

Selecting The Optimal transport Solution between Mail Centres of the South African Post Office

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Executive Summary

The South African Post Office is currently experiencing a decline in its mail volume, caused by the recent increased use of telecommunication technologies. This decline in volume makes a significant contribution to the declining revenue of the Post Office, as the majority of the revenue is generated by the Mail business department. Transportation cost accounts for most of the logistics cost, therefore improving the transportation system will create an economic opportunity and provide competitive advantage as transportation drives the supply chain. This project focuses on reducing the transport cost of traveling between the Mail Centre's (Hubs).

The problem at the South African Post Office has been solved by developing a mixed integer linear mathematical optimization model. The purpose of this model is to select between transportation modes such as road transportation, air transportation (intermodal road-air) and rail transportation (intermodal road-rail). The model further specifies the volume of mail to be transported by each transportation mode. The South African Post Office measure the success of a business activity through using a scorecard that measures economic, environmental and operational performance, for this reason the model developed is a multiple objective model which minimizes cost, operation time and carbon emissions.

Preemptive goal programming is used to solve the model where cost was optimized first, followed by operation time, then carbon emission. The model proposed provides a cost saving of R64 355 610 per-year and operation time savings of 2496.93 hours per year. Although the model provides an increase in carbon emission of 10.36 Kg/letter per year when compared to the current transportation system that only uses road transportation, the model provides a reduction of 27 percent in trucks on main roads, improving the traffic congestion problem faced in South Africa.

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Acronyms

BFN	Bloemfontein
CFG	Courier & Freight Group
CP	Cape Town
DOCEX	Document Exchange
ICT	Information Communication and Technology
JHB	Johannesburg
KZN	Kwa-Zulu Natal
MC	Mail Centre's
PE	Port Elizabeth
SAPO	South African Post Office
TSH	Tshwane

1. Introduction and Background

The South African Post Office (SOC) Limited is the national postal service of South Africa and state-owned by the government. The South African Post Office (SAPO) consists of five functional core business units namely Mail, Logistics, Financial services, Property and Information Communication and Technology (ICT). Figure 1 illustrates where the core functional business units are found in the company’s high level organogram. The efficiency of the business units will depend on shared support services, which consist of Transport, Channels, Transactional Services and Corporate Services (Post Office , 2008).

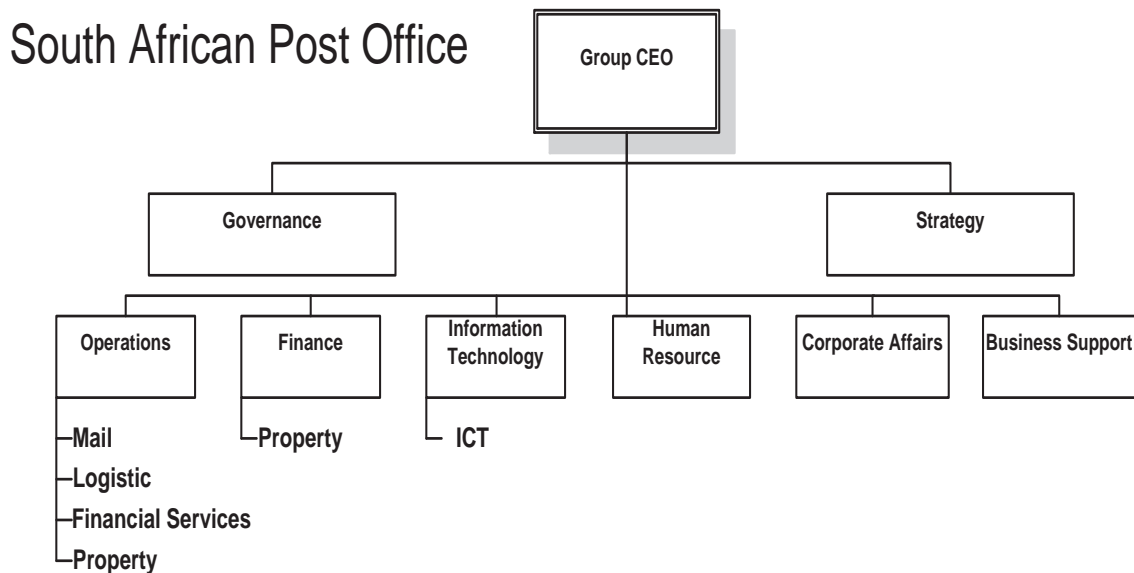


Figure 1: SAPO high-level organogram

The transport Service at SAPO is shared between the Mail business unit and the Logistics business unit. The Mail business unit handles the mail and parcels of SAPO, while the Logistics business unit integrates the transportation services to offer a full logistics solution. Express courier, freight, container and value added services are services that are integrated in the Logistics business unit. The Logistics division is also responsible for international deliveries. SAPO has a Courier and Freight Group (CFG). The CFG consist of the following companies: XPS freight, PX, Speed Service and Document Exchange (DOCEX). Some of the companies are

subsidiaries of SAPO and some are fully owned by SAPO. This project focuses on the Mail business unit transport service system.

The Mail business unit's primary functions is to the collect, process and deliver all mails and parcels within three days, in good quality and with maximum cost-efficiency. Transportation links the processes carried out by the Mail business unit between its facilities. Figure 2 illustrates the national footprint of SAPO, showing in each region the number of Mail Centres (MC), Depots (Postal agencies) and Branch Offices (Post Offices).

The mail business process is initiated by the customer placing the mail or parcels at SAPO's collection points such as lobbies, post boxes and Branch Offices which are then delivered to the MC by leased trucks. Bulk mail is delivered directly to the MC. The mails and parcels are sorted with respect to national postal code and addresses. This process is called Outwards Sorting. The mail is then transported to the relative national regions' MC by a Third Party Logistics (3PL) provider respective. This transportation is known as national transportation. An Inward Sorting process then occurs, firstly the mails and parcels are sorted by cities then delivered by leased trucks to the Depots. Then these mails and parcels are sorted at the Depots by suburbs and delivered by trucks to the Branch Offices. This type of transportation is known as regional transportation. The Branch Offices then distributes the mails and parcels to the final destination by vehicle, foot and bicycles. Figure 3 illustrates the process described above where LMC are the MC and DB is the Branch Offices.

Transportation drives the Mail business unit and helps with the effective management of SAPO's primary function. The transportation solution of SAPO does not support their strategic objective, which leads to an ineffective transportation system. A transportation solution that can provide reliability and cost saving to the SAPO is therefore required.

SAPO uses scorecards to help guide its business units to sustain the triple-bottom-line reporting where economic, environmental and social performances are considered to measure success. For this project the performance measures that will be used include, improving the financial position of SAPO, providing a transportation solution that has minimum environmental impact, and a system that will provide better operational efficiency and reliability.

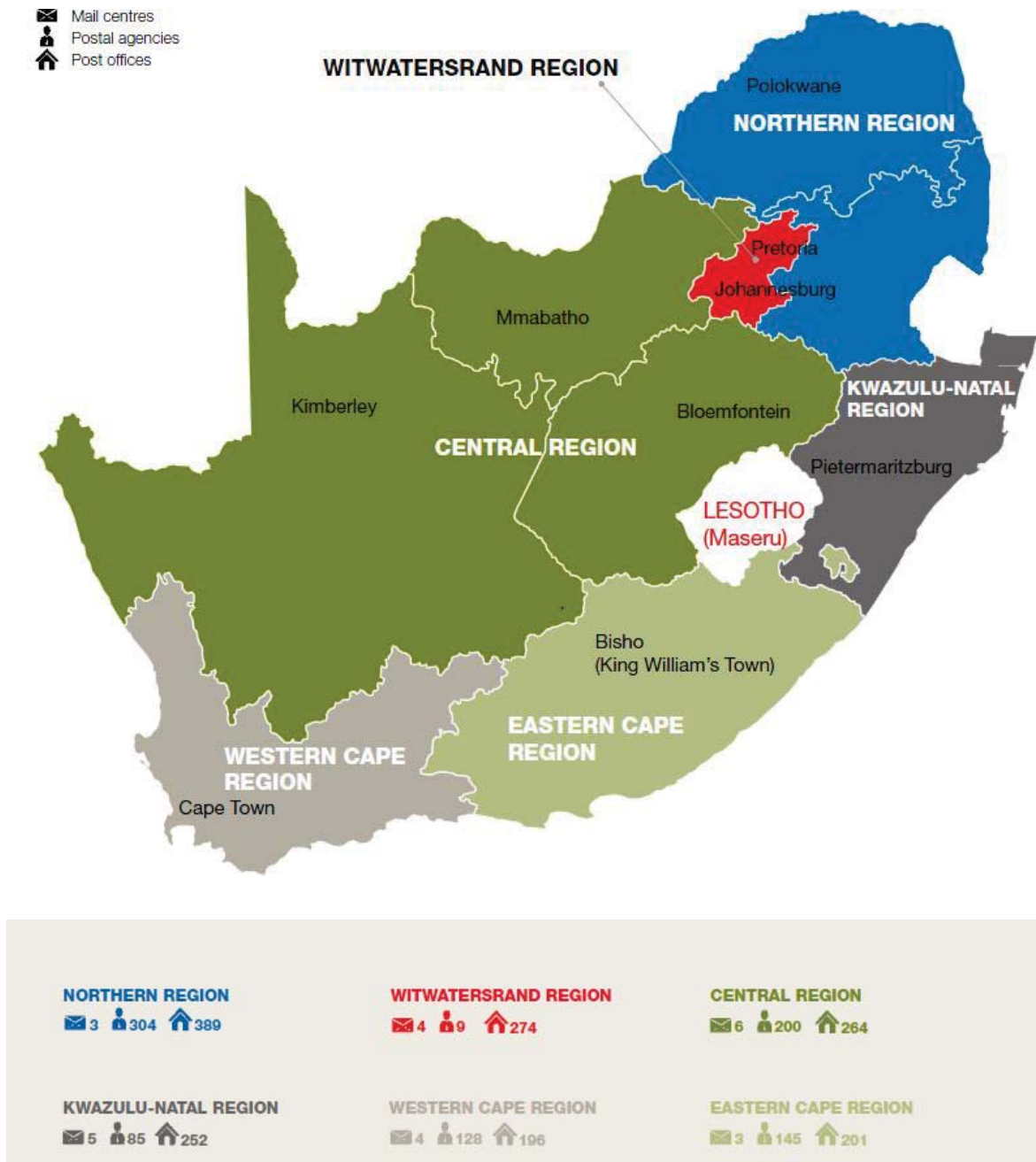


Figure 2: The National Footprint of SAPO (Post Office, 2012)

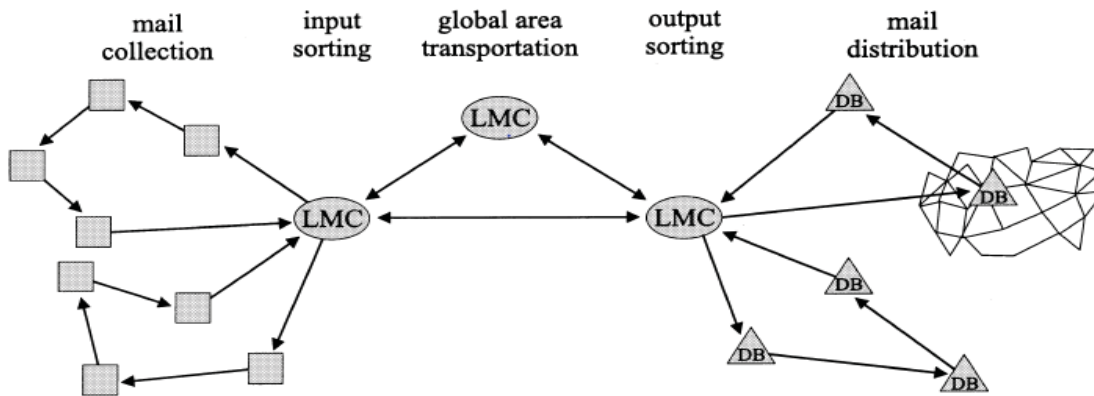


Figure 3: The postal service network (Tore Grunert, 2000)

1.1. Problem statement

The SAPO still has the monopoly in the mail industry in South Africa. The Mail business within SAPO constitutes the majority of its business, contributing to 67% of the business unit's overall revenue. SAPO experienced a decline of around 4.3% in mail volumes in 2014. This decline is caused by traditional mail being substituted by the new telecommunication technology including emails, SMS, and the internet, as well as new competitors such as DHL. These courier companies provide services that can deliver goods quicker than average delivery times. With a decline in mail volume, this provides an opportunity to investigate if the current transportation system is effective to the current demands, as it was created for a system with high volume demands. The current transportation solution of the SAPO was designed for the network built in 1993. This network has mushroomed due to the fact that, it is regulated to deliver to every destination including the informal settlements that the system was not designed for (Post Office, 2014).

In the past decade, transportation cost have been the largest component of the total logistics cost in most companies. In 2012 transportation costs accounted for 61.2% of the total logistics cost (CSIR, 2013). For SAPO transportation cost is the second largest expense after labour. The transportation cost for the year 2014 was R747 353 000 (Post Office, 2014). The mode of transportation used and where it is used influences the transportation cost. When mode selection is not optimized, the SAPO overspends with regard to transportation cost. Questions that the Post

Office manager has, includes: which transportation mode should be used for which route? What savings can the business achieve?

1.2. Project aim

The project aim is to develop a transportation solution that will answer the questions that the SAPO's manager has, through a mathematical model. The model must help the SAPO select which mode of transportation should be utilized to maximize the transportation system and existing infrastructure. This model should be for the national transportation system as the regional transportation system generates fewer expenses relative to the national transportation system. The model must select which mode should be used to facilitate transportation within the MC on a national grid.

The mode selected must provide security for the parcels and mails being transported and time reliability to ensure mails and parcels are delivered within the time frame. It should also provide cost reduction and must have the capability to transport the volume specified. When the correct mode is used transportation costs will be minimized, which will help in generating more revenue for the SAPO. This will also provide SAPO with a Mail business unit that is synchronized and effective.

1.3. Project approach

The methodology that was used to solve this project was the "Engineering Design Process" illustrated in Figure 4 (Science Buddies, 2014). The following steps were taken:

- I. The problem at SAPO was defined and investigated. This step also included an analysis of the departments and processes involved before the problem could be solved. For the purpose of this project an interview with the transportation manager was conducted.
- II. Research on which methods, tools and mathematical models can be used to solve the problem was conducted.

- III. The collection of data to estimate the values of the parameters that affect SAPO’s problem was conducted. The data collected was used to develop and evaluate the mathematical model that was created.
- IV. Formulation of a mathematical model of the problem will be developed, using the research and data collected.
- V. The model will be validated and verified to ensure the model developed is an accurate representation of the problem at SAPO.
- VI. A suitable model that best meet SAPO’s objectives from alternative models was selected.
- VII. The results, conclusion and recommendation will be presented to SAPO’s manager.

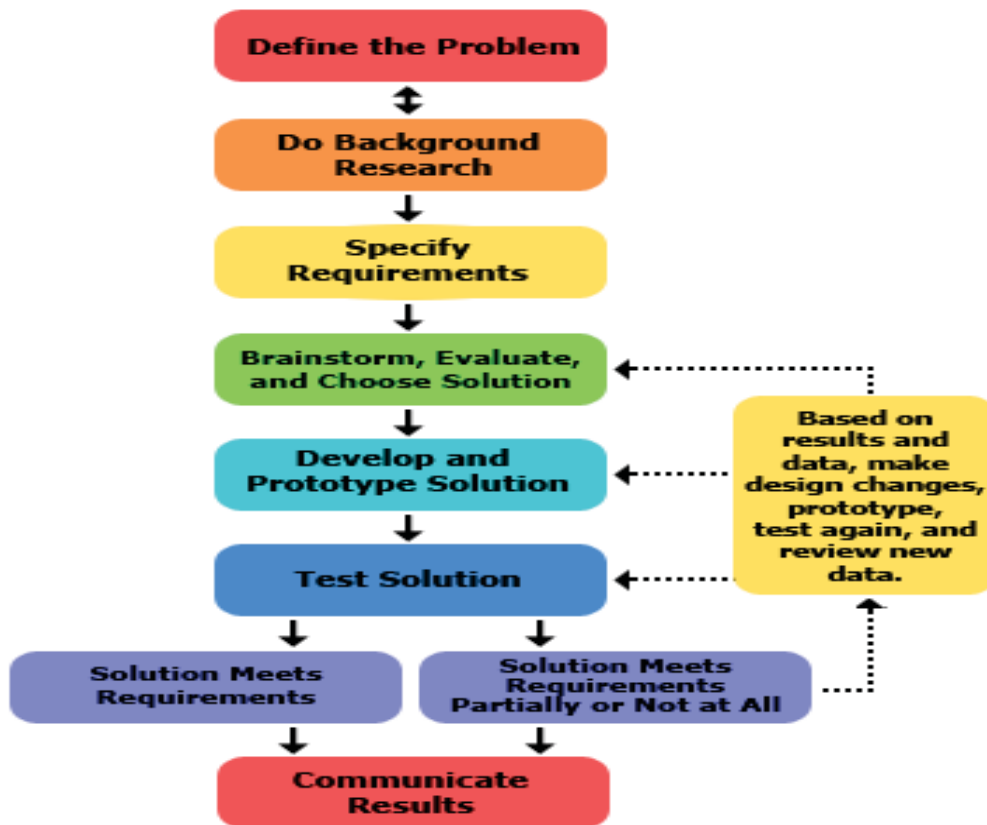


Figure 4 :“The Engineering Design Process” (Science Buddies, 2014)

1.4. Scope

The model will only consider transportation between the MCs. Post Office requires that the attributes to be selected for this project consist of security, reliability (time), cost and volume (mails and parcels). Within the network infrastructure, the MCs to be used for the model are MCs that are connected nationally, but not regionally due to data limitations.

1.5. Deliverables

The project will produce a transportation model which meets the following criteria:

- The model must investigate if the current system used is cost effective and if there is a better reliable, safe and more cost effective solution that exist.
- A model must be able to represent the problem at SAPO, and be able to determine which mode of transportation must be used between the MC.
- The model developed must align to the triple-bottom-line reporting economic, environmental and operational performance measure scorecards used by SAPO
- The model must ensure certain SAPO constraints are adhered to, and make sure that the demand flow between the origin-destination pairs is met.
- The model chosen should ensure that the transportation solution chosen can deliver the demand in three days.

1.6. Document structure

Chapter one includes the background of SAPO, the problem definition and the deliverables of the project. The remaining part of the report will be divided into six chapters. Chapter two provides a detailed literature review that identifies methods, tools and techniques to solve the SAPO's problem. Chapter three provides a more detailed investigation of the problem at SAPO and uses the information and chapter two's information to formulate the problem. Chapter four provides data analysis of the input data of the model formulated in chapter three. Chapter five provides the alternative solutions of the model formulated, while chapter six provides solution

validation of the alternative chosen in chapter five. Finally chapter seven provides the conclusion that offers the final results and recommendation to the problem at SAPO.

2. Literature Review

To select the better transportation mode within the MC, the different transportation modes and their characteristics have to be distinguished. The set of choices that exist for companies to choose the modes of transportation from includes air, road, rail, sea and pipeline. Due to the characteristics of the product (mail and parcels) being transported, SAPO can only utilize air, road, rail, or the combination of two (intermodal). This illustrates that the characteristics (bulk, liquid, distance travelled) of the product limits the mode that can be used. In most cases global organizations use air and sea for their global trades and regional or national trades is mostly performed by road, air, and sea. When the product is time sensitive the use of air is mostly preferred, while for bulk volume products, road and rail are mostly used.

Given the different modes, each mode possesses a given set of characteristics such as speed, transit time and the cost to use the mode. These characteristics determine the performance of the mode selected. Table 1 shows the characteristics of the modes and illustrates the strengths, limitations, and primary role of each mode. Within the supply chain, transportation enables the flow of goods and information, therefore if the transportation system is not operating effectively; it results in the whole supply chain not operating effectively (Mary *et al.*, 2008).

The transportation system is for the inbound and outbound movements of goods for the firm. Key decisions relating to the transportation system consist of multiple attributes, where managers have to select attributes that promote the business objective and strategy. Most sources states that cost, transit time and quality, are the primary attributes that logistics managers select. The primary attributes results in systems that require minimizing transit time and maximizing service reliability, within the specified quality parameters (performance). The challenge is that some of the attributes are qualitative and hard to quantify resulting in the selection process being difficult. In practice the important attributes differ from sector-to-sector and within organizations in the same sector. An increase in number of attributes that can be considered due to the changes within the supply chain, results in more factors being considered in decision making, which result in the development of different methods to solve the problem. This results in models that provide multiple objectives and involves multiple factors (Murphy and Farris, 1993).

MODE	STRENGTHS	LIMITATIONS	PRIMARY ROLE	PRIMARY PRODUCT CHARACTERISTICS	EXAMPLE PRODUCTS
Truck	<ul style="list-style-type: none"> • Accessible • Fast and versatile • Customer service 	<ul style="list-style-type: none"> • Limited capacity • High cost 	<ul style="list-style-type: none"> • Move smaller shipments in local, regional, and national markets 	<ul style="list-style-type: none"> • High value • Finished goods • Low volume 	<ul style="list-style-type: none"> • Food • Clothing • Electronics • Furniture
Rail	<ul style="list-style-type: none"> • High capacity • Low cost 	<ul style="list-style-type: none"> • Accessibility • Inconsistent service • Damage rates 	<ul style="list-style-type: none"> • Move large shipments of domestic freight long distances 	<ul style="list-style-type: none"> • Low value • Raw materials • High volume 	<ul style="list-style-type: none"> • Coal/coke • Lumber/paper • Grain • Chemicals
Air	<ul style="list-style-type: none"> • Speed • Freight protection • Flexibility 	<ul style="list-style-type: none"> • Accessibility • High cost • Low capacity 	<ul style="list-style-type: none"> • Move urgent shipments of domestic freight and smaller shipments of international freight 	<ul style="list-style-type: none"> • High value • Finished goods • Low volume • Time sensitive 	<ul style="list-style-type: none"> • Computers • Periodicals • Pharmaceuticals • Business to consumer (B2C) deliveries
Water	<ul style="list-style-type: none"> • High capacity • Low cost • International capabilities 	<ul style="list-style-type: none"> • Slow • Accessibility 	<ul style="list-style-type: none"> • Move large domestic shipments via rivers and canals • Move large shipments of international freight via oceans 	<ul style="list-style-type: none"> • Low value • Raw materials • Bulk commodities • Containerized finished goods 	<ul style="list-style-type: none"> • Crude oil • Ores/minerals • Farm products • Clothing • Electronics • Toys
Pipeline	<ul style="list-style-type: none"> • In-transit storage • Efficiency • Low cost 	<ul style="list-style-type: none"> • Slow • Limited network 	<ul style="list-style-type: none"> • Move large volumes of domestic freight long distances 	<ul style="list-style-type: none"> • Low value • Liquid commodities • Not time sensitive 	<ul style="list-style-type: none"> • Crude oil • Petroleum • Gasoline • Natural gas

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Table 1 : Characteristics of the different modes (Langley *et al.*, 2013)

Now that the different transportation modes and their characteristics have been distinguished and the attributes that can help solve the objective of the problem at SAPO are identified, the review of a model that will specify which transportation modes should be used between the MC is required. Models that are found in literature that best define the problem at SAPO are network design problems. From literature this project will consider the following network design problems.

- I. Network Equilibrium models and algorithms that model the movement of products individually.
- II. Multimode multi commodity freight flow over a multimode network that models the movement of multiple products at once.

III. An analytic hierarchy approach for multimodal freight transportation.

The rest of this section describes these different types of problems in more detail and the methods used to solve the problems.

2.1. Network equilibrium models and algorithms

Network equilibrium models aim to model the physical infrastructure of the network and compute the actual flows of one or more commodities within the network, which characterize the use of routes from origin to destination on the network under consideration. These models can be descriptive, trying to reproduce the behavior patterns of the transporters within the infrastructure or normatively trying to prescribe how to best use the network infrastructure. The network equilibrium models can be applied in a variety of problems including transportation of commodities, people, vehicles, water, data and information. In most cases the models can be formulated as nonlinear cost network optimization models (Florian M, 1995).

2.1.1. Traffic equilibrium models

This model is descriptive and aims at predicting the link flow and travel times that results from the way in which travelers, usually drivers of vehicles, choose routes from origin to destination on a specific transport network (Florian M, 1995).

Links are infrastructure (roads, rail tracks, airline network system) that promotes the movement of flow of the demand between two or more locations. A one directional link is referred to as an arc.

Sets

N – the set of Nodes, where $N = 1, \dots, 6$.

M – all the possible modes that can be used, within a specific origin-destination (i, j) pairs where $M = 1, \dots, 3$.

A – an arc link that only permits flow of one type of traffic where $A = 1, \dots, 72$.

P –the set of origin-destination (i, j) pairs where $P = 1, \dots, 24$.

K –the set of all paths, where $K = 1, \dots, 24$.

K_p –the set of paths for origin-destination (i, j) pair $p \in P$, where $K_p = 1, \dots, 3$.

Indices

i – the initial location(node) where the commodities are moved from where $i \in N$.

j – the location(node) where the commodities are going where $j \in N$.

Parameters

$s_a(v)$ –the given cost functions of travelling on a link $a \in A$.

t_p –the demand between the origin-destination (i, j) pairs where $p \in P$.

Decision Variables

v_a –the link flow of the demand on the link a , where $a \in A$.

h_k –the flow on path k where $k \in K$.

Model:

$$(\min)F = \sum_{a \in A} v_a s_a(v) \quad (1)$$

Subject to

$$\sum_{k \in K_p} h_k = t_p \quad \forall p \in P \quad (2)$$

$$h_k \geq 0, \quad \forall k \in K \quad (3)$$

$$v_a = \sum_{p \in P} \sum_{k \in K_p} \delta_{ak} h_k \quad \forall a \in A \quad (4)$$

$$\delta_{ak} = \begin{cases} 1 & \text{if link } a \text{ belongs to path } k \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

This model is a system-optimized flow model that minimizes the total cost of the system by equation (1). Equation (2) ensures the conservation of flow. Equation (3) ensures non-negativity flow within a path. Equation (4) provided the corresponding link flow to the path flows. Equation (5) provides the arc-path incidence. This model can be used to solve the problem at SAPO, accounting for minimizing the total transportation costs using path flow (rail, road and airline path).

2.2. Multimode multi commodity freight flow over a multimode network

Crainic *et al* (1997) provides a framework to model the network design problem. The framework “does not consider shippers and carriers as distinct actors in the decision making”, for the modelling of mode and carrier selection problems. This model was designed for regional or national transport planning in a strategic planning phase of the transport plan.

Crainic *et al* (1997) explains the word “modes” as the “means of transportation that has characteristics such as capacity, vehicle type and cost associated to use of the mode”. The model uses the infrastructure (network) that is currently available, providing all possible ways that the commodities may flow within the network (Crainic *et al*, 1997). The formulation of the model follows:

This model uses the same indices m, i, j and the decision variable h_k from the traffic equilibrium model by (Florian M, 1995).

Sets

T —when more than two modes are used, the location where the modes transfer from one mode to the other, where $T = 1, \dots, 10$.

\mathcal{C} —each product/commodity that is being transported, where $\mathcal{C} = 1,2$.

\mathcal{Z} —a single mode transportation where $\mathcal{Z} = 1, \dots, 24$.

Indices

$m(c)$ —the set of modes, that product $c \in \mathcal{C}$ can take, within a specific (origin-destination) trip

$K_{od}^{m(c)}$ —the set paths that product $c \in \mathcal{C}$ can take from origin $o \in \mathcal{N}$ to destination $d \in \mathcal{N}$, using only mode $m(c)$.

F —the total cost of the whole system.

Parameters

$g^{m(c)}$ —the demand matrix of product $c \in \mathcal{C}$, where $m(c)$ is the mode choice subset.

K^c —the set of all routes that may be used by product $c \in \mathcal{C}$.

Decision Variables

v_z^c —the flow of product $c \in \mathcal{C}$ on the single mode transportation $z \in \mathcal{Z}$.

v_t^c —the flow of product $c \in \mathcal{C}$ on with intermodal transportation, through the transfer at location $t \in \mathcal{T}$.

$s_z^c(v)$ —the volume of goods flow, moving on a single mode trip $z \in \mathcal{Z}$.

$s_t^c(v)$ —the volume of goods flow, moving on an intermodal mode trip $t \in \mathcal{T}$.

δ_{zk} — a binary variable that finds if a particular path is used or not on a single mode trip $z \in \mathcal{Z}$.

δ_{tk} — a binary variable that finds if a particular path is used or not on a intermodal mode trip $t \in \mathcal{T}$.

Model:

$$(\min)F = \sum_{c \in \mathcal{C}} c \left(\sum_{z \in \mathcal{Z}} s_z^c(v) v_z^c + \sum_{t \in \mathcal{T}} s_t^c(v) v_t^c \right) \quad (6)$$

Subject to

$$\sum_{k \in K_{od}^{m(c)}} h_k = g_{od}^{m(c)} \quad \forall o, d, m(c), c \quad (7)$$

$$h_k \geq 0, \quad \forall k \in K_{od}^{m(c)}, o, d, m(c), c \quad (8)$$

$$v_z^c = \sum_{k \in K^c} \delta_{zk} h_k \quad \forall z \in \mathbf{Z}, c \in \mathbf{C} \quad (9)$$

$$v_t^c = \sum_{k \in K^c} \delta_{tk} h_k \quad \forall t \in \mathbf{T}, c \in \mathbf{C} \quad (10)$$

$$\delta_{tk} = \begin{cases} 1 & \text{if } t \in \mathbf{K} \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

$$\delta_{zk} = \begin{cases} 1 & \text{if } z \in \mathbf{K} \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

This model's main objective (6) is to minimize the total cost of the logistic function. Cost in this model has different components that can include: monetary value cost, risk costs and delay costs etc. The model also provides flexibility of restricting certain products from being moved with a specific mode. Constraint (7) ensures the conservation of flow, with regards to demand. Total demand into a location is equal to total demand out of that location. Constraint (8) ensures that a path can either be taken or not. Constraints (9&10) make sure the total volumes within each trip for a specific product is equal the sum of each path for that trip. Constraint (11) Determines which transfer belongs to which path, if the two arcs that defines the transfer belong to it and constraint (12) identifies which arcs belong to which path.

This model was solved by a mathematical algorithm, which forms a "Gauss-Seidel process". The model above provides similarities to the problem faced at SAPO. The flexibility that the total cost consists of components means that the model can be used for the attributes selected by SAPO. The algorithm is linear and therefore can be solved with linear programming. This model proved to be successful in practice and has been used in many firms (Crainic, 1990b).

2.3. An analytic hierarchy approach for multimodal freight transportation

Gursoy M (2010) formulates a model for decision support using the analytic hierarchy process approach in the “textile” sector. The attributes used in the model consist of shipping cost, shipping speed or time, shipping safety, and accessibility of the shipping mode. The main objective of the model is to maximize the mode with the most points, using the attributes. Each attribute within the modes is given a preference weight. The weights are obtained from surveys. The mode with the most preference of the attributes is the mode that is to be used. The model was tested against the actual choice of the shipper and it provides a compatibility of 73%. The section below shows the formulation of the model.

Model:

Sets

Q – criteria, where $Q = 1, \dots, 4$ and 1 = Price, 2 = Time, 3 = Safety 4 = Accessibility.

R – the modes available, where $R = A, B, C$

Decision Variable

X_i – represents the weights of the mode choice criteria according to the surveys.

Y_{ji} – represents the distributed value of the mode choice criterion among the shipping modes.

Indices

i – represent the preference criteria where $i \in Q$.

j – represent shipping mode where $r \in R$.

The model formulation is as following;

$$Z = \text{MAX}_j \left[\sum_{i=1}^n X_i \cdot Y_{ji} \right] \quad \text{where } j \in \mathbf{R}, i \in \mathbf{Q} \quad (13)$$

Subject to

$$0 < X_i < 1 \quad \forall i \in \mathbf{Q} \quad (14)$$

$$\sum_{i=1}^4 X_i = 1 \quad (15)$$

$$X_i, Y_{ji} > 0 \quad (16)$$

Equation (13) determines the objective of the model. Equation (14) ensures that the preference weight is only between 0 and 1, equations (15) ensures the sum of the weights is equal 1 and equation (16) ensures the variables are positive. This method cannot be used to model the problem at SAPO, but will only help SAPO in choosing the best mode that is used in practice. This model will not provide the cost saving and be able to determine which mode must be used for which trip. Therefore for this project, this method is not suitable.

2.4. Multi objective decision making

The SAPO's problem consists of multiple objectives where the solution to the problem must be in line with the triple-bottom-line reporting where economic, environmental and social performances are considerations to measure success. These objectives cannot, however be all minimized simultaneously. Goal programming is the method chosen as its one of the most commonly used technique to solve multiple objective problems. This method sets a target of goal level that is desired as sufficient by the decision maker Preemptive (lexicographic) optimization and weighted sum multi-objective goal programming models will be considered in this project (Rardin, 1998).

2.4.1. Preemptive optimization

Preemptive goal programming is where the multi-objective problem is optimized one objective at a time. The most important objective is optimized first, and then its value is fixed at the optimal value of the second objective and so on. This model ensures that each objective regards another objective when being optimized and therefore it is advantageous.

2.4.2. Weighted sum of objective

Each objective is given a weight and the multi-objectives are combined into a single weighted sum objective. To minimize the single weighted sum function, weights for maximizing objectives must be negative and those for minimizing objectives should be positive. Each weight will have to reflect the importance of the objective. Each weight will have to reflect the importance of the objective. The disadvantage of this method is that it becomes difficult to select values for the weight of each objective and also it provides only one solution instead of a Pareto front consisting of a set of Pareto optimal solution. A Pareto optimal solution is where one objective cannot be made better off without making the other worse.

2.5. Types of algorithms

Optimization problems, either minimization or maximization problems, can be solved with different methods. Two types of algorithms, namely exact algorithms and heuristic (approximation) algorithms exist to solve optimization problems. The solution of the algorithms can either be a global optimum, which is the best feasible solution from all the feasible solutions to problem or be a local optimum, which is a feasible solution that is not the best feasible solution. Figure 5 illustrates the explanation of the global optimum and local optimum. The figure shows an arbitrary function $f(x)$ with parameter $-3 \leq x \leq 4$ and a user sample space $0 \leq x \leq 2$. Local minimums and maximums can only occur at turning points in the graph, while the global minimum and maximum occur only at the extreme points in the graph. The figure shows the local minimum at $f(0)$ and $f(2)$ and local maximum at $f(1)$, while the global minimum is at $f(2)$, and the global maximum is at $f(-3)$ (Stewart J, 2004).

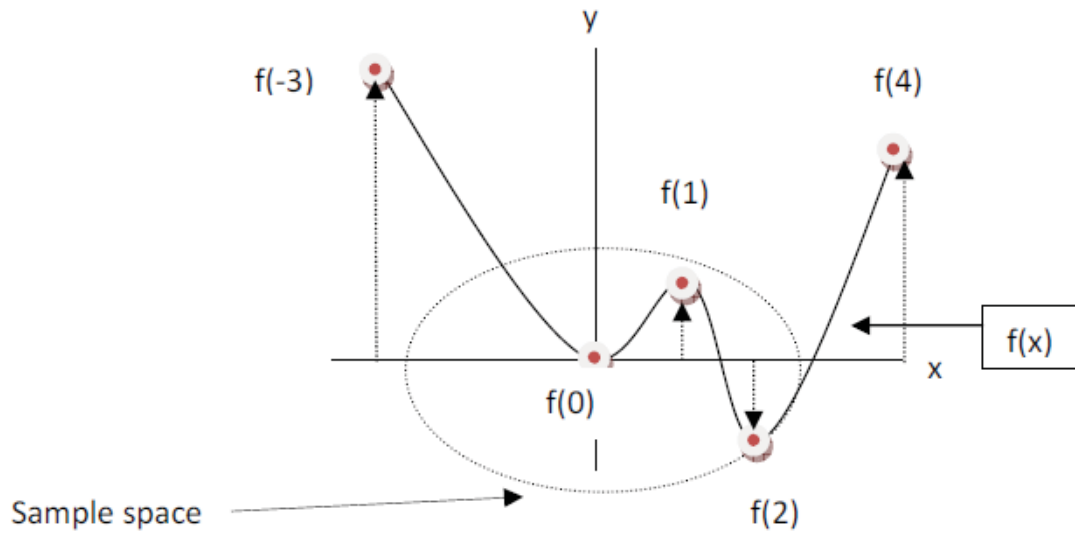


Figure 5 : A function $f(x)$ (Stewart J, 2004)

2.5.1. Exact algorithms

Exact algorithms will find the global optimum solution to a problem provided the problem is not too complex. A branch-and-bound method is used to solve integer linear programming problems exactly. Branch-and-bound is a systematic method approach that computes all possible combinations of the variables, and choose the best combination to the problem. The method is used to solve models with integer restrictions (Hillier F, 2010).

2.5.2. Heuristic algorithms

A heuristic algorithm is used to solve complex problems that the exact algorithm cannot solve. The algorithm will try to find a local optimum solution closest to the global optimum solution. The heuristic algorithm methods can be categorized into namely local search improvement methods, metaheuristic methods and constructive methods. The metaheuristic methods are the most used methods and consist of simulated annealing, genetic algorithms, tabu search and various other artificial intelligence (AI) base methods.

2.6. Software packages

Matlab, Python, C++ or any programming language can be used to code the exact and heuristic algorithms. Although all the programming languages require the algorithm to be coded, some of the software packages have extensions such as Matlab's optimization toolbox that can be used. Another software package that can be used is Lingo. Lingo is used to solve and analyse linear and nonlinear optimization problems. Lingo solves linear, quadratic, integer, nonlinear, second-order cone problems and also the combination of problems (Lindo Systems, 2010). Compared to the other software packages, Lingo has the exact and heuristic algorithms encoded into it, therefore to compute the algorithms the user utilizes the Lingo language and code the objective function and its constraints and Lingo solves the optimization problem..

3. Problem Investigations

The national transportation network is as follows;

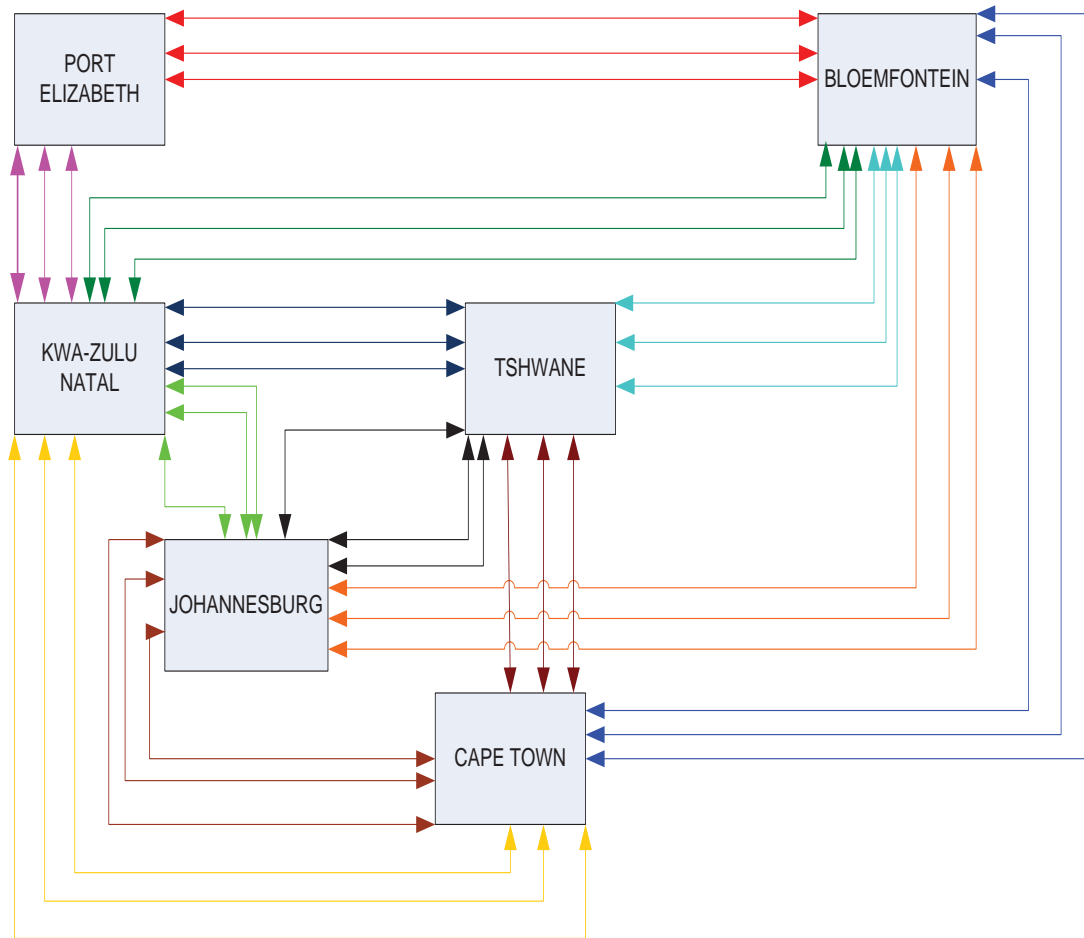
- I. Cape Town accommodates the entire Western Cape Province population.
- II. Port Elizabeth accommodates the Eastern Cape Province population.
- III. Kwa-Zulu Natal accommodates the entire provinces population.
- IV. Bloemfontein accommodates Free State, Northern Cape and half of North West province population.
- V. Tshwane accommodates Limpopo, Tshwane Metro, Mpumalanga and the remaining half of Northern West province population.
- VI. Lastly Johannesburg accommodates the Gauteng province population that excludes Tshwane Metro population.

For each location, Cape Town (CP), Port Elizabeth (PE), Kwa-Zulu Natal (KZN), Bloemfontein (BFN), Tshwane (TSH) and Johannesburg (JHB), the transportation network has to move demand from the origin location to the destination locations. Figure 6 shows the network infrastructure that SAPO uses. The rectangles in the diagram show the locations and each link (double arrow lines) illustrates the infrastructures of the road, rail and the airline network available that SAPO may utilize. As seen in the diagram PE only sends and receives demand flows from Bloemfontein and Kwa-Zulu Natal, while the other locations sends and receives demand flows between each other. Each location can use either of the network infrastructures, to move the origin-destination demand. The different infrastructures have different characteristics cost, price, reliability, time spend and safety.

The problem at SAPO restricts and constrains the model developed. One of the restrictions includes the time frame that the system has to operate in. Normal mail has a time delivery frame of 3 days from the time the customer places a request for delivery. All transportation (national and regional combined) have to be within the time frame. The regional transportation takes place at the beginning and end of the process, while national transportation is required at the middle of the process. The total regional transportation requires two days; the remaining 1 day is required

for national transportation. This implies that the mode of transportation chosen between the MC, has to perform the movement of letters within one day. This provides a restriction of time.

Currently SAPO only utilizes the road network infrastructure to perform its national transportation. The Mail business unit contributes 85 percent to the total transportation cost and Logistics contributes the rest, furthermore the national transportation cost contributes 75 percent of the total Mail transportation system (national and regional). SAPO has not yet utilized any form of operational research to assist them in making decisions about their transportation system. In the past they relied on the knowledge of the transportation management team, where they used previously gained experience in the field to make more informed decision.



LEGEND

- PE-BFN, BFN-PE
- PE-KZN, KZN-PE
- BFN-KZN, KZN-BFN
- KZN-TSH, TSH-KZN
- JHB-KZN, KZN-JHB
- CP-KZN, KZN-CP
- CP-BFN, BFN-CP
- CP-JHB, JHB-CP
- BFN-JHB, JHB-BFN
- TSH-BFN, BFN-TSH
- CP-TSH, TSH-CP

Figure 6: The actual network infrastructure of SAPO

3.1. Problem formulation

Based on the literature of transportation systems and the problem investigation, it is evident the SAPO's problem can be solved, and alternative design solutions can be developed.

3.2. SAPO transportation system requirements

To help identify which model will best solve the problem, the deliverables and scope of the model is revised. This includes:

- I. The model must investigate if the current system being used is cost effective and if there is a better reliable, safe and more cost effective solution that exists.
- II. A model must be able to represent the problem at SAPO, and be able to determine which mode of transportation must be used on which trip.
- III. The model solution must provide environmental, financial and social benefits, if any.
- IV. The model must ensure certain SAPO constraints are adhered to, and make sure that the demand flow between the origin-destination pairs is met.
- V. The model chosen should ensure that computation time of the operation is within the time frame required.

The models chosen to solve the problem must adhere to the requirement provided above, for the project objectives to be achieved.

3.3. Model alternatives and selection

From the requirements of the model, two of the model methods found in literature provides opportunity to solve the problem. This includes:

- I. The multimode multi commodity freight flows over a multimode network model by Crainic *et al* (1997).
- II. "Traffic Equilibrium Model" by Florian M (1995).

Both models provide useful information to formulate the problem at SAPO. The reason why the multimode multi commodity freight flows over a multimode network model by Crainic *et al* (1997) was not used entirely, is because it adds complexity of adding ten more nodes that are the transfer nodes (airports and railway stations). This complexity results in having to compute three links for each flow (two for the road transportation and one for either the air transportation or rail transportation) instead of one, while if one link is used the rest also have to be used. For this purpose the traffic equilibrium model by Florian M (1995) is used to model the link flow between the MCs that combines the three links into one, elimination the transfer nodes. The preemptive optimization method will be used as it provides an advantage that costs can be minimized first then operational time and finally carbon emission. Equations (17), (18) and (19) are the objective function for cost, operation time and carbon emission, respectively of the SAPO's problem.

Both the methods modelled path flow using binary variables (δ_{zk} , δ_{tk} and δ_{ak}) that assigned a path to a given link and the total link flow was the sum of the paths. For the SAPO's problem path flow are assigned to each transportation mode available, therefore binary variable are not used. The model will therefore choose which path to use and ensures that the total paths chosen between MC must be equal to the demand of letters that must be delivered (equation (20)). Additional constraints includes; equation (21) ensuring each transportation mode travelling time between the MC is not great than one day(3600 minutes), equation (22) ensuring a maximum of 3000 kg (3 tons) cannot be transported with the air transportation. Equation (23) and (24) ensures that when there is volume flow in a path, the time and carbon emission binary variable is one and if not the variable is zero, equation (25) and (26) ensure that for a single origin-destination pair the sum of the binary variables cannot exceed two, equation (27) and (28) is the time binary variable and the carbon emission binary variable and equation (29) making the path flow volume of letters to be integer values. The Lingo software package will be used instead of the other tools because of its ability to write the objectives function and its constraints, rather than coding the algorithm itself as the other tools (Matlab, Python, and C++ etc.).

The Model:

Sets

No – the set of Nodes, where $N = 1, \dots, 6$.

Mo – all the possible modes that can be used, within a specific origin-destination (i, j) pairs where $Mo = V, R, A$, where V = road transportation, R = rail transportation, A = air transportation.

Pa_{ijm} – the sets of path flow between origin node $i \in No$ and destination node $j \in No$ using mode $m \in Mo$, where $Pa_{ijm} = 1, \dots, 72$.

Indices

i – the initial location(node) where the commodities are moved from where $i \in N$.

j – the location(node) where the commodities are going where $j \in N$.

OD – the link between origin node $i \in No$ and the destination node $j \in No$.

Parameters

Co_{ijm} – the cost in (R/letters) of travelling between origin node $i \in No$ and destination node $j \in No$ using transportation mode $m \in Mo$.

Tm_{ijm} – the time in (minutes) taken to travel between origin node $i \in No$ and destination node $j \in No$ using transportation mode $m \in Mo$.

D_{ij} – the demand in (number of letters) that has to be used between origin node $i \in No$ and destination node $j \in No$.

MT – the maximum time any trip can take.

L – the maximum load capacity for the air transportation.

BIGM1 – a large constant value that forces the time binary function to be zero or one when the is volume flow.

BIGM1 – a large constant value that forces the carbon emission binary function to be zero or one when the is volume flow.

Decision Variables

H_{ijm} – the path flow volume in (letters) transported between origin node $i \in \mathbf{No}$ and destination node $j \in \mathbf{No}$ using transportation mode $m \in \mathbf{Mo}$.

$B1_{ijm}$ – a time binary variable that is one when the is volume flow between origin node $i \in \mathbf{No}$ and destination node $j \in \mathbf{No}$ using transportation mode $m \in \mathbf{Mo}$ and zero otherwise.

$B2_{ijm}$ – a carbon emission binary variable that is one when the is volume flow between origin node $i \in \mathbf{No}$ and destination node $j \in \mathbf{No}$ using transportation mode $m \in \mathbf{Mo}$ and zero otherwise.

Formulation:

$$(\min)z = \sum_{i \in \mathbf{No}} \sum_{j \in \mathbf{No}} \sum_{m \in \mathbf{Mo}} 1.0444727 \times C_{o_{ijm}} \times H_{ijm} \quad (17)$$

$$(\min)z = \sum_{i \in \mathbf{No}} \sum_{j \in \mathbf{No}} \sum_{m \in \mathbf{Mo}} T_{m_{ijm}} \times B1_{ijm} \quad (18)$$

$$(\min)z = \sum_{i \in \mathbf{No}} \sum_{j \in \mathbf{No}} \sum_{m \in \mathbf{Mo}} 1000 \times C_{O2_{ijm}} \times B2_{ijm} \quad (19)$$

Subject to

$$\sum_{m \in \mathbf{Mo}} H_{ijm} = D_{ij} \quad \forall i, j \in \mathbf{No} \quad (20)$$

$$T_{m_{ijm}} \leq MT \quad \forall i, j \in \mathbf{No}, m \in \mathbf{Mo} \quad (21)$$

$$\sum_{m=A \in \mathbf{Mo}} H_{ijm} = L \quad \forall i, j \in \mathbf{No} \quad (22)$$

$$H_{ijm} \leq \mathbf{BIGM1} \times B1_{ijm} \quad \forall i, j \in \mathbf{No}, m \in \mathbf{Mo} \quad (23)$$

$$H_{ijm} \leqslant BIGM2 \times B2_{ijm} \quad \forall i, j \in No, m \in Mo \quad (24)$$

$$\sum_{m=A \in Mo} B1_{ijm} \leqslant 2 \quad \forall i, j \in No \quad (25)$$

$$\sum_{m=A \in Mo} B2_{ijm} \leqslant 2 \quad \forall i, j \in No \quad (26)$$

$$B1_{ijm} = \begin{cases} \text{if } H_{ijm} \text{ has path flow} \\ 0 \text{ otherwise} \end{cases} \quad \forall i, j \in No, m \in Mo \quad (27)$$

$$B2_{ijm} = \begin{cases} \text{if } H_{ijm} \text{ has path flow} \\ 0 \text{ otherwise} \end{cases} \quad \forall i, j \in No, m \in Mo \quad (28)$$

$$H_{ijm} \geqslant 0, \text{ integer} \quad \forall i, j \in No, m \in Mo \quad (29)$$

3.4. Model assumptions

A number of assumptions should be noted:

- I. Trucks are fully available at all times within the network at all of the Mail Centre's.
- II. Airplane flights and trains are always available at any time to be used, no waiting time at the railway stations and airports.
- III. Time taken to put the mails in the trucks at the MC, also when interchanging from road to either rail or air and back to road is not considered when calculating time taken between the MC.

4. Data Analysis

The reliability of the model to obtain information that can be used to make decisions requires the data used for the model to be accurate or an accurate estimated. The method chosen requires the input of the following data:

- I. The demand flow required to be moved between the locations within the network.
- II. The geographic location of the Mail Centres, to be able to determine the distance between the locations.
- III. The distance between the locations in the infrastructure.
- IV. The time it takes from one facility to the other.
- V. The cost associated with using the specific network infrastructure between the locations.
- VI. The carbon dioxide emission produced when traveling between the different MC, with the different transportation mode.

The rest of the chapter will present the analysis of the input data required by the model formulated for the SAPO's problem. This data includes the required mentioned above.

4.1. Demand flow between the facilities

The lack of an accurate determination of the demand of mails and parcels results in using the population of the locations as the demand that needs to be moved. This method of estimation comes with consequences as it does not consider the companies, which constitute a major customer to SAPO. This method tries to improve the estimate by assumption that the majority of mail will tend to flow towards industrial provinces. The distribution of letters by province is as following:

- I. A province will distribute 40% of its mail to Cape Town and 40% to Johannesburg, and the remaining 20% will be distributed to the rest of the provinces that it delivers, that can be checked in Figure 6 in section 3.

E.g. Johannesburg will be Gauteng (13°200°300) minus Tshwane Metro (2 921 488) and yields 10 278 812, 10 278 812 will be distributed as following:

- I. Cape Town (40%)
- II. Tshwane (20%)
- III. Bloemfontein (20%)
- IV. Kwa-Zulu Natal (20%)

This example will yield the values given in the Table 16 in the appendices. Table 15 in the appendices shows the estimated population of the individual provinces in 2015. Figure 7 below shows the percentage of the total demand that has to be delivered to the respectively Mail Centre's from the others, it also shows that most of the mails are delivered to CP and JHB as they are the industry hubs.

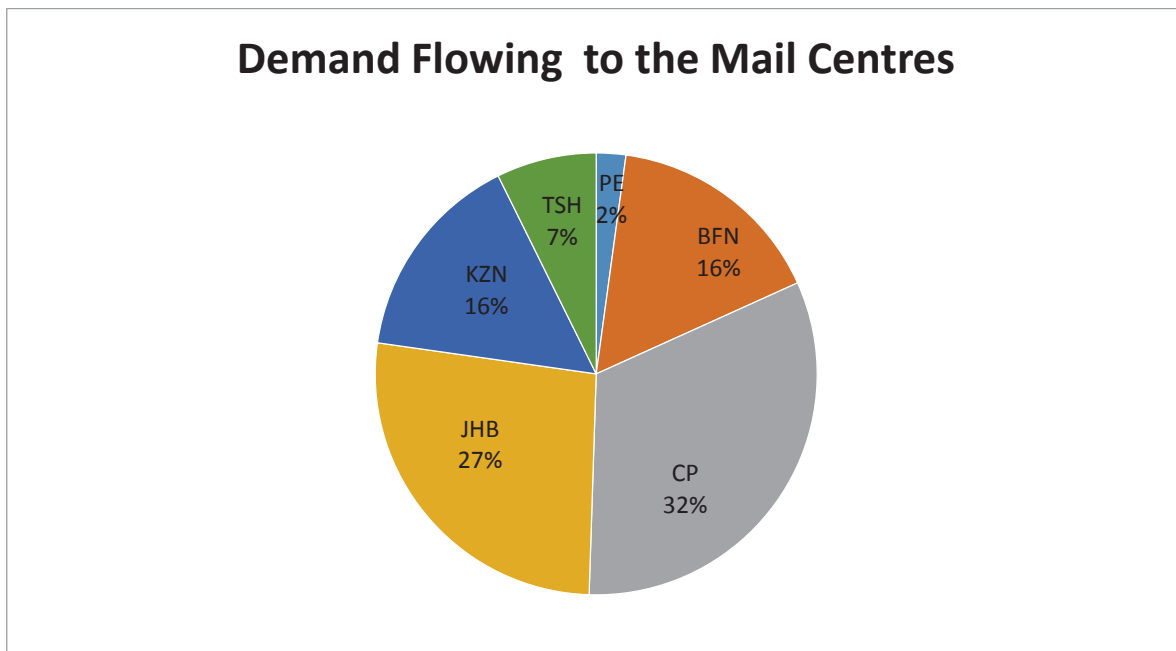


Figure 7: The total demand delivered to the specific Mail Centres

Figure 8 below shows a pie chart of the demand of the respective MC relative to each other. As seen in the figure majority of the mail originates from the Witwatersrand region, Northern region and the Kwa-Zulu Natal region, which constitutes most of economic working urban regions.

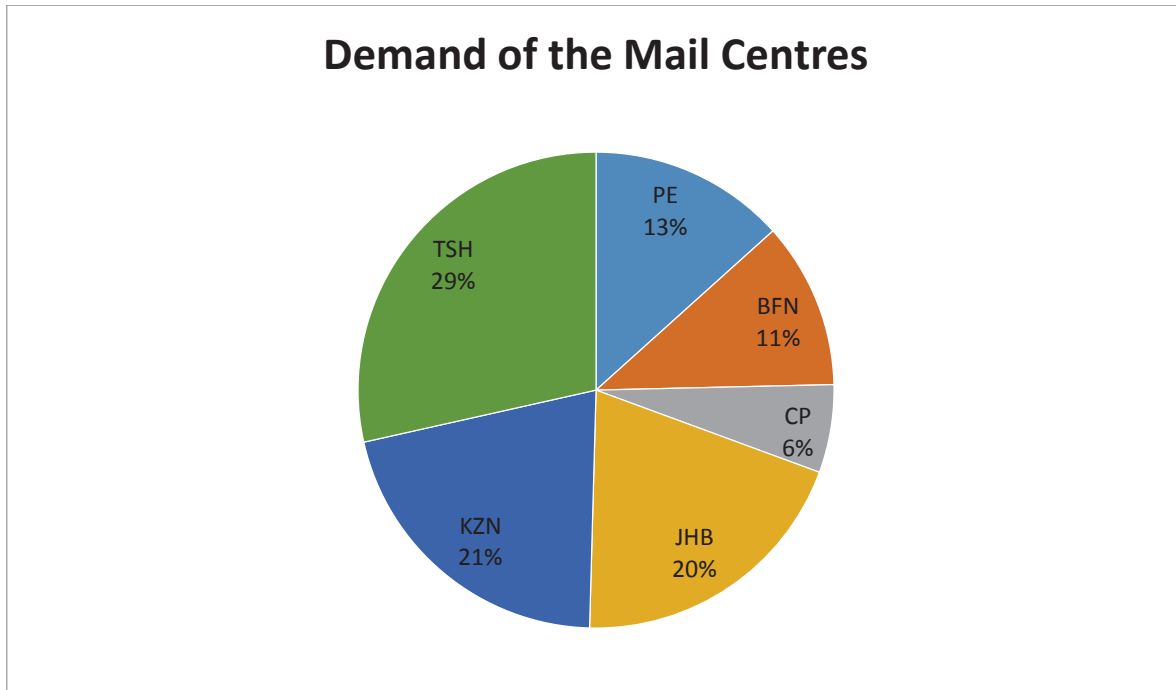


Figure 8 : The total demand of the specific Mail Centres

4.2. The geographic location of the facilities

The location of the Mail Centre’s could not be provided because the facilities contain valuable commodities of customers, therefore a landscape of or place next to the facilities were provided by the SAPO management team. The nearest airports to the landscapes provided were used to obtain the airports used. The information of the rail network was received from Feleza H(2015) from Prasa. Table 17, Table 18 and Table 19 in the appendices respectively shows the addresses of the Mail Centre’s, the location and names of the airports nearest to the Mail Centre’s and lastly the railway stations used for the different Mail Centre’s. As shown in Table 18 and Table 19 in the appendices, Tshwane and Johannesburg share the same railway station and airport.

4.3. Air transportation maximum capacity

The air transportation must have a maximum capacity of three tonne. This is converted to letter by multiplying 3 tonnes by conversion factors (1 tonne/ 1000 Kg) and (1 Kg/ 81 Letters). This

results in a maximum capacity of 243000 letters that can be transported in the air transportation between the Mail Centre's.

4.4. The distance, time and cost of traveling between facilities

The distance and time between the locations was determined using Google Map. The routes that were chosen were the routes that require the least amount of time and least distance between the locations. Distance is required to help compute the cost associated with traveling between Mail Centres.

4.4.1. Road transportation

The distance matrix in kilometer (Km) and time matrix in minutes (min) between the Mail Centre's are computed and shown in Table 2 and Table 3 below respectively. The units of the cost function for the model must be expressed in (R/letters), but currently the cost is expressed in (R/Km Kg). The conversion from Kg to letter is (1Kg/81 Letters). The average cost of travelling within the road network is R 0.007/Km-Kg and obtained from the SAPO management team. The conversion factor (1Kg/81 Letters), the average cost R 0.007/Km-Kg and the distance in Table 2 are multiplied to obtain the cost matrix in (R/Letters) values shown in Table 4.

Table 2 : The distance matrix (Km) of the road transportation between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	675	754	1060	918	1125
BFN	675	-	1000	388	636	454
CP	754	1000	-	1386	1634	1451
JHB	1060	388	1386	-	576	61
KZN	918	636	1634	576	-	617
TSH	1125	454	1451	61	617	-

Table 3 : The road transport time matrix (min) between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	393	469	591	617	624
BFN	393	-	567	211	382	245
CP	469	567	-	773	933	807
JHB	591	211	773	-	326	41
KZN	617	382	933	326	-	349
TSH	624	245	807	41	349	-

Table 4 : The cost matrix (R/Letters) of the road transport between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	R 0.0583	-	-	R 0.0793	-
BFN	R 0.0583	-	R 0.0864	R 0.0335	R 0.0550	R 0.0392
CP	-	R 0.0864	-	R 0.1198	R 0.1412	R 0.1254
JHB	-	R 0.0335	R 0.1198	-	R 0.0498	R 0.0053
KZN	R 0.0793	R 0.0550	R 0.1412	R 0.0498	-	R 0.0533
TSH	-	R 0.0392	R 0.1254	R 0.0053	R 0.0533	-

4.4.2. Rail transportation

Moving letters by rail requires an intermodal transportation solution, where mail is transported from the origin Mail Centre to its railway station, then transported by rail to the rail station of the destination Mail Centre, then moved again by road to the destination Mail Centre. The distance and time from the Mail Centre's to the rail stations by the road transportation are calculated and shown in Table 21 in the appendices. The distance from one railway station to another is summed with the values in Table 21 in the appendices to obtain Table 5. The time it takes from one rail station to the other is calculated from the schedule received from Feleza H(2015) from Prasa in Table 23 in the appendices.

The total time it takes for the road-rail intermodal transportation is the sum of values in Table 21 in the appendices and calculated values from the schedule in Table 23 in the appendices, to obtain the Table 6 below. The total cost matrix in (R/ Letters) shown in Table 7 below is obtained for each origin-destination pair the sum of the road and rail component. The road components distance in Table 21 in the appendices is multiplied by the conversion factor

(1Kg/81 Letters) and the average cost R 0.007/Km-Kg to get the cost in (R/Letters), and the rail component cost in (R/ 12 Kg Bags) found in Figure 16 in the appendices with the units (R/Kg) is multiplied by the conversion factor (1Kg/81 Letters) to get the cost in (R/Letters).

Table 5 : The distance matrix (Km) of the rail transportation between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	688.2	-	-	956.2	-
BFN	688.2	-	1024.1	460.4	673.2	478.6
CP	-	1024.1	-	1462.3	1674.1	1480.5
JHB	-	460.4	1462.3	-	636.4	-
KZN	956.2	673.2	1674.1	636.4	-	654.6
TSH	-	478.6	1480.5	-	654.6	-

Table 6 : The rail transport time matrix (min) between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	824	-	-	-	-
BFN	824	-	-	437	-	480
CP	-	-	-	894	-	937
JHB	-	437	894	-	888	-
KZN	-	-	-	888	-	931
TSH	-	480	937	-	931	-

Table 7 : The cost matrix (R/Letters) of the rail transport between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	R 0.0535	-	-	-	-
BFN	R 0.0535	-	-	R 0.0401	-	R 0.0401
CP	-	-	-	R 0.0802	-	R 0.0802
JHB	-	R 0.0401	R 0.0802	-	R 0.0535	-
KZN	-	-	-	R 0.0535	-	R 0.0535
TSH	-	R 0.0401	R 0.0802	-	R 0.0535	-

4.4.3. Air transportation

Transporting letters by air also consist of an intermodal transportation solution, where mail is transported from the origin Mail Centre to its airport, then transported by air to the airport of the

destination Mail Centre, then moved again by road to the destination Mail Centre. The distance and time from the Mail Centre to the airports by the road transportation are calculated and shown in Table 22 in the appendices. The distance values in Table 22 in the appendices plus the distance between the airports is computed, to result in Table 8 below showing the total distance between MC through the rail transportation.

The time taken between the airports is obtained in Table 24 in the appendices. The total time it takes for the road-air intermodal network is shown in Table 9 below and is the sum of values in Table 22 in the appendices and values from Table 24 in the appendices for the origin-destination pairs.

The total cost matrix in (R/ Letters) shown in Table 10 below is obtained for each origin-destination pair the sum of the road and airline component. The road components distance in Table 22 in the appendices is multiplied by the conversion factor (1Kg/81 Letters) and the average cost R 0.007/Km-Kg to get the cost in (R/Letters). The airline cost component depends on the time the origin-destination pair flight takes. Table 20 in the appendices provides the cost for the different ranges of flight time and the information was obtained from the SAPO management team. The flight time for the origin-destination pair from Table 24 in the appendices is compared to the ranges to charge the flight. The cost obtained is in (R/ Kg). The cost is multiplied by the conversion factor (1Kg/81 Letters) to convert the cost to (R/ Letters).

Table 8 : The distance matrix (Km) of the air transportation between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	688.2	-	-	956.2	-
BFN	688.2	-	1024.1	460.4	673.2	478.6
CP	-	1024.1	-	1462.3	1674.1	1480.5
JHB	-	460.4	1462.3	-	636.4	-
KZN	956.2	673.2	1674.1	636.4	-	654.6
TSH	-	478.6	1480.5	-	654.6	-

Table 9 : The air transport time matrix (min) between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	261	101	125	91	142
BFN	261	-	124	98	74	115
CP	101	124	-	173	144	190
JHB	122	98	173	-	108	-
KZN	91	74	144	108	-	125
TSH	121	115	190	-	125	-

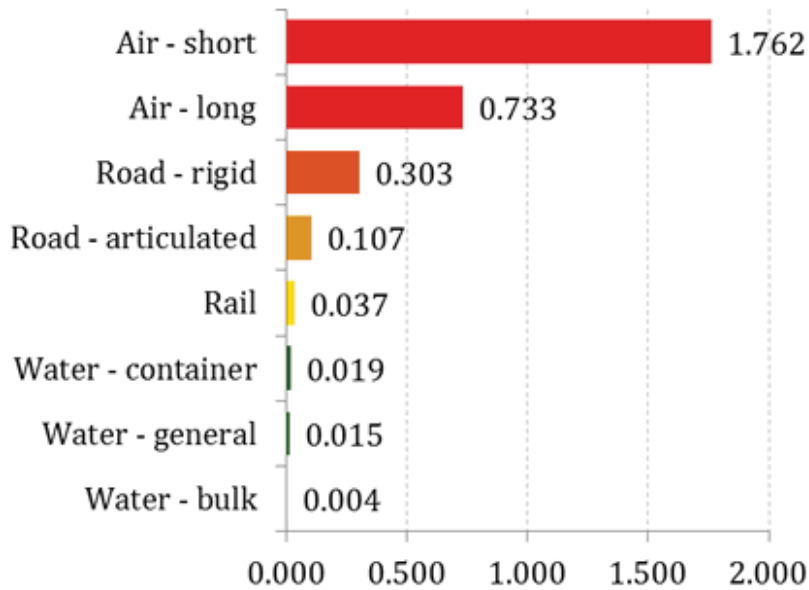
Table 10 : The cost matrix (R/Letters) of the air transport between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	R 0.1481	-	-	R 0.0741	-
BFN	R 0.1481	-	R 0.1111	R 0.0741	R 0.0741	R 0.0741
CP	-	R 0.1111	-	R 0.1111	R 0.1111	R 0.1111
JHB	-	R 0.0741	R 0.1111	-	R 0.0741	-
KZN	R 0.0741	R 0.0741	R 0.1111	R 0.0741	-	R 0.0741
TSH	-	R 0.0741	R 0.1111	-	R 0.0741	-

4.5. Carbon dioxide emission by the transport modes between the Mail Centres

The carbon emission for each transportation mode is taken from Figure 9 below. In the figure the carbon emission is given in (Kg/ tonne-Km). Road-rigid (0.303), air short (1.762) as all the distances are lesser than 3700 Km and rail (0.037) are used as (Kg/ tonne-Km) values. For each origin-destination pair, the values are multiplied by the respective total distance (Table 2, Table 5, and Table 8). This results in the carbon emission (Kg/ tonne), which are then multiplied by conversion factors of (1 tonne/ 1000 Kg) and (1Kg/81 Letters) result in the following tables below:

Freight Transport Emissions: kg CO₂e/t.km



Note: All figures are kilograms carbon dioxide equivalents per tonne kilometre (kg CO₂e/t.km). Figures based on a well-to-wheels analysis of fuel used and average loading per vehicle. For air freight long is greater than 3,700 km while short is less than it, no RFI multiplier is used. Road vehicles are based on UK diesel truck averages. Rail based on UK diesel and electric trains. All water vessels are ships, not ferries.

Sources: DEFRA



Figure 9 : Carbon dioxide emission by transportation mode (Anon., 2014)

Table 11 : The carbon emission (Kg CO₂e/letter) for the road transportation between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	0.0025	0.0028	0.0040	0.0034	0.0042
BFN	0.0025	-	0.0037	0.0015	0.0024	0.0017
CP	0.0028	0.0037	-	0.0052	0.0061	0.0054
JHB	0.0040	0.0015	0.0052	-	0.0022	0.0002
KZN	0.0034	0.0024	0.0061	0.0022	-	0.0023
TSH	0.0042	0.0017	0.0054	0.0002	0.0023	-

Table 12 : The carbon emission (Kg CO₂e/letter) for the rail transportation between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	0.0003	-	-	-	-
BFN	0.0003	-	-	0.0002	-	0.0002
CP	-	-	-	0.0007	-	0.0007
JHB	-	0.0002	0.0007	-	0.0003	-
KZN	-	-	-	0.0003	-	0.0003
TSH	-	0.0002	0.0007	-	0.0003	-

Table 13 : The carbon emission (Kg CO₂e/letter) for the air transportation between the Mail Centres

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	0.0150	-	-	0.0208	-
BFN	0.0150	-	0.0223	0.0100	0.0146	0.0104
CP	-	0.0223	-	0.0318	0.0364	0.0322
JHB	-	0.0100	0.0318	-	0.0138	-
KZN	0.0208	0.0146	0.0364	0.0138	-	0.0142
TSH	-	0.0104	0.0322	-	0.0142	-

5. Solutions

The data obtained in the previous chapter was used as input to solve the formulated multi objective of SAPO’s problem in section three. To help validate the solution of the preferred solution an As-is scenario is modeled. Another two proposed solutions are modelled. This chapter will provide the results of all the models and select the preferred solution.

5.1. As-Is scenario

Figure 10 illustrate the current situation at SAPO where all the mails is delivered by road transportation between the MC using the routes that are show in the legend.

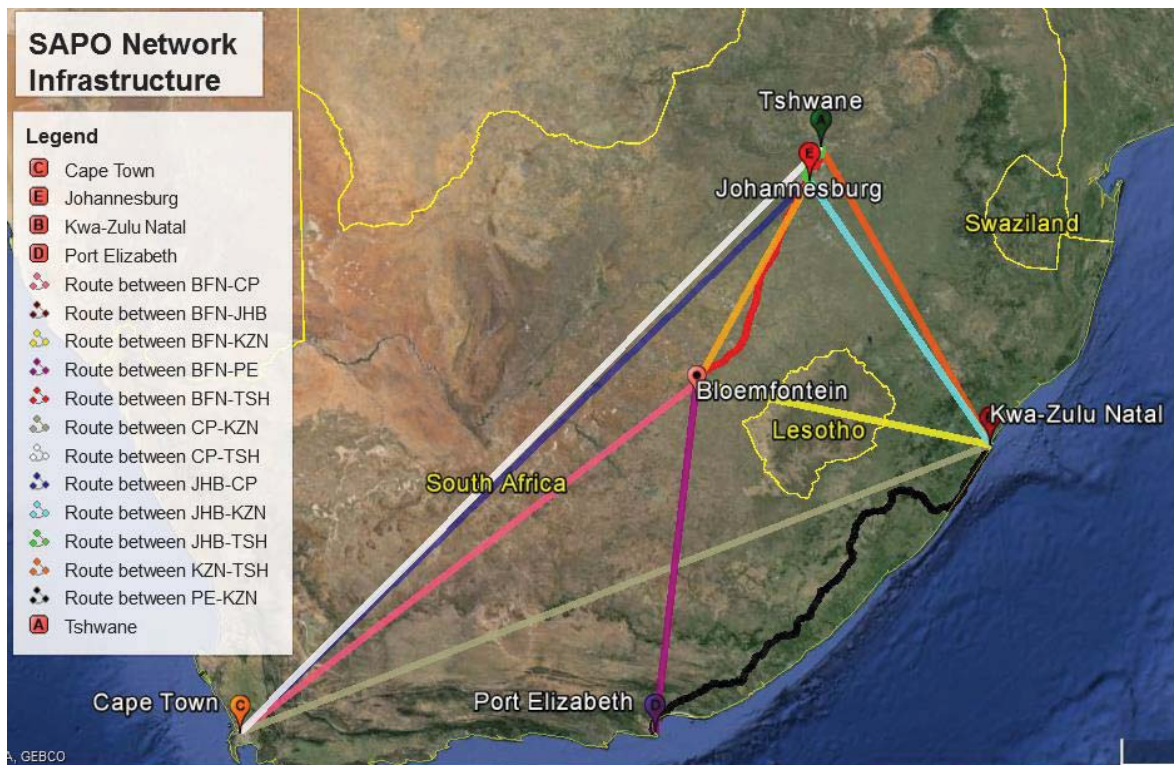


Figure 10 : The SAPO Network infrastructure of the road transportation

This current scenario results in a mixed integer linear program having the following multi objective national transportation solution per delivery cycle of three days; the total cost of R3 905 227, with all the trucks combined taking 188.13 hours (11 288 minutes) of operational

time and the whole road network having a carbon emission of 73.2 grams/letter. This model provides a baseline to compare the proposed models and to evaluate if they produce any savings.

5.2. Model 1

Model 1 is the first proposed solution which is the results of the formulated model in Section 3 without forcing it to select any transportation mode. This model results in a mixed integer linear program having the following multi objective national transportation solution per delivery cycle of three days; the total cost of R3 338 183, with all the mode selected combined taking 218.7 hours (13 122 minutes) of operational time and the whole transport network selected by the model having a carbon emission of 173.8 grams/letter. Figure 11 below shows the resulting volume of letters and the mode of transportation that is selected by model 1, while Figure 12 shows the mode distribution by the number of letters that model 1 result in.

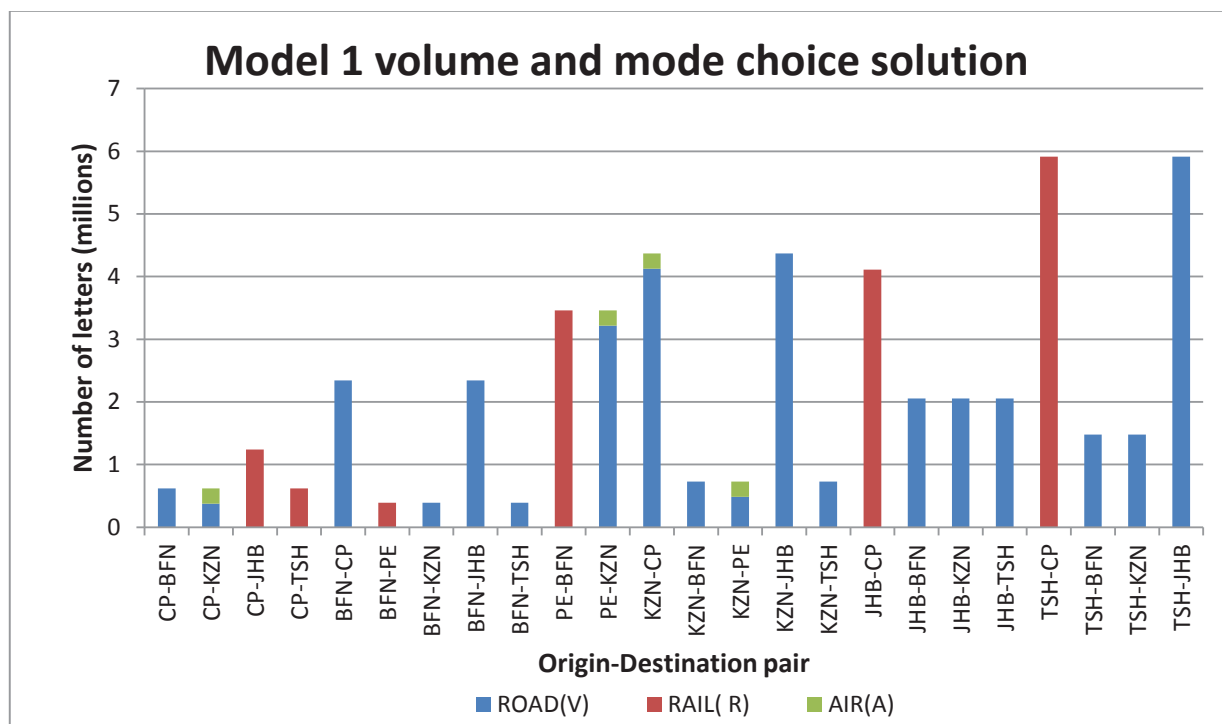


Figure 11 : Model 1 mode transportation and volume between the Mail Centres

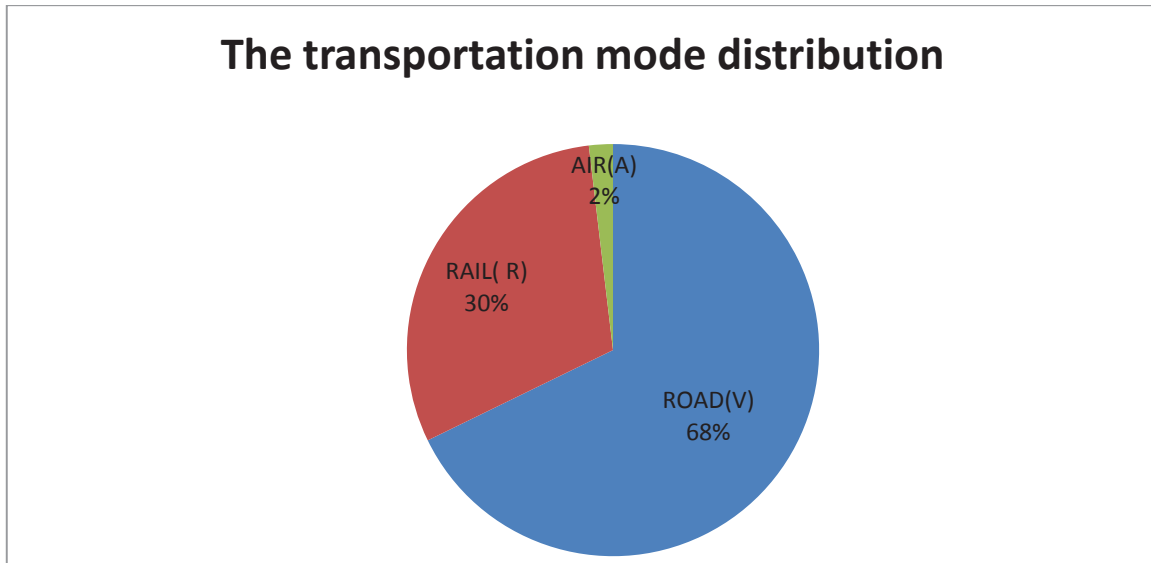


Figure 12 : The transportation mode distribution of model 1

5.3. Model 2

Tshwane and Johannesburg share the same railway station and airport. This model proposes a change in the transport infrastructure where instead Cape Town, Bloemfontein and Kwa-Zulu Natal sends Tshwane's mail volume to Johannesburg and Johannesburg sends all the demand of Tshwane. Furthermore Tshwane will send all its demand of the other MC to Johannesburg and Johannesburg will distribute it. Figure 13 below shows the network infrastructure discussed above. This model results in a mixed integer linear program having the following multi objective national transportation solution per delivery cycle of three days; the total cost of R3 377 722, with all the mode selected combined taking 167.7 hours (10 060 minutes) of operational time and the whole transport network selected by the model having a carbon emission of 158 grams/letter. Figure 14 shows the mode distribution by the number of letters that model 2 results in, while Figure 15 below shows the resulting volume of letters and the mode of transportation that selected by model 2.

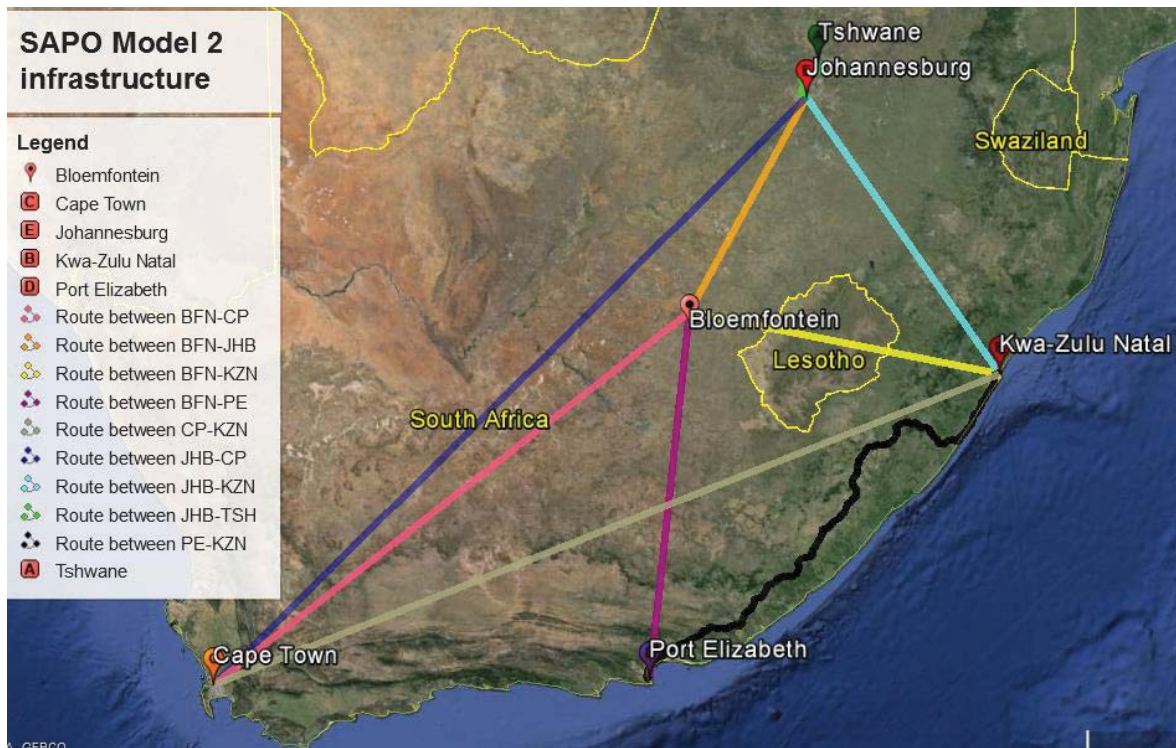


Figure 13 : The SAPO Network infrastructure of model 2

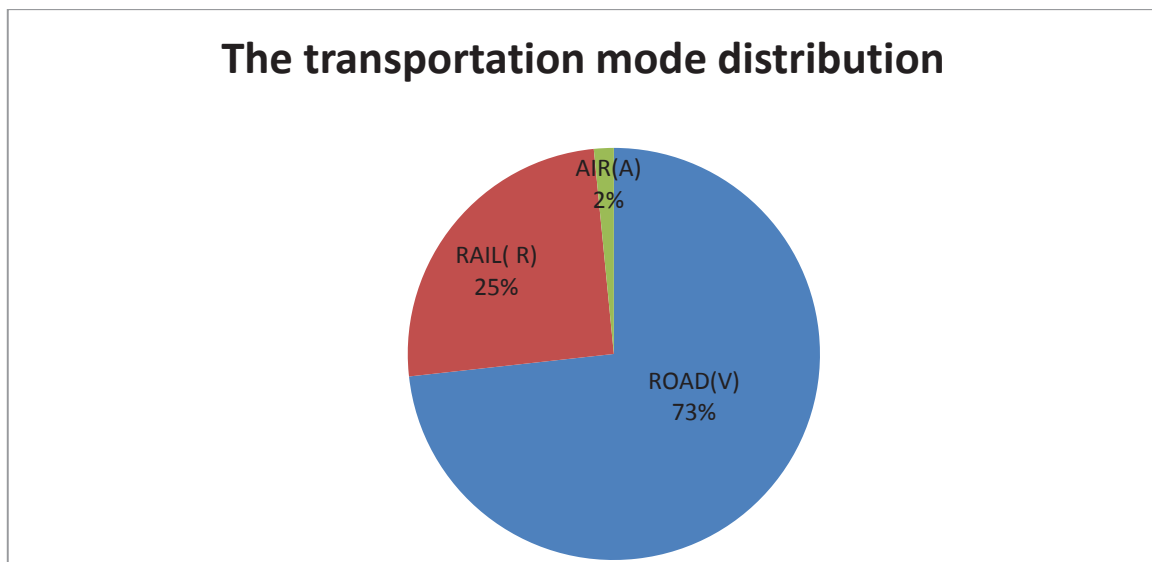


Figure 14 : The transportation mode distribution of model 2

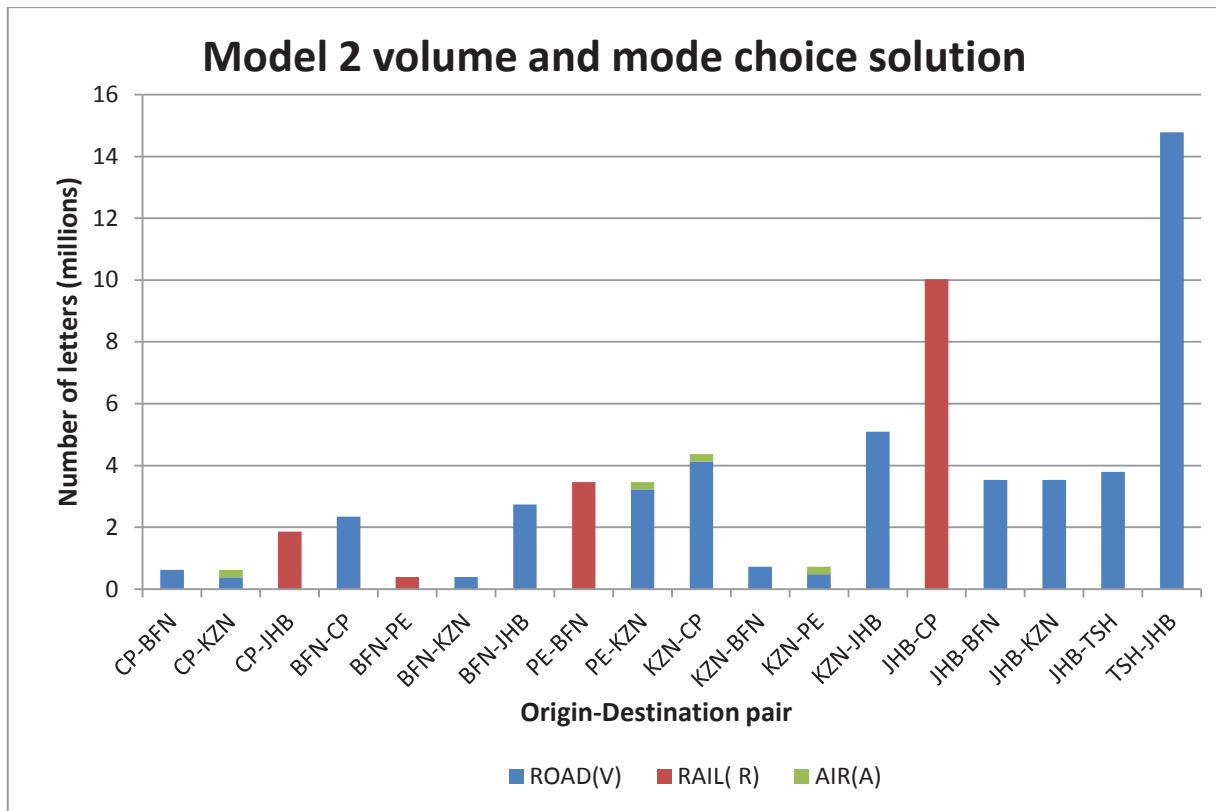


Figure 15 : Model 2 mode transportation and volume between the Mail Centres

5.4. Preferred solution

Model 1 provides the following results compared to the As-Is scenario (baseline model).

- I. An economic saving of R69 179 368 per year
- II. Although the operation time and total carbon emission is over by 3729.13 hours (223 748 minutes) and 12.27 Kg/letter respectively in a year.

Model 2 provides the following results compared to the As-Is scenario.

- I. An economic saving of R64 355 610 per year and operation time saving of 2 496.93 hours (149 816 minutes) per year.
- II. Although the total carbon emission is over by 10.36 Kg/letter per year.

Both model 1 and 2 provide economic saving but model 2 also provide operational time. Model 2 provides R 4 823 758 better economic saving in a year than model 1. Model two also provides operation time saving whereas model 1 does not. Both models have more total carbon emission than the baseline model. Due to the nature of multiple objective model 2 can optimize both cost and operational time than model 1, therefore making model 2 the preferred model solution.

6. Solution Validation

To validate the solution of the model formulated for the SAPO's problem in Section 3, the multi objective model is removed to only model a single economic objective. The single objective model is then forced to select the path volume flow to only be the road transportation, this yields the current situation at SAPO. The total transportation cost for the Logistics and Mail business units for the year 2014 was R747 353 000 (Post Office, 2014). This cost is multiplied by 85 percent as the Mail business unit utilizes 80 percent of the total transportation cost. The result is further multiplied by 75 percent to separate the national transportation to the total transportation (national and regional). This results in the national transportation of R476 437 537.5 per year. Each delivery cycle takes three days and there are 122 delivery cycle in a year. The total national transportation cost for 2014 is divided by the total number of delivery cycles to obtain the cost of R3905225.7 per delivery cycle.

The cost per delivery cycle is compared to the cost R3 738 946 per delivery cycle that the formulated model before adjustment obtained. This yields a difference of R166 279.7 that is relatively low. This difference is due to the estimated data. The solution of the model is validated as the model is a good representation of the current situation at SAPO. To better compare the proposed solution model 2 to the current situation, the model formulated for the SAPO's problem in Section 3 is adjusted by multiplying the economic objective of equation (17) by a factor 1.0444727. This eliminates the data error caused by the estimates resulting in the model formulated to provide the national transportation cost of R3 905 225.7 per delivery cycle instead of the cost R3 738 946 per delivery cycle previously obtained. The rest of the chapter will consist of a sensitivity analysis of the model formulated and validation of the preferred solution model 2 to the project deliverables.

6.1. Sensitivity analysis

Sensitivity analysis is performed to ensure the robustness of the solution from the model formulated. The analysis provides the effects of changing certain input parameters and checking the robustness of the solution with the effected change. This analysis will highlight weaknesses within the model formulated or will confirm the robustness of the formulated model. The

parameters that are of interest include; the cost associated with travelling in different transportation mode between the MC, the demand that has to be transported between the MC and the maximum capacity of letters that the air transportation can move at once. The effect that is of most important is checking how the change in the parameters changes the way mail is transported through the different transportation modes (mode selection of the model).

From the formulated model in Section 3, it can be seen that the cost objective function is the only objective that is depended on the variable H_{ijm} which is the volume of mail moved and the transportation mode it is moved in between the MC. The environmental and operation time objective will only change if the transportation mode distribution changes. Therefore the economic objective will be considered first to check if there is change in the distribution and if so the effect on the operation time and environment objective will be considered. Table 14 below shows the results obtained from the sensitivity analysis, it confirms the models robustness as there is no effect in the parameters that changes the mode selection of the solution but the change in the parameters only increase the demand volume of the already selected transportation modes. This results in all the changes having the same environmental and operation total time objective values obtained in model 1 in the previous Section. The economic objective function increase and decrease with the respective changes.

Table 14 : Sensitivity analysis on the SAPO's problem

Change	Objective function	Effect to transportation mode selection
No change	R3 377 722	No effect
2 x travelling cost	R6 676 366	No effect
0.5 x travelling cost	R1 669 091	No effect
2 x demand volume between MC	R6 694 284	no effect to mode selection but every volume of the road/rail transportation increase by the increased demand but air transportation remains constant

Change	Objective function	Effect to transportation mode selection
0.5 x demand volume between MC	R1 673 571	no effect to mode selection but every volume of the road/rail transportation decreased by the reduced demand but air transportation remains constant
2 x air transportation capacity	R3 320 264	no effect to mode selection but where air transportation exist its demand is its maximum capacity and the remaining demand is the road transportation
0.5 x air transportation capacity	R3 347 142	no effect to mode selection but where air transportation exist its demand is its maximum capacity and the remaining demand is the road transportation

6.2. Validating the preferred solution to the project deliverables

The models formulated investigates if the current system in use is cost effective and provides a preferred solution of model 2 that ensures the triple-bottom-line reporting where economic, environmental and operational performances are considered to measure success. The model provides savings on two of the three objective's function with the most important cost being optimized the most. With the introduction of using other modes of transportation and not road alone, the solution also provides a reduction of 27 percent of trucks on the road, reducing traffic conjunction in the main road of the South African road network. The model further answers the question that the SAPO's transportation manager asked on which transportation mode should be used between the MC and the distribution of the number of letters between them. The models ensured that the solution is within the given constraints of time and all the demand between the MC is delivered.

7. Conclusion

Transportation cost constitutes majority of the logistics cost. Any opportunity in reducing this cost must be investigated. This project provides an opportunity for the Post Office to investigate whether transportation cost can be reduced. The literature and problem investigation favors the use of a mathematical optimization models. Therefore this model solves the problem using multiple objective mixed integer programming. The solution proposed is to move all of Tshwane's demand through Johannesburg, as already Tshwane uses the airport and rail station that is within the Johannesburg area. This model provides a cost saving of R64 355 610 per year and operation time saving of 2 496.93 hours (149 816 minutes) per year. For the implementation of this solution the South African Post Office must investigate the model assumptions that are made that include the flights and trains, which are always readily available. Future work to this project includes The South African Post Office acquiring more accurate actual input data as most of the data were estimates of the actual data.

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9. Appendices

9.1. Tables and Figures

9.1.1. Demand Tables

Table 15: Mid-year population estimates by province, 2015 (Stats SA, 2015)

	Population estimate	% of total population
Eastern Cape	6 916 200	12,6
Free State	2 817 900	5,1
Gauteng	13 200 300	24,0
KwaZulu-Natal	10 919 100	19,9
Limpopo	5 726 800	10,4
Mpumalanga	4 283 900	7,8
Northern Cape	1 185 600	2,2
North West	3 707 000	6,7
Western Cape	6 200 100	11,3
Total	54 956 900	100,0

Table 16 : The demand matrix (number of letter)

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	3458100	-	-	3458100	-
BFN	390467	-	2342800	2342800	390467	390467
CP	-	620010	-	1240020	620010	620010
JHB	-	2055762	4111525	-	2055762	2055762
KZN	727940	727940	4367640	4367640	-	727940
TSH	-	1478569	5914275	5914275	1478569	-

9.1.2. Location Tables

Table 17 : The location address of the Mail Centres

Location	Locations Name
BFN	Kruger Ave, Bloemfontein, 9323
JHB	Reynolds St, Johannesburg South, 2091
PE	The Boardwalk Hotel and Casino, Marine Drive, Port Elizabeth, 6019, South Africa
CP	GrandWest Casino and Entertainment World, 1 Vanguard drive, Cape Town, 7460, South Africa
KZN	Moses Mabhida Stadium, Isaiah Ntshangase Road, Durban
TSH	Kgosi Mampuru II Management Area Dog Unit, Balsaminie Street, Pretoria, 0183, South Africa

Table 18 : The location of the airport in each Mail Centres region

Location	Airports Location
BFN	Bloemfontein Airport, Bloemfontein, 9300
JHB	O.R. Tambo International Airport, O R Tambo Airport Rd, Johannesburg, 1627
PE	Port Elizabeth International Airport, Allister Miller Dr, Port Elizabeth, 6070, South Africa
CP	Cape Town International Airport, Cape Town, 7490, South Africa
KZN	King Shaka International Airport, k e, 15 K E Masinga Road, Durban, 4063, South Africa
TSH	O.R. Tambo International Airport, O R Tambo Airport Rd, Johannesburg, 1627, South Africa

Table 19 : The location of the train stations in each Mail Centres region

Location	Rail station Location
BFN	Linquinda Street, Bloemfontein, 9301
JHB	Harrison St & Leyds St, Johannesburg, 2000
PE	Settlers Hwy, Port Elizabeth
CP	South African Railways / Shosholozza Meyl Bookings, Adderley Street, Cape Town City
KZN	Durban Station
TSH	Harrison St & Leyds St, Johannesburg, 2000

9.1.3. Time, Distance and Cost Tables and Figure

Table 20 : The cost per range that the airline charges

MIN	R/Kg
0-80	6
80-160	9
160-MORE	12

Table 21 : The distance (Km) and time (Min) from Mail Centres to railway Stations

Location	Distance(KM)	Time(MIN)
JHB-JHB	8.9	13.0
PE-PE	7.9	9.0
CP-CP	16.4	25.0
BFN-BFN	6.7	9.0
KZN-KZN	2.6	5.0
TSH-TSH	55.8	56.0

Table 22 : The distance (Km) and time (Min) from Mail Centres to Airports

Location	Distance(KM)	Time(MIN)
JHB-JHB	30.3	36
PE-PE	6.1	9
CP-CP	12	17
BFN-BFN	5.1	7
KZN-KZN	4.1	7
TSH-TSH	48.5	53

Table 23 : The time between rail stations and the frequency of use

FROM	TO	DEP. TIME	ARR. TIME	FREQUENCY
Port Elizabeth	Bloemfontein	15H00	04h26	Wednesdays, Fridays & Sundays
Bloemfontein	Port Elizabeth	20h30	09h15	Wednesdays, Fridays & Sundays
Port Elizabeth	Johannesburg	15h00	11h35	Wednesdays, Fridays & Sundays
Johannesburg	Durban	18h40	09h10	Fridays & Sundays
Cape Town	Johannesburg	10h00	12h16	Wednesdays, Thursdays, Fridays, Sundays
Johannesburg	Bloemfontein	13h15	20h10	Wednesdays, Fridays & Sundays
Durban	Johannesburg	19h15	09h35	Fridays & Sundays

The bags weight 12 kg each. On average the following bags have to be moved.

3558 bags have to move from Port Elizabeth to Bloemfontein;
 402 bags have to move from Bloemfontein to Port Elizabeth;
 3558 bags have to move from Port Elizabeth to Kwa-Zulu Natal;(JHB)
 3558 bags have to move from Johannesburg to Durban (Kwa-Zulu Natal)
 749 bags have to move from Kwa-Zulu Natal to Port Elizabeth;
 638 bags have to move from Cape Town to Bloemfontein;
 2410 bags have to move from Bloemfontein to Cape Town;
 1276 bags have to move from Cape Town to Johannesburg;
 4230 bags have to move from Johannesburg to Cape Town;
 638 bags have to move from Cape Town to Tshwane;(JHB)
 6085 bags have to move from Tshwane (JHB) to Cape Town;
 749 bags have to move from Kwa-Zulu Natal (Durban) to Bloemfontein;
 402 bags have to move from Bloemfontein to (Durban)Kwa-Zulu Natal;
 4494 bags have to move from Kwa-Zulu Natal (Durban) to Johannesburg;
 2115 bags have to move from Johannesburg to Kwa-Zulu Natal;
 749 bags have to move from Kwa-Zulu Natal to Tshwane (JHB);
 3042 bags have to move from Tshwane (JHB) to Kwa-Zulu Natal (Durban);
 638 bags have to move from Cape Town to Kwa-Zulu Natal;
 4494 bags have to move from Kwa-Zulu Natal to Cape Town;
 2115 bags have to move from Johannesburg to Tshwane;
 3042 bags have to move from Tshwane to Johannesburg;
 2115 bags have to move from Johannesburg to Bloemfontein;
 2410 bags have to move from Bloemfontein to Johannesburg;
 3042 bags have to move from Tshwane to Bloemfontein;
 402 bags have to move from Bloemfontein to Tshwane (JHB);

@ R52.00 per bag = R185 016.00
 @ R52.99 per bag = R20 904.00
 @ R78.00 per bag = R277524.00
 @ R52.00 per bag = R185016.00
 @ R130.00 per bag = R97370.00
 @ R117.00 per bag = R74646.00
 @R117.00 per bag = R281970.00
 @R78.00 per bag = R99528.00
 @R78.00 per bag = R329940.00
 @R78.00 per bag = R49764.00
 @ R78.00 per bag = R474630.00
 @ R91.00 per bag = R68159.00
 @ R91.00 per bag = R36 582.00
 @ R52.00 per bag = R233688.00
 @ R52.00 per bag = R109980.00
 @ R52.00 per bag = R38948.00
 @ R52.00 per bag = 158184.00
 @ R130 per bag = R82940.00
 @ R130.00 per bag = R584220.00
 @
 @
 @ R39.00 per bag = R82485.00
 @ R39.00 per bag = R93990.00
 @ R39.00 per bag = R118638.00
 @ R39.00 per bag = R15678.00

Figure 16 : The cost(R/ 12 Kg) to move mail through the railway within the rail stations

Table 24 : The time matrix (min) between the airports

TO \ FROM	PE	BFN	CP	JHB	KZN	TSH
PE	-	245	75	80	75	80
BFN	245	-	100	55	60	55
CP	75	100	-	120	120	120
JHB	80	55	120	-	65	-
KZN	75	60	120	65	-	65
TSH	80	55	120	-	65	-

9.2. Glossary of models variables

Sets

- N – the set of Nodes, where $N = 1, \dots, 6$.
- M – all the possible modes that can be used, within a specific origin-destination (i, j) pairs where $M = 1, \dots, 3$.
- A – an arc link that only permits flow of one type of traffic where $A = 1, \dots, 72$.
- P – the set of origin-destination (i, j) pairs where $P = 1, \dots, 24$.
- K – the set of all paths, where $K = 1, \dots, 24$.
- K_p – the set of paths for origin-destination (i, j) pair $p \in P$, where $K_p = 1, \dots, 3$.
- $m(c)$ – the set of modes, that product $c \in C$ can take, within a specific (origin-destination) trip
- $K_{od}^{m(c)}$ – the set paths that product $c \in C$ can take from origin $o \in N$ to destination $d \in N$, using only mode $m(c)$.
- $g^{m(c)}$ – the demand matrix of product $c \in C$, where $m(c)$ is the mode choice subset.
- K^c – the set of all routes that may be used by product $c \in C$.
- T – when more than two modes are used, the location where the modes transfer from one mode to the other, where $T = 1, \dots, 10$.
- C – each product/commodity that is being transported, where $C = 1, 2$.
- Z – a single mode transportation where $Z = 1, \dots, 24$.
- Q – criteria, where $Q = 1, \dots, 4$ and 1 = Price, 2 = Time, 3 = Safety 4 = Accessibility.
- R – the modes available, where $R = A, B, C$
- No – the set of Nodes, where $N = 1, \dots, 6$.

Mo –all the possible modes that can be used, within a specific origin-destination (i, j) pairs where $Mo = V, R, A$, where V = road transportation, R = rail transportation, A = air transportation.

Pa_{ijm} –the sets of path flow between origin node $i \in No$ and destination node $j \in No$ using mode $m \in Mo$, where $Pa_{ijm} = 1, \dots, 72$.

Indices

i – the initial location(node) where the commodities are moved from where $i \in N$.

j – the location(node) where the commodities are going where $j \in N$.

OD – the link between origin node $i \in No$ and the destination node $j \in No$.

Parameters

$s_a(v)$ –the given cost functions of travelling on a link $a \in A$.

t_p –the demand between the origin-destination (i, j) pairs where $p \in P$.

Co_{ijm} –the cost in (R/letters) of travelling between origin node $i \in No$ and destination node $j \in No$ using transportation mode $m \in Mo$.

Tm_{ijm} –the time in (minutes) taken to travel between origin node $i \in No$ and destination node $j \in No$ using transportation mode $m \in Mo$.

D_{ij} –the demand in (number of letters) that has to be used between origin node $i \in No$ and destination node $j \in No$.

MT –the maximum time any trip can take.

L –the maximum load capacity for the air transportation.

$BIGM1$ – a large constant value that forces the time binary function to be zero or one when the is volume flow.

$BIGM1$ – a large constant value that forces the carbon emission binary function to be zero or one when the is volume flow.

Decision Variables

v_a – the link flow of the demand on the link a , where $a \in A$.

h_k – the flow on path k where $k \in K$.

F – the total cost of the whole system.

v_z^c – the flow of product $c \in C$ on the single mode transportation $z \in Z$.

v_t^c – the flow of product $c \in C$ on with intermodal transportation, through the transfer at location $t \in T$.

$s_z^c(v)$ – the volume of goods flow, moving on a single mode trip $z \in Z$.

$s_t^c(v)$ – the volume of goods flow, moving on an intermodal mode trip $t \in T$.

δ_{zk} – a binary variable that finds if a particular path is used or not on a single mode trip $z \in Z$.

δ_{tk} – a binary variable that finds if a particular path is used or not on a intermodal mode trip $t \in T$.

X_i – represents the weights of the mode choice criteria according to the surveys.

Y_{ji} – represents the distributed value of the mode choice criterion among the shipping modes.

H_{ijm} – the path flow volume in (letters) transported between origin node $i \in N_o$ and destination node $j \in N_o$ using transportation mode $m \in M_o$.

$B1_{ijm}$ – a time binary variable that is one when the is volume flow between origin node $i \in N_o$ and destination node $j \in N_o$ using transportation mode $m \in M_o$ and zero otherwise.

$B2_{ijm}$ — a carbon emission binary variable that is one when the is volume flow between origin node $i \in \mathbf{No}$ and destination node $j \in \mathbf{No}$ using transportation mode $m \in \mathbf{Mo}$ and zero otherwise.

9.3. Lingo Code

```

MODEL:
! THE LINGO CODE OF THE NETWORK EQUILIBRIUM TRANSPORTATION MODEL ;

SETS:

Modes/ V , R, A /; ! the modes of transportation available m e M where V = road, R = Rail,
A = Air;

Nodes/CP BFN PE KZN JHB TSH/; ! the nodes in the network i,j e N;

Paths( Nodes, Nodes); ! all links within the network;

ENDSETS

DATA:
! The network infrastructure of the problem;
Paths =
  CP BFN
  CP KZN
  CP JHB
  CP TSH
  BFN PE
  BFN KZN
  BFN JHB
  BFN TSH
  PE KZN
  KZN JHB
  KZN TSH
  JHB TSH
;
ENDDATA

SETS:
  Paths2( Nodes, Nodes) | @IN( Paths, &1, &2) #OR# @IN( Paths, &2, &1): D; !
  origin_destination pairs;

  Links( Paths2, Modes): H, S, T, B1, CO2, B2; ! One directional arcs that are available
  to link node i and j through mode m ;

  LinksToZero( Links);

!Function Variables;

!D - the given demand/flow in [letters] to flow between i and j where i= origin, j=
  destination and i,j e N;
!H - the amount in [letters] that flows from node i to node j using mode m, where i=
  origin, j=destination, m = modes
  and i,j e N and m e M;
!S - the given cost in [R/letters] of moving from i to j using mode m, where i=origin,
  j=destination, m=mode and
  i,j e N and m e M;
!T - the given time in [minutes]of moving from i to j using mode m, where i=origin,
  j=destination, m=mode and
  i,j e N and m e M;

ENDSETS

DATA:
  S =! road cost rail cost air cost;
!CP BFN; 0.0864, 0, 0.1111
!CP KZN; 0.1412, 0, 0.1111
!CP JHB; 0.1198, 0.0802, 0.1111
!CP TSH; 0.1254, 0.0802, 0.1111
!BFN CP; 0.0864, 0, 0.1111
!BFN PE; 0.0583, 0.0535, 0.1481
!BFN KZN; 0.0550, 0, 0.0741
!BFN JHB; 0.0335, 0.0401, 0.0741
!BFN TSH; 0.0392, 0.0401, 0.0741

```

```

!PE BFN; 0.0583, 0.0535, 0.1481
!PE KZN; 0.0793, 0, 0.0741
!KZN CP; 0.1412, 0, 0.1111
!KZN BFN; 0.0550, 0, 0.0741
!KZN PE; 0.0793, 0, 0.0741
!KZN JHB; 0.0498, 0.0535, 0.0741
!KZN TSH; 0.0533, 0.0535, 0.0741
!JHB CP; 0.1198, 0.0802, 0.1111
!JHB BFN; 0.0335, 0.0401, 0.0741
!JHB KZN; 0.0498, 0.0535, 0.0741
!JHB TSH; 0.0053, 0, 0
!TSH CP; 0.1254, 0.0802, 0.1111
!TSH BFN; 0.0392, 0.0401, 0.0741
!TSH KZN; 0.0533, 0.0535, 0.0741
!TSH JHB; 0.0053, 0, 0
;
T =! road cost rail cost air cost;
!CP BFN; 567, 0, 124
!CP KZN; 933, 0, 144
!CP JHB; 773, 894, 173
!CP TSH; 807, 937, 190
!BFN CP; 567, 0, 124
!BFN PE; 393, 824, 261
!BFN KZN; 382, 0, 74
!BFN JHB; 211, 437, 98
!BFN TSH; 245, 480, 115
!PE BFN; 393, 824, 261
!PE KZN; 617, 0, 91
!KZN CP; 933, 0, 144
!KZN BFN; 382, 0, 74
!KZN PE; 617, 0, 91
!KZN JHB; 326, 888, 108
!KZN TSH; 349, 931, 125
!JHB CP; 773, 894, 173
!JHB BFN; 211, 437, 98
!JHB KZN; 326, 888, 108
!JHB TSH; 41, 0, 0
!TSH CP; 807, 937, 190
!TSH BFN; 245, 480, 115
!TSH KZN; 349, 931, 125
!TSH JHB; 41, 0, 0
;
CO2 =! the carbon emission in kg/letter between the mail centres;
!CP BFN; 0.0037, 0, 0.0223
!CP KZN; 0.0061, 0, 0.0364
!CP JHB; 0.0052, 0.0007, 0.0318
!CP TSH; 0.0054, 0.007, 0.0322
!BFN CP; 0.0037, 0, 0.0223
!BFN PE; 0.0025, 0.003, 0.0150
!BFN KZN; 0.0024, 0, 0.0146
!BFN JHB; 0.0015, 0.0002, 0.0100
!BFN TSH; 0.0017, 0.0002, 0.0104
!PE BFN; 0.0025, 0.0003, 0.0150
!PE KZN; 0.0034, 0, 0.0208
!KZN CP; 0.0061, 0, 0.0364
!KZN BFN; 0.0024, 0, 0.0146
!KZN PE; 0.0034, 0, 0.0208
!KZN JHB; 0.0022, 0.0003, 0.0138
!KZN TSH; 0.0023, 0.0003, 0.0142
!JHB CP; 0.0052, 0.0007, 0.0318
!JHB BFN; 0.0015, 0.0002, 0.0100
!JHB KZN; 0.0022, 0.0003, 0.0138
!JHB TSH; 0.0002, 0, 0
!TSH CP; 0.0054, 0.0007, 0.0322
!TSH BFN; 0.0017, 0002, 0.0104
!TSH KZN; 0.0023, 0.0003, 0.0142
!TSH JHB; 0.0002, 0, 0
;

```

```

! the demand of letters that has to be moved between the origin_destination pairs;
D =
  620010,620010,1240020,620010,2342800,390467,390467,2342800,390467,3458100,3458100
  4367640,727940,727940,4367640,727940,4111525,2055762,2055762,2055762,5914275,1478569
  1478569,5914275
;
! Johannesburg and Tshwane share the same airport and therefore have no flow within and
the is
no link between some rail stations;
LinksToZero =
  KZN,PE, R
  PE,KZN, R
  CP,BFN, R
  BFN,CP, R
  BFN,KZN, R
  KZN,BFN, R
  CP,KZN, R
  KZN,CP, R
  JHB,TSH, R
  TSH,JHB, R
  JHB,TSH, A
  TSH, JHB, A;

L = 121500;
MT = 3600;
BIGM1 = 10e9 ;
BIGM2 = 10e9 ;
ENDDATA

SUBMODEL OBJ_COST:
MIN = TTL_COST;
ENDSUBMODEL

SUBMODEL OBJ_MIN_TOTAL_TIME:
MIN = TOTAL_TIME;
ENDSUBMODEL

SUBMODEL OBJ_TOTAL_CO2_EMISSION:
MIN = TOTAL_CO2;
ENDSUBMODEL

SUBMODEL BASE:
! The objective function of minimizing the total cost of the transportation system;
TTL_COST = @SUM( Links( I, J, M): 1.0444727*S( I, J, M) * H( I, J, M));

! the total time the national transportation takes;
TOTAL_TIME =
  @SUM( Paths2( I, J):
    @SUM( Modes( M): T( I, J, M) * B1( I, J, M)
  );
! the total carbon emission of the national transportation;
TOTAL_CO2 =
  @SUM( Paths2( I, J):
    @SUM( Modes( M): 1000*CO2( I, J, M) * B2( I, J, M)
  );
!Flow conservation-For each Origin-Destination pair, the volume moved on each path of the
different modes,
must equal the total demand required to be transported;
@FOR( Paths2( I, J):
  [R_DEMAND] @SUM( Modes( M): H( I, J, M) = D( I, J)
);
!Ensuring the deliveries are within the 1 day time limit;
@FOR( Paths2( I, J):
  @FOR(Modes (M) : T( I, J, M )<= MT));
! the links that dont have the rail and air infrastructure for the origin_destination
pair;
@FOR( LinksToZero( I, J, K): H( I, J, K) = 0);
!Capacity of the airline;

```

```

@FOR(Paths2( I, J) :
  @FOR( Modes( M) | M#EQ#@INDEX(Modes, A ) : H( I, J, M) <= L ));
!non negative constaints, for the volume flow between the provinces;
@FOR(Links(I, J, M) : @GIN( H( I, J, M) );
);
! ensures that when the is flow within a link, the binary integer for the link time is one
else 0;
@FOR( Paths2( I, J):
  @FOR(Modes (M) :
    H( I, J, M) <= BIGM1*B1( I, J, M);
    @BIN(B1( I, J, M));
  ));
@FOR( Paths2( I, J):
  @SUM(Modes (M) : B1( I, J, M ))<= 2);
! ensures that when the is flow within a link, the binary integer for the link co2 is one
else 0;
@FOR( Paths2( I, J):
  @FOR(Modes (M) :
    H( I, J, M) <= BIGM2*B2( I, J, M);
    @BIN(B2( I, J, M));
  ));
@FOR( Paths2( I, J):
  @SUM(Modes (M) : B2( I, J, M ))<= 2);
! boundaries ;
@BND( 0, TTL_COST, BNDU_COST);
@BND( 0,TOTAL_TIME, BNDU_TOTAL_TIME);
ENDSUBMODEL

CALC :

!Free up bounds;
BNDU_COST = 1.E10;
BNDU_TOTAL_TIME = 1.E10;

!Solve to minimize cost;
@SOLVE( OBJ_COST, BASE);
!Fix total cost to optimal value;
BNDU_COST = TTL_COST;

!Re-solve to minimize the total system time;
@SOLVE(OBJ_MIN_TOTAL_TIME , BASE);
!Fix total time to optimal level;
BNDU_TOTAL_TIME = TOTAL_TIME;

!Re-solve to minimize total carbon emission;
@SOLVE(OBJ_TOTAL_CO2_EMISSION , BASE);

ENDCALC

END

```