Chapter 1

Research problem

South Africa's level of urbanization closely follows international trends in developed countries, with the highest level of economic activity focused in a few metropolitan areas; attracting both people and investments. The good functioning of these metropolitan areas is of strategic importance to the country, as these areas are the main focus for economic and social development. The level of service of transport provided impacts directly on the efficiency and the quality of the development in the metropolitan areas. South African metropolitan areas are experiencing rapid growth, and are having difficulties in controlling the physical urban expansion. Both public and freight transport costs are negatively impacted by these phenomena. As demand for transport increases faster than the supply of these services, commuting and freight transportation costs increase at a rate higher than inflation. The community at large also experiences the higher expenses required to support demands for more extensive infrastructure and services.

1.1 Motivation for the project

South Africa provides a fascinating interface between the developed and the developing world. In a critical review, Leinbach and Stansfield [28] have emphasized that Industrial Engineers should re-adopt a systematic view. They argue that the perception of Industrial Engineers has been negatively impacted by their ability to model the obvious, and in the over-simplification of their models, to the extent that the reality is not represented comprehensively. Industrial engineers should therefor appreciate the complex and intertwined relationships between social, political, and economic factors influencing urban freight transport systems.

Freight carriers are sharing the road network with various modes of public transport. The use of private vehicles have rapidly increased. The increase can be attributed to both an increase in the number of trips undertaken, and increased journey lengths [5, 48]. Road network performance is negatively impacted by the higher usage of private vehicles and results in higher levels of congestion, and a significant reduction in operating speeds. Public transport performance is impacted negatively when operating speeds decrease, resulting in increased operating costs for the carriers, and thus impacting negatively on its attractiveness. As a result, the economically able part of the population turn to their private vehicles for a reliable source of transport, and unknowingly contributes to the hyper-congestion phenomenon.

The concept of *City logistics* has emerged to address a new area in transport planning. The objective of the concept is to support the sustainable development of cities and to address challenging problems such as high levels of traffic congestion, negative environmental impacts, high energy consumption and a shortage of trained labour. Taniguchi *et al.* [57] states that *City logistics* is the process of totally optimizing urban logistics activities by considering the social, environmental, economic, financial and energy impacts of urban freight movement. In an earlier article Taniguchi *et al* [55] emphasizes that the optimization drive is focussed on private shippers and carriers in a free market economy, although consideration is given to the costs and benefits for both the private and public stakeholders. Usually one or more of the following initiatives are included:

- *Advanced information systems* utilize the ever-increasing computational ability to analyze and rationalize existing logistics operations.
- *Co-operative freight transport systems* allow for a reduced number of vehicles in the system by means of load consolidation.
- *Public logistics terminals* are implemented with success in the northern hemisphere. These terminals are typically located on the outskirts of cities, and are helpful promoters of the co-operative transport systems mentioned previously.
- *Load factor controls* are also new initiatives where certificate systems are introduced for carriers. The concept has been successfully implemented for freight vehicles in parts of Europe. Service vehicles, such as telecommunication service providers, refuse removal, plumbing and electrical contractors, are dealt with ineffectively. Service vehicles transport *service providers*, as opposed to *freight*. The objective of service vehicles is to provide a reliable service, either on schedule, or when requested. Load factor controls, as a performance measure, are therefore ineffective. The load factor initiative aims to reduce the number of vehicles in congested central business districts by promoting load consolidation. This results in higher fleet utilization, and thus reducing the number of large freight vehicles with small loads.

- *Underground freight transport systems* are innovative, yet costly solutions for freight transport problems. Ooishi and Taniguchi [40] evaluate a proposed initiative in Tokyo, and conclude that the overall effects upon the society and the economy is positive.

It is important to quantify the consequences of such *City Logistics* initiatives as this will enhance the evaluation of the significance and benefits thereof, especially when designing new, or improving existing, urban infrastructure and freight transport activities. Models, representing the various stakeholders and their particular objectives, should be used to quantify the changes in logistics costs, traffic congestion, fleet utilization, hazardous gas emissions, accident occurrences, etc. of proposed initiatives.

1.2 Overview of the subject

The existing urban structures in South Africa have been brought about by apartheid policies over many generations. Spence [48] argues that the extent of the separation between people – black and white, rich and poor, advantaged and disadvantaged – and the resources and opportunities which they require, has produced urban conditions that are morally, socially, politically, and economically, unsustainable. The separation resulted in inequitable spatial development and economic structures that favored growth in existing well-resourced areas. More specifically, the urban land use disposition produced low-density residential development and urban sprawl with opportunities concentrated in the vicinities of the more affluent and privileged areas. Conversely, the majority of the population are settled in remote areas with few opportunities or social amenities. Lipman and Monaghan [30] elaborate on the spatial planning, indicating that the legacy from past spatial planning policies has resulted in long travel distances and insufficient residential densities for effective transport services. With the national transport policies under revision, a deliberate focus on transport is essential [34]. Transport in itself is a key factor in creating sustainable economic growth.

1.2.1 Stakeholders

Various key stakeholders participate in the economy and often have competing and egocentric objectives.

Residents

The community, or *residents*, are the people that live, work, shop, and entertain in the metropolitan areas. Their objectives include minimizing traffic congestion, noise, air pollution due to traffic, and traffic accidents. Residents do not welcome large freight carrying vehicles in residential areas [42]. Nevertheless, these carriers are required as residents have an expectation to

Table 1.1: Distances and average time spent in commuting in the main cities

	Distance between black township(s) & CBD (in kms)	**Average time spent in transport (minutes per journey)**
Johannesburg (bus \ train)	20.0	77
Johannesburg (taxi \ cars)	20.0	44
Pretoria	52.0	75
Durban	20.0	n.a.
Bloemfontein	58.4	86
Port Elizabeth	16.1	n.a.
East London	21.4	n.a.
Cape Town	18.8	65
Average	28.3	69

receive their commodities at convenience stores scattered all over residential areas. The South African transport system, from the residents' frame of reference, is a dual system. For the more affluent portion of the population the system imitates the American way of life with houses, malls, services and offices distributed abundantly, necessitating automobile use, as they are geographically dispersed. The malls are small, and do not offer the shopper a comprehensive range of products. This is in contrast with European models where cities have a central business district, offering the visitor a full range of products and services in a small area, accessible on foot, and in close proximity of a well-established public transport system. On the other hand, given the distorted spatial structure, a large portion of the urban population simply aspires to minimize their commuting expense and ensure their safety while commuting. Here the less affluent move through various modes, from on-foot transportation or bikes, to busses, minibus taxis, commuter trains, and to a lesser extent cars and trucks. Saint-Laurent [18] presents the distances and average time spent commuting by commuters in South-Africa in table 1.1.

Carriers

Carriers represent both public and private stakeholders executing the logistic and distribution functions. The *cargo* is not limited to freight, but also encompasses passengers in the form of public transport. Freight carriers are continuously expected to provide higher levels of service at lower rates, and therefor try to minimize their logistic costs, and maximize their profits.

Modes of public transport in South African urban areas are limited to *commuter trains* (9%), *busses* (16%), *minibus taxis* (24%), and *cars* (50%).

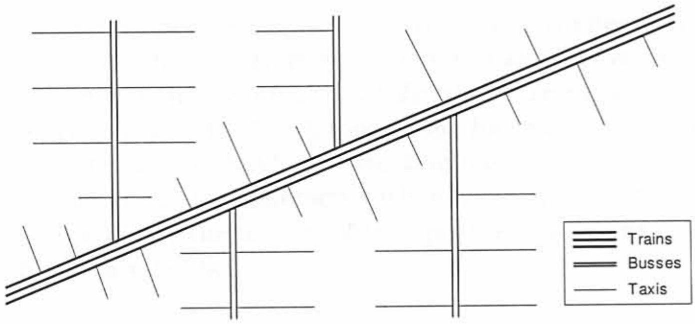

Figure 1.1: The ideal mode configuration

The values in brackets indicate the market share of each mode with respect to urban trips, based on the number of passengers multiplied by the distance travelled [18]. These different modes of public transport are often in competition for passengers. This is in contrast to the ideal of being cooperative and integrated. An ideal configuration would see trains forming the backbone of the network and supplying the major (primary) routes; busses on secondary routes, and taxis on local routes; feeding into primary and secondary routes, as is indicated in figure 1.1.

Shippers

Shippers are the customers of carriers, and often receive (or send) goods from (to) other shippers, or residents. Examples of shippers include manufacturing plants, wholesale and retail outlets, and mail centers. The objective of the shippers is to maximize their level of service, which can be a function of cost, reliability, and/or traceability. Shippers place requirements on carriers for specific collection and delivery times. These requirements are referred to as time windows.

Administrators

Administrators represent local, provincial, and national government whose objective is to resolve conflict between stakeholders involved in urban freight transport, while facilitating sustainable development of urban areas.

Transport authorities are responsible for planning, coordination, implementing, monitoring, funding and applying law-enforcement of land transport in provincial and local government spheres. Traffic densities and road construction costs are much higher in urban areas. Municipal resources for transport is also severely restricted due to issues such as housing, safety, and education that enjoy preference in the urbanized environment. Public transport has a better cost and space effectiveness for mass transportation.

Public-transport should therefor be considered a serious alternative in urban areas. Not only do administrators appreciate the alternative, but they also directed the focus of the *National Land Transport Transition Bill* towards public passenger transport [37] . Although the freight transport industry is largely deregulated in South Africa, attention has been given to freight operations in urban areas, as it interacts with other modes and traffic streams. Nothnagel [34] outlines the history of transport legislation as it progressed since South Africa's independence in 1994.

Regulation of urban freight transport is a powerful tool for improving the efficient use of transport networks and infrastructure. Numerous regulations have been implemented internationally [55], and include:

- Weight limits
- Load factor control
- Designated routes
- Zoning
- Time windows

A recent, and controversial, event has seen the mayor of London introduce a *congestion charge* for all vehicles entering the central district [7]. Baseman [6] illustrates that congestion is neither a new, nor a unique problem to our century, and mentions that Julius Caesar placed limits, and raised taxes, on the number of vehicles entering Rome in A.D. 125.

1.2.2 The *City Logistics* approach

It is appropriate to distinguish between the various *impacts* that the transport network and infrastructure can have on the stakeholders identified in section 1.2.1.

- *Financial* impacts relate to, but is not limited to, commuting costs for residents; the payback period of investments that shippers consider making in establishing facilities in new locations; fuel and fleet costs for shippers; and *internal rate of return* (IRR) for administrators investing in public transport capacity such as train wagons and busses.
- *Social* impacts relate to equity for various user and non-user groups of transport, and could include the impact of accidents, accessibility to transport, or even business competition in the case of taxi operators servicing the same area.

- *Economic* impacts are more comprehensive than financial impacts. Cost benefit analysis does not simply focus on the immediate financial implications, but rather the viability of a transport scheme over the period of the scheme's entire life. *Costs* could include the upfront acquisition of capital equipment and maintenance costs throughout the operational life, while *benefits* could represent the reduced travel times experienced by commuters or reduced fleet operating costs experienced by carriers on items such as consumables and maintenance.

- *Energy* conservation is becoming more important since there is a limited amount of natural resources. Petroleum and automotive diesel oil are the two main sources of energy for the transport industry. *City Logistics* initiatives, such as *route optimization*, could potentially reduce the total amount of fuel consumed by freight and public transport vehicles, if the objective of the exercise is to reduce route lengths.

- *Environmental* effects pose a direct risk on human health. Greenhouse gasses produced by vehicles constitute of the following pollutants:

  - Carbon monoxide (CO)
  - Oxides of nitrogen (NO_x)
  - Suspended particulate material (SPM)
  - Hydrocarbons (HC)

  Noise pollution is also an area of concern, especially in urban areas.

To be able to limit the scope of an investigation or optimization exercise, Taniguchi *et al* [57] introduce a third *spatial* boundary to the transport system, as figure 1.2 indicates.

A *terminal* refers to a single location, node, or venue, in the transport system, for example a distribution center or a bus stop. The infrastructure along which carriers move between two terminals are referred to as a *link*. Examples could include a bus route between two stops, or a segment of rail track between two stations. Multiple links make up an *area*, for example Centurion in Gauteng, South Africa. A *corridor* refers to a number of directly-connected areas. The Mabopane-Centurion corridor would serve as an example. It is significant to distinguish between the various spatial elements, as each element holds unique improvement opportunities.

To address problems, or opportunities for improvement, models could be created that is used to represent the transport system, and predict the effects of proposed solutions and improvements. Taniguchi *et al.* [55] elaborate on three distinct types of models:

- *Supply models* are created when the performance of the road system is represented or predicted through, for example, simulation models.

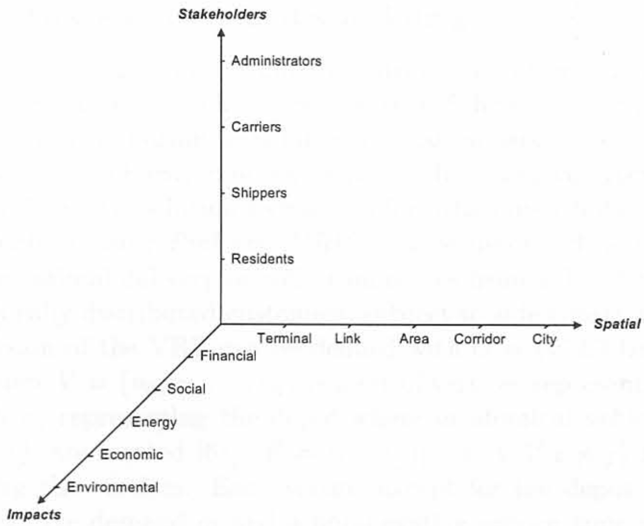

Figure 1.2: System boundaries

These models include the various cost factors associated with routes, vehicles, and terminals. Supply models are created with the suppliers' objective in mind, such as minimizing outbound logistic costs, distribution strategies for a given network, etc.

- *Demand models* focus on commodity flows and vehicle trips. Models include mode choice (e.g. rail, road, etc.) that is based on commodity (freight) generation; distribution of freight; and vehicle routing and scheduling.
- *Impact models* are used to estimate and predict various environmental, economic, and social impacts that a transportation system might have on stakeholders.

In establishing the scope of a *City Logistics* project, it is therefore necessary to identify the stakeholders that will form the object of the study. The next step would be to determine the need of the stakeholders, and thus identify the relevant impacts under consideration. Once these foci have been set, an appropriate model can be developed.

1.2.3 Vehicle routing and scheduling

Vehicle routing and scheduling problems are well-researched in the field of *Operations Research*. The main objective of these types of problems are to minimize the distribution costs for individual carriers. Given the complexity of the type of problem, extensive research has been conducted to develop exact and heuristic solution techniques for urban distribution problems.
The *Vehicle Routing Problem* (VRP) can be described as the problem of assigning optimal delivery or collection routes from a depot to a number of geographically distributed customers, subject to side constraints. The most basic version of the VRP can be defined with $G = (V, E)$ being a directed graph where $V = \{v_0, v_1, \ldots, v_n\}$ is a set of vertices representing customers, and with v_0 representing the depot where m identical vehicles, each with capacity Q, are located [61]. $E = \{(v_i, v_j)|v_i, v_j \in V, i \neq j\}$ is the edge set connecting the vertices. Each vertex, except for the depot $(V \backslash \{v_0\})$, has a non-negative demand q_i and a non-negative service time s_i. A distance matrix $C = \{c_{ij}\}$ is defined on E. In some contexts, c_{ij} can be interpreted as travel cost or travel distance. Hence, the terms distance, travel cost, and travel time are used interchangeably. The VRP consists of designing a set of m vehicle routes having a minimum total length such that

- each route starts and ends at the depot,
- each remaining vertex $(V \backslash \{v_0\})$ is visited exactly once by one vehicle,
- the total demand of a route does not exceed Q, and

- the total duration (including service and travel time) of a route does not exceed a preset limit L

The VRP is a hard combinatorial (*np*-hard) optimization problem for which Laporte [27] has indicated several exact and approximate solution algorithms. An *np*-hard problem implies that the solution space will increase at an exponential or factorial rate (non-polynomial) as the number of customers/vertices increases. Early researchers such as Clarke and Wright [14] realized that exact algorithms can only solve relatively small problems, but a number of heuristic (near-optimal) algorithms have proved very satisfactory.

The basic VRP makes a number of assumptions, including utilizing a homogeneous fleet, a single depot, one route per vehicle, etcetera. These assumptions can be eliminated by introducing additional constraints to the problem. This implies increasing the complexity of the problem, and, by restriction, classifies the extended problem as an *np*-hard problem. The various side constraints, and their application, are discussed in more detail in chapter 2. It should be noted that most of these additional side constraints are implemented in isolation, without integration, due to the increased complexity of solving such problems.

1.3 Research questions

The concept of *City Logistics* is as important in South Africa as it is in the rest of the world. To contribute to the school of subject knowledge, the following general research question could be asked.

> *How can we "Glocalize"*[1] *the concept of* City Logistics *in South African urban environments?*

Urban environments are complex societies with various stakeholders. Although the perceptions and motivation of stakeholders vary, their objective towards freight movement is uniform: civilize the truck. One way of achieving the objective is to reduce the number of freight vehicle trips. Residents will appreciate the alleviated congestion; shippers welcome reduced shipping and receiving transactions; and carriers are happy to reduce their fleet operating costs as a result of the reduced number of trips. Trip optimization is a key focus area of *City Logistics*, and vehicle routing and scheduling procedures provide core techniques in the modelling of *City Logistics*. Most practical distribution problems are not limited to occurrences of isolated VRP variants. No literature, however, could be found that integrate an appropriate number of these variants. To make the proposed demand model for carriers more applicable to the South African environment, the aim of this dissertation is to answer the following research question:

[1] To have a problem, or opportunity, with global relevance, yet with local application.

Is it possible to solve a vehicle routing problem with multiple integrated constraints?

The dissertation aims to investigate the feasibility of integrating a number of these side constraints into a single problem instance, referred to as the *Vehicle Routing Problem with Multiple Constraints* (VRPMC).

1.4 Research design and methodology

Mouton [33] notes that theory-building studies aim to develop new models to explain particular phenomena. The *phenomena* in this particular dissertation would be the routing of vehicles to service a number of geographically dispersed customers. The VRP and its variants are well-researched problems in academic literature but, as stated, lack integrated models. One of the limitations of model-building studies are their ineffectiveness if the models make implausible claims on reality. To ensure that the most common trap – over-abstract formulation – is avoided, figure 1.3 illustrates the proposed *Operations Research* process, as adapted from Rardin [43].

The objective of the dissertation is to address a particular *problem*; both empirical data and actual problem instances exist that could be used to understand the actual problem and its underlying assumptions. Given the problem and the available literature, a representative *model* could be formulated. The model will consist of:

- *decision variables* that will indicate the decisions (solution space) open to decision makers,
- a set of *constraints* that limit the decision choices, and
- an *objective function* that will indicate preferred decisions.

The modelling task includes the process of evaluating the assumptions made in literature, and criticizing the assumed reality the model is based on. Figure 1.4 from Taha [49] illustrates the modelling task appropriately.

It is believed that, as is the case for most VRP variants, the modelling of the problem is relatively simple. In the case of the VRP variants, the *model* is only the first step of the *Operations Research* process. *Solving* the model involves finding an initial solution, and then optimizing the solution until a local, or optimistically, a global, optimum is found. The objective of this dissertation is to document the initial solution algorithm, and to code the algorithm in an appropriate language, such as *MATLAB*, for testing purposes using empirical data. To make conclusions from the results, it is necessary to evaluate the quality of the results generated. Solomon [46] developed sets of test problems representing various environments. These test sets have become a popular benchmark for result comparisons. Although

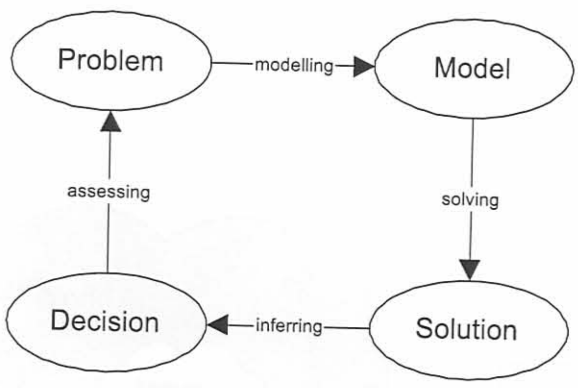

Figure 1.3: *Operations Research* process

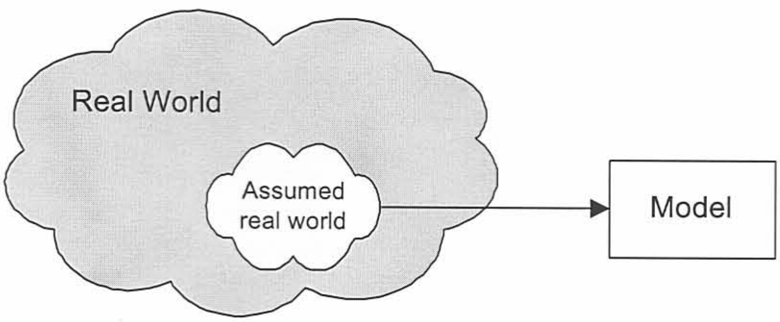

Figure 1.4: Levels of abstraction in model development

the sets may not adhere to the perceived model reality of the dissertation's proposed model, it could be used as point of departure when developing test sets for the model. Only once the model *solutions* are verified and validated, could they be used to support *decisions* regarding the problems experienced in reality.

1.5 The project outline

A comprehensive two-part literature review is undertaken in Chapter 2. The aim of the review is to firstly introduce the concept of *City Logistics* with specific reference to the South African particularity.
The latter part of the literature review elaborates on vehicle routing and scheduling, focussing on the VRP variants, and finding an appropriate point of departure for the proposed model.

Due to the complex nature of the proposed model, and as a result of additional constraints introduced to the model, a new concept of *Time Window Compatibility* is introduced in Chapter 3. The concept serves as a means to reduce the computational complexity of the solution algorithm. In Chapter 4 the proposed model is defined, and the initial solution algorithm introduced.

Results are presented in Chapter 5, followed by interpretation and related discussions. The dissertation is concluded with a research agenda for *City Logistics* studies and applications.