# Labour fatigue constraints in Capacitated Arc Routing

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September 28, 2016

## Abstract

Municipal waste collectors have limited physical capabilities because of task related fatigue factors. However, minimal attention has been paid to fatigue and its recovery in the Capacitated Arc Routing Problem (CARP), despite their significant impacts on collection performance. To understand the dynamic impacts of workers' physical constraints on collection performance, we propose three models. The first model is an acute-physical-cardiac fatigue model that quantifies the work pulse rate of the workers as a function of work rate. The second is a transportation-capacity (TC) model which determines the total amount of bins that can be serviced in a single shift by a collection crew for both the without-fatigue and with-fatigue states. Lastly, a service time model was developed, which takes the fatigue model, TC model and an arbitrary collection route as input. The service time model determines as output, the total collection time and how the labour fatigue changes throughout the route. The proposed models have the potential to decide alternatives for waste collection. That is, to do better route planning and to develop better routes. This will secure high productivity without compromising workers' health and safety. Ultimately, the proposed models highlight and address the research gap of the CARP with respect to human factors, specifically, labour fatigue.

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# Chapter 1

# Introduction

The collection and transportation of waste is both a vital and a costly service provided by municipalities. Therefore, we have recently witnessed a rapidly growing body of research focused on the routing of vehicles to optimise the routes of waste collection vehicles [16].

## 1.1 Background

The Capacitated Arc Routing Problem (CARP) is a variation of the arc routing problem. In the context of waste collection, arc routing selects the best possible path in a road network. The path is based on the route itself. That is, the edges rather than the nodes. Additionally, there is a vehicle capacity constraint associated with the CARP. In the context of waste collection, the vehicles have a limit on the volume of waste that can be collected.

### 1.1.1 CARP constraints

Our research effort focuses on extending the CARP with application to municipal waste collection, where crews manually collect either trolley bins or bags or both, and load them into the collection vehicle. The heuristics that have the capability to compute feasible solutions for the CARPs have an objective function to either minimise total transportation costs or the size of the collection fleet [16]. These heuristics are restricted by various constraints.

Current constraints consider time restrictions on each vehicle route and capacity constraints of the collection vehicles, but not the impact of labour fatigue. That is, the more efficient the route, the harder the labourers are working. This is only good to a point, after which, the labour efficiency decreases. Our research effort primarily focuses on the influence of labour fatigue on the collection routes which may influence the decisions made by route planners.

### 1.1.2 Research motivation

Waste collectors have to step off of the back of the collection vehicle, walk to the bin, attach the bin to the hydraulic tipper, empty it and perch again until the next stop. The same applies to waste bags, except the bags are tossed into the collection vehicle without the use of a hydraulic tipper. The time to perform this series of tasks is defined as the 'transportation and emptying time' of the bins. Current CARP models assume that the 'transportation and emptying time' per bin is constant. This assumption implies that in real life, the workers are equally as productive in the beginning of the day as they are at the end. This is possible, however, it is improbable.

In literature, several issues have been studied on both cardiac- and muscle-fatigue for municipal waste collection. Several studies from different countries reported that the energetic workload limit of 30% $VO_{2max}$ for an eight hour working day is exceeded for collecting two-wheeled bins [6].

Studies on health complaints among waste collectors in South Africa reported an increased risk for musculoskeletal complaints. The body region most affected is the lower back. Other frequently affected areas are the shoulder, knee and neck. The affected areas depends on the method of collection, that is lifting, pushing or pulling. The high biomechanical workload in waste collecting is seen as an important risk factor for these musculoskeletal complaints [4].

In industry, fatigue is seen as a risk factor which requires management. Labour fatigue is usually managed by scheduling workers appropriately. This is possible for jobs with a variety of different tasks types. However, the job of a waste collector only has one task type, that is the collection and emptying of bins. This task is repeated the entire day, everyday of the week. Therefore, with the application to waste collection, a plausible technique to manage worker fatigue is to consider the physical strains of the workers in the preplanned collection route itself.

As an end goal, by measuring labour fatigue and considering it as a constraint in the CARP, the new route offers the following advantages; improved productivity because of better labour efficiency, it may reduce health and safety risks of workers, reduce absenteeism, improve employee retention, reduce health claim costs and prevent industrial action.

### 1.1.3 Problem statement and aim

The more efficient waste collectors are in servicing bins consecutively, the harder they are working. This is only good to a point, after which their efficiency decreases as either; the workers' productivity goes down or there are harmful health and safety effects. These harmful health and safety effects may cause labour strikes, negatively affecting the waste collection process.

Therefore, the aim of our research effort is to develop a model able to quantify the fatigue of municipal waste collectors over any arbitrary collection route. The research question is; "Should municipal waste collection route planners consider labour fatigue when developing collection routes?".

## 1.2 Research Design

According to Manson [9], 'Research Design' is a process of using knowledge to design and create useful artefacts, and then using various rigorous methods to analyse why, or why not, a particular artefact is effective. The outputs of our research effort were the following three artefacts.

### 1.2.1 Artefact one: fatigue model

An acute-physical-cardiac labour fatigue model is identified from literature. The fatigue model uses work pusle rate (WPR) as the metric. The model is an algebraic function shown on a graph. The dependent variable represents the WPR and the independent variable represents the work rate (WR) measured in bins serviced per minute. This model is then used as an input for artefact two.

### 1.2.2 Artefact two: transportation-capacity model

A transportation-capacity (TC) model results in the total amount of bins that one collection crew can service in a single day or shift.

This model comprises of two algebraic functions shown on a graph. The first function represents the as-is, or the without-fatigue TC as a function of the work rate (WR) of the workers. The second function represents the with-fatigue TC as a function of the WR. The with-fatigue function takes the fatigue model and the recovery time equation as input. The dependent variable represents the TC measured in bins per shift. The independent variable represents the work rate measured in bins per minute. The two functions can then be used to compare the difference in transportation-capacity for any predetermined work rate.

### 1.2.3 Artefact three: service time model

Lastly, the developed computer programming model took both the transportation-capacity model and an arbitrary collection route as input. The model determines as output, how the fatigue is quantified over the route as well as the service time throughout the route.

Ultimately, the output of the three proposed models includes; work rate in bins per minute, the dynamic heart rate throughout the route, the recovery time required per road segment, without-fatigue TC per day, with-fatigue TC per day, and the service time of the route. Our research effort was completed once the service time model was evaluated and validated.

## 1.3 Research Methodology

In Section 1.2 a design research process was proposed. Therefore, the research methodology closely followed the design research methodology of Kuechler and Vaishnavi [5] as adapted by Manson [9], shown in Figure 1.1.

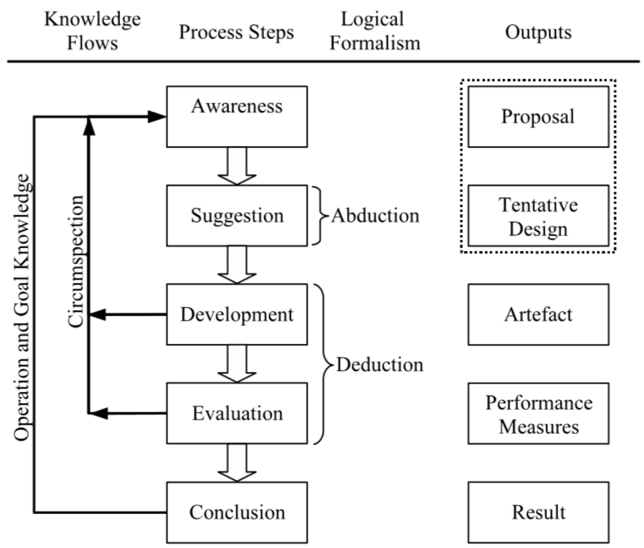


**Figure 1.1:** The general methodology of design research [9].

### 1.3.1 Awareness of the problem

We began our new research effort by becoming aware of the problem. This involved writing a formal proposal that answers the questions; "Why is this research important?", "Why do we want to measure labour fatigue?", and "Why should we or should we not consider labour fatigue when developing collection routes?".

### 1.3.2 Suggestion

In this phase, there was a critical validation of the suggested fatigue models. These fatigue models were suggested in the literature review. It was then determined which model, or combination of models, is the best to use for this problem.

### 1.3.3 Development

The development phase represents the process whereby the three artefacts were built. In this phase, the process and people data was collected and analysed. Following data analysis, artefact two and artefact three were built. The artefacts answers the question, “What will act as a solution?”.

### 1.3.4 Evaluation

The solution was evaluated and validated by discussing the results and how it met all the requirements set out in Chapter 1. The deviations from the predetermined expectations were critically evaluated and tentatively discussed. Necessary modifications were made to the models and the validation process was repeated until the results were effectively validated. This marks the conclusion of our research effort.

### 1.3.5 Conclusion

The results were then consolidated. The produced knowledge was defined as either ‘firm’ or as ‘loose-ends’. Firm knowledge includes facts that can be repeatedly applied to any collection route. Loose-ends include anomalies that can not be factually explained, and may be the subject of future work.

## 1.4 Document structure

In Chapter 2, a critical literature review was conducted which includes the versions and variants of the problem and metrics of labour fatigue that have already been dealt with in literature. Various development techniques appropriate to our research effort were also critically reviewed.

In Chapter 3, the necessary process data and people data was collected and analysed. After data analysis, the full scale models of artefact two and artefact three were developed, documented, and critically described in Chapter 4.

Chapter 5 comprises of a results and scenarios section where the service times and labour fatigue was quantified and illustrated. This chapter contains the results of the model and validates the solution.

Lastly, Chapter 6 comprises of a conclusion where judgement and decision was reached by reasoning. The conclusion ultimately answered the research question, “Should municipal waste collection route planners consider labour fatigue when developing collection routes?”.

# Chapter 2

# Literature review

In the literature review chapter we critically reviewed research articles and motivated why the literature can or cannot be used in our research effort. The literature we critically reviewed includes; the types of labour fatigue, the problem, labour fatigue metrics, and various advanced model development techniques.

## 2.1 Types of labour fatigue

Consensus on a single definition of labour fatigue has not been achieved. However, literature often distinguishes acute fatigue and chronic fatigue. Simply put, acute fatigue goes away with rest, whereas chronic fatigue does not. Fatigue can be further differentiated into; mental, physical and psychomotor fatigue.

Although different forms of fatigue must be acknowledged, for the application to waste collection, we restrict our use of the term to acute-physical-fatigue. We focus on acute fatigue because no research has been found on fatigue complaints for waste collectors on a long term basis [6]. We also focus on acute fatigue because we want to focus on the influence of the recovery period on workers; that is, statutory rest breaks, dead-heading and journeys to intermediate facilities.

We focus on physical fatigue because the responsibilities of a waste collector can be characterised by frequent pushing, pulling, carrying, and lifting of heavy bins and/or bags causing both cardiac and muscular strain. Therefore, mental and pshycomotor fatigue was assumed to have no contribution to waste collector fatigue and is thus not considered in our definition of labour fatigue.

Physical fatigue is further differentiated into its two main subgroups; cardiac fatigue and muscle fatigue. A physiological study on waste collectors was done by Preisser et al. [11]. The study concluded that pulse rate as well as the measurement of oxygen uptake ($VO_2$) are valuable tools for examining the physiological workload on waste collectors.

Therefore, in the context of our research effort, both acute-physical-cardiac fatigue and acute-physical-dynamic-muscle fatigue are the relevant types of labour fatigue with the application to municipal waste collection. The problems in literature related to these two types of fatigue were investigated.

## 2.2 Problem investigation

Labour fatigue is a cause of many work and worker related problems. In the context of waste collection, the problem is categorised into two major parts, poor labour productivity and poor health and safety of the workers.

### 2.2.1 Labour fatigue's effect on productivity

A study titled "The Impact of Fatigue on Labour Productivity" by O'Neill and Panuwatwanich [10] investigates the influence of fatigue on the productivity of construction workers. The study involved upgrading the Gold Coast dam in Austrailia. To examine the influence of fatigue on productivity, two analyses were done to identify any association that exists between productivity and fatigue. These analyses included doing a Psychomotor Vigilance Task (PVT) on the workers. The PVT is an equipment that tests the reaction time of an individual. The other tool used is the Labour Utilisation Factor (LUF) that mathematically determines the performance, quality and availability of workers.

The results of the study by O'Neill and Panuwatwanich [10] indicated that with an increase in worker fatigue, there is a decline in productivity. This relationship was validated by a correlation analysis. This analysis confirmed that fatigue does have a negative association with productivity level. As part of the study, the productivity analysis concluded that the average expense from fatigue causing a production decrease was $50,000 every year for a crew of ten workers.

With the application to waste collection, the result of a decreased productivity would be similar. This is because the fatigue of construction workers is similar to that of waste collectors because both are concerned with physical fatigue. As a result, less bins would be collected per hour by a collection crew. A drop in productivity would lead to either uncollected bins or labourers working overtime. This is more costly to the municipalities and working overtime may cause harmful effects on the health and safety of the workers.

### 2.2.2 Labour fatigue's effect on health and safety

Human errors that are induced by fatigue can have extremely negative consequences, not only on productivity but on the health and safety of workers. A recent study by the National Institute for Occupational Safety and Health (NIOSH) in the United States of America reviewed 52 reports. The reports evaluated the relationship between shiftwork and performance, behaviour, injuries and illnesses [7]. The study found that long working hours has an association with; increased levels of sleepiness, decreased levels of cognitive functionality, and increased levels illness, injuries and mortality.

Therefore, implementing effective means to decrease the physical strain on waste collectors is vital to protect their health. In the context of our research effort, by optimising the collection routes, it causes the waste collectors to service more bins and/or bags per unit time. This increases the fatigue of the workers resulting in energetic and musculoskeletal health problems. Not only is this harmful to workers, but it can lead to industrial action and poor labour efficiency. To better manage and reduce the risk of labour fatigue through collection routes, a metric to quantify labour fatigue and its recovery is required.

## 2.3 Labour fatigue metrics

Labour fatigue is a complex phenomenon. Metrics of labour fatigue remain subjective and problem specific, with no gold-standard available in the literature. The labour fatigue metrics identified in the literature review are presented in Figure 2.1. The bold path indicates the critically selected labour fatigue type and metric.

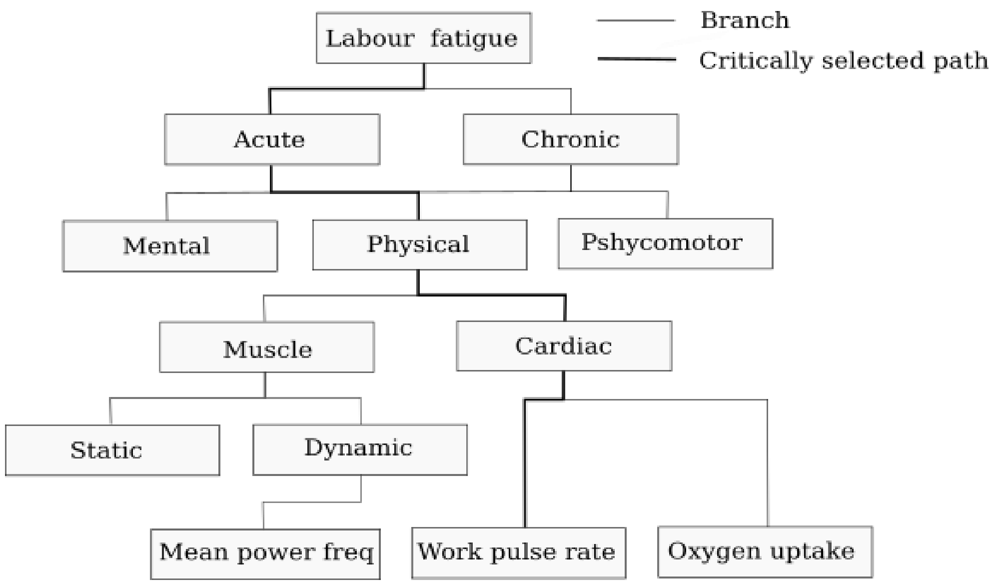


**Figure 2.1:** Labour fatigue metrics diagram.

### 2.3.1 Best-practice metric

Questionnaires are prescribed as the best-practice for the measure of labour fatigue [2]. The questionnaires' answers are quantified using fatigue scales. We are not aware of a fatigue scale developed specifically for the waste collection industry and none consider the influence of the recovery period of workers. Through the past decade, there has been more sophisticated methods developed for measuring labour fatigue and recovery.

We therefore, in the context of our research effort, ignored the best-practice metric and critically reviewed the state-of-the-art measures of labour fatigue with application to municipal waste collection.

### 2.3.2 Mean oxygen uptake as a metric

A study by Preisser et al. [11] aimed to examine the physical endurance of waste collectors based on mean oxygen uptake ($VO_2$) and comparing it to the maximum mean oxygen uptake ($VO_{2max}$). The study compares and evaluates the relationship between $VO_2$ and the workload of waste collectors over an entire shift for waste collectors.

The study was done on waste collectors in Hamburg, Germany and included a sample of 65 subjects. The sample comprised of residual, organic, and street sweeping waste collectors. The performance of the workers was evaluated by cardiopulmonary exercise testing, done under the conditions of a laboratory. The $VO_2$ was recorded for an hour for every individual using a portable spiroergometry system. Results showed that every subject had a mean oxygen uptake above 30% of $VO_{2max}$.

In the context of our research effort, we aim to focus on the recovery period of fatigue. The study by Preisser et al. [11] measures the oxygen uptake over one hour without considering the effects of rest on the workers. Therefore, the results from this study are not entirely relevant to our research effort.

### 2.3.3 Mean power frequency as a metric

An experiment by Shin and Kim [14] identifies the association between the cumulative fatigue and recovery time of an individual's muscles in his trunk, primarily the lower back region. A dynamic lowering and lifting experiment of a lifting weight evaluates the mean power frequency in the individuals for both asymmetric and symmetric postures.

A total of ten middle aged individuals participated in the experiment. The subjects would repetitively lower and lift a weight for nine minute periods set at a mass of 25% of the subject's maximum voluntary condition. The experiment focuses on the recovery time of the workers. Between every period, recovery times of one, two, three, four and five minutes were applied respectively. The frequency of lifting and lowering was aimed at four lifts per minute. Electromyography (EMG) signals measured the mean power frequency (MPF) of the ten major trunk muscles before and after each nine minute period. The MPF in dependence of recovery time was plotted on graphs. The study concluded that with an increase in mean power frequency, there is an increase in the recovery time required for every trunk muscle.

In the context of our research effort, the study is relevant because it measures the cumulative fatigue of trunk muscles which is the same muscles that waste collectors use most [6]. The results from this study can also assist in the design of the amount of recovery time required. These results seemed promising, although other approaches to quantifying recovery time of fatigued workers have also been identified from literature.

### 2.3.4 Labour fatigue recovery time

The change in heart rate, also denoted work pulse rate (WPR), can be used to determine the duration of the recovery period required. The recovery period is sufficient if the heart rate has decreased to a resting pulse rate, that can range anywhere between 50 to 100 beats per minute, depending on the individual. A total of 36 experiments were carried out by Sieber [15]. Each lasting one hour, five healthy male subjects performed different work on a bicycle ergometer. Their pulse rates were measured continuously before, during and after each examination. Statistically significant correlations were found to exist between the subjects' WPR and recovery period ($R_t$), which is described by the following exponential function:

$$R_t = 3.86 \times \mathrm{e}^{0.035 \times WPR} - 7.23. \tag{2.1}$$

In the study by Sieber [15], the recovery period is defined as the amount of time required for one's heart rate to return to its resting level while laying on one's back. In the context of our research effort, the recovery period, or rest breaks of waste collectors are usually spent in a sitting position or even walking rather than in a supine position. With differing conditions between the experiment and real life conditions of waste collectors, it was assumed that there is a substantial difference in the recovery time calculated. Therefore, we did not use Equation 2.1 in the context of our research effort.

A study by Bartels-Ferreira et al. [1] tested the goodness of a first order exponential equation for describing heart rate (HR) recovery post resistance exercise. The results showed reasonable coefficients of determination, where $R > 0.75$. The heart rate ($HR_{R_t}$) as a function of recovery time ($R_t$) is defined by Equation 2.2:

$$HR_{R_t} = HR_0 + HR_\Delta \times \mathrm{e}^{-\dfrac{R_t}{T}}. \tag{2.2}$$

$HR_0$ is the resting heart rate, otherwise known as the 'asymptotic value' or 'resting plateau'. $HR_\Delta$ is the difference between $HR_{peak}$ and $HR_0$ and $T$ is the heart rate decay constant. Equation (2.2) is the critically selected recovery time equation.

### 2.3.5 Work pulse rate as a metric

To use Equation 2.2, we require the WPR of the waste collection workers. Work-physiological investigations were conducted for three waste collection shifts by Luttmann et al. [8]. The study included six waste collectors, all males between the ages of 40 and 56. The electrocardiogram (ECG) was tested on all of the waste collectors during their shift by taping electrodes on the surface of the waste collectors' skin. The ECG test measures the work pulse rate (WPR) of the workers. The work rate (WR) is defined as the average amount of bins per collection area divided by the average time for all operations within one collection area.

The actual measurements of a waste collector's heart rate throughout a day's work is shown in Figure 2.2. The actual task performed at that heart rate done is also shown. Below the heart rate diagram is a WR diagram from the study and illustrates the amount of bins serviced per minute.

Waste collection crews operate from 08:00 AM to 17:00 PM. In the initial 20 minutes, crew members are seated in the collection vehicle travelling to their first collection area. At this time the collection workers' resting pulse rate ranges anywhere within 80 beats per minute and 90 beats per minute, as shown in Figure 2.2. When the workers arrive at their first designated collection area, they immediately start transporting and emptying the bins into the collection vehicle. In the first few hours the WR has an average of 0.6 bins per minute, corresponding to approximately 1.7 minutes per bin. During this section of work, the beats per minute of the worker's heart reaches a maximum of 125 beats per minute. In the next hour the work rate decreased by 0.1 bin per minute. That is servicing half a bin per minute. Correspondingly, the heart rate drops to range within 90 and 110 beats per minute. After two hours of transporting and emptying bins the collection vehicle has reached its storage capacity and so, the collection vehicle travels to the intermediate facility for dumping. After the intermediate facility, there is statutory lunch break of 60 minutes long. After the rest break there is another trip to the following collection area. The collection crew then continues collecting bins at an averagely higher WR for 1.5 hours. Once again, the beats per minute reaches consistently high values. Later in the day there are two additional sections of transporting and emptying bins as well as two more trips to the intermediate facility. The average amount of bins that have been serviced per minute is not as high after noon as compared to the morning. The heart rate also decreases, caused by the decrease in WR. This decrease in WR is because of the workers feeling fatigued after a long day of manual labour. As seen in Figure 2.2, the heart rate consistently increases and decreases in short time intervals. The higher heart rates are reached during the transporting of bins, and the lower values are associated with the workers walking or being driven between the collection areas.

Figure 2.2 illustrates that heart rate is dependent on work rate. This association was observed for all six subjects. The findings are shown on Figure 2.3. The WPR represents the change in heart rate from rest. It is evident that there is a direct increase in the WPR with an increase in WR.

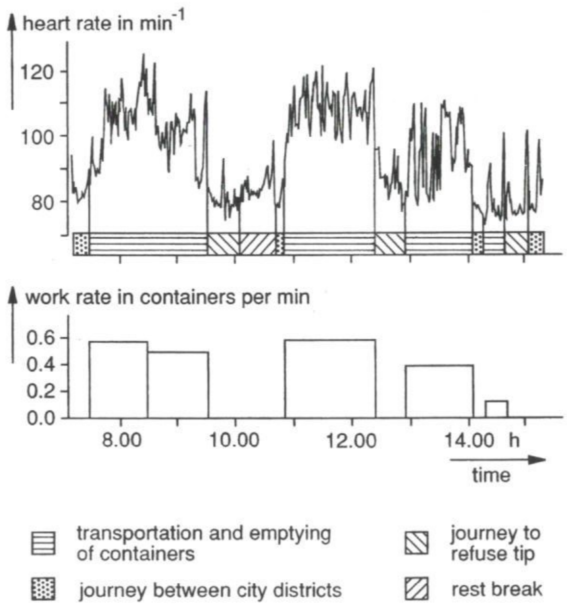


**Figure 2.2:** Original heart rate and work rate recordings of a waste collector [8].

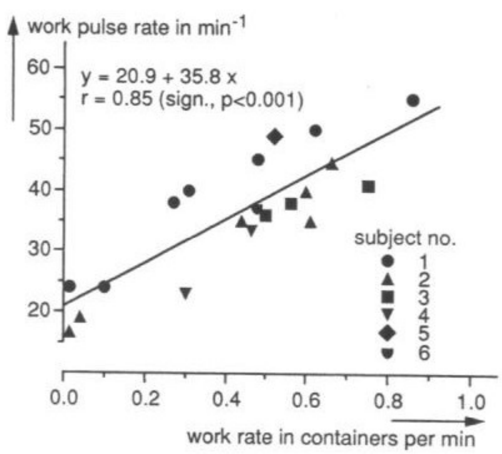


**Figure 2.3:** WPR for six waste collectors as a function of WR [8].

The association between the work pulse rate and work rate can therefore be defined by the following regression approximation:

$$WPR = 20.9 + 35.8 \times WR. \tag{2.3}$$

### 2.3.6 Critical analysis of the selected metric

Work pulse rate is the selected metric, as defined in Equation 2.3. In the context of our research effort, the residential waste collection crews in South Africa also comprise of two waste collectors. However, the waste bins in South Africa are 0.24 $m^3$ (240 $L$) which is approximately a quarter of the bin size used in the study by Luttmann et al. [8]. Larger bins consequently result in heavier bins, and thus would cause more strain on the muscles of workers. This may imply that Equation 2.3 is not applicable to our research effort because the WPR will differ for bins of lower mass. However, bins are emptied into the waste collection vehicles using hydraulic tippers. The worker fatigue will then only be influenced while pushing the roller bin to the collection vehicle, because the heavy-strain lifting task is done by the hydraulic tipper of the collection vehicle. Therefore, it was assumed that the WPR of the workers only minimally depends on the size of the bins.

Figure 2.1 shows the hierarchy of the definition of labour fatigue. The bold path indicates the current critically selected metric, which is work pulse rate. In concluding the literature review, the suggested metric of labour fatigue was WPR. As previously mentioned, mean power frequency from muscle fatigue can also be used as a metric in our research effort, but because a cardiac fatigue study with the direct application to waste collection has already been done in literature, it was our selected metric and labour fatigue model.

### 2.3.7 Application of the selected metric

The WPR fatigue model (artefact one) was used as input to a with-fatigue TC model (artefact two). The output of the with-fatigue TC model was the amount of bins that can be emptied by a collection crew comprising of one driver and two waste collectors. Additionally, the WPR fatigue model was used to quantify the labour fatigue in the service time model (artefact three).

The development technique used to build artefact three required a sophisticated advanced technique because of the complexity of the model's inputs and outputs. To select the most appropriate and viable development technique, various development techniques were critically reviewed.

## 2.4 Development techniques

The third process step of design research in Figure 1.1 is the development of the artefacts. The development technique referred to in this section refers to the technique that is required for the development of artefact three in Subsection 1.2. The purpose of the development technique is to build the servicing time model which is able to quantify the fatigue and service time through any arbitrary collection route.

### 2.4.1 Discrete event simulation

The works of Seo et al. [13] closed the gap of Discrete Event Simulation (DES) in terms of labour fatigue with the direct application to construction workers. The construction workers who do hard labour construction operations have limited physical capabilities because of personal and activity related fatigue aspects. A worker oriented simulation of construction operations determines the influence on the construction productivity, based on the physical capabilities of the workers. The simulation is integrated with a muscle-fatigue model. Ultimately, the simulation has the capability to predict productivity levels. The model can be used for construction planning while considering the health and safety of the workers.

In the context of our research effort, DES is relevant in terms of the inputs and outputs required. By using DES with the application to municipal waste collection, it can account for the variability of inputs, such as the fatigue model and the distributions of activity times. Therefore, simulation is a plausible tool to use to solve this problem. However it is not the only tool. Computer programming from first principles is also an efficient and effective tool to develop such a model.

### 2.4.2 Computer programming from first principles

The works by Hsie et al. [3] present a model that schedules work and rest activities for blue collar workers. The objective of the model is to minimize the job completion time by minimizing the energy expenditure (EE). It minimised the EE of labourers by eliminating irrelevant activities that cause the workers to work for a longer time than the maximum accepted duration of manual labour. A genetic based algorithm is used. This search heuristic searches the Pareto front, which is an effective means to solve multi-objective optimization problems.

In the context of our research effort, the work-rest schedule is not of primary relevance. However, the objectives can be replicated and adapted to minimise any extra energy expended by municipal waste collectors by allowing recovery time at high levels of fatigue.

Computer programming from first principles was the selected development technique instead of DES for the sake of its versatility.

## 2.5 Conclusion

There were three key conclusions of the critical literature review. The first conclusion was that labour fatigue decreases labour efficiency and productivity and it can be very costly to an organisation. Labour fatigue can also have harmful health and safety effects on workers which can further lead to industrial action.

The second conclusion was the selected labour fatigue metric. The selected metric is work pulse rate which is an acute-physical-cardiac type of labour fatigue. The fatigue model (artefact one) is defined by Equation 2.3. This equation was used together with Equation 2.2, which was used to quantify the influence of recovery time on the workers.

The third conclusion from the critical literature review was the selected development technique for the service time model. The selected development technique was computer programming from first principals. This development technique was used to build artefact three.

Equation 2.2 is a formula which comprises of variables and a constant T. However, no values of the decay constant T were found in literature that are relevant to our research effort. Therefore, the necessary data was collected to develop a decay constant to use in the formula, and is presented in Chapter 3.

# Chapter 3

# Data analysis

Two types of data were required for the service time model development. These include process data and people data. The process data refers to the data of the actual waste collection process. That is, the average time it takes for each step in the waste collection process. The people data refers to the data relating to the human aspects of our research effort. That is, the heart rate and recovery time data.

## 3.1 Process data: waste collection time

The activity time-line in Figure 3.1 illustrates a schematic diagram of the sequencing of the waste collection activities. Each activity as defined in Table 3.1 occupies a specific amount of time during the waste collection process.

**Table 3.1:** Glossary of waste collection activity symbols.

| Activity symbol | |
|---|---|
| N | Average number of collection areas |
| n | Average number of bins per collection area |
| $T_E$ | Average time to transport and empty a bin |
| $T_D$ | Average time to walk from one collection area to the next |
| $T_A$ | Average time to perform all of the required tasks at a collection area |
| $T_T$ | Average time to transport the waste to the intermediate facility |
| $T_W$ | Average time of the actual work done in a nine hour shift |

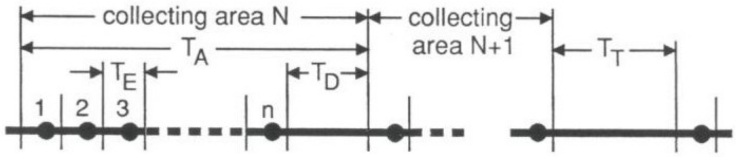


**Figure 3.1:** Waste collection activity time-line.

The term $T_E$ represents the average amount of time to collect, empty, and return one bin. After this activity is completed, the collection vehicle slowly moves to the subsequent collection area, this time is represented by the term $T_D$. The term 'collection area' denotes a zone where there are bins waiting to be serviced. Throughout the $T_D$, waste collectors either perch on the vehicle, standing on a foot board, or they walk to the next collection area if it is close enough. According to Wilson and Baetz [17], collection takes place until the collection vehicle reaches its capacity of 12 $m^3$ and then the vehicle drives to the intermediate facility for dumping. This time is defined as $T_T$. The data provided in Table 3.2 is the same as that used by Wilson and Baetz [17].

**Table 3.2:** Average values describing the waste collection activity time-line.

| Activity symbol | Average time (min) |
|---|---|
| $T_E$ | 0.8 |
| $T_D$ | 0.25 |
| $T_T$ | 30 |

The $T_W$ is calculated by subtracting all the break times from the actual shift time of nine hours. The data provided in Table 3.3 is the same as that used by Luttmann et al. [8].

**Table 3.3:** Average values describing the actual working time within a nine hour shift.

| Activity | Average time (min) |
|---|---|
| Nominal shift time of a nine hour day | 540 |
| Less operations on the collection vehicle | 25 |
| Less return trip to the intermediate facility | 60 |
| Less return trip to the vehicle depot | 60 |
| Less private time | 10 |
| Less lunch break | 60 |
| $T_W$ | 325 |

This concludes the process data collection. The process data provided in Table 3.2 and Table 3.3 was used in the development of the transportation-capacity model. Along with the process data, people data is also required for the quantification of labour fatigue. The people data that was collected and analysed was heart rate recovery time data.

## 3.2 People data: recovery time

Two Minutes Recovery Test (TMRT) data was collected from the University of Pretoria's High Performance Centre. The TMRT is used to assess one's fitness level; the quicker one's heart rate recovers, the more fit one's heart and body is. The data includes 157 readings of the peak heart rate reached by individuals and their heart rate after two minutes of recovery. The heart rate is measured in beats per minute (bpm). The TMRT data is shown in Figure 3.2. The data combines tests that were done on individuals that range from unfit to very fit. This is why some individuals almost fully recovered after two minutes as opposed to some individuals who barely recovered. The purpose of this data was to deduce the decay constants to use in the heart rate recovery time formula.

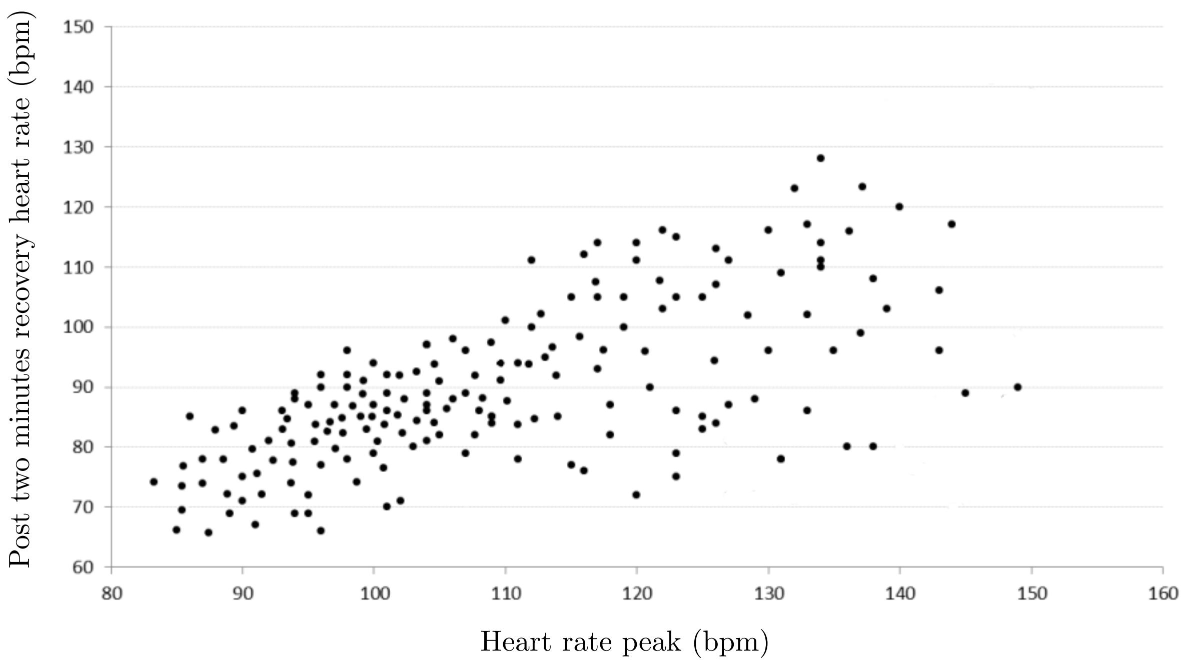


**Figure 3.2:** TMRT data.

As discussed in the literature review, Equation 2.2 is a first order differential equation solution that can be used to fit heart rate recovery. The gradient or 'steepness' of the curve is influenced by the decay constant (T). That is, a smaller T, the quicker the recovery back to the resting heart rate. The influence of T on heart rate is shown in Figure 3.3. With a peak heart rate of 115 bpm, a resting heart rate of 65 bpm and a decay constant of T equal to one, it would take an individual approximately five minutes to get back to a resting heart rate of 65 bpm. In contrast, a larger T of five would require approximately 20 minutes of recovery time to get back to one's resting heart rate.

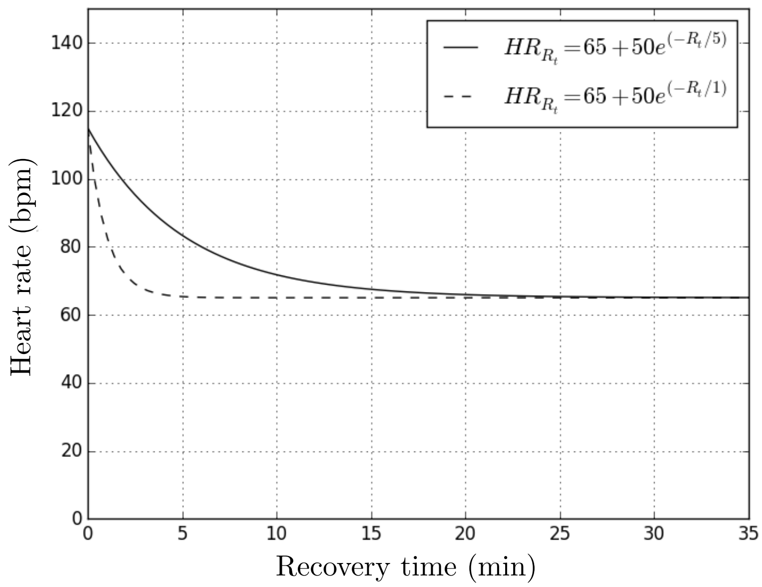


**Figure 3.3:** Heart rate versus recovery time.

As a result, it is evident that a relationship exists between the decay constant T and the recovery time $R_t$. This relationship is approximated by Equation 3.1 and is shown in Figure 3.4:

$$T = 0.2094 + 0.4150 \times R_t. \tag{3.1}$$

The coefficient of determination ($R^2$) is equal to 0.9582 which suggests a strong linear relationship between $R_t$ and T. Therefore, because the data is closely fitted to the regression line, Equation 3.1 is a reasonable approximation of T.

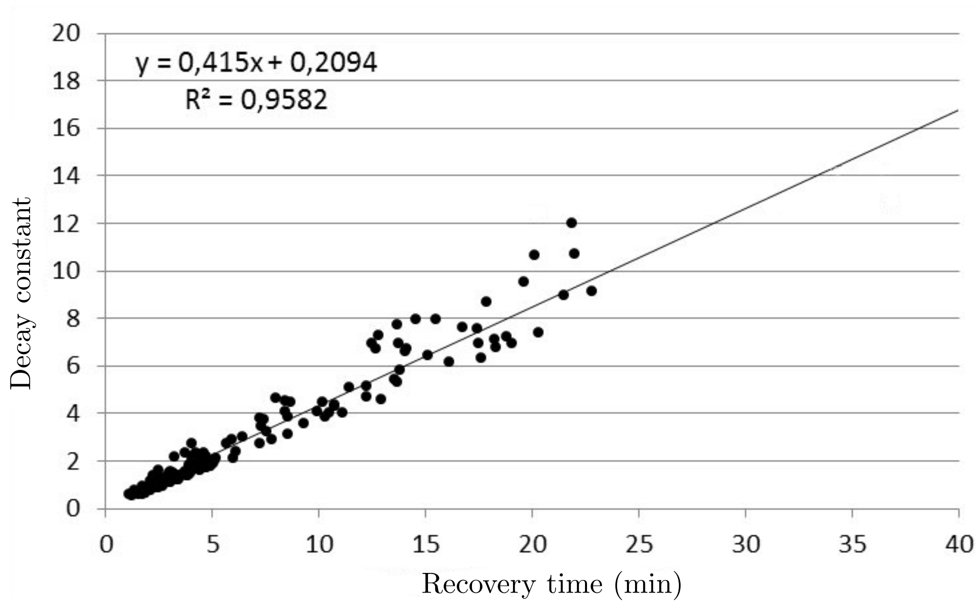


**Figure 3.4:** Heart rate decay constant versus recovery time.

With the development of a function describing the decay constant, we substitute Equation 3.1 into Equation 2.2 forming Equation 3.2:

$$HR_{R_t} = HR_0 + HR_\Delta \times \mathrm{e}^{-\dfrac{R_t}{0.4150 \times R_t + 0.2094}}. \tag{3.2}$$

If we expect one's heart rate to recover back to one's resting heart rate we require $HR_{R_t} - HR_0$ to equal zero bpm. However, this would render an unsolvable equation because of the asymptote in the natural logarithmic function. Therefore, we make the assumption that $HR_{R_t} - HR_0$ is equal to five bpm. The value of five bpm is used as a cut off point because as the limit tends to zero, an infinitely longer recovery time is rendered. Therefore, $HR_0$ plus five bpm is sufficient to represent the resting heart rate. However, any value above five is moving too far away from the targeted $HR_0$. Therefore, setting $HR_{R_t} - HR_0$ to five and solving for $R_t$, renders Equation 3.3:

$$R_t = \frac{-0.2094 \times \ln(\dfrac{5}{HR_\Delta})}{0.4150 \times \ln(\dfrac{5}{HR_\Delta}) + 1}. \tag{3.3}$$

It is evident in Figure 3.5 that Equation 3.3 is a logarithmic function. According to the example data, the maximum change in heart rate reached that is shown by the asymptote tends to 55 bpm. Therefore, if we take a maximum cut off point of 50 bpm, it implies a maximum of approximately 11 minutes that is required to recover back to one's resting heart rate. Equation 3.3 was useful in the model development when calculating the amount of recovery time required at a given change in heart rate and visa versa.

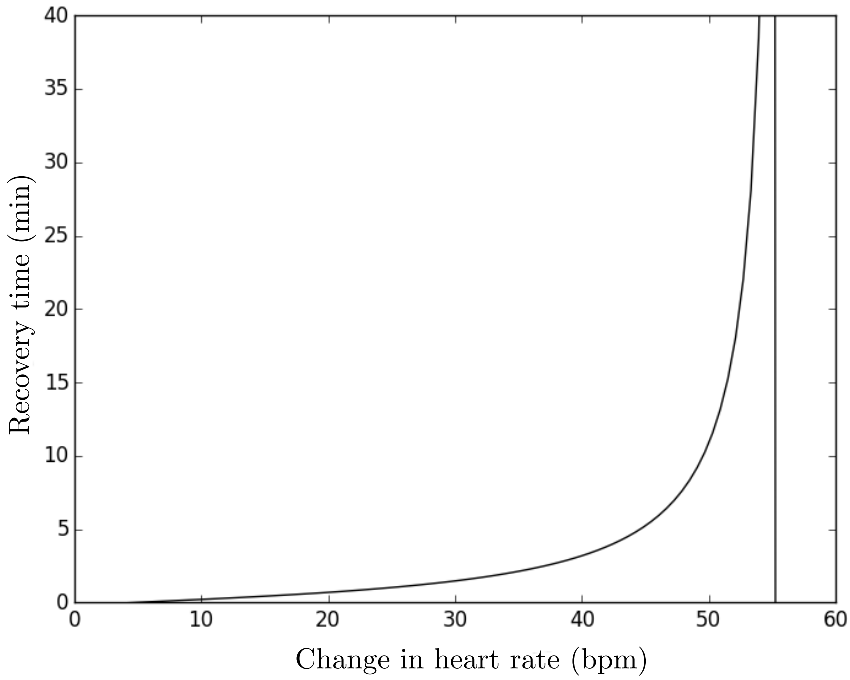


**Figure 3.5:** Recovery time to get back to one's resting HR after a change in HR.

## 3.3 Conclusion

We used the process data and people data as input for the model development. The process data was used for the development of the transportation-capacity model. The people data was used to derive Equations 3.2 and 3.3 for developing the service time model.

# Chapter 4

# Model development

To understand the dynamic impacts of workers' physical constraints on collection performance, two models were developed. The first model was the transportation-capacity (TC) model which determined the total amount of bins that can be serviced in a single shift by a collection crew for both the without-fatigue and with-fatigue states. The second model was the service time model, which took the fatigue model, TC model and an arbitrary collection route as input. The service time model determined as output, the total collection time and how the labour fatigue changed throughout the route.

## 4.1 Transportation-capacity model

The term $TC_{without-fatigue}$ represents the optimal utilisation of the waste collection crew. In contrast, the $TC_{with-fatigue}$ represents the ergonomic utilisation of the waste collection crew. These two functions can be used to compare and contrast the difference in transportation capacity for the without-fatigue and with-fatigue states.

### 4.1.1 TC model derivation

The TC is the product of the average work rate (WR) and the average work time $T_W$. The $TC_{without-fatigue}$ does not consider the recovery time required by the workers. Therefore the $TC_{without-fatigue}$ can be defined by Equation 4.1:

$$TC_{without-fatigue} = WR \times T_W. \tag{4.1}$$

For the $TC_{with-fatigue}$ equation, recovery time is considered. In Chapter 3 we derived a formula to calculate the recovery time ($R_t$) to reach a resting heart rate of 65 bpm after a change in heart rate ($HR_\Delta$). The $R_t$ is defined by Equation 3.3. Therefore, the TC model with-fatigue is defined by Equation 4.2:

$$TC_{with-fatigue} = WR \times (T_W - R_t). \tag{4.2}$$

The total amount of time for all operations within one collection area ($T_A$) is defined by:

$$T_A = n \times T_E + T_D. \tag{4.3}$$

To calculate the work rate we divide the number of bins per collection area by $T_A$. Therefore, the average work rate amounts to:

$$WR = \frac{n}{T_A} = \frac{n}{n \times T_E + T_D}. \tag{4.4}$$

The $TC_{without-fatigue}$ is derived from a combination of Equation 4.1 and Equation 4.4, therefore:

$$TC_{without-fatigue} = \frac{n \times T_W}{n \times T_E + T_D}. \tag{4.5}$$

The $TC_{with-fatigue}$ is derived from a combination of Equation 4.2 and Equation 4.4, therefore:

$$TC_{with-fatigue} = \frac{n \times (T_W - R_t)}{n \times T_E + T_D}. \tag{4.6}$$

### 4.1.2 TC model description

Equations 4.5 and 4.6 demonstrate that the TC is dependent on the numerous variables shown in Table 3.2. Several variables are dependent on the collection area conditions with no influence from the waste collectors themselves. These variables include the average amount of bins per collection area (n) which is assumed to equal one, intermediate facility journeys ($T_T$) and the average duration for a drive between two successive collection areas ($T_D$). Variables can also be independent of the collection area conditions, and are primarily influenced by the workers. This includes, the average duration for the transportation and emptying of a bin in minutes ($T_E$). The outputs to the TC model is shown in Figure 4.1 and the results are shown in Table 4.1. It is evident in Figure 4.1 that labour fatigue does influence the TC because fewer bins can be serviced per shift with in increase in work rate. We observe that for any work rate between 0 and 0.5 bins per minute, there is no difference in the amount of bins collected per shift. The difference is only evident with a work rate larger than 0.5 bins per minute. That is one bin serviced every two minutes. The larger the work rate the larger the difference in transportation-capacity between the two states. With the example data collected, we calculate a work rate of 0.95 bins per minute. At this work rate we observe a transportation-capacity difference of 18 bins per shift.

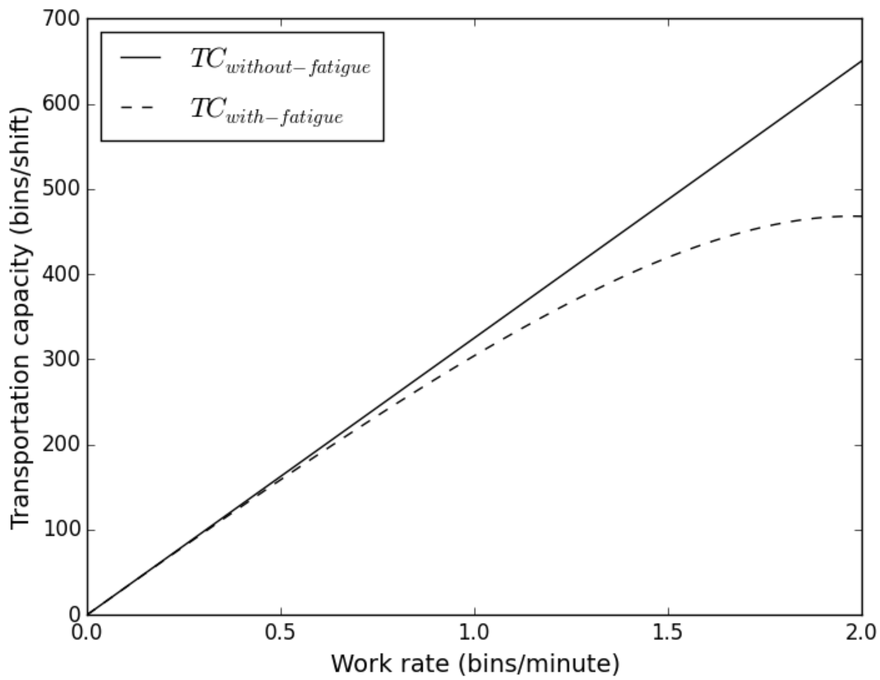


**Figure 4.1:** Transportation-capacity model.

In comparing the without-fatigue and with-fatigue states of the TC model, we observe a transportation-capacity increase of 18 bins per shift. The TC model has the potential to predict the total amount of bins to be serviced for both the with-fatigue and without-fatigue states. Therefore, the model serves its purpose to demonstrate that there is a quantifiable difference in TC. However, the TC model is only a stepping stone to waste collector fatigue quantification. Using the TC model we developed a service time model that quantifies heart rate, recovery time and service time through any arbitrary collection route.

**Table 4.1:** Output of the transportation-capacity model for one shift.

| Description | Symbol | Output |
|---|---|---|
| Work rate (bins/minute) | WR | 0.95 |
| With-fatigue transportation-capacity (bins/shift) | $TC_{with-fatigue}$ | 308 |
| Without-fatigue transportation-capacity (bins/shift) | $TC_{without-fatigue}$ | 290 |

## 4.2 Service time model

The service time model is comprised of two functions. The dead-heading function and the servicing function. The dead-heading function quantifies both the heart rate and time while the collection vehicle is moving and the labourers are not servicing bins, such as back tracking along a street that has already been serviced to get to another part of the service network. In contrast, the servicing function quantifies both the heart rate and time while the waste collector is servicing bins. The route was then animated illustrating the heart rate while both servicing and dead-heading.

### 4.2.1 Dead-heading function description

Each **road** represents a road segment in a road network. Each **road** has data assigned to it. The data includes; the origin node **from**, the destination node **to**, the number of collection areas **collection_area**, the speed of the collection vehicle in kilometres per hour **speed**, the distance of the road in kilometres **dist**, and the average number of bins per collection area **bins**. The roads form a network of roads **road_network**, that defines a collection route. Dead-heading also occurs when traversing to and from intermediate facilities and depots.

In Algorithm 1, we quantify the influence of dead-heading on both the heart rate and servicing time. The function in Algorithm 1 takes the **road_network** as input and returns the work pulse rate list, total WPR list, change in recovery time list, total recovery time list and the servicing time list as output.

Line 1 calculates the dead-heading time in minutes. Line 2 calculates the total recovery time required **RT**, after it is reduced during the dead-heading rest time. Using **RT**, line 4 calculates the total work pulse rate **totalWPR**, or change in heart rate. Lines 6 and 8 calculate the difference in the total work pulse rate and total recovery time needed respectively. Lines 3, 5, 7, 9, 10 and 11 append the calculated values to their respective lists. This function is only necessary for dead-headed roads and not for the serviced roads. Therefore, a servicing function is required.

**input** : road_network: A list of dictionaries containing road data of from, to, collection_area, speed, dist, bins

**output:** Change in heart rate, recovery time and service time values appended into lists after dead-heading

**Function** `deadheading`(*road_network*)

```
deadheadtime= (road[dist]/road[speed]) × 60 ;
RT = max(0, RT - deadheadtime) ;
append RT to Totalrecoverytimelist ;
totalWPR = max(0, totalWPR = 5 × exp(((10000 × RT )/(4150 × RT + 2094)))) ;
append totalWPR to totalWPRlist ;
WPR = max(0, last value in totalWPRlist - penultimate value in totalWPRlist) ;
append WPR to Workpulseratelist ;
RecovT = max(0, last value in Totalrecoverytimelist - penultimate value in Totalrecoverytimelist) ;
append RecovT to Changerecoverytimelist ;
append deadheadtime to Servicetimelist_with_fatigue ;
append deadheadtime to Servicetimelist_without_fatigue ;
return Workpulseratelist, totalWPRlist, Changerecoverytimelist, Totalrecoverytimelist, Servicetimelist_with_fatigue, Servicetimelist_without_fatigue_with_fatigue ;
```

**Algorithm 1:** Dead-heading function

### 4.2.2 Servicing function description

Algorithm 2 takes the **road_network** as input and returns the work pulse rate list, total WPR list, change in recovery time list, total recovery time list, the servicing time with fatigue list and the servicing time without fatigue list as output. Algorithm 2 quantifies the influence of servicing on the time it takes to service the route as well as the change in heart rate of the workers.

If workers service more bins per unit time, it would cause increased levels of heart rate. Therefore, both servicing time and heart rate is dependent on the work rate **WR**, of the waste collectors. This work rate is quantified in line 1 using Equation 4.4. Using the data from Table 3.2, $T_E$ is 0.8 minutes indicating that it takes a worker an average of 0.8 minutes to walk to a curb to get the bin, roll it to the collection vehicle, attach it to the hydraulic tipper, empty the bin, and then roll the bin back to the curb. $T_D$ is 0.25 minutes indicating that it takes a worker an average of 0.25 minutes to walk to the next collection area. The variable **RecovT** in the denominator of the **WR** equation is the recovery time required for each arc serviced. The recovery time in the denominator is inversely proportional to the work rate. The denominator of the **WR** equation calculates the service time to service a collection area and then walk to the next one. The recovery time is included in the **WRdenom** equation in line 2 because the model is based on the assumption that the workers need to recover to their resting heart rate before they continue servicing the next road. However, if we disregard this assumption, we then ignore the recovery time, and use the standard **WR** equation in line 3.

Line 4 in Algorithm 2 uses Equation 2.3. The equation calculates the change in heart rate **WPR**, as a function of work rate. Line 11 calculates the recovery time required to get back to one's resting heart rate after an increase in heart rate. Line 13 sets the condition that if the next road on the collection route has already been serviced, it is going to be dead-headed. The recovery period then begins while dead-heading. Lines 7, 8, 10, 13, 14 and 16 append the calculated values to their respective lists. This function is only necessary for serviced roads. The service time model combines both the dead-heading function (Algorithm 1) and the servicing function (Algorithm 2) into one integrated model (Algorithm 3).

### 4.2.3 Service time model description

The service time model is presented in Algorithm 3. Lines 1 through 5 of Algorithm 3 define a function that creates a list of duplicates. Line 19 uses the predefined **list_duplicates** function to determine if that road has already been serviced or not. If the road has been serviced, the dead-heading function is applied (line 21). Otherwise, the servicing function (line 23) is applied.

Lines 26 through 29 convert the change in heart rate list to a heart rate list by adding the resting heart rate of 65 bpm. This heart rate list is then used as an input for Algorithm 4 which animates the heart rate of a worker throughout a collection route.

**input :** road_network: A list of dictionaries containing road data including, from, to, collection_area, speed, dist, bins
**output:** List of change in heart rates, recovery times and servicing times

```
Function servicing(road_network)
    WR = road[bins]/((road[bins] × 0.8) + 0.25+ (RecovT
     /road[collection_area]));
    WRdenom = (road[bins] × 0.8) + 0.25 + (RecovT / road[collection_area]) ;
    WRdenomwithoutfatigue = (road[bins] × 0.8) + 0.25 ;
    WPR=20.9 + (35.8 × WR) ;
    WPR = (WPR × WRdenom × (road[collection_area])) / 60 ;
    totalWPR = totalWPR + WPR ;
    append totalWPR to totalWPRlist ;
    append WPR to Workpulseratelist;
    ServT = WRdenom × road[collection_area] ;
    append ServT to Servicetimelist_with_fatigue ;
    RecovT = max(0, (-0.2094 × ln( 5.0 / WPR ))/(0.415 × ln( 5.0 / WPR ) +
     1)) ;
    WPR = 5 × exp(((10000 × RecovT )/(4150 × RecovT + 2094))) ;
    if following road has been serviced then
        deadheadtime = ( road[dist] /road[speed] ) × 60
        delta = deadheadtime - RecovT
        if delta > 0 then
            append 0 to Changerecoverytimelist
            RT = RT + RecovT
            append RT to Totalrecoverytimelist
        end
        if delta < 0 then
            Y = RecovT - deadheadtime
            append 0 to Changerecoverytimelist
            append Y to Changerecoverytimelist
            RT = RT + Y
            append RT to Totalrecoverytimelist
        end
    end
    if following road is unserviced then
        RT = RT + RecovT
        append RT to Totalrecoverytimelist
        append RecovT to Changerecoverytimelist
    end
     ServT_without_fatigue= WRdenomwithoutfatigue × road[collection_area] ;
    append ServT_without_fatigue to Servicetimelist_without_fatigue;
    return Workpulseratelist, totalWPRlist, Changerecoverytimelist,
     Totalrecoverytimelist, Servicetimelist_with_fatigue,
     Servicetimelist_without_fatigue;
```

**Algorithm 2:** Servicing function

```
input  : road_network: A list of dictionaries containing road data including,
         from, to, collection_area, speed, dist, bins
output: A list of cumulative heart rates, recovery times, service times for any
         given road_network

Function list_duplicates(seq) is
    seen ← construct a new empty set object
    seen_add ← add if seen
    seen_twice ← set( x for x in seq if x in seen or seen_add(x) )
    return update seen_twice for (i ← 0 to 1)
end
set totalWPR to 0;
set RT to 0;
set RecovT to 0;
set totalWPRlist to empty list;
set Workpulseratelist to empty list;
set Totalrecoverytimelist to empty list;
set Changerecoverytimelist to empty list;
set Servicetimelist_with_fatigue to empty list;
set Servicetimelist_without_fatigue to empty list;
set Edgelist to empty list;
for road in road_network do
    append (road[from],road[to]) to Edgelist;
    already_serviced ← list_duplicates(Edgelist);
    if (road[from],road[to]) = last value in already_serviced then
        deadheading(road_network);
    else
        servicing(road_network);
    end
end
set heart_rate_list to empty list;
for item in totalWPRlist do
    item = item + 65
    append item to heart_rate_list
end
```

**Algorithm 3:** Service time model

```
input  : heart_rate_list
output: Fatigue route animation
image = read(filename.png);
points = list of x and y coordinates;
red = 255;
green = 255 ;
blue = 0;
i = 0;
while i < number of points in points list do
    green = abs(255 - 255 × (heart_rate_list[i]-70)/110 );
    draw line on image from points[i] to points[i+1] at thickness of 5;
    k = wait 190ms for key;
    if k == any button is pressed then
        break
    end
    i = i + 1;
end
```

**Algorithm 4:** Fatigue route animation

## 4.3 Conclusion

The service time model itself is the solution to our research effort. The service time model is very versatile and can be used to evaluate various scenarios; quantifying the heart rate, recovery time and service time through any collection route. Various heart rate recovery scenarios and results are discussed in Chapter 5.

# Chapter 5

# Scenarios and results

As mentioned in Chapter 4, the service time model itself is the solution to our research effort. Therefore, we validate the solution by presenting the results and describing how the solution does what it was originality set out to do. The developed service time model quantifies the labour fatigue through a waste collection route. The service time model is used to study the effects of heart rate recovery on a collection route, and to make predictions about fatigue behaviour. The aim of our research effort was to develop a model that quantifies the fatigue of municipal waste collectors in an effort to do better route planning and to develop better routes. The service time model takes as input any collection route and as an output quantifies both the fatigue and service time continuously throughout the route. Figure 5.1 illustrates a portion of a collection vehicle route which traverses through nodes, $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 4 \rightarrow 3 \rightarrow 2 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow 10 \rightarrow 1$. Each arc has specific data assigned to it for input to the service time model.

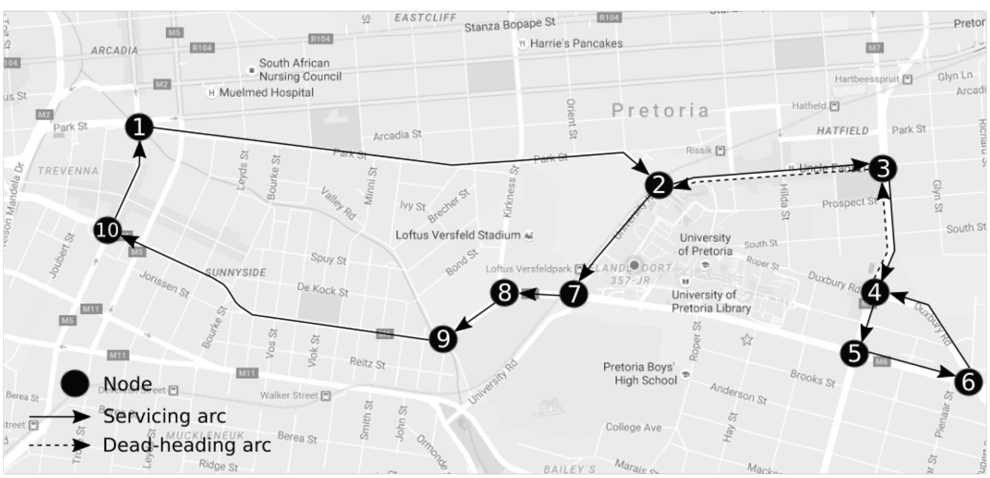


**Figure 5.1:** Arbitrary collection route.

Actual data of the arbitrary route in Figure 5.1 is presented in Table 5.1. The data includes the actual distance travelled by a collection vehicle in kilometres for each road segment. This distance was measured using the 'measure distance' function on Google Maps. Table 5.1 also includes the number of collection areas for each arc. This was determined by counting the total number of houses on each arc.

**Table 5.1:** Arc distance and collection area road data.

| Arc | Distance (km) | Number of collection areas |
|---|---|---|
| $1 \rightarrow 2$ | 3.040 | 60 |
| $2 \rightarrow 3$ | 1.070 | 21 |
| $3 \rightarrow 4$ | 0.610 | 12 |
| $4 \rightarrow 5$ | 0.294 | 10 |
| $5 \rightarrow 6$ | 0.601 | 12 |
| $6 \rightarrow 4$ | 0.711 | 14 |
| $4 \rightarrow 3$ | 0.610 | 12 |
| $3 \rightarrow 2$ | 1.070 | 21 |
| $2 \rightarrow 7$ | 0.690 | 13 |
| $7 \rightarrow 8$ | 0.323 | 11 |
| $8 \rightarrow 9$ | 0.417 | 12 |
| $9 \rightarrow 10$ | 1.720 | 34 |
| $10 \rightarrow 1$ | 0.521 | 10 |

Heart rate fatigue can be classified into three categories; minor, moderate and major fatigue. One's maximum heart rate (MHR) is roughly calculated as 220 bpm minus one's age [12]. The MHR is the upper limit of what one's cardiovascular system can handle during physical activity. Assuming 30 years of age as the average age of a waste collector and that major fatigue occurs at 70% of the MHR, we calculate a maximum major fatigue level of approximately 130 bpm. Minor fatigue occurs in the first third of the heart rate range. In contrast, major fatigue occurs in the last third of the heart rate range. This classification is shown in Figure 5.2. The service time model was used to evaluate three scenarios including; minor, moderate and major fatigue recovery.

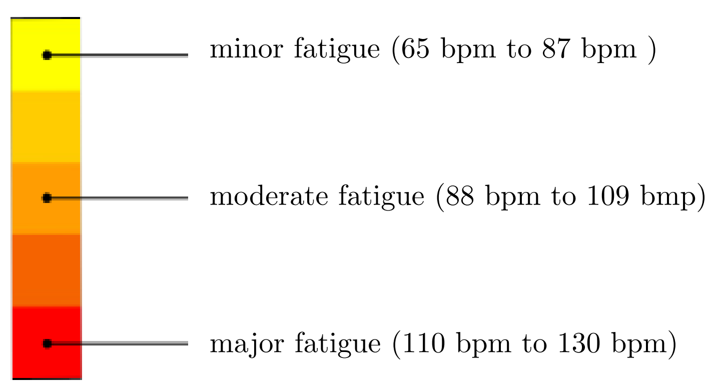


**Figure 5.2:** Heart rate fatigue scale.

## 5.1 Scenario one: minor fatigue recovery

Scenario one evaluates the recovery of minor fatigue. Minor fatigue recovery is the amount of recovery time required after reaching a minor fatigue level between 65 bpm and 87 bpm, to recover back to a resting heart rate of 65 bpm. Therefore, after servicing each arc a recovery break is modelled so that the workers recover back to their resting heart rate.

The fatigue route is shown in Figure 5.3. Evidently, most of the arcs are predominately yellow. This is because there is no immediate continuation of work between the arcs and thus only minor fatigue is endured. By allowing time for heart rate recovery after each arc, a waste collector's heart rate recovers to the resting heart rate of 65 bpm. This is then repeated for each arc.

The results of the minor fatigue recovery are shown in Table 5.2. The results include how much a worker's heart rate increased after servicing each arc, the corresponding recovery time needed to reach the resting heart rate and the service time per arc.

In arc 6 → 4 we see a heart rate increase of 7.37 bpm. However, the recovery time required for that arc is zero. This is because the following road is going to be dead-headed as shown in Figure 5.1, and therefore the recovery will occur while dead-heading. The total amount of recovery time needed in scenario one is 2.81 minutes and the total service time of the arbitrary route is 140.34 minutes. These two values are the base results with which the results found in scenario two and three were compared.

**Table 5.2:** Results of minor fatigue recovery.

| Arc | $HR_\Delta$ (bpm) | Recovery time (min) | Service time (min) |
|---|---|---|---|
| 1 → 2 | 31.48 | 1.63 | 40.63 |
| 2 → 3 | 11.59 | 0.27 | 13.92 |
| 3 → 4 | 6.39 | 0.06 | 7.86 |
| 4 → 5 | 5.27 | 0.01 | 6.51 |
| 5 → 6 | 6.30 | 0.05 | 7.85 |
| 6 → 4 | 7.37 | 0.00 | 9.10 |
| 4 → 3 | 0.00 | 0.00 | 0.61 |
| 3 → 2 | 0.00 | 0.00 | 1.07 |
| 2 → 7 | 6.82 | 0.07 | 8.52 |
| 7 → 8 | 5.80 | 0.07 | 7.22 |
| 8 → 9 | 6.31 | 0.06 | 7.86 |
| 9 → 10 | 17.86 | 0.57 | 22.67 |
| 10 → 1 | 5.44 | 0.02 | 6.52 |
| Total | | 2.81 | 140.34 |

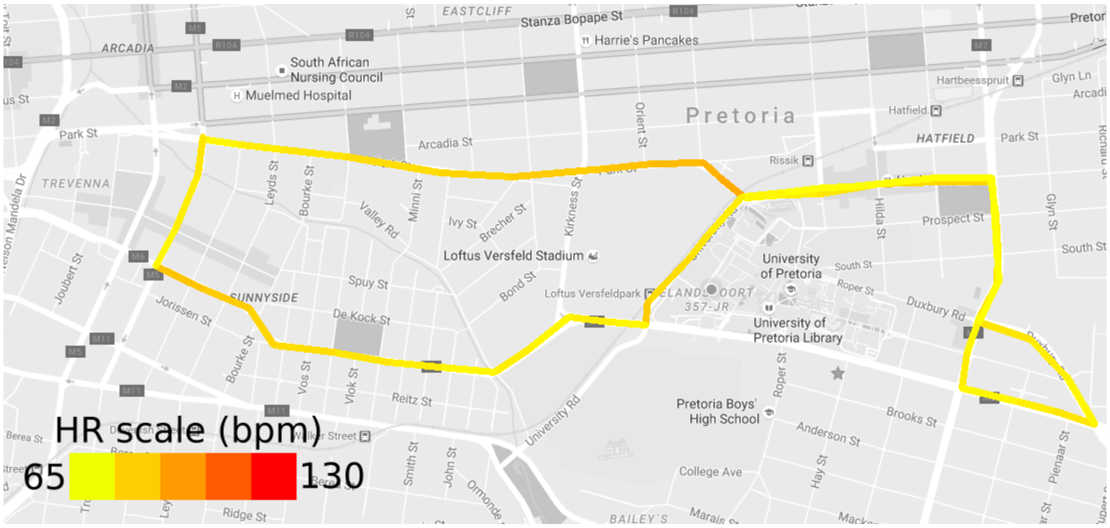


**Figure 5.3:** Minor fatigue recovery route.

## 5.2 Scenario two: moderate fatigue recovery

Scenario two evaluates the recovery of moderate fatigue. The model runs until a moderate fatigue level between 88 bpm and 109 bpm, and then recovers back to a resting heart rate of 65 bpm.

The pre-dead-heading and post-dead-heading fatigue routes are shown in Figure 5.4 and Figure 5.5 respectively. Figure 5.4 illustrates two signs of moderate fatigue. That is, the orange sections at the end of arc $1 \rightarrow 2$ and arc $6 \rightarrow 4$. We see the influence of the recovery period while dead-heading in Figure 5.5. Another sign of moderate fatigue appears at the end of arc $9 \rightarrow 10$. The worker then recovers for 2.43 minutes until the worker has recovered back to the resting heart rate.

The total amount of recovery time needed in scenario two is 4.95 minutes. The total service time of the arbitrary route is 142.48 minutes which is 2.14 minutes longer than scenario one. This increase in service time is because of the additional recovery time required.

**Table 5.3:** Results of moderate fatigue recovery.

| Arc | $HR_{\Delta}$ (bpm) | Cum HR (bpm) | Recovery time (min) | Service time (min) |
|---|---|---|---|---|
| $1 \rightarrow 2$ | 31.48 | 96.48 | 1.63 | 40.63 |
| $2 \rightarrow 3$ | 11.59 | 76.59 | | 13.65 |
| $3 \rightarrow 4$ | 6.39 | 82.98 | | 7.80 |
| $4 \rightarrow 5$ | 5.27 | 88.25 | 0.89 | 7.39 |
| $5 \rightarrow 6$ | 6.30 | 71.30 | | 7.80 |
| $6 \rightarrow 4$ | 7.37 | 78.67 | | 9.10 |
| $4 \rightarrow 3$ | 0.00 | 65.00 | | 0.61 |
| $3 \rightarrow 2$ | 0.00 | 65.00 | | 1.07 |
| $2 \rightarrow 7$ | 6.82 | 71.82 | | 8.45 |
| $7 \rightarrow 8$ | 5.80 | 77.62 | | 7.15 |
| $8 \rightarrow 9$ | 6.31 | 83.93 | | 7.80 |
| $9 \rightarrow 10$ | 17.86 | 101.79 | 2.43 | 24.53 |
| $10 \rightarrow 1$ | 5.44 | 70.44 | | 6.50 |
| Total | | | 4.95 | 142.48 |


**Figure 5.4:** Pre-dead-heading moderate fatigue recovery route.

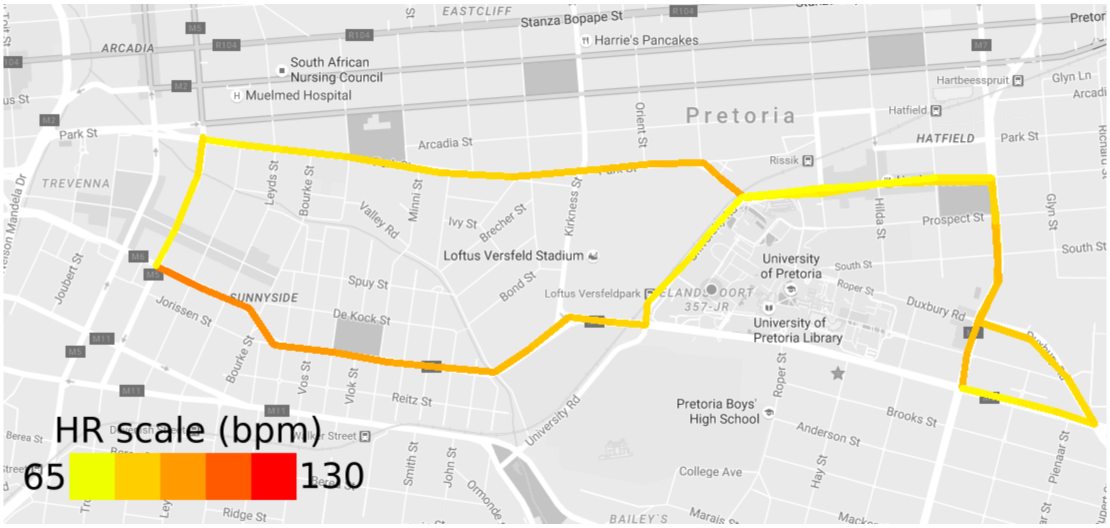


**Figure 5.5:** Post-dead-heading moderate fatigue recovery route.

## 5.3 Scenario three: major fatigue recovery

Scenario three evaluates the recovery of major fatigue. The model runs until a major fatigue level between 110 bpm to 130 bpm, and then recovers back to a resting heart rate of 65 bpm.

The pre-dead-heading and post-dead-heading fatigue routes are shown in Figure 5.6 and Figure 5.7 respectively. Figure 5.6 and Figure5.7 illustrate one sign of major fatigue, that is at the end of arc $2 \rightarrow 3$.

The total amount of recovery time needed in scenario three is 9.81 minutes. The total service time of the arbitrary route is 147.34 minutes which is 4.86 minutes longer than scenario two and 7.00 minutes longer than scenario one. This increase in service time is because of the additional recovery time required caused by the major fatigue endured.

**Table 5.4:** Results of major fatigue recovery.

| Arc | $HR_{\Delta}$ (bpm) | Cum HR (bpm) | Recovery time (min) | Service time (min) |
|---|---|---|---|---|
| $1 \rightarrow 2$ | 31.48 | 96.48 | | 39.00 |
| $2 \rightarrow 3$ | 11.59 | 108.07 | | 13.65 |
| $3 \rightarrow 4$ | 6.39 | 114.46 | 9.81 | 17.61 |
| $4 \rightarrow 5$ | 5.27 | 70.27 | | 6.50 |
| $5 \rightarrow 6$ | 6.30 | 76.57 | | 7.80 |
| $6 \rightarrow 4$ | 7.37 | 83.94 | | 9.10 |
| $4 \rightarrow 3$ | 0.00 | 65.25 | | 0.61 |
| $3 \rightarrow 2$ | 0.00 | 65.00 | | 1.07 |
| $2 \rightarrow 7$ | 6.82 | 71.82 | | 8.45 |
| $7 \rightarrow 8$ | 5.80 | 77.62 | | 7.15 |
| $8 \rightarrow 9$ | 6.31 | 83.93 | | 7.80 |
| $9 \rightarrow 10$ | 17.86 | 101.79 | | 22.10 |
| $10 \rightarrow 1$ | 5.44 | 107.23 | | 6.50 |
| Total | | | 9.81 | 147.34 |


**Figure 5.6:** Pre-dead-heading major fatigue recovery route.

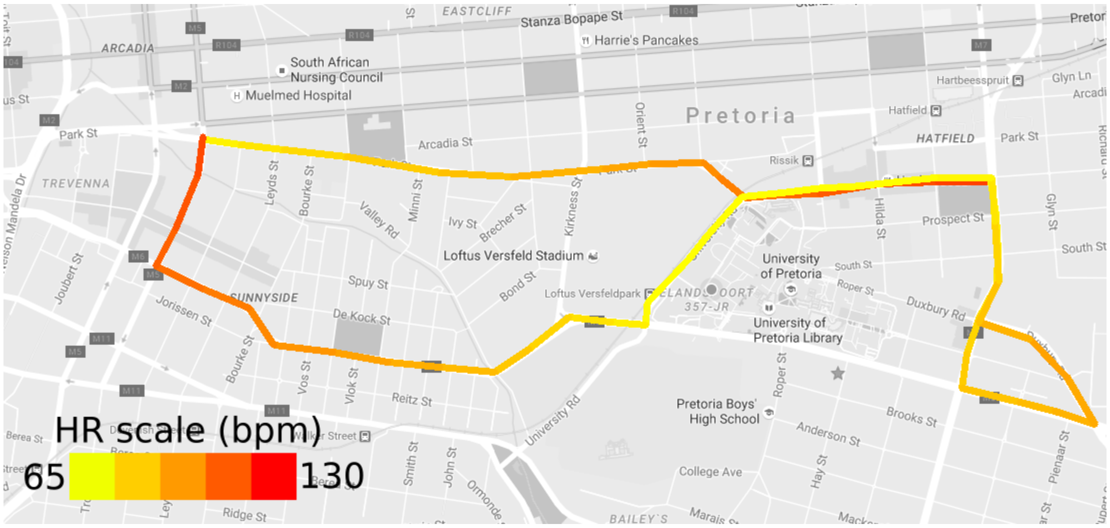


**Figure 5.7:** Post-dead-heading major fatigue recovery route.

## 5.4 Analysis of results

The heart rate is quantified at the end of each arc of the arbitrary collection route. The results of the three scenarios; minor, moderate and major fatigue recovery were computed using the service time model. The heart rate results are shown in Figure 5.8. Additionally, the service time results of the three tested scenarios are shown in Figure 5.9. The purpose of the evaluated scenarios are to demonstrate the influence of labour fatigue and its recovery on a waste collection route.

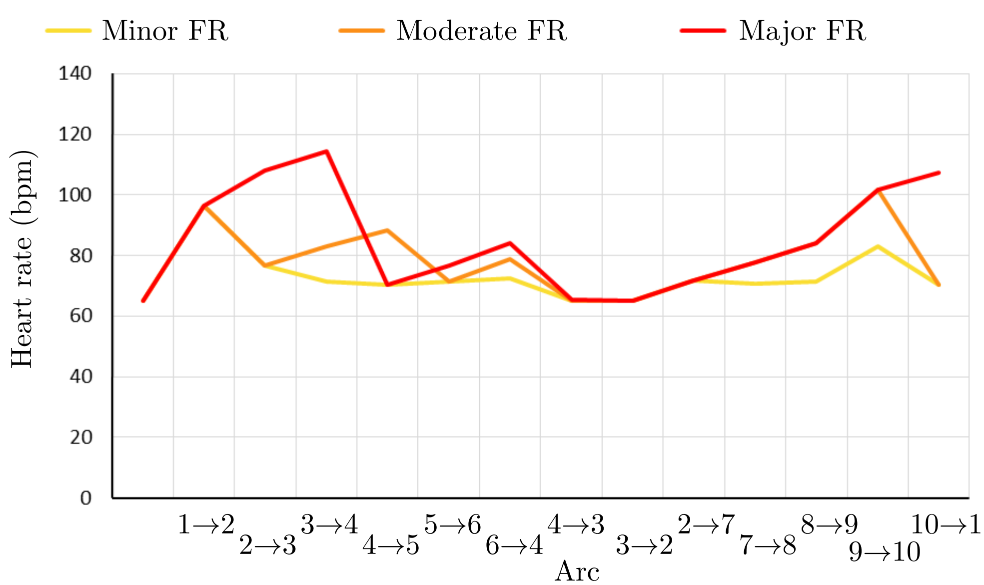


**Figure 5.8:** Heart rate results of the three scenarios.

Figure 5.8 illustrates the comparison of heart rates throughout the route of the three scenarios presented in this report. The lines on the graph with a positive gradient indicates an increasing heart rate while servicing the roads. The lines on the graph with negative or horizontal gradients indicate either a recovery break or dead-heading.

While dead-heading arcs $4 \to 3 \to 2$, we see a similarity with the three scenarios. In all three scenarios, the waste collector recovers back to the resting heart rate of 65 bpm. The worker is now well rested to continue servicing the following arcs.

Figure 5.9 illustrates the service times for each scenario. The lines on the graph with a steep gradient are present in arcs where servicing occurs. The lines on the graph with gradual slopes are present in the arcs where dead-heading occurs. Collectively, there is a minimal difference in the service time between the minor and moderate fatigue recovery scenarios. However, major fatigue recovery requires an identifiably larger service time. This is because of the exponential nature of the recovery time formula. The recovery time required increases from the minor to major fatigue recovery scenarios. Based on the example data used in our research effort, we observed that having many consistent and short recovery breaks results in a shorter total service time as compared to fewer but longer recovery breaks. Therefore, this demonstrates the large extent that dead-heading recovery has on the heart rate of workers.

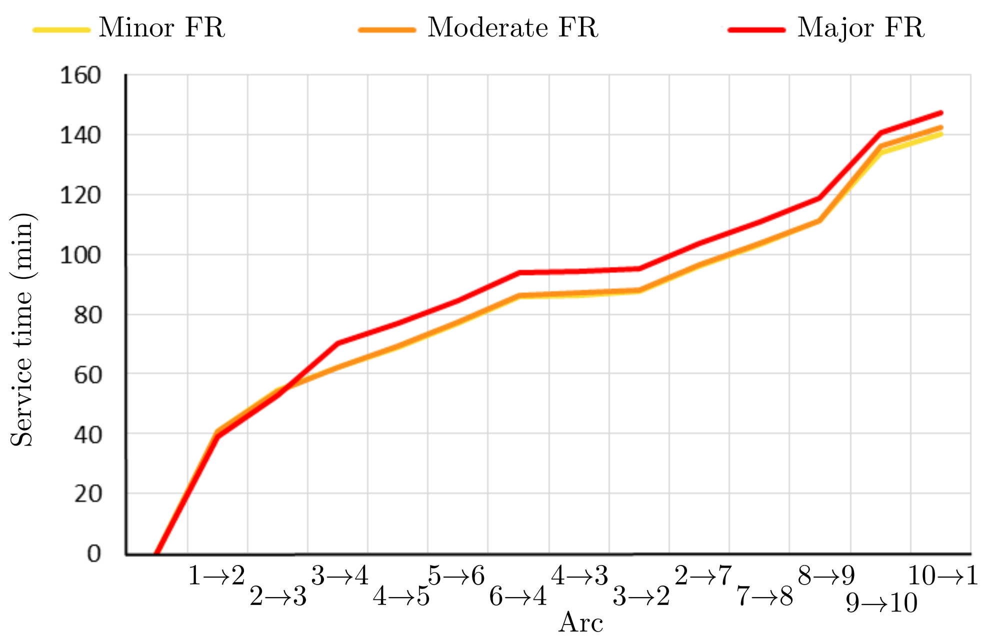


**Figure 5.9:** Service time results of the three scenarios.

## 5.5 Conclusion

The aim of our research effort was to quantify the fatigue and recovery of a waste collector in the form of heart rate. The developed service time model adequately met all of the requirements as set out in Chapter 1. That is, the model was able to quantify the fatigue and its recovery of a waste collector over any arbitrary collection route and compute the service time for each road segment, and the entire route. Therefore, the aim was successfully fulfilled and the solution was effectively validated.

# Chapter 6

# Conclusion and recommendations

The models developed in this report are able to quantify the fatigue and recovery of a waste collector in the form of heart rate. The service time model takes as input any arbitrary collection route and as yields as output, the dynamic heart rate throughout the entire collection route and the corresponding service time per road segment. The results are still limited, and an extension for future work is to validate the quantitative results of the service time model.

## 6.1 Strategy to validate the service time model results

The fourth process step in Manson's research methodology is 'evaluation', which involves validating the artefacts based on performance measures. In literature, minimal attention has been paid to fatigue and its recovery in the Capacitated Arc Routing Problem, and so, heart rate, recovery time and service time data is not easily available.

The real life validation data can be gathered experimentally by attaching heart rate monitors to waste collectors, and measuring the time it takes them to service each road segment with a stop-watch.

The heart rates and service times at the end of each arc can be compared to the service time model output to validate the model. If there are any major deviations in the model's results as compared to the real life data, the root causes of the deviations will be identified and critically evaluated. The necessary modifications will be made to either the model or the input data or both, and the validation process will repeat until the model's results have been effectively validated.

## 6.2 Limitations and extensions of the model

With reference to the literature review, Figure 2.1 illustrates that both mean power frequency and oxygen uptake can also be used as metrics of labour fatigue. A limitation of the models developed in our research effort was that they focus purely on work pulse rate as the metric. An extension of the model may be to include both a muscle fatigue metric combined with the current cardiac fatigue metric. This will allow for a more accurate representation of labour fatigue because waste collectors endure both cardiac and muscle strain.

An assumption made prior to the model development was that labour fatigue is mostly caused from work related fatigue factors and is not dependent on any other factors such as sleep, temperature, substance abuse, noise, nor the stench of the waste. These factors may also be significant contributing causes of labour fatigue. An extension of the model may be to consider the other causes of fatigue in the model development.

## 6.3 Concluding remarks

This report has highlighted and addressed phase one of our research effort, which is the quantification of labour fatigue and its recovery in the Capacitated Arc Routing Problem with the direct application to waste collection. Despite the limitations inherent in the proposed models, their novelty could hold some critical potential for further re-imagination of labour fatigue constraints in the Capacitated Arc Routing Problem. In this way the fatigue of waste collectors can be quantified over any arbitrary collection route, which can be used to do better route planning and to develop better routes. Based on the example data and the results presented in Chapter 5, route planners should consider labour fatigue when developing collection routes. Furthermore, the models and results presented in this report only form part of the first research phase of labour fatigue constraints in the Capacitated Arc Routing Problem, and an extension for future work is still required.

## 6.4 Future work

Heart rate and its recovery is highly dependent on the individuals that are doing the physical work. Phase one of our research effort simply used averages and heart rate distributions of other individuals. Therefore, the second phase would be a means to gather the necessary input data, including; resting heart rate and two minute recovery time data of the actual waste collectors servicing the collection routes.

Lastly, the third phase of our research effort would be to use the improved service time model with the necessary input data for the purpose it was built for. That is, to use the service time model together with the developed constructive heuristics for the Capacitated Arc Routing Problem. This may adapt the routes as to account for human factors when optimising the collection routes. Ultimately, the new routes will have the potential to secure high productivity without compromising the health and safety of waste collectors.

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