTR Corporation [6]. Therefore, fare box revenue is one of the determinant factors of transit system income. Increasing the fare box revenue of rail transit related to many factors and one of them is the integration between transit corridor and land use pattern. When the land use offers seamless movement of users, it may attract them to use the public service more frequently. In longer term, it generates more revenue for the business entities. Hence, appropriate land use strategy is required to attract users by arranging urban spatial structure through transit oriented development or TOD [7].

This paper is intended to fill the gap by offering linear programming-based optimization model of land use allocation in parcel-level of rail-based TOD to maximize rail transit ridership. As mixed-use development is the main characteristic of TOD, the planning involves several different developments to be built in a limited land around station to achieve maximum rate of transit ridership. This is a typical choice task of linear programming problem. The goal of the study is to obtain optimum gross floor area (GFA) of each development as an alternative approach for transit operator or property developer to conduct proper transit-oriented development planning.

## 2 Literature Review

TOD is a form of spatial development of high-to-moderate density, mixed-use, and pedestrian-friendly within walkable distance around transit station [8]. [9] defined TOD as mixed-use development within comfortable distance for pedestrians, which was about 2,000 feet or 10 minutes walking from transit station, while this distance magnitude may differ among areas depending on their physical features. TOD is a way to engineer the built environment around station area to modify the resident's travel behavior and encourages them to use active and transit modes and thus decreases their car dependencies [10]. It will increase transit ridership and revenue of transit operator to maintain the transit service [11, 12]. Therefore, transit ridership could be one for the main performance indicator on how a TOD is stated successful. TOD can also generate significant revenue for rail transit service by land value capture mechanism. That is potential to be an additional function to increase feasibility of railway projects, such as Jakarta-Surabaya High Speed Train (HST) Project [13], which is estimated to yield 51-57% of the total revenue.

TOD concept has been applied in many countries but such development concept relatively new in Indonesia. TOD started gaining its popularity in Indonesia since the construction of mass rapid transit (MRT) in greater Jakarta and its adoption as a strategy to improve MRT project feasibility through real estate development [14]. Several studies have focused on TOD planning in relation to increase transit ridership. [15]

established decision tree approach to forecast the number of boarding and alighting passengers based on land use acreage inputs in Chongqing, China. [16] investigated the correlation between percentage of land use in areas of 500 m radius around rail station and diurnal rail ridership pattern in Seoul Capital Area using ridership based station clustering approach. [6] provided several successful TOD cases in relation to rail ridership in Japan and Hong Kong, China. While analyzing Hong Kong's Rail and Property Development model, [8] investigated the model's performance in increasing rail transit ridership. To arrange the allocation of several land uses to increase ridership, [17] and [18] used genetic algorithm to generate non-dominated alternatives of land uses allocations in a station area in China while [19] utilized grey linear programming technique. [20] performed model development to obtain alternatives of optimum floor area ratio (FAR) as input in policy-making process regarding allowed FAR in TOD areas in Taiwan. However, these studies focused on station-area-level planning, not on parcel-level, which deals with gross floor area of land use development as its decision variable. [21] performed linear and nonlinear programming optimization to determine the best mix of uses a mixed-use area. However, neither of both were in TOD context.

## 3 Methodology

The Indonesian TOD designs are collected from reports and discussion meetings with the TOD developer of LRT Jabodebek. The existing designs collected in this study took place in five on- going LRT station areas. Using the model resulted from this study, the ridership generated by existing designs will be evaluated and compared to the proposed design from this research.

The mixed-use optimization problem is solved by using Linear Programming (LP) approach. LP is a form of mathematical programming in which all its functions, i.e. objective function and constraints, are linear [22]. Mathematical programming addresses optimization problems concerned with the allocation of competing needs (i.e. floor area of uses) in a valuable resource (a land parcel or a site) to achieve an objective [23]. Transit ridership in a station can be modelled as a linear equation involving gross floor area and transit trip generation rate per unit area of each use [20]. Therefore, LP becomes the suitable technique to solve this problem.

Establishing the model with three components of LP framework, i.e. objective function, decision variables, and constraints, must be determined. As mentioned above, the quantification of objective, i.e. maximizing ridership, as a function of decision variables, i.e. floor area of uses, is adopted from the model developed by. The issue is to define type of uses to be accompanied in the model. The type of uses is determined by benchmarking from the successful TOD practice based on relevant literatures. Considering the limited availability of references regarding the transit trip generation rate of specific type of uses in TOD area, the decision variables are defined as four categories of uses as defined in [24] and [25]: (1) residential, (2) office, (3) retail and commercial and (4) hotel. Thus, the objective function of the problem is modelled as:

$$\text{Maximize } Z = T_1X_1 + T_2X_2 + T_3X_3 + T_4X_4 \quad (1)$$

where is the amount of transit ridership as the objective variable $T_1$; $T_2$; $T_3$; and $T_4$ are transit trip generation rates, respectively, residential, office, retail and commercial, and hotel uses as parameters, while $X_1$; $X_2$; $X_3$; and $X_4$ are the decision variables of floor areas of the above-mentioned type of uses. The value of required input parameters, i.e. transit trip generation rates, are estimated by multiplying rail transit modal split and required space area per person in a building planning for abovementioned purposes (Table 1). Modal split value for commuting trip is obtained by a benchmark study from Tokyo, which rail transit act as the backbone modes of travel activity. On the other hand, non-commuting trip is retrieved from previous study conducted by [25].

**Table 1.** Required space per person in building planning.

| Purposes | Minimum required space per person (m2) | References |
|---|---|---|
| Apartment | 9,29 | Engineering Toolbox (2003) |
| Hotel | 5 | Engineering Toolbox (2003) |
| Mall and Shopping Center | 4,2 | Engineering Toolbox (2003); Adler (1999) |
| Office and bank | 4,645 | Engineering Toolbox (2003) |

The mandatory constraint related to the maximum gross floor area (GFA) permitted to be built in the site. It is the result of multiplication between floor-area ratio (FAR) and area of the land site. In other words, the mixed-use development gross floor area shall not exceed those figures. The conditional constraints are related to restriction on developing particular uses, such as, the maximum GFA of commercial areas, minimum GFA of residential area and other factors. it would be expressed in values or percentages. The last constraint is about non-negativity which inhibits model to generate negative value of decision variables. These are defined based on the benchmark study on three examples of successful TOD in Japan, Hong Kong, and South Korea.

Based on the above explanation, the TOD optimization model to maximize ridership is presented as follows:

$$\text{Maximize } Z = 0.08X_1 + 0.16X_2 + 0.09X_3 + 0.12X_4 \quad (2)$$

where A is the area of the site; and f is the maximum FAR in the site.

## 4 Results

The above model will be used to resolve optimization problem in TOD planning on a land parcel around five LRT station areas. Bekasi 1 LRT station area will be an example of the model application. The TOD of Bekasi 1 is planned to be built on a 50,000-m2 land. The planned floor-area-ratio (FAR) is 3.56, thus maximum GFA will be 178,100 m2. The existing TOD plan is residential development, supported by retail commercial and other development.

**Table 2.** Typical TOD design based on benchmark study.

| Property types | Proportion | Range |
|---|---|---|
| Residential | 44% | 24-56% |
| Office | 18% | 6-24% |
| Hotel | 10% | 4-15% |
| Retail | 16% | 8-34% |
| Others | 12% | 12-39% |

The first step is evaluating ridership using the typical TOD design from the benchmark study looked like on Table 2 [26]. Equation (2) will be utilized to evaluate rail transit ridership of Bekasi 1 LRT station. The value of decision variables, i.e. GFA of each land use, are the results of multiplication involving the maximum GFA of Bekasi 1 TOD (178,100 $m^2$) and each land use proportion (%). The result of this step is shown in Table 3.

**Table 3.** The typical TOD design applied in Bekasi 1 station area and its ridership.

| Development | Quantity | Unit | Proportion |
|---|---|---|---|
| Residential | 78,364 | $m^2$ | 44% |
| Retail | 28,496 | $m^2$ | 16% |
| Hotel | 17,810 | $m^2$ | 10% |
| Office | 32,058 | $m^2$ | 18% |
| Others | 21,372 | $m^2$ | 12% |
| Ridership | 15,921 | trip | |

The next step is to optimize TOD design using program linear optimization approach. Based on the case study above, the constraints will be as mentioned below:

$$X_1 + X_2 + X_3 + X_4 \leq 178.100 \quad (3)$$

$$X_1 \geq 42.744 \quad (4)$$

$$X_1 \leq 99.736 \quad (5)$$

$$X_2 \geq 10.686 \quad (6)$$

$$X_2 \leq 42.744 \quad (7)$$

$$X_3 \geq 7.124 \quad (8)$$

$$X_3 \leq 26.715 \quad (9)$$

$$X_4 \geq 14.248 \quad (10)$$

$$X_4 \leq 60.554 \quad (11)$$

$$X_5 \geq 21.372 \quad (12)$$

$$X_5 \leq 69.459 \quad (13)$$

Table 4 shows the optimum design of TOD from linear programming-based optimization model using the typical TOD design. Based on Table 3, ridership estimation of LRT Jabodebek generated by the typical TOD design is 15,921 trips per day, while the optimized design generates 1,407 additional trips. This increase is resulted from space optimization taken from residential proportion. Residential space is reduced by 20% to be allocated in retail, hotel, and office development based on their trip generation rates and the defined constraints.

**Table 4.** Optimum TOD design of Bekasi 1 station area.

| Development | Quantity | Unit | Proportion |
|---|---|---|---|
| Residential | 42,744 | $m^2$ | 24% |
| Retail | 44,525 | $m^2$ | 25% |
| Hotel | 26,715 | $m^2$ | 15% |
| Office | 42,744 | $m^2$ | 24% |
| Others | 21,372 | $m^2$ | 12% |
| Ridership | 17,328 | trip | |

The objective function has shown that the highest rate of transit trip boarding comes from the office user. This is in accordance with several studies revealing that workplace development near the station is the main determinant of transit ridership. The result of study conducted by [27] in Denver, Colorado, suggested that locating workplaces nearer to transit is more effective to encourage non car worker commute trips than that of residential places. [5] revealed that, every 1,000 feet further from the station in Washington Metro lines, the reduction of transit mode share regarding office location was 58% higher than of housing. More recent research on ridership determinant factors of Shanghai rail transit system uncovered that employment within 500 m from the station is the dominant factor of increasing rail passenger volume, thus suggested to be key component of TOD planning [28].

After obtaining the potential ridership of benchmark and optimized TOD design, the research compared it to the existing LRT station TOD design. The existing design contains residential development as its major use, and non-residential development are allocated less than 40%. Table 5 contains additional rate of ridership in each case study resulted from ridership evaluation of benchmark design and optimization process.

**Table 5.** Additional ridership of benchmark and optimized design compared to existing TOD design.

| Development | Percentage of additional ridership compared to existing TOD design | |
|---|---|---|
| | Benchmark design (%) | Optimized design (%) |
| East Jakarta 1 | 43 | 55 |
| East Jakarta 2 | 13 | 22 |
| Bekasi 1 | 25 | 36 |

| | | |
|---|---|---|
| Bekasi 2 | 39 | 51 |
| Bogor 1 | 15 | 25 |

The optimized design can boost LRT ridership up to 55% in East Jakarta 1, while the minimum increase took place at East Jakarta 2. The optimized design of TOD to gain maximum value of ridership is 24% residential, 25% retail, 15% hotel, 24% office, and 12% others.

## 5 Conclusions

This paper demonstrates the effectiveness of using mathematical programming approach to resolve optimization problem of mixed-use TOD planning. As TOD planning consists a typical task in allocating limited land resources among several competing uses and different mixes to achieve certain objective, linear programming would be a suitable analytical tool to analyze to that matter. This paper presents a linear programming framework by defining decision variables and formulating objective and constraint functions based on similar TOD in different cities. The objective function is to maximize transit ridership, by taking into account performance indicators of successful TOD. GFA of each development type is defined as decision variables, for instance residential, office, hotel and commercial. The constraints are formulated based on the range of total and each type of development's GFA derived from benchmark study of successful TOD.

Objective is quantified as a linear function consisting ridership as objective variable and different types of uses' GFA as decision variables. The value of required input parameters, i.e. transit trip generation rates, are obtained by multiplying transit modal split and required space area per person in a building planning. The highest rate of trip is generated by office development, while residential development generates the lowest rate of trip. The more mixed-use development design is potential to produce higher transit ridership as well as offers more livable communities than existing TOD development scenario, which dominated by residential use.

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