Shipment Consolidation Policy Project

A Case Study at The Integrated Logistics Product Area at the Case Company

Master Thesis

Division of Production Management
at Lund University, Faculty of Engineering, LTH

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Tom Wachtmeister, Carl Tornerhjelm
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Abstract

Title: Shipment Consolidation Policy Project. A case study at the Integrated Logistics Product Area at the Case Company.

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Background: Larger corporations that distribute products and goods globally face both internal and external demands from stakeholders. High service levels call for frequent shipping for goods to arrive on time. However, frequent shipping comes at a higher cost. Lately, this has become an issue for the case company. At its cross-docking warehouse - which ships unique orders - high safety stock is not an option. Therefore, to reduce the shipping cost, the company's alternative would be to increase lead times and consolidate shipments into larger batches. This will reduce the number of shipments and hence reduce the transportation cost. The key is to find a balance between these two alternatives to satisfy all parties by implementing an appropriate consolidation policy.

Purpose: The purpose of this thesis is to evaluate whether a new shipment consolidation policy could be implemented for selected test locations.

Research Questions: (1) Will a shipping consolidation policy reduce the total shipping costs while maintaining a reasonable service level? (2) For locations with different order frequencies, is the consolidation cost reduction benefit equal?

Methodology: The methodology framework was inspired by Höst et al. The process included first defining the problem to be able to acknowledge what relevant data needed to be collected. This included both quantitative and qualitative data, as well as the literature required to solve the research study. When all necessary data had been collected, statistical data analysis was completed for the order arrival time, weight and volume to use as input for the developed model.

Conclusion: The belief is that the case company should implement a consolidation policy for the selected locations. At reasonable service levels, all locations show significant shipping cost reductions. The researchers found that the cost reduction benefit is equal for different order frequency locations if the optimal Time and Quantity- based policy is implemented. However, due to the holding period restrictions set by the case company, the team recommends that the company focuses on high-frequency locations, as these show a greater cost reduction benefit for short holding periods. Furthermore, the data analysis found that the data can be used in the mathematical model obtained in the literature with some modifications. Moreover, the model is proven to be robust as the output is only slightly affected by changes in estimated parameter inputs.

Keywords: Shipment Consolidation Policy; Consolidated shipping; Dispatch policy; Time and Quantity Based Policy; Analytical Model; Cross-docking.

Table of Abbreviations

3PL	Third-Party Logistics
BA	Business Area
BU	Business Unit
CDF	Cumulative Density Function
ERP	Enterprise Resource Planning
IL	Integrated Logistics
L	Lead Time
OR	Operations Research
PA	Production Areas
PDF	Probability Density Function
PMF	Probability Mass Function
SS	Site Shipping
TQ	Time-Quantity
VBA	Visual Basics for Applications
WIP	Work in Progress

Definitions

Common carriage:	Public, for-hire transportation.
Cross-Docking	Unloading incoming materials to pack for immediate outbound departure with little or no storage time.
Decision Support System:	Interactive computer-based system to assist managers in their decision making.

Internal retailers:	AB Tetra Pak subsidiaries.
Order weight:	The order weight always refers to the selected invoiced weight. Meaning, the maximum value between actual weight (kg) and the volumetric weight.
Service Level:	Customer goods are dispatched within the specified time frame, in this case: 2 working days.

Contents

1. Introduction

This chapter will present the background to this master thesis project, the case company, and the problem formulation. Furthermore, this chapter will introduce the purpose with this thesis, scope and a brief discussion about the chosen delimitations.

1.1 Background

Studies on supply chain management more often involve the production and inventory control approach to support the decision-making process. Although useful, it neglects the nodes between these processes and the potential cost saving opportunities (Çetinkaya & Bookbinder, 2003). Shipment consolidation through aggregated orders aims at resolving this issue.

The objective when using consolidated shipping is to lower the transportation cost. The potential cost savings arise from the economies of scale, since the shipments are done in larger loads (Mutlu, Çetinkaya & Bookbinder, 2009). Other cost savings occur when multiple orders split the fixed costs that are associated with a shipment (Higginson & Bookbinder, 1995). There are three main policies regarding shipment consolidation, and these are: time-, quantity- and time-quantity-based consolidation. These different theories will be described in Chapter 3.

The overall objective with the study is to examine if shipment consolidation is a preferred solution to what is currently used at the case company. Today, all packages within a certain weight and size dimension is shipped individually from the shipping department in Lund, Sweden. Moreover, according to the company, this frequent shipping procedure comes at a high cost using the current distributor. The company, therefore, wants to evaluate if an alternative policy can be used to lower this transportation cost. (M. Gejde, 2018, Personal Communication, 19 Dec.)

Furthermore, shipment consolidation has been suggested to resolve this problem. Consolidated shipping is a method of dispatching multiple orders to the same destination, as a batch. When orders arrive at the designated destination, the batch is de-consolidated and individual orders are sent to their final destinations. (Global Negotiator, 2019) In this case, goods will be sent to the customer as a batch directly and will not be de-consolidated for further transportation.

Typical trade-offs when using consolidated shipment are lower service levels and higher waiting costs. This is a consequence of longer holding periods and less frequently shipped orders. The challenge is to find the balance between all parameters and choose the most appropriate shipping strategy. (Higginson & Bookbinder 1994)

1.2 The Case Company

This thesis is carried out in cooperation with AB Tetra Pak, part of the Tetra Laval Group. Hereinafter, AB Tetra Pak is referred to as “Tetra Pak”, “the case company”, “the company” unless stated differently.

In 1952, the company delivered its first machines which made tetrahedron-shaped packages. Ever since the company started, they have been world leading within the processing and packaging solutions market for food and other perishable goods. (AB Tetra Pak, 2019)

Today, Tetra Pak operates globally and is present in more than 160 countries with over 24,000 employees. In 2017, Tetra Pak had a total revenue of 16.1bn SEK and a total profit of 404m SEK (Retriever Business, 2019). The case company consists of the following business segments: Packaging, Processing, and Services. The company group focuses on being a specialist in processing, packaging and distributing perishable products. The motto “Protects what’s good” reflects its vision of making food safe and globally available. In 2008, over 141 billion units were produced by Tetra Pak’s machines. (AB Tetra Pak Annual Report, 2018)

This thesis will be completed in cooperation with and have its focus on the Integrated Logistics (IL) Product Area (PA), part of the Service Business Area. The PA handles shipments for the employees at the site in Lund. The products are shipped globally and range from machines to spare parts and documents.

1.3 Problem Description

The motivation for the problem stems from discussions with the IL PA and their current procedures for conducting internal shipping. Internal shipping refers to the internal retailers, i.e. other Tetra Pak subsidiaries. Furthermore, the department currently outsources to a 3PL distributor to ship all products - within certain weight and size dimensions - from the Shipping business unit (BU) in Lund, Sweden. All goods within this specified range are shipped using a global express service and are delivered to different retailers. Depending on the retailer location, the shipping is either conducted by air- or road freight. Due to the frequent orders and deliveries, the 3PL provider has a full-time employee at the case company's premises. All goods not specified within this weight and volume range is shipped separately using other 3PL providers. However, these goods will not be considered in this report. This project will only analyse orders shipped using the express 3PL and the orders falling within the specified weight and volume range. The current process satisfies customer service levels, but recently the company has started to experience higher costs related to this service.

As a result of this, the company wants to investigate whether it is possible to use an alternative method to reduce costs while maintaining a similar service level. After further investigation, the IL PA has suggested that a consolidated shipping policy could satisfy these requirements and should be further investigated for potential future implementation. The suggestion includes that goods departing to the same destination can be consolidated and shipped together. As freight costs are closely correlated to total size and weight of carried goods, this could potentially lower these costs when the orders are shipped in larger batches. As the consolidated shipment policy has not yet been implemented, this thesis will focus on investigating how such a distribution network would perform using empirical data. The consolidated shipment distribution channel must remain equal to the current process. This allows current and future shipment policies to be compared fairly.

1.4 Purpose of Study and Research Questions

The purpose of this thesis is to evaluate whether a new shipment consolidation policy could be implemented for selected test locations. The result will arise from the developed decision support system which will use case company parameters as inputs. The model can be adjusted and applied to any similar business facing similar problems. Hence, this report can be used as the basis of evaluation when a company is considering implementing a shipment consolidation policy. Furthermore, differences between companies are inevitable and shall be considered when making this evaluation.

The thesis objective is to answer the following research questions:

1. Will a shipping consolidation policy reduce the total shipping costs while maintaining a reasonable service level?
2. For locations with different order frequencies, is the consolidation cost reduction benefit equal?

1.5 Project Scope and Delimitations

The purpose of the thesis project is to evaluate if a change to a consolidated shipping policy can reduce transportation costs, as described in section 1.3. Due to time limitations, the authors have decided to limit the scope of the project in order to reach a conclusion within the given time frame. The conclusion can then be further used for additional structural change within the case company.

The case study includes shipments from one targeted warehouse in Lund, Sweden. The warehouse in Lund is the only warehouse considered in the scope of the thesis, as the majority of orders are sent from this location. The scope of the distribution will also be limited to the following destinations: Location A; Location B; and Location C. The motivation for selecting these three destinations are:

1. The selected locations have different order frequencies. Therefore, it will be possible to compare the benefit of consolidating orders for locations with different annual order volumes.
2. Goods are transported to all three destinations using Express freight. Meaning that the packages will be handled using a similar priority.

Delimitations include the following:

1. The goods parameters will be limited based on weight and dimensions, as these two parameters are the sole contributors to the transportation cost. The actual product and content itself will not be evaluated as it does not affect this cost.
2. Based on the location, the transportation time between the warehouse and the receiver is assumed to be constant.
3. All orders studied can be assumed to be of similar priority, i.e. the maximum acceptable waiting time for a customer is similar for all goods shipped to that location.
4. The only orders analysed in this report are the orders sent with the express 3PL provider that fall within the specified weight and volume range.

2. Methodology

This chapter will describe four different fundamental approaches to completing a research report. In addition to this, a more specific method for operations research (OR) will be described. Furthermore, this chapter will also describe and motivate the research strategy, data collection method and analysis approach chosen to conduct this report.

2.1 Research Strategy

The research strategy shall be different depending on the objectives and characteristics of the report. A strategy will generally be picked depending on the purpose of the report. These purposes are generally one of the following: descriptive, exploratory, explanatory or problem-solving. The descriptive study aims at describing how something works or is done. Like the descriptive study, the exploratory study aims at truly understanding the fundamentals of a process. Explanatory studies aim at figuring out cause and effect relationships and what these effects imply. Finally, the problem-solving studies - which are the most common at technology universities - purpose is to solve an identified problem. Furthermore, these purposes are not mutually exclusive and can change during the project. (Höst, Regnell & Runesson, 2006)

When the purpose of the study has been concluded, the appropriate method needs to be selected. To successfully use these methods, different “tools” will be used systematically to gather data and complete the analysis. These include surveys, interviews, observations, and document analysis. The four most relevant methods for master thesis work within applied disciplines will be described briefly in the following sections. (Höst, Regnell & Runesson, 2006)

2.1.1 Survey

A survey method is common when the purpose of the research report is descriptive. It aims at unveiling a certain phenomenon to gain greater understanding of what is studied. The survey is usually targeted at a sample from a certain population, meaning that you survey a sample that fairly represents the entire population. Furthermore, if the population is small, the survey can target the entire group.

The selection is based on a predefined list of individuals or units that the survey wants to study. To get a presentable result, the selection must be based on a randomly generated subset. It is common that the targeted sample is large. Thus, an effective system is needed to collect and analyse the selected data. Surveys with structured lists can be used to accommodate these issues. (Höst, Regnell & Runesson, 2006)

2.1.2 Case Study

A case study is a study with the purpose to describe something thoroughly. It is often used to describe contemporary phenomena. According to Yin 2009, this is when the studies phenomenon is hard to separate from its environment. The study can also be conducted in a series of case studies. Furthermore, this may result in a general pattern for the selected setting. However, unlike the survey method, the selected data is not random and cannot be "proof" of statistically secure results. It does, however, give a more in-depth description compared to the survey method.

In the case study, the following techniques for data collection are used: interviews, observation, and archive analysis. Interviews can be either structured (similar to an oral poll), half structured (set of predefined interview questions to support the interview flow), or openly directed (the interviewed mainly controls the interview). (Yin, 2009)

Observations mean that the observer studies an object and take note of the observation. The observer can be either partly or fully observing. The observer who is "partly observing" take an active part in the process by being part of it. Furthermore, this may lead to greater study validation as the observer feel more engaged. However, this can result in reduced understanding of the purpose of the engagement. On the contrary, the full observer does not allow this to happen. However, the full observer may lack the necessary insights needed due to a lack of participation. (Höst, Regnell & Runesson, 2006)

2.1.3 Experiment

To gain a greater understanding of the different phenomenon and their cause; a more directed method is required. The experiment method is one of them. When using this method, different solutions - with similar presumptions - can be compared to find the best solution. The method can also be used to study a single solution by tweaking different parameters to see how these influence the result. (Höst, Regnell & Runesson, 2006)

The experiment is fixed, meaning that it cannot be edited when the study has begun. Thus, extensive preparation is important along with well-defined study objectives. This is usually done by enunciating a hypothesis that is systematically tested until it is rejected, and the hypothesis is modified. Furthermore, if the hypothesis is not rejected, it is considered to be true. (Höst, Regnell & Runesson, 2006)

2.1.4 Action Research

Action research is a more extensive method used to study something thoroughly with the purpose to find a better solution. It is commonly used when the report has a problem solving characteristic and is often interpreted as a case study. However, Höst et al. choose to describe it separately. An action research method usually starts with a case study or survey to extensively clarify the problem. When the problem has been identified and clarified; it is solved using an iterative process to find an appropriate solution. The new solution is reviewed and modified if not satisfactory. When an approved solution has been found; it is reviewed using e.g. surveys, observations or interviews before being implemented. (Höst, Regnell & Runesson, 2006)

2.2 Research Approach

There are three main approaches to a research process: *deductive*-, *inductive* and *abductive* approach. The deductive process follows a very strict framework and moves from known existing theories (or “laws”) to a specific case. Furthermore, it uses prior literature and theoretical conclusions to test its empirical data to reach a final conclusion. On the contrary, the inductive approach uses real-life observations to reach a general theory (see Figure 1). The abductive approach uses a combination of the previous two approaches and tries to focus on the particularities of different structures that may deviate from general structures. Moreover, the deductive approach aims at using existing theories whilst the abductive and inductive aims at assessing this theory. The deductive approach seems to be the most predominant approach in business logistics research. It is also the approach assumed if nothing else is mentioned. This is surprising considering the fact that this field of research still is relatively new. On the contrary, few mentions using an abductive approach. (Kovács & Spens, 2005)

Abduction is often referred to as a very creative approach as it requires interpretation of different phenomenon and re-contextualizing this phenomenon within a contextual framework. It involves trying to continuously match the empirical observations with different theories, referred to as “theory matching”. This can often result in a “learning loop” until a final conclusion is reached. See Figure 1 for this illustration. Unlike the inductive approach, the researcher most often has some pre-preventions and previous theoretical knowledge when starting the project. In some cases, the abductive starts later in the process and the researcher has already determined what theory to use when conducting the empirical observation. The abductive reasoning begins when the researcher realise that empirical research does not match the previously collected theories and a creative iterative process begins to try to find matching frameworks. (Kovács & Spens, 2005)

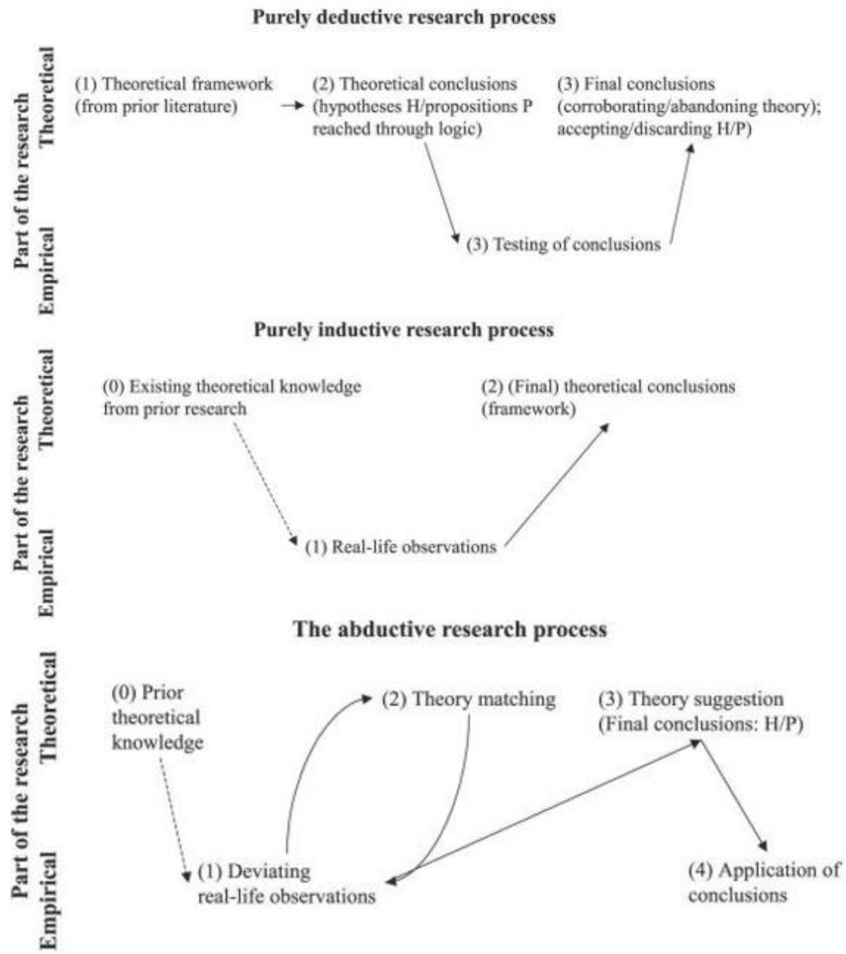


Figure 1: Different research approaches (Kovács & Spens, 2005).

2.3 Selected Research Strategy and Approach

The purpose of this study is *problem-solving* as the objective is to find a solution to a current identified problem. Furthermore, the study will use a *case study* methodology to solve this problem. The motivation for selecting this method is:

1. The problem is solved at a case company and the result is not claimed to be generalised as a solution for similar situations at different companies. This, together with the limited time frame motivates why the *action research* method shall not be selected as this solves a more general problem over an extensive period.
2. It is flexible, meaning that it can be adjusted during the course of its process. This is one of the main characteristics of the case study method and is not possible using e.g. the survey method.

The initial approach was to use a *deductive* method to complete this project. However, it became apparent in the initial stage of the study that the literature theories available was not sufficient to solve the case study using a purely *deductive* process. Instead, the approach was reconsidered to be *abductive*, as theory matching was continuously used. Using a case study methodology, another motivation to consider the approach abductive is that case study methods commonly use an iterative aspect between theory and empirical studies (Kovács & Spens, 2005).

2.4 Operations Research

Introduction to Operations Research by Hillier & Lieberman 2010 describes the process of researching the different processes within an organisation. More relevantly, it describes the process of *operations research modelling*. This includes placing things into better perspectives by describing all the major parts of an Operations Research (OR) study. The following subsections will list these parts sequentially and describe their purpose. (Hillier & Lieberman, 2010)

2.4.1 Defining the Problem and Gathering Data

Very often practical problems are presented in a very vague manner. To fully understand the context and magnitude of the problem, a pronounced definition is required. This includes the appropriate objective with clear research questions, constraints, and interrelationships between the studied activity and other interactive activities. As Lieberman simply describes it: “It is difficult to extract a “right” answer from the “wrong” problem”. During the course of the study, the team must continually report recommendations to the case company management team to allow them to make decisions based on the best judgement; to avoid cross-purpose. As mentioned previously, defining the objective of the report is crucial to avoid solving the “wrong” problem. This is done by identifying key managers of management who are responsible for making the decisions and truly understanding the individuals thinking process. As OR is part of the welfare for the entire organization; the research objectives shall ideally be aligned with the overall objective of the organization. However, this is not always convenient. Furthermore, another issue that may evolve when the objective is defined is that the necessary data has not been collected. Therefore, the team may need to implement a new management information system to assess the necessary data. In most cases, however, data is excessive rather than inadequate. (Hillier & Lieberman, 2010)

2.4.2 Formulate a Mathematical Model to Represent the Problem

When the definition has been made; the problem needs to be formulated in a convenient way for analysis. This is done by developing a mathematical model that represents the essence of the problem. Models are an integral part of everyday life and are usually expressed through mathematical symbols and expressions. A mathematical model consists of *decision variables,* whose respective values need to be determined. The measure of performance is a mathematical formula that consists of these variables and is commonly referred to as the *objective function*. Furthermore, *constraints* are restrictions which decide which boundaries the decision variable values can get. Moreover, *parameters* are constant values found in both the constraint and objective functions. (Hillier & Lieberman, 2010)

In a practical case; assigning the appropriate values to the parameters can be challenging and requires extensive data gathering. As mentioned previously, the correct parameter may not be available. The value must be estimated, and a *sensitivity analysis* can be conducted to see how the result would change for different parameter values. The mathematical model has many advantages, some of these include: describe problem concisely, find cause-effect relationships and form a bridge between high powered techniques (computers). However, pitfalls can occur if bad approximations and simplifying assumptions are made - resulting in an invalid representation of the real problem. (Hillier & Lieberman, 2010)

This process is very familiar to the one found in the typical abductive research approach. Once data has been gathered, the mathematical model is continuously tested and refined until fully developed. This refinement is an iterative process between available theories and the observed phenomenon, see Figure 1.

2.4.3 Develop a Computer-Based Procedure for Deriving Solutions to the Problem from the Model

According to Hillier & Lieberman, the part of the process when a process is derived to obtain the solution to the problem is simple. In most cases, this can be done by using built-in software algorithms. For the more experienced operations researcher, this is considered to be the fun part. The more extensive work of *post optimality analysing* (also referred to as what-if analysis) comes at a later stage and is described in the following sections. Furthermore, an "optimal" solution is hard to find as the mathematical model rarely represent the real problem exactly. OR rarely seek only one optimal solution. In many cases, several models are developed to find alternative solutions. Moreover, a what-if analysis is required to grasp what would happen if different assumptions are made. (Hillier & Lieberman, 2010)

2.4.4 Test the Model and Refine it as Needed

The first version of a model often contains many bugs and needs to be tested over a long period of time to allow for continuous improvement. The model will most likely also include a lot of flaws due to inaccurate estimations. This process of testing and improving is usually referred to as *model validation*. Eventually, the team concludes that the model gives valid results and can be reliably used. An alternative method for validating the model is to use the model to replicate the past. By comparing the result with the actual historical data, the model can be validated. However, this assumes that historic data can be used to represent the future. (Hillier & Lieberman, 2010)

2.4.5 Prepare for Ongoing Application of the Model as Prescribed by Management

When the previous steps have been completed and the model is found to be acceptable, the next step is to install a well-documented system for applying the model. In many cases, this system is computerised and may provide updated input data every time it is used. An interactive computer-based system called a *decision support system* is installed to assist managers in their decision making. In larger OR studies, this computer-based system can take several months to develop and install. This process includes developing maintenance systems to adapt the system for future requirements and use. (Hillier & Lieberman, 2010)

2.4.6 Implement

The final step of the OR study is to implement the developed system - i.e. implement the result from the study. In order to be successful, this requires support from both top management and the OR team. To gain support from top management, good communication is essential between the parties to ensure that the final outcome is in accordance with management expectations. Implementation usually occurs in several steps, these include: explain how the new system works and relates to current activities; teach staff how to use the system and review the system; and make necessary adjustments. (Hillier & Lieberman, 2010)

2.5 Data Collection

In a thesis, there are multiple ways of collecting data. This subchapter will describe the different methods for data collection and motivate the method selected to complete this thesis.

2.5.1 Log Book

When writing the thesis project a large amount of data is collected, consciously or unconsciously. The collected data will be observed and analysed and will lead the project in different directions and it is therefore important to be able to describe and reflect over the choices made. An easy way of doing so is to write a logbook. (Höst, Regnell & Runesson, 2006)

The logbook does not need to include all the details, but it should show what has been done and when it was done. Meetings, interviews, internal thesis work, etc is important to document. Other parts of the thesis that is important to document include the literature studied and other background material. The logbook should reflect when *activities* were performed rather than the information itself (these are instead presented in the theory chapter). Two types of logbooks can be written: electronic or paper based. If most of the work is done on computers an electronic logbook is preferred, but if field studies and meetings are the most commonly used data collection in the thesis a paper-based logbook is preferred. (Höst, Regnell & Runesson, 2006)

2.5.2 Surveys

A survey is a questionnaire that often has fixed questions and predefined answers. Surveys are usually used to collect opinions and perceptions from a larger group of people. There are several ways of distributing a survey:

1. Postal surveys, which are sent out by paper and are returned via a prepaid reply envelope.
2. Group surveys are distributed to people who regularly meet in one place, i.e. a workplace.
3. Questionnaire to visitors is dealt out to people who of one's own accord visit a certain location; it can be a physical store or a webpage.
4. A computer poll is often distributed via email.
5. The questionnaire for the interested party is the final survey method and is often handed out as an appendix for a paper or together with a product.

The foundation for how well the answers to the surveys can be used and generalized depends on how the selection was made, i.e. how the population that was offered to answer to the survey was chosen. As there are several ways of distributing a survey, there are five ways to select the targeted population, these include:

1. Census is used if one wants to target everyone in a certain population, but this is only practical in the cases where the population is small.
2. Unbound random selection is when a randomiser helps to target a subset of the population. Everyone in the population has the same chance of being chosen in order to get representative responses.
3. Systematic selection means that every N:th person in the population is targeted. This way of choosing a subset can be risky, especially if the list of the population has some periodicity.
4. Two-stage selection can make the practical handling of the survey easier since the targeted population lives close geographically. When using this method, one randomly selects a subset of a cluster and then the population is randomly selected from this subset.
5. Stratified selection reminds of the two-stage selection, but now it is a systematic difference between the clusters and the different clusters are belonging to different categories.

After the way of distributing the survey and how the selection of the targeted population has been made the remaining part is to receive answers. There are two different losses of information, the first one being an external loss, which means that some in the targeted population did not answer the survey. The other loss is called internal loss, and this is when a question in the survey is not answered. To reduce the number of external loss one can have rewards for answering etc. It is important to remember not to add any more people from the larger population to the targeted since that would compromise the randomness in the selection. (Höst, Regnell & Runesson, 2006)

2.5.3 Interviews

An interview is a systematic questioning of respondents and the information from the interviews are usually comments or proposals for solutions. The answers to the questions should either be written down during the interview or/and be recorded. An interview can be carried out through a physical meeting or via skype or over the phone. (Höst, Regnell & Runesson, 2006)

As in the case of surveys, the respondents are selected out of a population. If people are selected based on categories such as men-women or newly employed-experienced the answers cannot be generalized but one can make a deep qualitative analysis. (Höst, Regnell & Runesson, 2006)

The interview should start with a brief description of the interview and answer questions: What is the purpose? Why is the respondent selected? How will the information be handled and worked with? And if the interview will be recorded the respondent should be informed. The interview should then proceed to the starting questions, and these should be about age, education and duties. When this phase is done the main questions for the interview should be asked, and in an order that is logical for the respondent. Finally, the interview should be summarised briefly, and the respondent should be given the opportunity to add some final answers. (Höst, Regnell & Runesson, 2006)

2.5.4 Observations

To study a phenomenon or a course of events in a thesis one can use direct observations. This means that with the help of technical tools or by one’s own minds collects data about what happens in different situations. The level of interaction for the observer can vary from being active to only observe. An observing participant tries to become as integrated as possible in the observed group and the group is fully aware that the observer is there. The data collection is usually done by taking notes and using a logbook. (Höst, Regnell & Runesson, 2006)

When instead using full participation, the observer is also an integrated part of the observed group. However, the observed group does not know that they are being observed. As in the previous observation method, the preferred way of collecting the data is by taking notes and using a logbook. (Höst, Regnell & Runesson, 2006)

The *participating observer* is known and recognised by the observed group. Often the group knows the objective that the researcher has but the interaction between the group and the researcher is limited. The researcher wants to play a neutral role and not interfere with work. (Höst, Regnell & Runesson, 2006)

The *full observer* does not take part in the operations and is completely invisible. The data collection is done completely hidden, e.g. with a camera or tape recordings. In the cases when the observer is fully visible there is a risk that he or she affects the observed phenomenon, but in the other case, such as this one, the ethical questions arise. (Höst, Regnell & Runesson, 2006)

2.5.5 Measure

Measurements can be direct or indirect. Measuring a distance with a ruler is a direct measurement but measuring velocity is an indirect measurement. Velocity is an indirect measurement since it is measured by using distance and time. A scale is often used to put the collected data into different categories and in practice for scales are commonly used, these can be seen below.

1. Nominal scale - Categorising of the observed in different classes, i.e. red, yellow and green.
2. Ordinal scale - Ranking of the entities based on a criterion and this is more complex.
3. Interval scale - A ranking where the difference between levels has a meaning, i.e. temperature on a Celsius scale.
4. Ratio scales - A scale where there is a meaningful zero. Thus, the quota between two measurements gets a meaning, i.e. temperature on a Kelvin scale.

Measurement errors often occur when measuring physical phenomena and the errors are often divided into three categories. These are gross errors, systematic errors and temporary errors. (Höst, Regnell & Runesson, 2006)

2.5.6 Data that Others have Collected

If one wants to use already collected data in order to speed up the process one can find four different types of data, these are the following:

1. Processed data - Data that have been collected and processed in a scientific context, i.e. academic publications and theses.
2. Available statistics - Data that have been collected and processes but where no analysis has been carried out on the results.
3. Registry data - Data that have been collected for any purpose and the data is available in an unprocessed format, this can for example be customer records.
4. Archive data - Data that have not been systemised as data, i.e. protocols, correspondence, and project documentation

The four types of data have one thing in common: collected data has previously been used for a different purpose. As the data is collected by another person it is important to critically evaluate both the material and analysis. (Höst, Regnell & Runesson, 2006)

2.5.7 Experiments

If several factors affect a phenomenon and one can manipulate factors and combinations, the number of combinations of factors increase quickly. This is the case for experiment- and simulation studies. Instead of varying one factor at a time and examine its effect one can use systematic methods for experiments, e.g. 2k factor analysis. If used correctly, conclusions can be drawn to how they affect the phenomena separately and how they affect each other. (Höst, Regnell & Runesson, 2006)

2.6 Data Collection used in this Project

In this project, a couple of the above-listed methods of data collection have been used. The most predominant method being data that others have collected. The rationale behind this is that this project mainly will use quantitative data, which the case company already has gathered. Observations will be used to see how the case company operates today, as this thesis project evaluates if a new way of operating would lead to potential cost reductions. Unstructured interviews with people from different management levels in the organisation will be carried out to understand the product flow, organisation structure and to get key insights and answers on questions that arise during this project. Furthermore, indirect data will be measured to use in the analysis.

2.7 Data Analysis and Validity

To make good use of the data and fully interpret it, it needs to be analysed. According to Höst et al., this data analysis can be separated into two main categories depending on what characteristics the data has. These characteristics are either *quantitative or qualitative.*

2.7.1 Quantitative Analysis

This method denotes the analysis of quantitative data, referring to data that can be represented in digits and numerical values. Furthermore, this type of analysis is conducted using statistical theory to make further use of the data. The statistical techniques can be used to explore data for further understanding or to use as proof for stated hypotheses and cause and effect relationships. Moreover, the most common measurements to explore a set of data are: Average values and deviations. If data is on an ordinal scale, the median (the middle value in a sorted series) value is commonly used. In other cases, the mean value is used. To measure the deviation of a dataset, a common method is to calculate the data variance (Blom 2005). (Höst, Regnell & Runesson, 2006)

Other ways to explore data is to use graphical tools to describe it. These include histograms, “Box-plots and xy-diagrams. Histograms make use of bins to understand how data is distributed. This is commonly used as a first step when trying to evaluate the distribution function of a dataset (Axsäter, 2015). Boxplots use mean, median, quartiles and boundaries to display data which makes it very useful as it does not require distribution assumptions or scales. The xy-diagram is often used to find correlation patterns between different data points These diagrams can also be used early in the process to identify faulty and misleading data. (Höst, Regnell & Runesson, 2006)

2.7.2 Qualitative Analysis

Qualitative data, on the other hand, cannot be used to calculate mean values. In this type of analysis, words, word frequency, and descriptions play a central role. Moreover, traceability is important to be able to connect information with its source. This is also strengthening the credibility of the conclusion. The qualitative analysis process can often be separated into the following parts: data collection, coding, formation, and conclusion. (Höst, Regnell & Runesson, 2006)

2.7.3 Validity

A commonly neglected part of a model design process is model validation. The purpose of the validation is to investigate if the developed model adequately represents the studied phenomenon. If the model is intended to be used by others; it is recommended that they are involved in the model development process to give useful feedback. A semi-structured interview could be adequate to validate this type of model. Furthermore, if the model is not intended to be used by others, i.e. a computer-based system, it can be validated by using data that have a known output. If the current ERP system data is known, it can be used as a reference when developing a new model. (Höst, Regnell & Runesson, 2006)

Conclusions made on the model results also need to be validated. Questions such as: Is the result reasonable? Is the model sensitive to variations in the assumed parameter? Interviewing experienced people and conducting sensitivity analysis can help to minimize these risks. Triangulation is often used to gather the same data from different sources. This can both validate the data and allow the researcher to get a second perspective. The expression is derived from geometry when calculating a point reference distance using different paths. (Höst, Regnell & Runesson, 2006)

2.7.4 Data Analysis and Validity Methods used in this Project

This subchapter will explain and motivate the data analysis and validity methods used in this report.

2.7.4.1 Data Analysis Approach

This thesis mainly consists of *quantitative* data analysis collected from the internal ERP system. The data was first filtered into separate locations. This was carried out to analyse what distribution functions the data sets replicated at each location. Statistical data analysis methods were mainly used to carry out these fits. When the parameters for the different distribution functions were obtained; they could be further used in mathematical models. Stat::fit, an add-on to the simulation software ExtendSim, was used to analyse the data and fit it to a correct distribution function.

However, if the data does not prove to follow any given distribution function. Other measures will be taken to ensure that the developed model fairly represents the situation. These measures are discussed in Chapter 5.

2.7.4.2 Validity

Throughout this project, triangulation has been used to ensure that the quantitative order data is legitimate. To ensure this, primary data has been collected from the internal ERP system and from the external distributor. These data sets have then been matched to ensure its validity.

Furthermore, model output has been compared to actual annual data to validate that the results are reasonable. Moreover, the separate functions in the mathematical model have been tested separately using input and a known expected output to ensure proper execution.

3. Theoretical Background

This chapter will go through the theoretical background required to understand the results of this project. The term "Logistics" and its part within supply chain management is described before looking at the different transport patterns and the three different policies for consolidated shipping. Furthermore, an overview of relevant statistics theory, distribution functions, and distribution fitting will be explained as it is an integral part of the selected models. These models have been obtained from selected articles discussed in the final part of this chapter.

3.1 Logistics

Logistics is the part within supply chain management that handles the forward and reverse flow and storage of goods, services and related information between the point of origin and the point of final consumption. It can also be described as the doctrine of effective material flows. It is a term that describes all the activities which allow materials to be at the right place at the right time, with the purpose to maximize benefit; both in respect of time and place. These benefits are aligned with shareholder interest to increase economic advantages and gain competitive advantage. (Jonsson & Mattsson, 2011)

Logistics objectives can be separated into two different categories: structural and control. The structural objective encompasses the way the production, distribution and material flow systems shall be designed to meet different demands. Moreover, this decision is based on the quantity, lead time and customer demands. To make the best use of the implemented system, the control objective encompasses how the implemented system is best managed. It can be briefly described as the decision process when an item shall be moved from one BU to another. (Jonsson & Mattsson, 2011)

Customer service has a great impact on income and is closely related to the activities which target to fulfill customer demands and deliver a product or service. In logistics, customer service levels can be increased by delivering items on time and effectively communicating material flow information to customers. Moreover, customer service levels can be measured solely on the quantity delivered. This depends on customer preference. Ideally, the customer receives the ordered quantity at the selected time. According to Jonsson & Mattsson (2011), some of the key service elements are the delivery times and on time delivery, i.e. how often this expected delivery time is met. Another key service element is the degree of delivery flexibility, i.e. the degree of which the supplier is able to change predefined delivery dates and quantities. (Jonsson & Mattsson, 2011)

A cost closely associated with logistics is the holding cost. The holding cost is often hard to define as it is defined as the cost to hold a unit for a period of time. In most cases, the cost of storing a unit is used as the holding cost. Another cost typically included as a holding cost is capital tied up. Capital tied up is separated into two categories: fixed and current assets. Fixed assets include equipment that is used for a longer period. This includes machines, computer systems, and other large investments. Unlike fixed assets, current assets are not used for a longer period and are consumed, sold or stored somewhere in the production process. This includes materials, WIP and accounts receivable. Tied up capital can affect both the cash flow (the company's ability to pay) and generate an alternative cost. The alternative cost equals the risk-free dividend that the capital would generate if invested somewhere else. For example, if a delivery is available but has been delayed, payments will be delayed, and current assets will tie up capital for a longer period - thus increase costs. (Jonsson & Mattsson, 2011). In general, the holding cost can be separated into the following categories:

1. Inventory carrying cost - Capital cost (Lambert D, 1976)
2. Inventory service cost - Tax, insurance, etc. (Lambert D, 1976)
3. Storage space cost - All costs associated with storing an item for a period of time (rent, maintenance, etc.) (Lambert D, 1976)
4. Risk cost - Deterioration and theft (Lambert D, 1976)

The holding cost is often assumed to be equal to Equation (1) below. The main reason is that the capital cost c makes up most of the holding cost (Axsäter, 2000). In Equation (1), r is often determined by the interest rate, from literature or consultants.

$$h = r * c \tag{1}$$

3.2 Shipping

The most traditional and simple transport pattern is to ship individual orders directly from the distributor to the final customer. This allows for a great deal of transport flexibility and the order can be sent at any given point in time. However, in most cases, it comes at a high cost. The necessity for flow coordination happens when an order has many order lines, i.e. one customer orders multiple goods. The goods can then be consolidated to make better use of transport vehicle space. (Jonsson & Mattsson, 2011)

Shipment consolidation allows the company to accumulate orders over a time period. This may allow the distributor to reduce the shipping cost by spreading the fixed cost over a larger number of items, thus benefiting from economies of scale (Jonsson & Mattsson, 2011). However, this implies that the customer is willing to wait an additional period before the goods are received. Therefore, before deciding on if a consolidation policy shall be implemented; company management must review a couple of the following questions and decisions:

1. What products can be consolidated.
2. What events will trigger the release of products, i.e. when will the consolidated load be dispatched.
3. In which part of the supply chain does the potential consolidation take place?
4. Who is responsible for performing the consolidation? Is the consolidation performed by the company or a third party?
5. What type of shipment-release policy shall be selected?

This decision process is the first part of a two-stage process. Management must first decide on what approach to select based on the previously described decision variables. The second stage of the process is to implement the selected shipment-release policy. In this report, the first stage of this process is in focus. Currently, three shipment release policies are commonly used, these will be described more in detail in the following sections. (Higginson & Bookbinder, 1994)

3.2.1 Quantity-Based Consolidation Policy

Under a quantity-based policy, orders are accumulated until a target quantity is reached (often measured as weight). This ensures that economies of scale are successively achieved (Mutlu et al., 2010). However, if order frequency is low, this may lead to long consolidation cycles. Moreover, the target quantity is most commonly determined based on cost considerations. Resulting in long customer waiting times and risk of lower service levels. A quantity-based release policy is the easiest of the three policies to implement as it only requires discrete time reviews. Every time a new order arrives, the system is updated to check if the quantity criteria is reached. (Higginson & Bookbinder, 1994)

3.2.2 Time-Based Consolidation Policy

Time-based shipping, also referred to as “scheduled shipping”, is when shipments are released in periodic intervals (also referred to as release epochs). The accumulation cycle can either start when a consolidated load has just been dispatched or when the first item after a dispatch arrives (Mutlu et al., 2010). The first scenario is equivalent to releasing items at fixed time intervals. Contrary to the quantity-based shipping policy, the time-based dispatch policy is a continuous review system and thus harder to implement as it requires to be updated regularly (only if the load is released at non-specified time intervals). Moreover, if order arrivals are volatile, shipments are released regardless of accumulated quantity weight. This eliminates the risk of exceeding the acceptable waiting time for customers. (Higginson & Bookbinder, 1994)

3.2.3 Time-Quantity-Based Consolidation Policy.

Under the TQ-based shipping policy, both the quantity and time parameter are considered when deciding when to dispatch a load. The consolidated load is either released if the consolidated load reaches a predefined quantity or when the minimum acceptable accumulation time is reached (Mutlu et al., 2010).

Naturally, this implies that the system must be continuously reviewed and thus can be harder to implement than e.g. the quantity-based policy. (Higginson & Bookbinder, 1994)

3.2.4 Policy Comparison

In general, the cost performance of a quantity-based policy is superior to the time-based approach if the holding period, i.e. the consolidation period, of the time-based policy is short. This is because the accumulated weight will not reach a sufficient volume to benefit from the transportation cost reduction associated with larger volume freight. However, a time-based policy can be advantageous if order arrival rates are high. This is because there is no limit in the number of accumulated orders; the policy is more likely to qualify for volume freight rates. (Higginson & Bookbinder, 1994)

Furthermore, if the holding time is short and the arrival rate is low, the cost benefits of a time-based policy can be disadvantageous. It results in frequent, low volume shipments which will never benefit from the economies of scale benefits associated with high volume shipping. Moreover, a time-based policy result in great variations of per load volume compared to both the other policies. According to Higginson and Bookbinder (1994), this variation can be twice as large as that of a time-quantity-based policy (TQ policy) and as much as five times that of a quantity policy. (Higginson & Bookbinder, 1994)

It would be expected that a TQ policy would outperform both the quantity and time-based policies as it combines both principles. However, if arrival rates are low, this may not be true. The loads produced by a time-based policy will never be exceeded by a TQ policy, as the latter is constrained by a maximum quantity level. Thus, on a per order weight basis, in some cases, the quantities produced by a TQ policy will not qualify for the quantity discounts. However, this may be the case for the time-based policy. (Higginson & Bookbinder, 1994)

3.3 Statistics in General

Statistics can be found within almost every science, e.g. natural science, engineering, social science, linguistics, and experimental research. It is also present in our day to day life with statistical surveys. When conducting a survey, one studies a population in some form. The population is the total quantity of elements of a group and can consist of people, orders, objects, etc. Furthermore, a population data set contains all members of a group. Due to the quantity of data; it can be difficult to study the entire population of elements. This can be managed by studying a sample of the entire population. However, it is important that the sample represents the entity of the total population for the survey to be legitimate.

When the sample data has been collected, it is natural that the mathematical model assumes that the values of the observations are stochastically independent with the same distribution function. Moreover, it then follows that one has a random sample from the distribution function F.

The stochastic variables are of great importance within the field of statistics. A stochastic variable is not known before the experiment but is decided upon the result that arises, i.e. by chance. The definition of a stochastic variable can be seen below in Definition 1.

Definition 1. A stochastic variable is a real valued function defined on a sample space.

A probability density function (PDF) is used to calculate the probability that a stochastic variable is equal to a given value of x, which is defined within the sample space, in the continuous case. When calculating the same probability in the discrete case it is instead called the probability mass function. The outcome of these two functions is the likelihood of x occurring and is always between the values 0 and 1.

The cumulative distribution function (CDF) is used when calculating the probability for the stochastic variable to be below or over a certain given value x, which must be defined within the sample space. In the continuous case and discrete case, the CDF function is notated as Equation (2) and (3), respectively. It is important to remember as in the case with the PDF and PMF that the calculated probability interval always lies between 0 and 1.

$$F_X(x) = P(X \leq x) = \int_{-\infty}^{x} f_X(t)\,dt \qquad (2)$$

$$F_X(x) = P(X \leq x) = \sum_{j \leq x} p_X(j) \tag{3}$$

As previously stated, the stochastic variables probability of being a given value is calculated with the PDF in the continuous case and PMF in the discrete case. Moreover, it is of importance to know where the probability mass is located, i.e. the mean value of the sample. To get a deeper understanding of how the stochastic variable varies, the standard deviation is frequently used. It is the square root of the variance, which is one of the most commonly used measurements of dispersion. (Blom et al., 2005)

A commonly used statistic method is the so-called hypothesis testing. One decides a null hypothesis H_0 and evaluates if it can be rejected or not. When performing a hypothesis test, a frequently used term is the significance level, denoted α. The significance level is the probability of rejecting the null hypothesis H_0, even if it is true. E.g. if α = 1%, the hypothesis will be rejected 1% of the time, even though it should not. (Blom et al., 2005)

3.4 Distribution Functions

The distribution function is used to describe the probability distribution for a random variable. Given the sample data, one may want to test whether the data collected can be represented by a certain distribution function. There are multiple methods to perform this test, including Chi-squared and Kolmogorov-Smirnov tests. These will be described further in subchapter 3.5. (Blom et al., 2005)

When an appropriate distribution function has been found, it can be used to represent the randomness of the studied phenomenon. The functions can then be used in mathematical models and programs to replicate the behaviour of an event. (Blom et al., 2005)

3.4.1 Exponential Distribution

The Exponential distributions PDF is defined in Equation (4) shown below. If the random event X is a stochastic variable following an Exponential distribution, it is notated as X € Exp(λ). The CDF can be derived from the PDF and is stated in Equation (5) below. (Blom et al., 2005)

$$f(x;\lambda) = \begin{cases} \lambda e^{-\lambda x}, x \geq 0 \\ 0 \quad\quad , x < 0 \end{cases} \tag{4}$$

$$F(x;\lambda) = \begin{cases} 1 - e^{-\lambda x}, x \ \geq 0 \\ 0, \quad\quad\quad x \ < 0 \end{cases} \tag{5}$$

The Exponential distribution function has the intensity λ and the mean and variance are seen in Equation (6) and (7) below, respectively. The Exponential distribution has the interesting property of being memoryless. This means that the probability that a certain event will occur within t time units is always the same irrespective of the elapsed time until one starts to measure the t time units. This can be explained with the lifetime of a component. If the component has an expected lifetime of x and has been running for some time, the probability of it surviving to x is the same as when it was new. (Blom et al., 2005)

$$E[X] = \frac{1}{\lambda} \tag{6}$$

$$Var[X] = \frac{1}{\lambda^2} \tag{7}$$

3.4.2 Poisson Distribution

The Poisson distribution occurs when studied phenomenon happens randomly in time or space. The PMF for the Poisson distribution is defined in Equation (8) below. The stochastic variable is notated as X € Po(λ).

$$f(x;\lambda) = \frac{\lambda^k e^{-\lambda}}{k!} \tag{8}$$

Phenomenon's that happen randomly in time refers to occurrences that happen at any time, independently of each other. Therefore, future events are not affected by previous ones. It is assumed that the phenomenon occurs with a constant intensity, λ. Thus, the number of phenomena during a time period t is λt and the stochastic variable X is defined as X € Po(λt). Theorem 1 and 2 below defines some useful properties of the Poisson distribution. (Blom et al., 2005)

Theorem 1. If X is $Po(\mu)$ it results in that $E(X) = \mu$, $V(X) = \mu$ and $D(X) = \sqrt{\mu}$.

Theorem 2. If X € $Po(\mu_1)$, and Y € $Po(\mu_2)$, where X and Y is independent, is holds that X + Y € $X + Y \in P_0(\mu_1 + \mu_2)$.

In Theorem 1 the expected value and variance both are equal to λ. For the Poisson distribution function μ is estimated by calculating the sample mean.

The Poisson distribution is related to the Exponential distribution. If an event occurs randomly in time and X is the number of events in the interval (0, t], then T represents the time until the first event occurs. Furthermore, then it is true that {T > t} = {X = 0}. For t > 0, Equation (9) is obtained, which shows that T € Exp(λ), and in a similar fashion one can show that the successive events are independent and following an Exponential distribution. As a result, the time to the n:th phenomena is the sum of an independent Exp(λ) distributed stochastic variables. Such a sum is Erlang distributed (see Equation (10) below). (Blom et al., 2005)

$$F_T(t) = P(T \leq t) = 1 - P(T > t) = 1 - P(X = 0) = 1 - e^{-\lambda t} \qquad (9)$$

$$S_n = \sum_{i=1}^{n} X_i \quad then\ X_i \sim Exponential(\lambda)\ and\ S_n \sim Erlang(n, \lambda) \qquad (10)$$

3.4.3 Empirical Distribution

If the data sample cannot be represented by a known distribution function, an empirical distribution function can be created. For each of the data points $x_1, \ldots, x_n$ one can create the empirical distribution by calculating the probability in every data point x_j as *1/n*. Moreover, if k data points have the same value; the probability is k/n instead. (Blom et al., 2005)

For large data samples the data can be grouped up in bins to reduce the number of intervals. The frequencies can then be established in each bin. Thus, all the frequencies in a specific bin, notated as f_i, is evaluated as if they have the same value and the probability for an observation in a bin is calculated as f_i/n. (Blom et al., 2005)

For a discrete empirical distribution, the mean value from a grouped data set is calculated using Equation (11). One often uses the square sum of the arithmetic mean Q to calculate the approximated variance, see Equation (12) and (13) respectively where y_i represents the bin value, f_i the bin frequency and n is the number of observations. (Blom et al., 2005)

$$\bar{x} = \frac{1}{n}\sum_{j=1}^{n} f_i y_j \tag{11}$$

$$Q = \sum_{j=1}^{k} f_j\left(y_j - \bar{x}\right)^2 = \sum_{j=1}^{k} f_j y_j^2 - \frac{1}{n}\left(\sum_{j=1}^{k} f_j y_j\right)^2 \tag{12}$$

$$s^2 = \frac{Q}{(n-1)} \tag{13}$$

When a data set is continuous, it can be classified into classes. Meaning that data which falls within a *similar* range is grouped – contrary to the discrete case where exact values were matched. Then y_j is replaced by the mean value of each class in the Equation 11-13 above.

3.5 Distribution Fitting

There is no best way to perform a goodness-of-fit test for any given situation, but if the data sample has above 30 observations and is discrete, the preferred test is the Chi-squared. When the data sample has fewer observations and has a continuous random variable the Kolmogorov-Smirnov test is recommended. Below the two tests will be explained in more detail and how they are performed. (Laguna and Marklund, 2009)

3.5.1 The Chi-Square Test

The Chi-square test evaluates how well a data sample fits to a distribution function. The test got its name from the fact that it uses the Chi-square distribution to test whether a distribution function can be used to represent the sample data at a certain level of significance. (Laguna and Marklund, 2013)

The test starts by determining bin sizes and then plotting a histogram over the sample data. In the histogram the actual frequency for each bin can be seen. The test variable, seen in Equation (14), can then be calculated. Furthermore, n is the total number of observations in the sample data; O_i is the number of observations in bin i, N is the number of bins and p_i is the probability for an event to be within bin i. (Laguna and Marklund, 2013)

$$T = \sum_{i=1}^{N} \frac{(O_i - n \cdot p_i)^2}{n \cdot p_i} \tag{14}$$

Equation (14) compares the expected frequency from the distribution function and the actual frequency from the sample data and squares the result for every bin. The calculated test variable is then compared to a value from a Chi-squared distribution table. The Chi-square distribution have *(N-k-1)* degrees of freedom, where *N*, as previously stated, is the number of bins. The *k* represents the number of estimated parameters in the distribution function, i.e. for a Normal distribution and a Poisson distribution k would equal 2 and 1, respectively. The most commonly used level of significance, notated α, is either 1% or 5%. (Laguna and Marklund, 2013)

If the value χ^2 - for the established degrees of freedom - in the Chi-squared table is higher than the test variable T, i.e. χ^2 >T, the tested distribution function can be used, and the hypothesis cannot be rejected at the chosen level of significance. (Laguna and Marklund, 2013)

It is important to have bin sizes big enough so that the expected frequency in each bin is at least five. If this condition is not met, the test will not be performed correctly and thus give inaccurate results. One way to resolve this problem is to simply merge the bin with an adjacent one and continue to do this until the expected total frequency is higher than five. Given this problem, the initial histogram can give the wrong implications in the beginning due to the reason that it has incorrect bin sizes. This means that one might have to do the Chi-squared test again but for another distribution function. (Laguna and Marklund, 2013)

Even though the test has its flaws, it is a good way of performing a goodness-of-fit test as it gives reliable results. If the bin sizes are selected so that they all have the same probabilities of finding an observation the precision in the test can be increased. (Laguna and Marklund, 2013)

3.5.2 The Kolmogorov-Smirnov Test

The Kolmogorov-Smirnov test is also commonly used when performing a goodness-of-fit test but should only be used when the data is continuous. Two advantages with the Kolmogorov-Smirnov test include: reliable results when the data sample is small; does not require a histogram over the sample data. (Laguna and Marklund, 2013)

One major setback with the Kolmogorov-Smirnov (KS) test is that all the parameters for the distribution function must be known before the test can be performed. As these parameters are often estimated depending on the distribution, the test can sometimes be difficult to perform. Some modifications of the test exist, and these modifications fixes the stated problem, but this only applies for the Normal, Exponential and Weibull distribution. (Laguna and Marklund, 2013)

The steps to perform the KS test can be seen below:

1. Order the sample data from the smallest to largest value
2. Compute $D^+$and D^-using the theoretical CDF
    a. $D^+ = \max_{1 \le i \le n} \left[\frac{i}{n} - \hat{F}(x_i)\right]$
    b. $D^- = \max_{1 \le i \le n} \left[\hat{F}(x_i) - \frac{i-1}{n}\right]$
3. Calculate $D = \max(D^+, D^-)$
4. Find the KS value for the specified level of significance and the sample size n
5. If the critical KS value is greater than or equal to D, then the hypothesis that the field data come from the theoretical distribution is not rejected

When using the KS test to see whether a chosen distribution function can be used, the hypothesis may sometimes be rejected, even though it is a suitable distribution function to use. (Laguna and Marklund, 2013)

3.6 Analytical Literature Review

As this report is of abductive character, there are few articles with analytical methods that solve an identical problem. Thus, this report needs to utilize methods from articles with similar problems but make necessary adjustments to solve the problem at hand. There are mainly two articles that have been used to approach this problem: "*An Analytical Model for Computing the Optimal Time-And-Quantity-Based Policy for Consolidated Shipments*", by Mutlu et al. (2010) and "*Policy Recommendations for a Shipment-Consolidation Program*" by Higginson and Bookbinder (1994). The former is the first paper that develops a fully analytical model to evaluate how a TQ policy would perform given a set of parameters. This is of high relevance for this case study as the model becomes highly flexible and the result can be studied in both respect of quantity and time. Furthermore, these articles are used as references in this section unless stated differently.

In the article by Mutlu et al., an analytical model is computed to find the optimal TQ policy for consolidated shipments by calculating the long-run average of the expected cost $\breve{G}(q, T)$, see Equation (25). This is the main model used in this research study. See the literature selection motivation under section 5.1 in this report.

Except for the article by Mutlu et al. and Higginson & Bookbinder, some related consolidated shipment literature has been reviewed in this project, these include:

1. Stochastic models for the dispatch of consolidated shipments by Çetinkaya and Bookbinder
2. A Tree-Structured Markovian Model of the Shipment Consolidation Process by Cai, He and Bookbinder
3. Markovian Decision Processes in Shipment Consolidation by Higginson and Bookbinder

Inventory Control in Divergent Supply Chains with Time-Based Dispatching and Shipment Consolidation by Marklund.

3.6.1 Denotations and Characteristics

Before considering this consolidation problem, a couple of denotations and characteristics associated with this problem needs to be defined. Please note that all the following denotations are summarised in Table 1 at the end of this section. The literature assumes that the customer orders arrive at the depot following a Poisson process with parameter λ. Each order is of unit size and is shipped to a destination in close proximity. Hence, the selected holding period T represents the additional time a customer is willing to wait. Following a traditional TQ policy, the consolidated load is dispatched either when the number of orders waiting exceeds q, or when the waiting time of the first order exceeds a maximum time T. The time between two dispatches is called the "*consolidation cycle*".

The objective of this analytical model is to find the decision variables q and T which minimizes the long-run average cost $\check{G}(q, T)$. In most cases, however, there is some restriction and upper bound on at least one of these decision variables. For example, a customer may only be willing to wait for a certain timeframe, leading to a restriction on the decision variable T. Moreover, a fixed cost $\check{K}$ and a variable per unit cost c are associated with each shipment. As the distribution is conducted by a 3PL supplier, truck capacity is assumed to be infinite. Furthermore, as presented in section 3.1, a waiting cost parameter w incurred for delaying an order for a unit of time. This is one of the more difficult parameters to estimate, as it is computed differently in each case and requires further investigation.

To compute the exact analytical expression *Ğ(q, T),* a couple of denotations are required:
$S_0 = 0$ and $S_i = \sum_{j=1}^{i} X_j, i = 1,2,3 \ldots$, where $X_j, j = 1,2,3$ denotes the arrival times between orders. Also, we let $N(t) = sup\{i: S_i \leq t\}$

N(t) is the counting process registering the number of arrived orders over a time period t. This counting process follows a Poisson distribution with parameter λt, and as described previously, this suggests that the interarrival time X_j follows an Exponential distribution with mean $E[X_j] = 1/\lambda$. Given this information and the decision variable T, it is possible to denote the density, distribution, and complementary distribution functions, given by Equation (15), (16) and (17) below.

$$p(n,t) = p\{N(T) = n\} = \frac{e^{-\lambda T}(\lambda T)^n}{n!} \quad (15)$$

$$F(x,T) = \sum_{n=0}^{x} p(n,T) \quad (16)$$

$$\bar{F}(x,T) = \sum_{n=x+1}^{\infty} p(n,T) \quad (17)$$

Where Equation (15) represents the density function – the probability that *exactly* n values arrive at time period *T*; Equation (16) represents the distribution function, i.e. the probability that *at least x* values arrive within *T* time units; and Equation (17) represents the complementary distribution function of N(t) which represent the probability that *greater* than *x* units arrive within *T* time units. Each time an order is received the number of orders waiting to be released is updated in order to instantly know if the current number of orders waiting is exceeding *q*. Or In other words, when the number of orders waiting is *q* + 1.

As orders arrive according to a Poisson process, shipments always clear the system stochastically. Each of these shipments is referred to as a "regeneration epoch". Hence, the long-run average cost can be expressed as $\check{G}(q, T) = E[C_C]/E[L]$ where $E[C_C]$ and $E[L]$ represents the expected cost and length of a consolidation cycle, respectively. It is easy to see that if orders were to be sent directly, i.e. $q = 0$ or $T = 0$, the result would be that $E[C_C] = \check{K} + c$ and $E[L] = 1/\lambda$. Hence Equation (18) below,

$$\check{G}(q, 0) = \check{G}(0, T) = \check{K}\lambda + c\lambda \tag{18}$$

This equation will be used later in the analytical model.

Table 1: Denotation summary for analytical model.

Denotation	**Description**
λ	Arrival intensity
L_i	Fixed transportation time from warehouse to customer
q	Decision variable, target quantity load for dispatch
T	Decision variable, target time for dispatch
$\check{G}(q, T)$	Long-run average cost
$\check{K}$	Fixed cost associated with each shipment
c	Per unit cost associated with each shipment
w	Waiting cost for delaying an order for a unit of time
X_j	Interarrival time between orders

3.6.2 Expected Cycle Cost

The expected cycle cost E[C_C] consists of two components: expected shipping cost E[C_S] and the expected waiting cost E[C_W]. In the following subchapters these will be explained in more detail. For more detail regarding the evidence of the assumptions made to arrive at each expression, please see reference list. Firstly, the expected shipping cost will be derived.

3.6.2.1 Expected Shipping Cost

Before deriving the expected shipping cost, the expected cycle length E[L] needs to be derived. This is the expected cycle length of the random variable L, i.e. the length of a consolidation cycle. E[L] is expressed as Equation (19) below.

$$E[L] = \frac{1}{\lambda} + \frac{q}{\lambda}\bar{F}(q,T) + TF(q-1,T) \tag{19}$$

Were the first term represents the time it takes for the first order to arrive. $\bar{F}(q,T)$ is the probability that an order is dispatched because the decision variable q is reached and $F(q-1,T)$ represents the probability that an order is dispatched because T is reached. By using this equation, it is possible to find the expected shipping cost E[C_S]. As stated previously, each order is associated with a per unit cost *c*. The expected number of orders within a consolidation cycle is expressed as λE[L], i.e. the intensity which customers arrive multiplied with the expected time they will be arriving for. Also, the fixed cost $\check{K}$ associated with each shipment must be included. Thus, the expression for the expected shipping cost E[C_S] becomes:

$$E[\mathrm{C_s}] = \widetilde{K} + c\big(1 + q\bar{F}(q,T) + \lambda TF(q-1,T)\big) \tag{20}$$

3.6.2.2 Expected Waiting Cost

Previous in this report, the capital tied up was discussed as a cost. In this report, this cost is referred to as the waiting cost, *w*, and occurs as consolidating shipments delays deliveries and may require additional storage. Compared to the expected shipping cost E[C_S], the expected waiting cost E[C_W] is somewhat more difficult to calculate and will require some effort. (Mutlu et al., 2010)

Before approximating a good value for *w*, one must determine the (additional) expected time a customer must wait for an order to arrive. To find this, the expected waiting time for the first order in a consolidation cycle must be determined. This is expressed by Equation (21) below.

$$E\big[\min\big(Y_q, T\big)\big] = \frac{q}{\lambda} \cdot \bar{F}(q, T) + TF(q-1, T) \tag{21}$$

$$\text{were,} \qquad Y_q = \sum_{j=2}^{q+1} X_j, i = 1, \ldots., q \tag{22}$$

Furthermore, the expected waiting time for the remaining orders in the cycle, denoted as E[W], is derived using Equation (23).

$$E[W] = \frac{(q-1)}{2} \frac{q}{\lambda} \bar{F}(q, T) + \frac{T}{2} \sum_{n=0}^{q-1} np(n, T) \tag{23}$$

Adding Equation (21) and (23), one gets the expression for the expected waiting time for a consolidation cycle. Multiplying this with a waiting cost per time unit *w*, the full expected waiting cost expression seen in Equation (24) is obtained.

$$E[C_W] \; = \; w(\frac{q}{\lambda} \bar{F}(q, T) + TF(q-1, T) + \frac{(q-1)}{2} \frac{q}{\lambda} \bar{F}(q, T) + \frac{T}{2} \sum_{n=0}^{q-1} np(n, T)) \tag{24}$$

3.6.3 Long-Run Average Cost

When both the expected costs for shipment and waiting has been obtained it is possible to present the long-run average cost. Noting that $E[C_C] = E[C_S] + E[C_W]$ and using Equations (19), (20) and (24) one gets Equation (25):

$$\check{G}(q,T) = \frac{E[C_C]}{E[L]} = \frac{\check{K} + w(q / \lambda\bar{F}(q,T)) + TF(q-1,T) + ((q-1)q\bar{F}(q,T) / 2\lambda) + (T / 2)\sum_{n=0}^{q-1} np(n,T)}{(1 / \lambda) + q\bar{F}(q,T)/\lambda + TF(q-1,T)} + c\lambda \quad (25)$$

Note that $E[C_C]$ represents the total cost given a time period T. To get the average cost per unit, simply divide this sum by the expected cycle length E[L]. Furthermore, this expression can be used to calculate the cost for immediate dispatching. Observe that this yields $\check{G}(0, T) = \check{G}(q, 0) = \check{K}\lambda + c\lambda$ which is equal to the previous result (see Equation (18)).

Moreover, letting $K = 2\check{K}\lambda$, $t = \lambda T$ and redefining p, F and $\bar{F}$ as functions of q and t while also letting

$$\psi(q,t) = 1 + q\bar{F}(q,t) + tF(q-1,t) \quad (26)$$

and

$$G(q,t) = \frac{K + wq(q+1)\bar{F}(q,t) + wt\left[\sum_{n=0}^{q-1} np(n,t) + 2F(q-1,t)\right]}{\psi(q,t)} \quad (27)$$

One can see that the cost function in Equation (25) can be represented as $\check{G}(q, t)/2 + c\lambda$. In most cases, this expression is enough to study the phenomenon and can be used for sake of simplicity.

4. Integrated Logistics Product Area at AB Tetra Pak

This chapter aims at providing the reader with general information regarding the case company infrastructure, Integrated Logistics business units and products shipped. Furthermore, the different modes of transport will be described, and under which circumstances each mode is used.

4.1 Organization and Business Areas

As previously mentioned, Tetra Pak is divided into three business areas (BA). Each BA is then further divided into several different product areas (PA). These PAs work independently of each other towards unique objectives. The purpose of this strategy is to increase the performance at every PA so that the aggregated result for the entire Tetra Pak Group is enhanced.

Tetra Pak has a global objective set out for 2019 which is called ‘One Tetra Pak’, meaning that their strategy is to insource the parts of the company that currently is outsourced. The objective is to be more centralized and to increase the control of their products and to reduce the risks of companies replicating their product portfolio - especially in Asia.

This project is carried out at the PA named Integrated Logistics (IL), which is a part of Tetra Pak Services BA. Moreover, the IL PA does not work with external clients. Therefore, rather than making a profit, their main objective is to lower costs and to help other organizations within Tetra Pak.

4.2 Integrated Logistics Business Units

IL is divided into three business units (BU): Shipping & Customs, Packing, and Warehouse & Material Planning. These BUs are under one PA, i.e. IL, in order to avoid duplication, capitalize on the scale and capture synergies. This report will focus on the Shipping & Customs BU and the products that they ship. More specifically, it will focus on the Site Shipping (SS) part of this BU which is responsible for shipping a wide range of goods globally using a 3PL (see Figure 2).

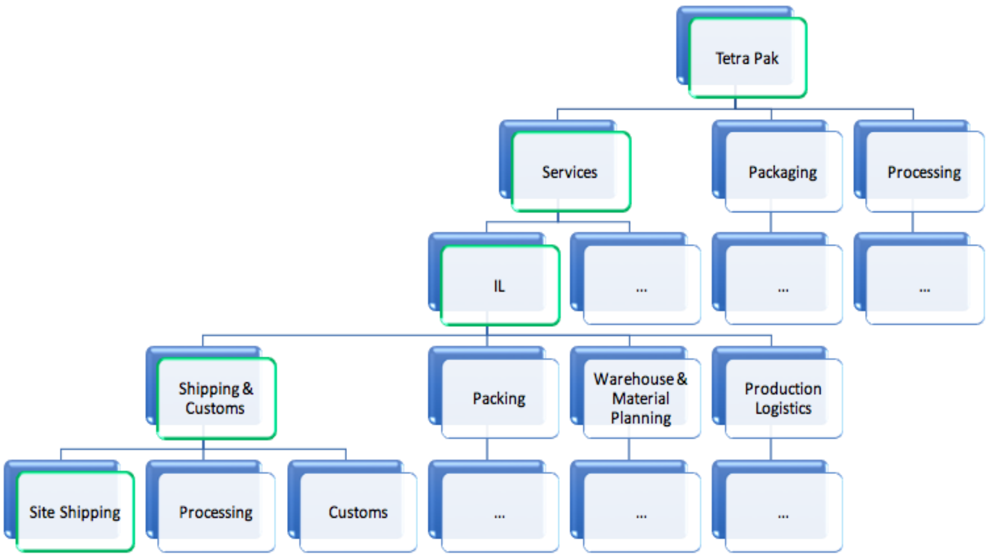


Figure 2: Tetra Pak company structure (simplified).

SS serves different internal customers (also referred to as "clients") at the Lund premises whenever they need to dispatch or receive goods. An order is received through an internal ERP system including necessary data about the goods, such as duty value, number of pieces, type of product and the latest date of arrival. Moreover, information regarding the weight and volume dimensions of the packaged goods is received from the Packing BU.

To increase their current service levels, SS is conducting multiple large customer service projects. These include evaluating if the cargo can be sent by rail to Asia and *if orders can be consolidated to lower shipping costs while maintaining a reasonable service level*.

The Packing BU mainly focuses on packaging activities such as: packing management, resource and material planning and packaging development (packaging development involves developing technology and materials as well as defining, developing and implementing a global packing standard at Tetra Pak). At the Warehouse & Material planning BU, the focus is inbound transport, warehouse management, consolidation, and material replenishment planning. As previously stated, IL is a part of Tetra Pak Services and all the BUs at IL have the objective of lowering the costs, reach break-even and be of service to all the other PAs at Tetra Pak.

4.3 Products Shipped at Site Lund

At SS most of the goods shipped are of smaller size and require urgent delivery. The different type of goods ranges from lightweight products such as documents up to heavier items, e.g. small machines which can weigh up to a couple of tonnes. Other frequently sent products include spare parts, equipment, tools and packaging materials.

4.4 Transport Modes and 3PL Services

As previously stated, SS ships goods globally daily, and three transportation modes are used. These include air-, sea- and road freight. Each transport mode will be further described in the following subsections. The chosen 3PL service is often based on weight, volume and/or level of urgency. As can be seen in Figure 3 below, express freight is the most frequently used service. In Figure 3, "Other" represents orders within Tetra Pak Lund.

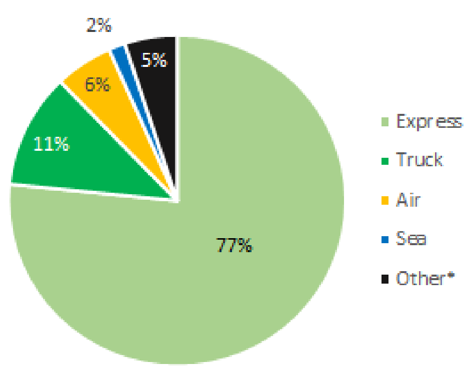


Figure 3: Transport mode distribution. (*Internal shipping)

4.4.1 Air Freight

If the receiver of the goods is located outside of Europe, air freight is the preferred transportation mode. Classical air freight is used when the goods can be delivered at the receiver airport within a couple of days (up to a week) or when the weight or dimensions are large. Today air freight accounts for 6% of SS's total shipments.

The 3PL used for shipping goods by air sends trucks to the IL facilities at Tetra Pak daily to collect the goods that have been booked with the 3PL. The 3PL then transports the goods to their respective departure airports, most often Malmö or Copenhagen Airport. The delivery is made to the closest airport, i.e. classic air freight does not include door-to-door service.

When sending goods with air freight the two incoterms used are Carriage Paid To (CPT) and Delivery at Place (DAP). When CPT is used SS's, responsibility ends when the 3PL picks up the goods. However, when DAP is used SS has the responsibility of the goods all the way to the customs at the delivery airport.

4.4.2 Sea Freight

Sea freight is the least used mode of transport at the Shipping BU. This is because the department mostly sends "low weight" items with a relatively short delivery deadline. Thus, sea freight is not the optimal transport mode of choice. However, it can be used if larger projects are being carried out, e.g. when multiple machines need to be delivered to a new factory. Out of all the order, the percentage of sea freight is 2%, which can be seen in Figure 3. As with air freight, sea freight is not used when goods are shipped within Europe.

4.4.3 Road Freight

When goods are sent within Europe, road freight is the preferred mode of transport (except when delivery is very urgent). Tetra Pak outsources this service and uses country-specific 3PLs. These 3PLs is continuously reviewed on key performance indicators such as delivery date, pick-up date, costs, etc.

Domestic road freight is also used for relatively small and pallet sized goods as the average delivery time is like that of express freight, i.e. one day.

4.5 Express Freight

Today, the most commonly used transportation mode at the SS department is express freight. It accounts for 77% of all the shipments done in a year, see Figure 3. The express freight product is most often used when the client needs to deliver their goods quickly. The goods that are shipped with express freight must be within the 3PLs determined dimensions and weight, i.e. a package cannot weigh more than 300KG and cannot have one side exceeding 300cm.

Due to the frequent use of express freight, the 3PL provider has allocated a full-time employee at the SS office. The 3PL employee is responsible for booking and collecting the goods while also coordinating shipments with the other employees at SS. Within Europe, the goods arrive at their destination the day after they are sent with the 3PL. On a worldwide perspective, it depends on the destination, mainly due to customs clearance.

There are few countries that do not accept an express delivery from the 3PL that Tetra Pak is using, thus some small goods are sent to the marketing companies using classic air freight. This usually results in a higher cost. These countries include Brazil, Argentina, Pakistan, and India. Thus, the decision support system will not be applicable to these countries.

5. Final Model Construction

This chapter will go through the literature selection motivation and the assumptions and adjustments made to the original model used in that literature to account for the setting differences. These differences and modifications include the variable cost for shipping goods and the waiting cost associated with delaying an order for a unit of time. These will be described and motivated before presenting the final model used to calculate the Long-Run Average Cost.

5.1 Literature Selection Motivation

After studying the related literature presented in section 3.6, none included an analytical model with similar settings. Therefore, an abductive research approach was necessary to get to a conclusion. The article by Mutlu et al. included a model that required the least amount of adjustments. Moreover, as mentioned by Mutlu et al., their article was the only one that presented an analytical model for the TQ policy. Tetra Pak ships orders globally with differences in customer frequencies. Due to these differences, the TQ policy is a good fit as it combines the benefits of both the quantity and time-based policies (see section 3.2.4). Furthermore, being an analytical model, it simplifies future usage as it only requires new input.

5.2 Assumptions and Adjustments

As this case does not assume that the customer is in close proximity, the selected holding period T represents the additional time a customer is willing to wait. Furthermore, one of the main assumptions made to use the selected literature is that the system is of continuous review. Meaning, that the accumulation cycle starts when the first package after a dispatch arrives. Also, the weight and size restrictions described in section 4.5 are assumed to be exceedingly high and can be discarded as limits.

To use and apply the related theory on consolidated shipping, a few adjustments needed to be made in order to make full use of the theoretical model presented in section 3.6.3 and for the results to be viable. This is due to the difference in input and problem characteristics. These differences are listed below:

1. The selected article problem setting is at a 3PL collection depot and is thus not identical to the one in this report.
2. In the related literature, units are of equal size and the quantity parameter is measured based on the number of packages rather than accumulated weight. This is not true for the case company as units are not of equal size. As unit weights differ; the variable cost *c* associated with each order is not constant and needs to be estimated.
3. There is no known waiting cost *w* associated with holding a unit for a period of time at the case company. This cost needs to be evaluated.

The second and third point are the most relevant differences between the selected article and this case study and requires careful consideration. Given the case company situation, how to adjust for these differences and find a reasonable variable input is presented in the following sections.

5.1.1 Expected Variable Cost

In this case study there is no obvious cost *c* associated with each order. Instead, the cost is associated with the weight of each order. To derive this, one must use statistics to estimate the expected cost per unit shipped E[c]. First, the distribution of the weights of each order must be obtained using distribution fitting (see section 3.4), When the distribution fits at a satisfactory significance level, one can use Equation (28) to find E[c].

$$E[c] = \int_{0}^{x_1} c_1 x \Phi_w(x) dx + \int_{x_1}^{x_2} c_2 x \Phi_w(x) dx \ldots + \int_{x_{n-1}}^{x_n} c_n x \Phi_w(x)\, dx \qquad (28)$$

Were c_i - the variable cost for adding a kg to the consolidated load - represents the cost in each weight bracket (it is assumed to be linear within each bracket) for $i = 1,2,3...n$. Furthermore, x represents the weight and $\Phi_w(x)$ represents the PDF of the weight distribution function.

5.1.2 Expected Waiting Cost

Today, the case company dispatches goods from the IL department instantly and does not let the customer wait. Hence, there is no waiting cost. If a consolidation policy were to be implemented, it would implicate that orders would be delayed and therefore a waiting cost should be taken into consideration. These costs have been discussed previously in section 3.1 as “holding costs”.

In this report, the case company has limited the maximum waiting time for each order. Also, the goods are not perishable and can be stored for the specified time interval without becoming obsolete. Therefore, all costs described in section 3.1 can be negligible, except one: storage space cost. The model used in this report describes the waiting cost as a cost per unit of time. Therefore, the storage space cost must be described in a similar fashion.

To calculate the storage space cost. One must first calculate the expected volume of a packaged good. When this value is obtained, it can be multiplied with the storage holding cost (h) of storing a volume unit for a unit of time. See the full expression in Equation (29). In this study, the holding cost is assumed to be constant and Equation (29) can therefore be expressed as Equation (30). $\Phi_v(v)$ represents the PDF of the volume distribution function.

$$E[w] = \int_{0}^{v_1} h_1 \mathrm{v} \Phi_v(v) dv + \int_{v_1}^{v_2} h_2 \mathrm{v} \Phi_v(v) dv \ldots + \int_{v_{n-1}}^{v_n} h_n \mathrm{v} \Phi_v(v)\, dv \qquad (29)$$

$$E[w] = E[v] * h \qquad (30)$$

In this case study, the storage holding cost h has been calculated by taking the rental cost per m^2 multiplied with the shelf length and shelf depth and dividing this by the height of the storage shelf. This gives the cost of storing a unit (m^3) for a month. This number is simply divided by 20 to get the cost per working day.

Table 2: Holding cost denotations and descriptions

Denotation	Description
SL	Shelf length
SD	Shelf depth
SH	Shelf height
D	Number of working days
H2	Holding cost per square meter

Using the denotations found in Table 2 above, one can calculate the holding cost using Equation (31) below.

$$h = \frac{H2 * SL * SD}{SH * D} \tag{31}$$

5.3 Final Model

When the raw data has been collected, filtered and analysed for each location, the distribution functions are used to calculate the input data. This includes the parameters described in the previous sections of this chapter. The mathematical model is computed using Visual Basic for Applications (VBA) in MS Excel. The model output is a result of Equation (32) below.

$$\check{G}(q,T) = \frac{E[C_C]}{E[L]} = \frac{\check{K} + E[w](q / \lambda\bar{F}(q,T)) + TF(q-1,T) + ((q-1)qE(qT) / 2\lambda) + (T / 2)\sum_{n=0}^{q-1} np(n,T)}{(1/\lambda) + q\bar{F}(q,T)/\lambda + TF(q-1,T)} + E[c]\lambda \tag{32}$$

As can be seen, Equation (32) is simply a result of replacing *w* and *c* in Equation (27) with E[w] and E[c]. The result is used to calculate the Long-Run Average Cost. Figure 4 is used to illustrate the process from raw data collection to final model output and highlights the part of the process when the constructed model is used.

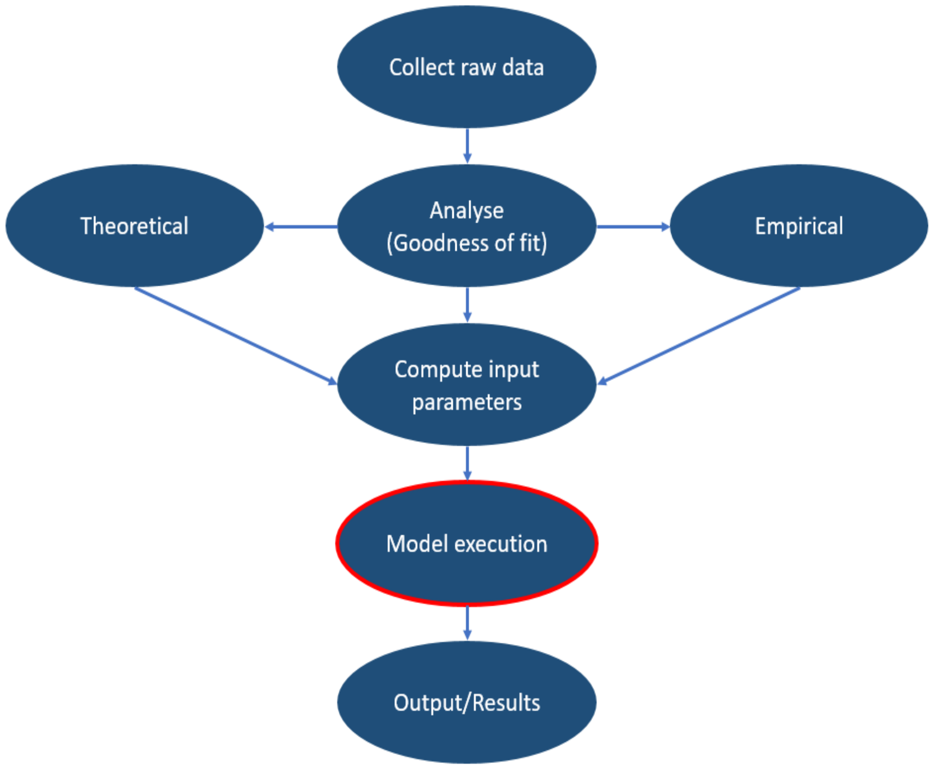


Figure 4: Work-process illustration

6. As-Is Analysis

This chapter aims at providing a snapshot of the current shipping situation at the IL PA and the costs and data associated with this system. The chapter includes a review of the PA's markets and how shipment volume is distributed amongst the different regions. Also, the chapter includes histograms of the order arrivals and weights for each selected location. Finally, the annual shipment cost for each of these locations is reviewed.

6.1 Market Situation

The case company is a well-established global player and ships its products and components to various places around the globe. To put this in context, in 2018, the IL department shipped its smaller goods using the express 3PL supplier to 105 countries (to all continents except Antarctica). However, the frequency differs, and some destinations are more frequently shipped to than others. This pattern can be illustrated using a heatmap. Figure 5 and Figure 6 illustrates the number of orders shipped and the average weight per order at destination, respectively. (AB Tetra Pak Internal Data, 2018)

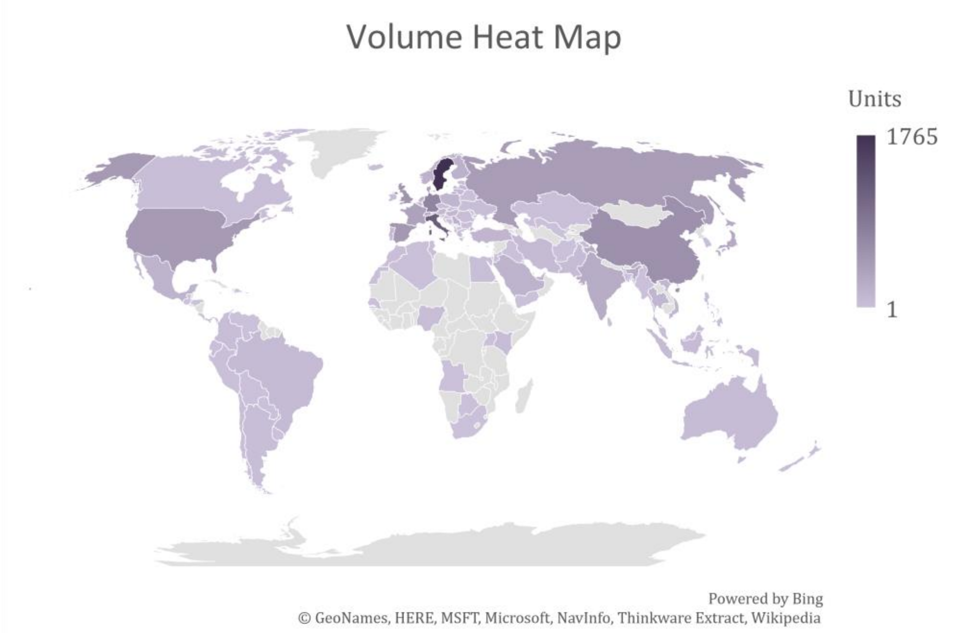


Figure 5: Heatmap illustrating annual volume shipped to each country 2018 (ibid.).

As can be seen in Figure 5 above, Italy and Sweden are the most frequent customer locations within Europe. When studying the total weight shipped to each location (see Figure 6), one can see that the colouring looks somewhat different from Figure 5. By studying this difference, it is possible to draw conclusions on what types of products are being shipped to each location.

Both heat maps will help to give a fair hint if the selected locations contain large customers suitable for consolidated shipping. Furthermore, differences in color scale help to find smaller customers which can be used to either confirm/oppose the benefit of consolidated shipping. This information is of great relevance when conducting this report as the benefit of consolidated shipping is compared amongst customers with different annual order volumes.

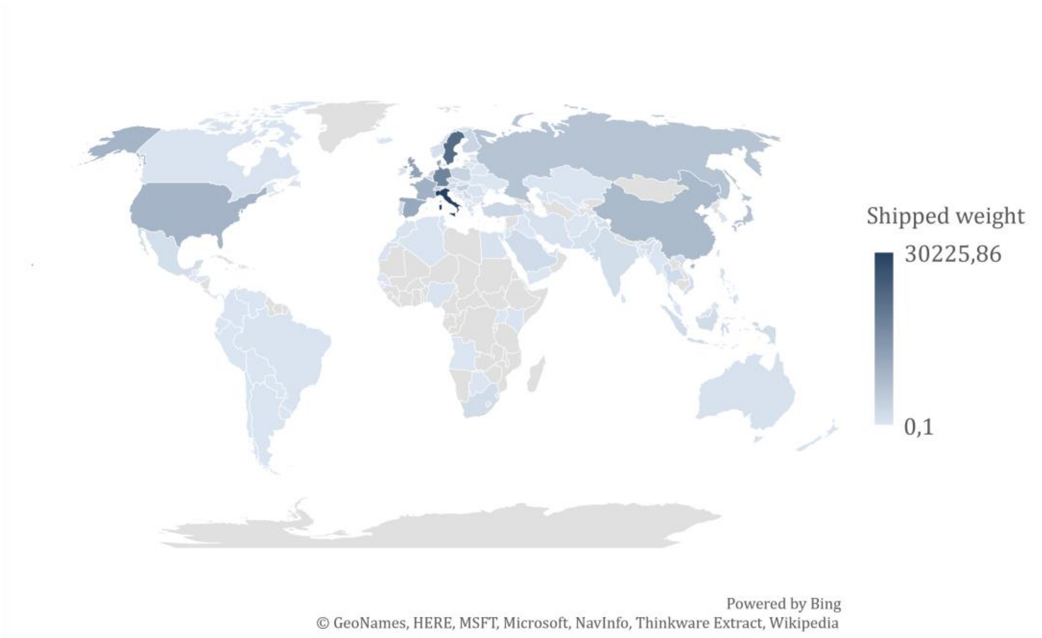


Figure 6: Heat map illustrating total weight in each country 2018 (Ibid.)

As each country generally contains several customers, it is difficult to draw conclusions on the characteristics of specific customer orders. To do this, it is more appropriate to look at the total weight divided number of orders ratio at each location. This ratio is presented in Figure 7 together with the cubic meter per order data for each location.

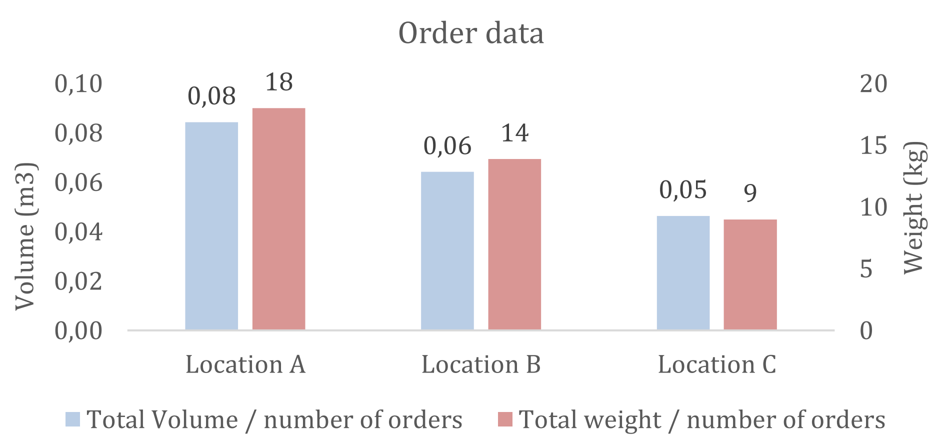


Figure 7: Total weight to number of orders ratio for each selected location

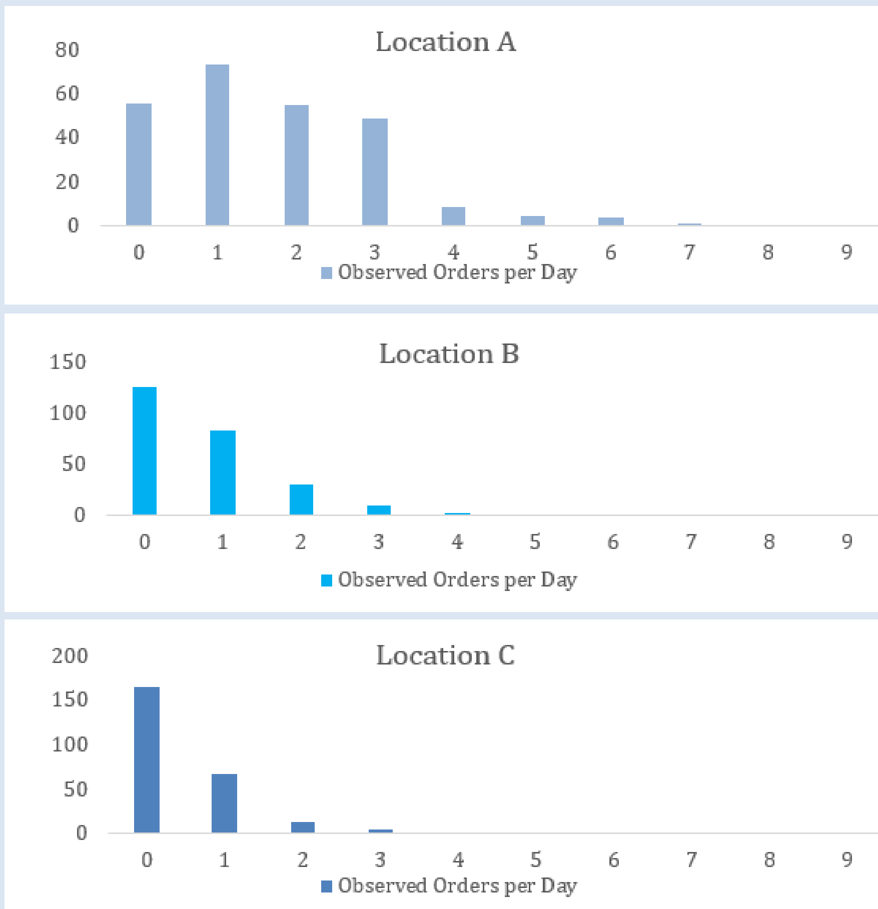
6.2 Distribution Plots

In 2018, a total of 11,336 orders were sent with the express 3PL from the IL PA. Furthermore, these orders have multiple attributes which result in more than half a million data points. This data needs to be filtered so that each location can be studied individually, and irrelevant data points can be removed. To do this, MS Excel VBA was used. The reason VBA was used is because it made it easy to divide the data by city and filter the relevant attributes. When the data has been filtered and selected, it is possible to start plotting histograms and estimate the different distributions. These estimations will later be confirmed using a Chi-squared test (see Chapter 7).

To put this in context, in this research study, Location A has been selected as one of the most frequently shipped locations outside of Sweden, with a total of 423 orders-lines in 2018. To use the analytical model described earlier in this study, the distribution of order arrivals, order weights and order volume will be estimated. This process will be repeated for each of the studied locations. To find these distributions, data for the order arrivals, weights, and volumes are plotted in histograms to use as a starting point when finding the correct distributions.

In Exhibit A below, histograms regarding order arrivals for Location A, Location B and Locations C are plotted. At first glance, a Poisson Distribution function seems to be a good fit for all three locations.

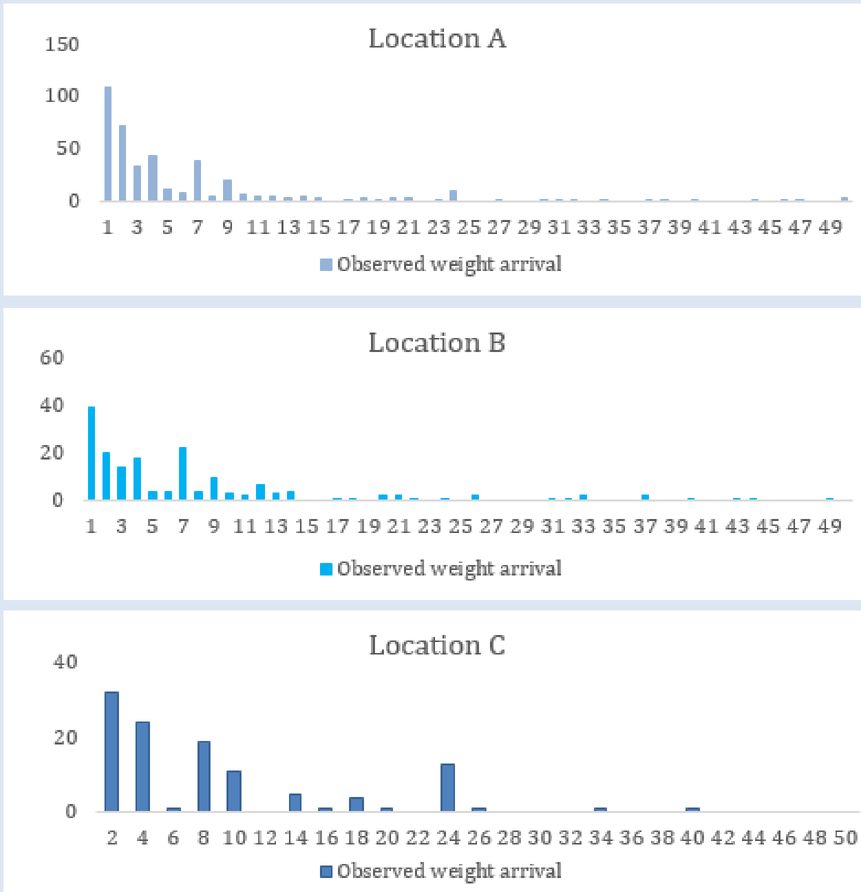
Exhibit A: Observed order arrivals for the three locations.



The histograms show the order arrival frequency and represents how many orders were sent per day. The initial hypothesis is that the order arrivals can be approximated by using a Poisson distribution function. It is important that this is true as the analytical model is built based on this assumption.

For the weight distribution, the hypothesis is that the weights are Exponentially distributed for all locations. The hypothesis arises from Exhibit B below, where the observed order weights have been plotted. The Figure representing Location A indicates that the hypothesis cannot be rejected. The other two Figures in Exhibit B gives a hint that the hypothesis will be rejected for Location B and C.

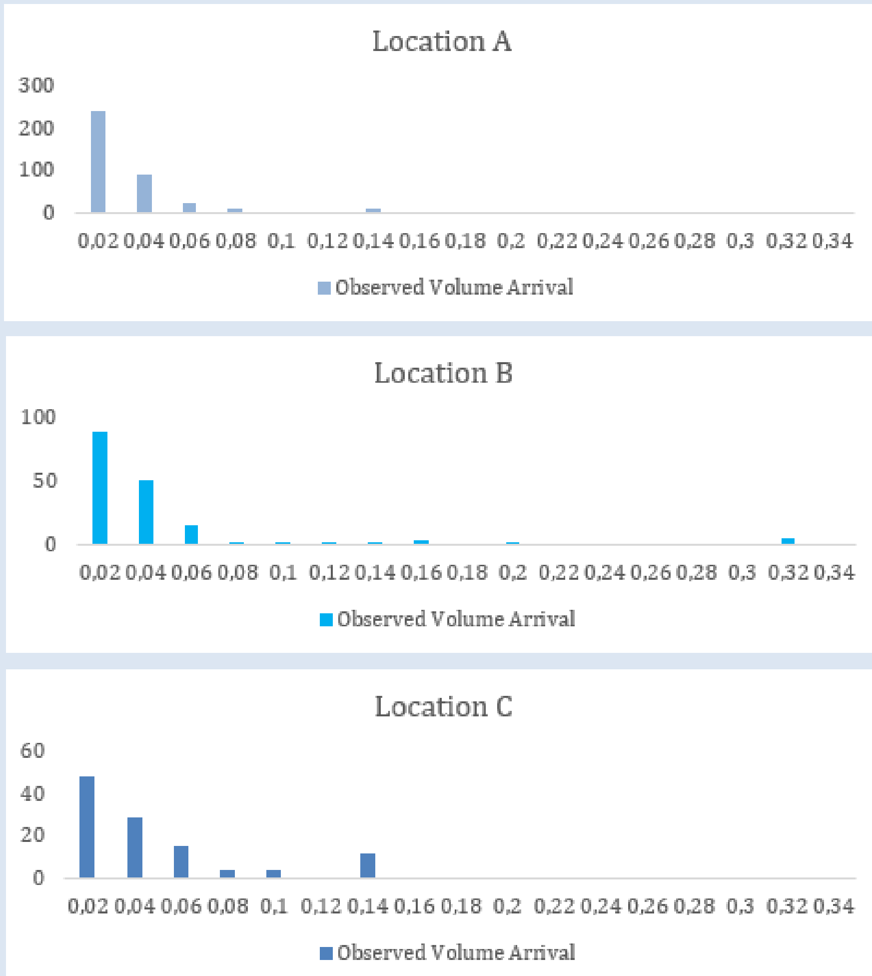
Exhibit B: Observed order weight data for the three locations.



The three figures show the observed number of orders with a specific weight. The initial hypothesis was that the order weights could be represented by a Weibull or Exponential distribution function. As the figures shows, the hypothesis is likely to be rejected for Location B and Location C. It will be confirmed with a Chi-squared test. (The number of bins has been reduced in the illustration)

The Figures in Exhibit C illustrates the volume frequency for all three locations. As can be seen, the order volume data does not resemble any well-known distribution. Thus, the hypothesis for the volume distribution is that an Empirical distribution will be required to use the analytical model.

Exhibit C: Observed order volume data for the three locations.



The three figures all show the frequency of packages with different volumes sent to each location. The bin-sizes are chosen in this due to standardized package-sizes. At this point there is no hypothesis regarding what distribution function that could represent the volume distribution. (The number of bins has been reduced in the illustration)

6.3 Shipment Costs to each Location

To be able to make an informative decision on whether or not to implement a consolidation policy, it is of great importance that the inputs used in the analytical model are somewhat realistic. To decide if this is true or not, actual values need to be computed to use as a benchmark when validating the numbers. In this report, the actual total annual costs for each location was calculated to use as this benchmark.

The total annual shipment cost for each location was calculated and can be found in Figure 8 below. These values will be compared to the annual expected shipping cost (Equation 18) for immediate dispatching. Moreover, the cost per weight at each location can also be found in Figure 8.

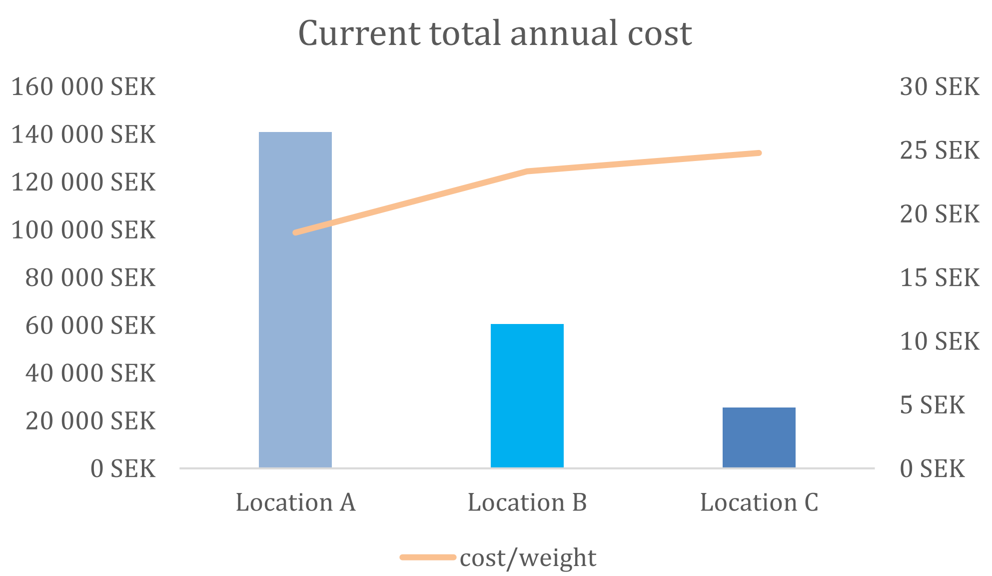


Figure 8: Current total annual cost for each location together with the average cost per unit.

7. Result

This chapter presents the results obtained when conducting the methods presented previously in the report. The distribution testing result is presented together with the associated test parameters. Moreover, the calculated expected variable cost and the expected waiting cost are provided to use as input in the constructed mathematical model. Finally, the model construction and the Long-Run Average Cost is unveiled.

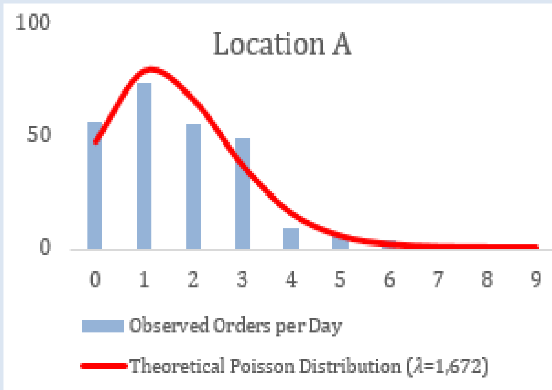
7.1 Demand Data

To be able to use the model developed in this project; the arrival distribution needs to follow a Poisson distribution function. For the weight distribution the hypothesis was that the data follows an Exponential distribution function, and that the volume distribution did not follow any well-known distribution function. In the following subsections, the results from Stat::fit regarding the arrival, weight and volume distributions were used to test these hypotheses.

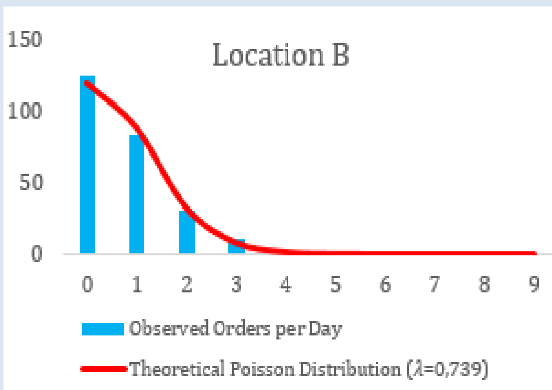
7.1.1 Arrival Distribution

To confirm the hypothesis that the order arrivals could be approximated with a Poisson distribution function, the arrival intensity λ was calculated for each location. When λ had been obtained using Theorem 1, it was possible to plot the theoretical curve with an order per day histogram to see if the bar chart and curve followed a similar pattern (see Exhibit D). This gave the first indication that the hypothesis could not be rejected.

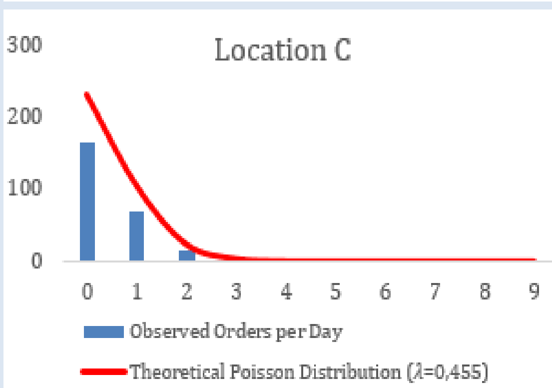
Exhibit D: Results for the order arrival distribution fitting.



Distribution function	T	χ2	Acceptance
Poisson	5.05	7.81	Do not reject
Negative Binomial	8.31	9.49	Do not reject
Geometric	28.7	7.81	Reject
Discrete Uniform	195	12.6	Reject



Distribution function	T	χ2	Acceptance
Poisson	5.537	5.99	Do not reject
Negative Binomial	0.039	5.99	Do not reject
Geometric	N/A	-	Reject
Discrete Uniform	314	7.81	Reject



Distribution function	T	χ2	Acceptance
Poisson	4.64	7.81	Do not reject
Negative Binomial	1.01	7.81	Do not reject
Geometric	4.21	7.81	Do not Reject
Discrete Uniform	512	7.81	Reject

To validate this, the Stat::fit software program was used to perform a Chi-squared test for each location. The program automatically adjusts the bin sizes to “equal probability”, meaning that the expected frequency of order arrivals in each bin is equal. However, when performing a Chi-squared test with equal probability on the order arrival data for Location C; there are too few (net) intervals to perform a good Chi-squared test. Resulting in that the test for Location C was performed using the “equal length” bin setting.

At a 5 percent significance level, the hypothesis could not be rejected at any location. Thus, the order arrivals can be assumed to follow a Poisson distribution function. All test parameters can be found in Table 3 below. In addition to this, the test showed that the order arrivals could be represented as a Negative Binomial distribution function for the studied locations (see Exhibit D). To see all distribution functions tested, please see Appendix 1.

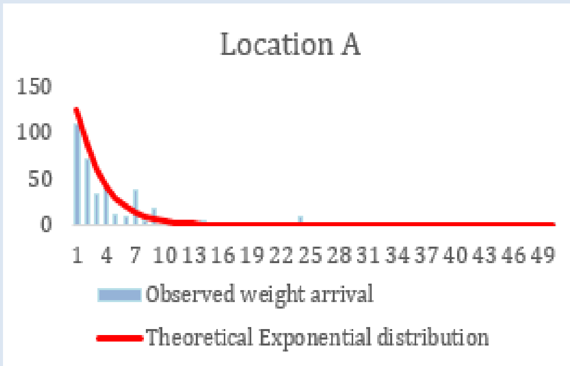
Table 3: Test parameters Chi-squared test, Poisson Distribution.

City	Location A	Location B	Location C
Alpha	0.05	0.05	0.05
Lambda	1.67194	0.73913	0.454545
Number of bins	8	6	6
Interval type	Equal probability	Equal probability	Equal length
Net bins	4	3	4
Degrees of freedom	3	2	3
T Obs	5.05	0.537	4.64
T	7.81	5.99	7.81
Status	Do not reject	Do not reject	Do not reject

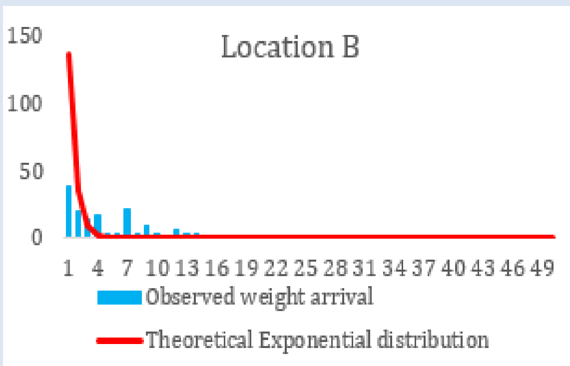
7.1.2 Weight Distributions

The initial hypothesis was that the order weight followed an Exponential distribution. After obtaining μ (Equation (6)) and λ, the exponential theoretical curve was plotted together with the weight histogram for each location (see Exhibit E). To confirm the hypothesis, a Chi-squared test was performed using Stat::fit. The results showed the hypothesis was rejected for each location at a 5% significance level. According to the results in Exhibit E this was true for all distribution function; no other distribution function could be used to approximate the weight distribution. The order weight data is continuous, but price ranges are based on discrete price data brackets. Therefore, the data has been rounded up to the closest bracket and the *discrete method* described in section 3.4.3 has been used to create the Empirical distribution function. The results from the test for all distribution functions can be found in Appendix 1.

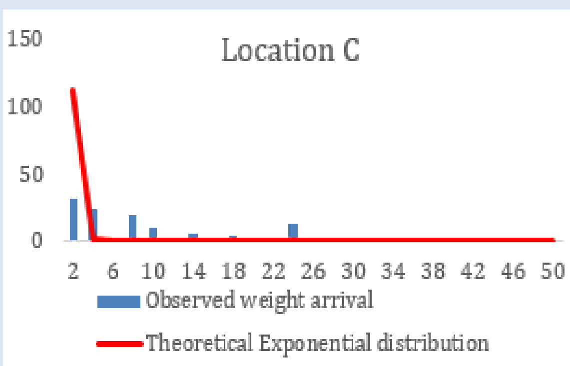
Exhibit E: Results for the order weight distribution fitting.



Distribution function	T	χ^2	Acceptance
Exponential	761	41.3	Reject
Weibull	501	41.3	Reject
Pearson 5	339	41.3	Reject
Inverse Weibull	323	41.3	Reject



Distribution function	T	χ^2	Acceptance
Exponential	127	26.3	Reject
Weibull	64.9	26.3	Reject
Pearson 5	67.5	26.3	Reject
Inverse Weibull	67.5	26.3	Reject

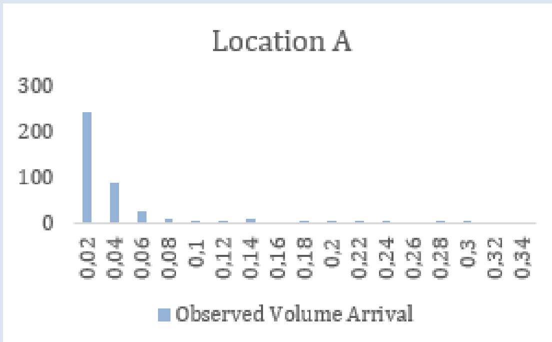


Distribution function	T	χ^2	Acceptance
Exponential	72.7	25	Reject
Weibull	78.5	25	Reject
Pearson 5	88.5	25	Reject
Inverse Weibull	88.5	25	Reject

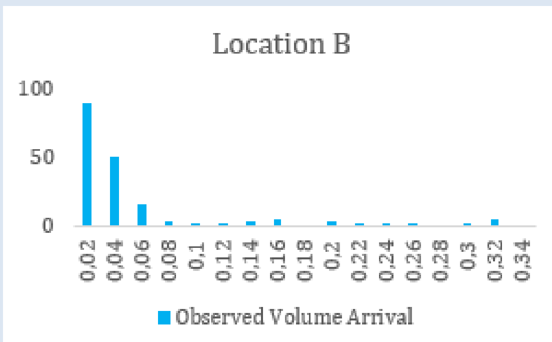
7.1.3 Volume Distribution

In Exhibit F below, the order volume distribution results from Stat::fit can be found. The results show that there is no applicable distribution function to represent the package volume for the selected locations. Therefore, the result implies that an Empirical distribution method should be used to represent the volume distribution. Package volume data is continuous and has been *classified* (see section 3.4.3) to create the empirical distribution. Tests results for all distributions can be found in Appendix 1.

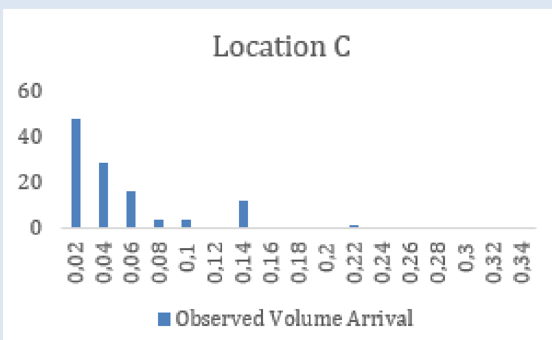
Exhibit F: Results for the order volume distribution fitting.



Distribution function	T	χ2	Acceptance
Exponential	1060	47.4	Reject
Weibull	1150	47.4	Reject
Pearson 5	1170	47.4	Reject
Inverse Weibull	1120	47.4	Reject



Distribution function	T	χ2	Acceptance
Exponential	242	25	Reject
Weibull	223	25	Reject
Pearson 5	174	25	Reject
Inverse Weibull	263	25	Reject



Distribution function	T	χ2	Acceptance
Exponential	102	25	Reject
Weibull	89.7	25	Reject
Pearson 5	93	25	Reject
Inverse Weibull	102	25	Reject

7.2 Cost Data

In the following subsections, the data used as input in the final mathematical model is presented. This includes the Expected Variable and Waiting Cost.

7.2.1 Expected Variable Cost

As a single distribution function could not be used to represent the order weights (see Exhibit E), the weight distribution needed to be represented using an empirical distribution function (see section 3.4.3). This function was then used to find the expected variable cost per dispatch E[c] using Equation (28). The obtained result for each location can be seen in Figure 9 below.

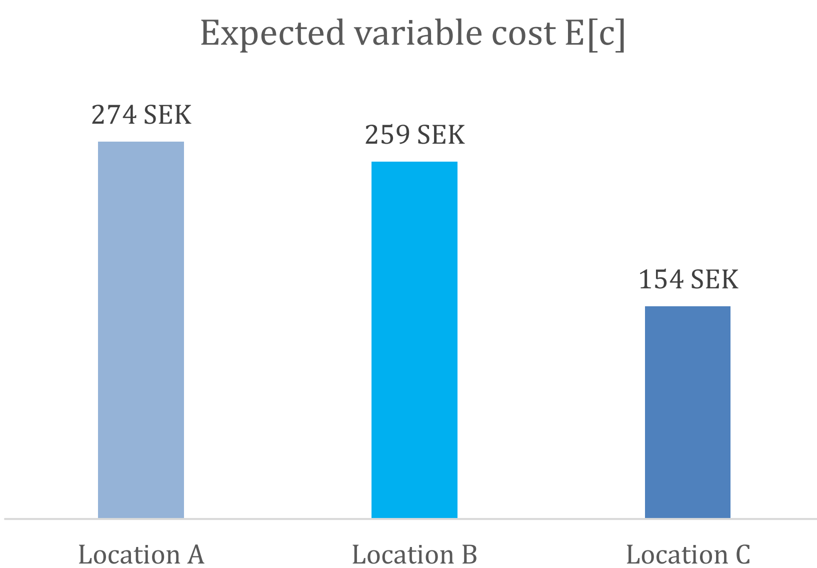


Figure 9: The expected variable cost E[c] for the studied locations.

7.2.2 Expected Waiting Cost

Like section 7.2.1, a distribution function representing the volume did not exist and the distribution needed to be expressed using the Empirical distribution function. Thus, Equation (29) is used with the empirical method and the result can be seen in Figure 10 below. Figure 10 also presents the expected volume E[v] per package.

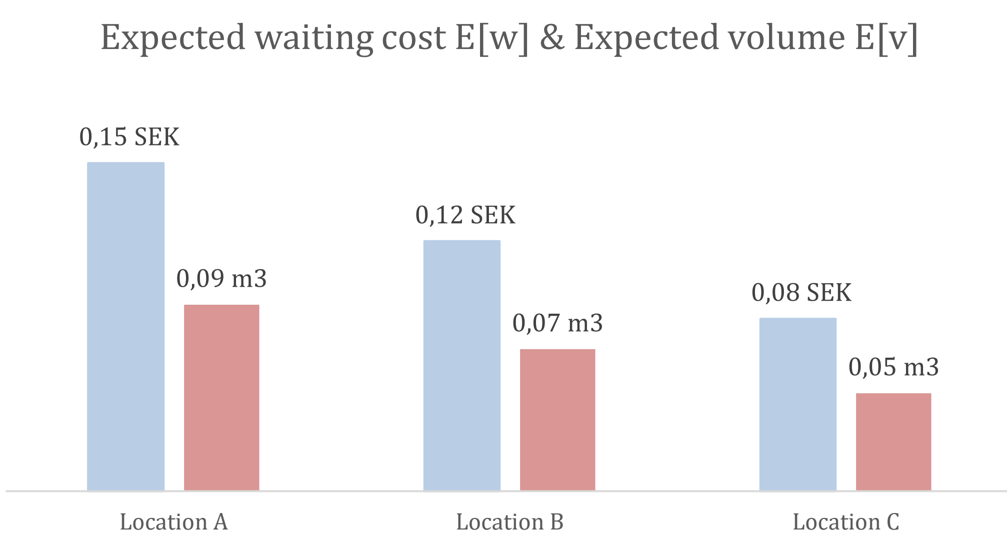


Figure 10: The expected waiting cost E[w] and expected volume E[v].

7.3 Mathematical Model Results

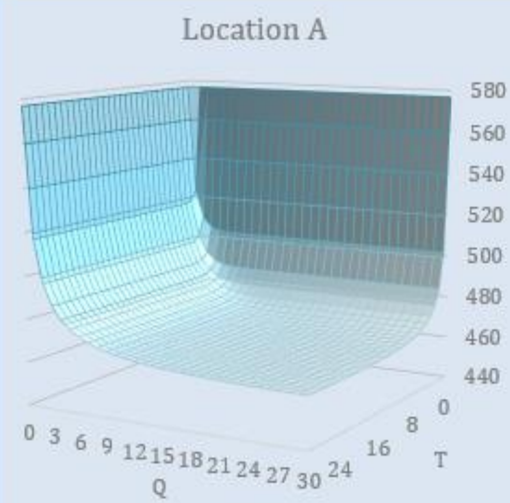
The code used to implement the final model can be found in Appendix 2. Furthermore, the model results include the long-run average cost for different combinations of T and q, which is of importance due to the restriction on the variable T from the case company. These are presented in the following subsections.

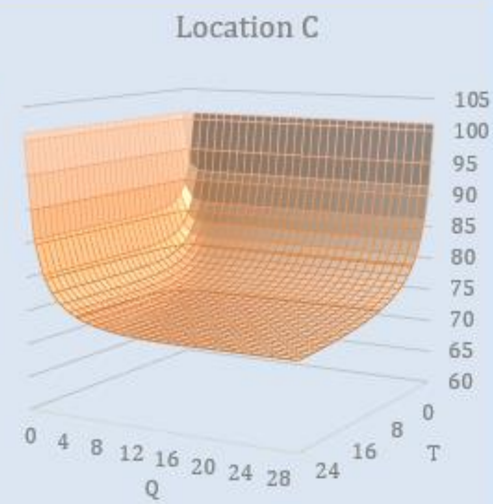
7.3.1 Long-Run Average Cost G

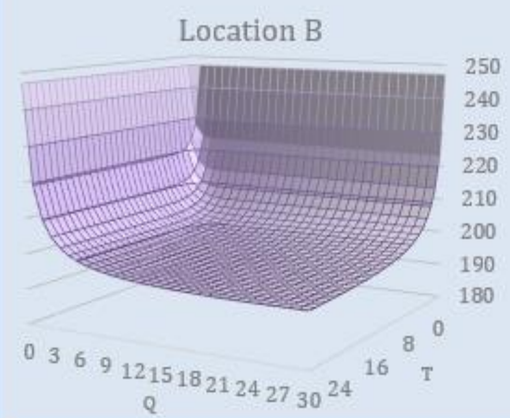
The optimal (opt) and time constrained (T = 2) long-run average cost for each location is presented together with the quantity and time values in Exhibit G below. To find the exact values for each variable point, please see Appendix 3.

$\breve{G}(q, T)$ can be expressed for all $q, T \geq 0$ to find the local minimum and the optimal consolidation policy. Note that when $q, T = 0$, this represents instant dispatching and the same values obtained in Equation (18). In Exhibit G, 3D plots of $\breve{G}(q, T)$ are illustrated for each location. The minimum long-run average cost values in the plot represents the optimal policy (see Table in Exhibit G).

Exhibit G: 3D Long-run Average Cost plots for each location.







	Location A	Location B	Location C
$q_{opt \mid T=2}$	13	10	8
q_{opt}	30	25	18
T_{opt}	20	30	30
$G(q_{opt}, T_{opt})$	463,67	195.18	72.85
$G(q_{opt \mid T=2}, T=2)$	485.37	214.09	86.41

8. Analysis

This chapter presents the analysis made on the previously obtained result. It will go through the analysis of the demand data, cost data as well as the results from the model. Finally, a sensitivity analysis will be carried out to test the result reliability, or more in particular: the holding cost parameter. Moreover, the percentage point cost savings for different holding periods will be analysed.

8.1 Goodness of fit

The results in section 7.1.1 shows, as the initial hypothesis suggests, that the order arrival can be approximated with the Poisson distribution function for each selected location. As the locations have been selected to cover the full range of customers based on their order frequency, it can be assumed that the order arrival process for all cities can be approximated using the Poisson distribution function. This approximation will make it easier for the management team to analyse new locations and decide if a consolidation policy should be implemented.

Exhibit D in section 7.1.1 shows that the negative binomial distribution function can be used to approximate the order arrivals for the selected locations. However, this distribution function will not be used in the model as the selected literature by Mutlu et al. assumes that order arrivals occur according to a Poisson process. Table 3 shows that the Chi-squared test for Location C required the bin sizes to be of "equal length" instead of "equal probability". As stated in section 3.5.1, the results for this location are therefore not as accurate. However, it is assumed to be sufficient to use in the model.

As can be seen in section 7.1.2 and 7.1.3, the distribution fitting resulted in that an Empirical distribution function needed to be used for the order weights and volume as no distribution function could represent this data. Therefore, for future use of the model, the empirical method can be used to represent the weight and volume shipped to any location. This makes it easier for management to apply the model at new locations as it does not require any specific software to perform the distribution fitting. Moreover, such software can be both expensive and require additional training to use and would make an implementation phase more complex. Furthermore, the results show that the hypothesis regarding the weight distribution, i.e. that it is Exponential distributed, can be rejected at a 5% significance level.

8.2 Expected Variable Cost

At first glance, the expected variable cost - in absolute numbers - seems to be rather reasonable at each location. As previously seen in Figure 9, the expected variable cost at Location A is almost 78 percent greater than for Location C. An explanation for this difference could be that the types of products shipped to Location A are of larger size and weight resulting in a higher variable cost per order. This is confirmed in Figure 7 in Chapter 6 as Location A shows the highest total weight to orders ratio (two times greater than for location C).

To validate the obtained expected variable cost per dispatch E[c] for each location, the result was compared to the actual annual cost for 2018. Using Equation (18) to get the expected cost per day of a consolidation cycle with immediate dispatch and multiplying this value by the number of working days in a year, one gets the expected annual cost. This cost can then be compared to the historic actual annual cost to ensure that the expected variable cost per order E[c] is reasonable. The comparison can be found in Figure 11 below.

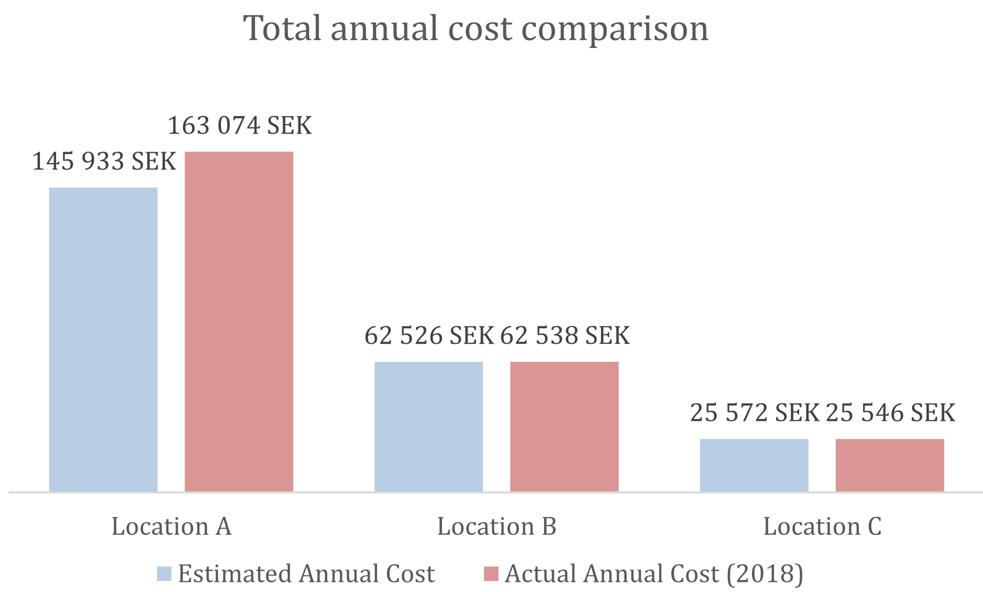


Figure 11: Total annual cost comparison used as variable cost validation

Figure 11 confirms that the Expected variable cost E[c] gives a reasonable approximation of the variable cost per order when looking over an annual cycle. Moreover, the difference between the actual and estimated cost becomes smaller as the order arrival intensity decreases. An explanation for this could be that the fixed costs are equal in both the current and estimated scenario. This, in combination with a low weight to order ratio, implies that the variable cost is a smaller part of the total cost, resulting in a smaller difference.

8.3 Expected Waiting Cost

The expected waiting cost has been calculated with the help of the case company and, as Figure 10 in section 7.2.2 shows, it resulted in a low cost for the selected locations. Although it was calculated in collaboration with the case company, the expected waiting cost is uncertain. Mainly due to the reason that the holding cost at the cross-docking warehouse is defined in square meters and not cubic meters. As the data given by the case company only included the volume and not the dimensions of the goods, it was necessary to make assumptions about the holding cost, which resulted in an uncertain expected waiting cost. As this is the most uncertain input to the model, it is of great importance to keep it updated. This input will later be tested in the sensitivity analysis (section 8.6).

Furthermore, Figure 10 shows that the expected waiting cost differ between the different locations. For example, Location A has the highest expected waiting cost. This is not due to the order frequency but rather the size of the packages shipped. This can be confirmed by looking at Figure 7 in Chapter 6.

The reason for only using the "Storage space cost" in section 3.1 is due to the characteristics of the items and situation. The goods are not perishable, are of low value and are only stored for a short period of time. Therefore, the risk, service, and inventory costs are negligible and can be disregarded.

The literature stated that the holding cost only included the points mentioned in section 3.1, but as customers are not willing to wait indefinitely, in this project one could argue that it should also include a penalty fee. Meaning, if goods are not shipped within the specified timeframe (T = 2 in this case), an additional cost will be added to the waiting cost. Depending on customer preference and urgency, this penalty cost can increase linearly or exponentially. Therefore, one could argue that it is reasonable to add a penalty fee to the model. This would, in turn, affect the optimal solution and move it closer to the origin.

8.4 Long-Run Average Cost

Looking at the resulting Long-Run Average Cost plots for each location in Exhibit G; all plots show a similar pattern. An implementation of a consolidation policy would in fact reduce the Long-Run average cost, given that the assumptions are correct. The steep surface slope when increasing q and T indicates that even a minor increase in the holding time and number of packages consolidated would reduce this cost with a significant amount. As can be seen in Exhibit G, this slope eventually flattens as both these values continue to increase. The flatness of the surface is caused by the low expected waiting cost E[w]. An increase in this cost would result in an optimal dispatch point closer to the origin and a more convex surface. As discussed previously, if a penalty fee was to be implemented, the Long-Run Average Cost plot would look different. To illustrate this, Figure 12 shows the Long-Run Average Cost with a linear penalty fee w_p= 0.2 (SEK/day) when the maximum holding time policy is breached for Location A.

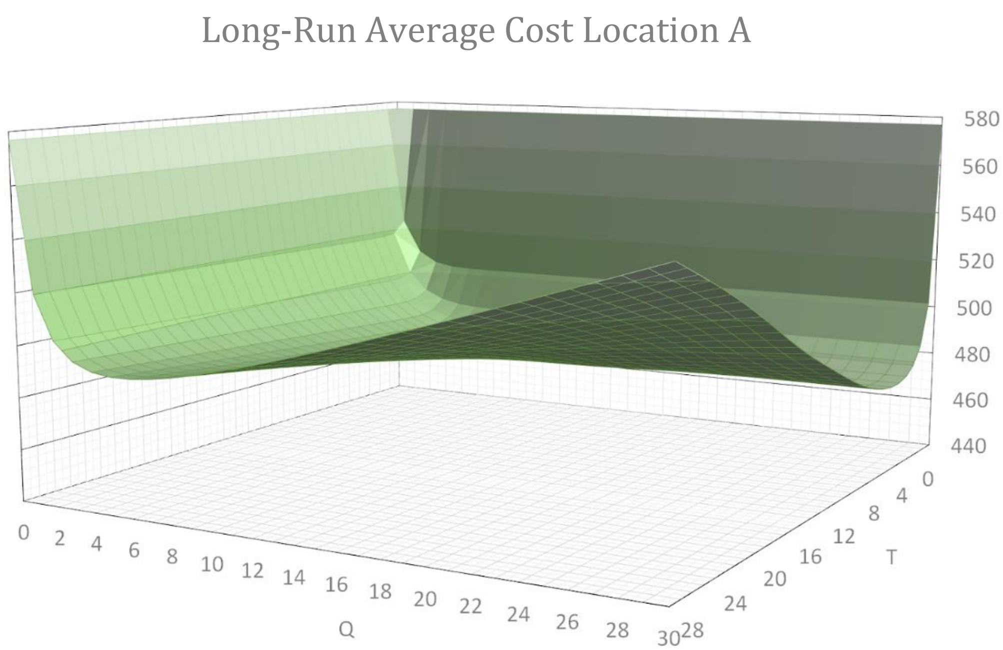


Figure 12: Long-Run Average Cost with a 0.2SEK/day penalty fee.

Furthermore, the shape of Figure 12 shows that a short holding time results in a low cost for all dispatch quantities >5; the opposite is also true for a low dispatch quantity. This is intuitive as the lower restriction in each case is expected to occur, i.e. the policy is mainly restricted by one of the variables.

8.4.1 Annual Cost Comparison

To easier grasp the potential cost savings, the annual cost for each policy and location will be calculated in absolute numbers. These will then be analysed to evaluate if a consolidation policy is reasonable in terms of potential cost savings. If reasonable, it shall also be obvious if this also is true for the time constraints set by the case company. This cost will be compared to that of an optimal consolidation policy.

Figure 13 illustrates the potential cost savings in absolute numbers when implementing a consolidation policy for different restrictions in T, i.e. today's annual costs are compared to the restricted T (the time constraint given by the case company) and optimal TQ policy. Figure 13 also shows the potential percentage point cost savings for each location. The annual cost is obtained by multiplying the cost per cycle length with the number of cycles over a year.

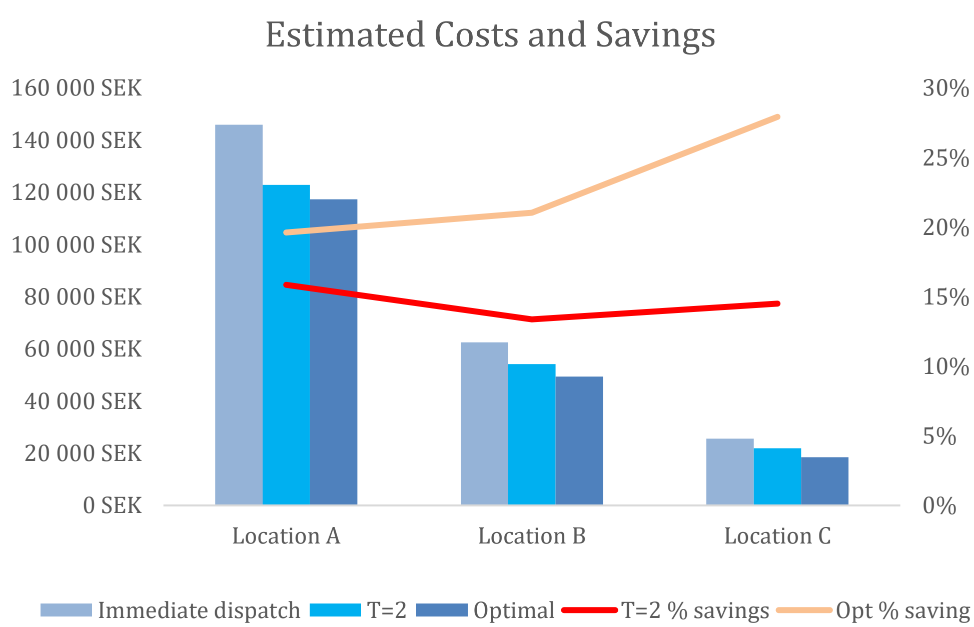


Figure 13: Annual costs for different policies in absolute numbers and potential cost savings.

Figure 13 shows a great cost saving potential for each location with an optimal policy with cost reduction ranging from 19 to 28 percent. Furthermore, it shows that the potential cost savings with a restricted T policy also results in a significant cost saving potential ranging from 13 to 16 percent. It is important to note, looking at Exhibit G, that the difference between the optimal time policy and the restricted (T=2) policy is greater than 17 days for all locations. I.e. the difference between the two lines is the percentual cost saving benefit when waiting for this extensive period. This is closely related to the flatness of the surface in Exhibit G.

8.4.2 Optimal q in Practice

Due to the low holding cost, the optimal *q* in a TQ policy becomes a high value. However, with a short holding period restriction set by the case company, this value is greatly decreased (see Exhibit G). This makes it easier for the company to keep track of the number of packages being consolidated and to know when to dispatch an order based on the quantity. One can use the expected volume of the packages to approximate how much storage space shall be used before dispatching an order. To make an example, Location A has a $q_{opt \mid T=2} = 9$ and a $0.14m^3$ expected order volume. With a box storage space of $0.18m^3$, this means that the dispatch should occur when seven[1] storage slots have been occupied. This assumes that the storage space is perfectly packaged, which rarely is the case. Thus, this value can be assumed to be slightly underestimated.

8.5 Volume-Cost-Benefit

To test the second research question, i.e. that there are potential cost reduction benefits associated with shipping larger volumes and consolidating orders, one can look at the cost savings per volume quota. This quota is obtained by dividing the absolute cost savings (obtained from Figure 13) by the total number of orders shipped to that location. Figure 14 illustrates this quota for each location.

[1] (9*0.14) / 0.18 = 7

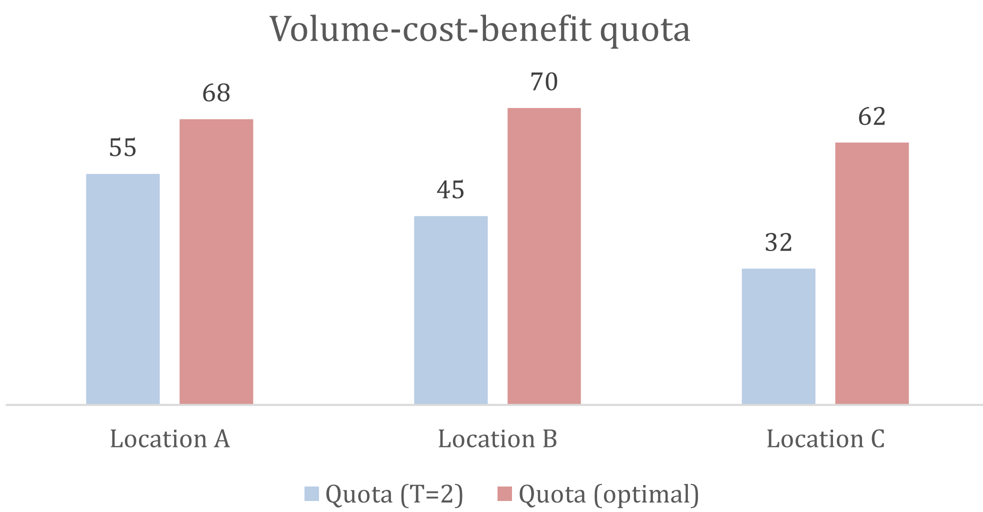


Figure 14: Volume cost benefit quota for the studied locations.

As can be seen in Figure 14 above, the volume-cost-benefit quota is similar for all locations when the optimal TQ policy is implemented. This means that if the optimal TQ policy was used, it would be equally beneficial to consolidate shipments to all studied locations. However, the optimal policy will not be used by the case company as it results in long holding periods, which their customers cannot accept. Therefore, it is of interest to analyse the quota when T is restricted to two days, as this is the case company's delimitation. Analysing Figure 14, one can see that when T=2, the volume-cost-benefit quota is higher for high order frequency locations. The hypothesis is therefore confirmed, i.e. that in the practical case, it is more useful to consolidate shipments when a larger volume is shipped. Moreover, the answer to the second research question is obtained. However, as Figure 13 suggests, a consolidation policy will result in cost reductions and can be used for any location, even though not equally beneficial.

8.6 Sensitivity Analysis

8.6.1 Holding Cost

As mentioned in Chapter 2, assumed parameters need to be tested using sensitivity analysis to see how an increase or decrease in this parameter would impact the overall result. In this report, the holding cost is the most uncertain model input and needs to be investigated further. Hence, the potential percentage cost savings for different holding costs for both the optimal TQ- and restricted policy will be analysed.

Figure 15 illustrates the potential percentage cost savings for the optimal TQ policy for different holding costs. The holding cost (highlighted in Figure 15) used to obtain the previous result is equal to 1.76 SEK.

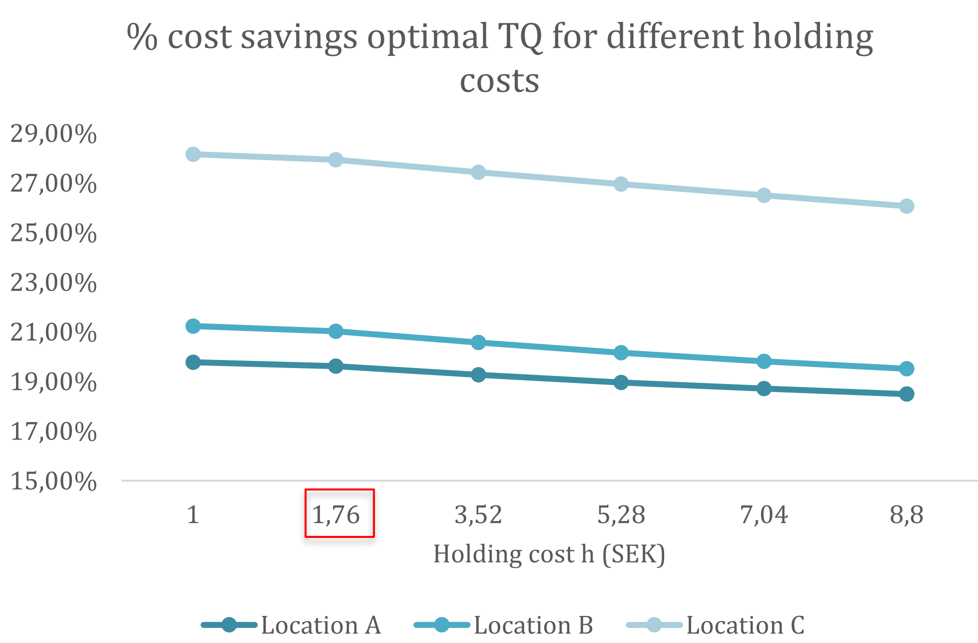


Figure 15: Optimal cost savings in percentage with different holding costs.

The Figure shows that there is very little change in the cost saving benefit when increasing the holding cost. For example, if the holding cost is increased by 400 percentage, the potential cost savings are only reduced by 1.46 percentage points. The biggest difference is found at Location C, were a 400 percent holding cost increase would result in a 2.2 percent difference in potential cost savings. However, these changes are very small and a significant increase in the holding cost is required for the results to be different.

The same pattern is found when studying the potential cost savings when there is a restriction in the holding period (T=2), see Figure 16. In this case the difference is even smaller than in the case for the optimal TQ policy. A 400 percent increase in the holding cost results in a difference smaller than 2 percentage points for all cases.

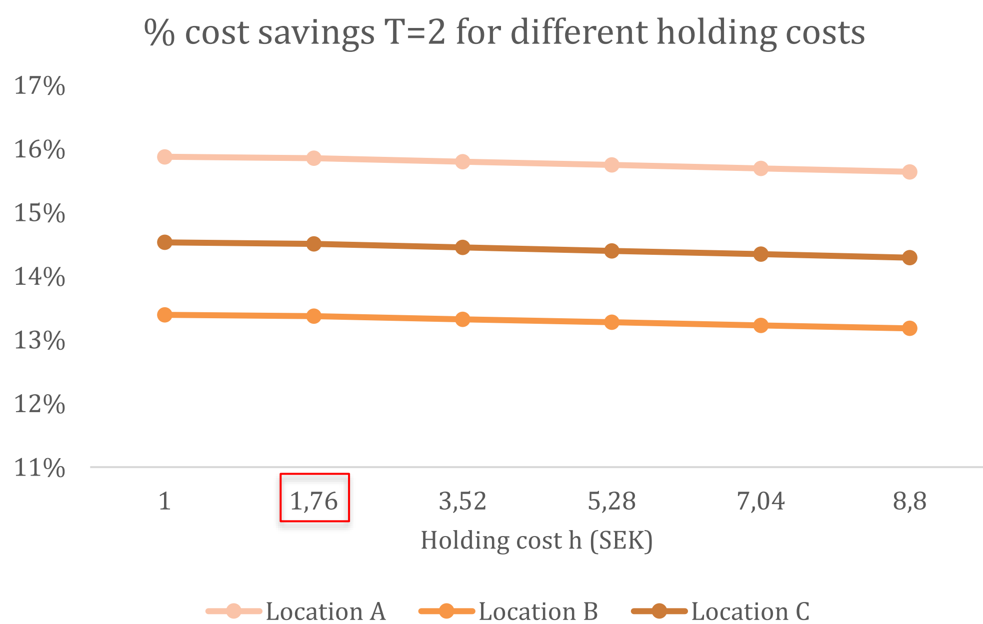


Figure 16: T=2 cost savings in percentage with different holding costs.

A key takeaway from this analysis is that there is no major output difference when adjusting the holding cost input. As this cost represents one of the most significant estimations made in this case study, it is fair to say that the model is stable and that the result obtained in this report is not affected by an inaccurate estimation.

8.6.2 Holding Period

The company has specified a maximum allowed holding period of two working days. Like the holding cost, the cost saving benefit, i.e. the potential percentage point cost saving, for different holding periods T needs to be evaluated to see how sensitive this parameter is to change. When calculating the cost saving benefit for different holding periods, the dispatch quantity q is optimal for each holding period T. Figure 17 below shows the percentage point cost saving benefit for different time policies.

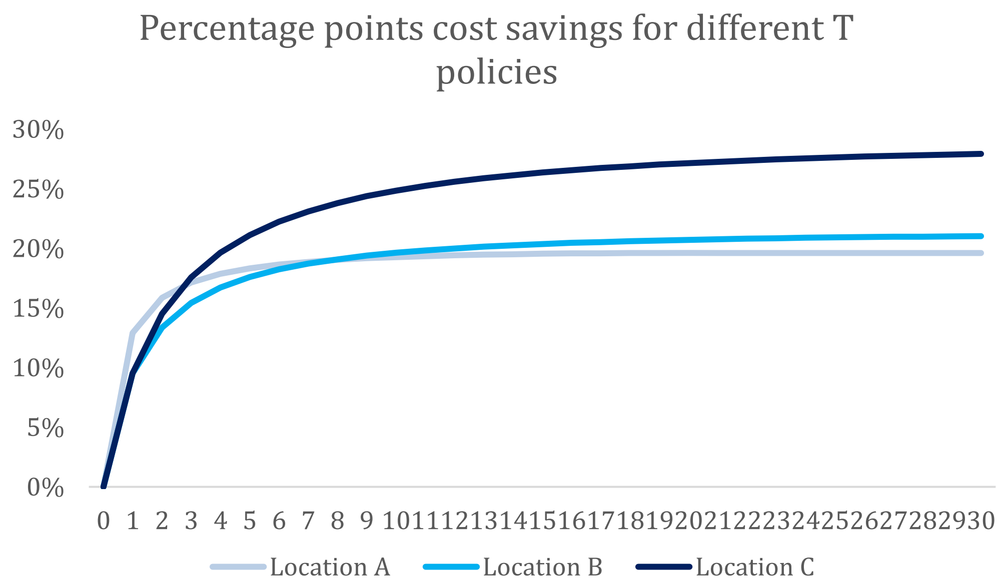


Figure 17: Cost savings potential for different TQ-policies at each location.

As can be seen in Figure 17, the percentage point cost-saving benefit slope for different time policies decreases as T increase. The steep slope suggests that implementing a consolidation policy with a small increase in the holding period would lead to great cost reductions. This is true for all locations. Looking at Figure 17, it is also possible to conclude that when the slope flattens, an increase in the holding period will only lead to a minor cost reduction benefit. For future evaluation, if the company can hold the packages for a longer period, it is possible to use this graph to evaluate if storing the package for the entire period is worthwhile.

9. Conclusion

This chapter will present the general conclusion based on the obtained result and the analysis made. The conclusion is specific for the case company.

To conclude this project, it is the team's belief that the case company could implement a consolidation policy for all studied locations based on the holding time constraints of the company. Given these constraints, the result shows that a 13-16 percentage point annual cost reductions could be possible at the studied locations. This answers the first research question. However, when looking at this cost reduction in absolute numbers, it seems more reasonable to focus on large volume customers.

It is also possible to conclude that the consolidation cost reduction benefit is equal for locations with different frequencies if orders are dispatched using the optimal TQ-based policy. However, given the time constraints set by the case company; the cost reduction benefit will be greater for locations with higher order frequencies. This answers the second research question.

Furthermore, the result shows that the order arrival can be approximated with a Poisson distribution function. This was true for all different order arrival frequencies, ranging from 115 to 423 packages per year. Moreover, the company can assume that this is true for other locations operating within the same frequency span.

Another conclusion from the project is that the result is robust; a 400% increase in the holding cost only slightly changes the potential cost savings. The benefit of increasing the holding period is greatly decreased after only a few working days, before reaching the optimal TQ policy. Moreover, the selected policy should also be based on conversations with the customers at selected locations to evaluate their maximum allowed additional waiting time before adding a potential penalty cost.

To summarize, the first research question of this study was to evaluate if a consolidation shipping policy would reduce the total shipping costs while maintaining a reasonable service level. The team concludes that this is true for all studied locations but recommends the company to focus on evaluating high-frequency locations for future policy implementations. This recommendation is based on the findings from the second research question as well as potential cost savings in absolute numbers.

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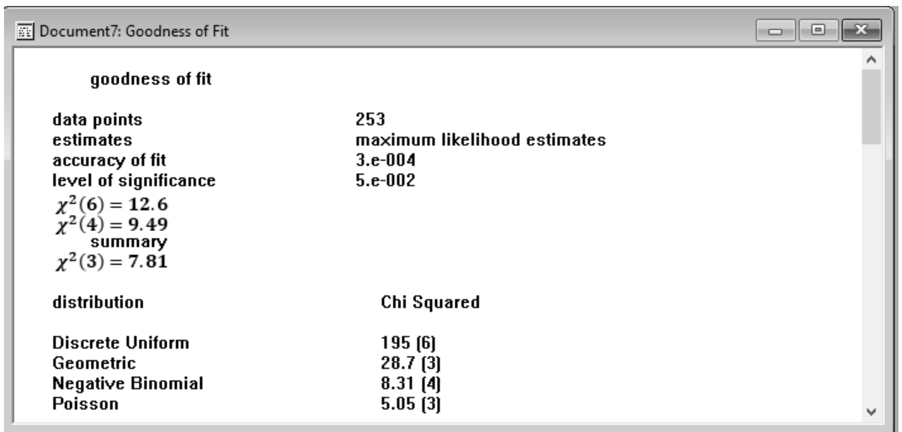
Appendix

Appendix 1: Distribution Fitting

Arrival Rate

Location A:



Document7: Goodness of Fit

goodness of fit

data points	253
estimates	maximum likelihood estimates
accuracy of fit	3.e-004
level of significance	5.e-002

$\chi^2(6) = 12.6$

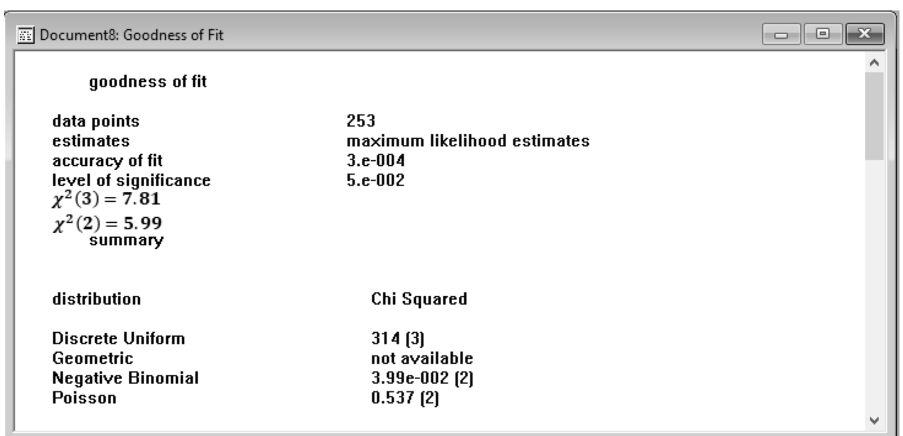
$\chi^2(4) = 9.49$

summary

$\chi^2(3) = 7.81$

distribution	Chi Squared
Discrete Uniform	195 (6)
Geometric	28.7 (3)
Negative Binomial	8.31 (4)
Poisson	5.05 (3)

Location B:



Document8: Goodness of Fit

goodness of fit

data points	253
estimates	maximum likelihood estimates
accuracy of fit	3.e-004
level of significance	5.e-002

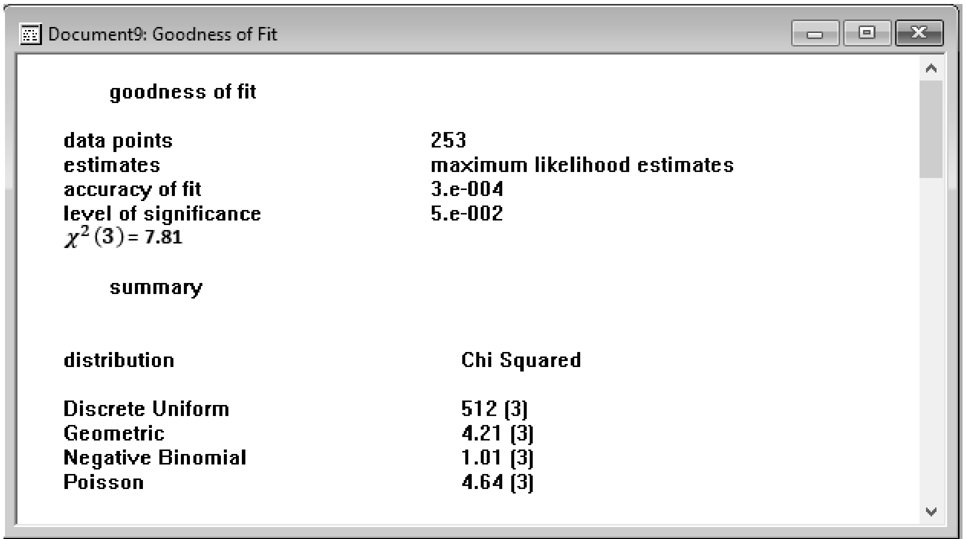
$\chi^2(3) = 7.81$

$\chi^2(2) = 5.99$

summary

distribution	Chi Squared
Discrete Uniform	314 (3)
Geometric	not available
Negative Binomial	3.99e-002 (2)
Poisson	0.537 (2)

Location C:



Document9: Goodness of Fit

goodness of fit

data points	253
estimates	maximum likelihood estimates
accuracy of fit	3.e-004
level of significance	5.e-002

$\chi^2(3) = 7.81$

summary

distribution	Chi Squared
Discrete Uniform	512 (3)
Geometric	4.21 (3)
Negative Binomial	1.01 (3)
Poisson	4.64 (3)

Order Weight

Location A:

Document2: Goodness of Fit

data points	423
estimates	maximum likelihood estimates
accuracy of fit	3.e-004
level of significance	5.e-002

$\chi^2(28) = 41.3$

summary

distribution	Chi Squared
Beta	671 [28]
Cauchy	680 [28]
Chi Squared	3.96e+003 [28]
Erlang	1.18e+004 [28]
Exponential	761 [28]
Extreme Value IA	4.91e+003 [28]
Extreme Value IB	5.41e+003 [28]
Gamma	452 [28]
Inverse Gaussian	316 [28]
Inverse Weibull	323 [28]
Johnson SB	no fit
Johnson SU	366 [28]
Laplace	1.31e+003 [28]
Logistic	2.45e+003 [28]
LogLogistic	415 [28]
Lognormal	354 [28]
Normal	4.35e+003 [28]
Pareto	684 [28]
Pearson 5	339 [28]
Pearson 6	246 [28]
Power Function	912 [28]
Rayleigh	no fit
Triangular	8.8e+003 [28]
Uniform	9.91e+003 [28]
Weibull	501 [28]

Location B:

Document3: Goodness of Fit

data points	187
estimates	maximum likelihood estimates
accuracy of fit	3.e-004
level of significance	5.e-002

$\chi^2(16) = 26.3$

summary

distribution	Chi Squared
Beta	64.7 [16]
Cauchy	172 [16]
Chi Squared	no fit
Erlang	220 [16]
Exponential	127 [16]
Extreme Value IA	235 [16]
Extreme Value IB	968 [16]
Gamma	79.3 [16]
Inverse Gaussian	73.3 [16]
Inverse Weibull	67.5 [16]
Johnson SB	no fit
Johnson SU	80.4 [16]
Laplace	189 [16]
Logistic	375 [16]
LogLogistic	69.8 [16]
Lognormal	82.9 [16]
Normal	551 [16]
Pareto	220 [16]
Pearson 5	67.5 [16]
Pearson 6	144 [16]
Power Function	187 [16]
Rayleigh	no fit
Triangular	1.31e+003 [16]
Uniform	1.99e+003 [16]
Weibull	64.9 [16]

Location C:

Document5: Goodness of Fit

data points	115
estimates	maximum likelihood estimates
accuracy of fit	3.e-004
level of significance	5.e-002

$\chi^2(15) = 25$

summary

distribution	Chi Squared
Beta	54.9 (15)
Cauchy	86.9 (15)
Chi Squared	166 (15)
Erlang	72.7 (15)
Exponential	72.7 (15)
Extreme Value IA	147 (15)
Extreme Value IB	593 (15)
Gamma	72.7 (15)
Inverse Gaussian	75.2 (15)
Inverse Weibull	88.5 (15)
Johnson SB	88.8 (15)
Johnson SU	no fit
Laplace	165 (15)
Logistic	161 (15)
LogLogistic	80.8 (15)
Lognormal	59.3 (15)
Normal	204 (15)
Pareto	183 (15)
Pearson 5	88.5 (15)
Pearson 6	94.1 (15)
Power Function	146 (15)
Rayleigh	no fit
Triangular	477 (15)
Uniform	869 (15)
Weibull	78.5 (15)

Order Volume

Location A:

Document1: Goodness of Fit

data points	423
estimates	maximum likelihood estimates
accuracy of fit	3.e-004
level of significance	5.e-002

$\chi^2(33) = 47.4$

summary

distribution	Chi Squared
Beta	1.03e+003 [33]
Cauchy	1.32e+003 [33]
Chi Squared	1.17e+003 [33]
Erlang	1.4e+004 [33]
Exponential	1.06e+003 [33]
Extreme Value IA	1.49e+003 [33]
Extreme Value IB	6.79e+003 [33]
Gamma	1.16e+003 [33]
Inverse Gaussian	1.03e+003 [33]
Inverse Weibull	1.12e+003 [33]
Johnson SB	no fit
Johnson SU	no fit
Laplace	1.24e+003 [33]
Logistic	1.68e+003 [33]
LogLogistic	1.16e+003 [33]
Lognormal	3.34e+003 [33]
Normal	3.34e+003 [33]
Pareto	no fit
Pearson 5	1.17e+003 [33]
Pearson 6	1.66e+003 [33]
Power Function	1.3e+003 [33]
Rayleigh	no fit
Triangular	1.06e+004 [33]
Uniform	1.16e+004 [33]
Weibull	1.15e+003 [33]

Location B:

Document4: Goodness of Fit

data points	187
estimates	maximum likelihood estimates
accuracy of fit	3.e-004
level of significance	5.e-002

$\chi^2(19) = 30.1$

summary

distribution	Chi Squared
Beta	224 (19)
Cauchy	260 (19)
Chi Squared	311 (19)
Erlang	234 (19)
Exponential	242 (19)
Extreme Value IA	274 (19)
Extreme Value IB	1.97e+003 (19)
Gamma	237 (19)
Inverse Gaussian	217 (19)
Inverse Weibull	263 (19)
Johnson SB	no fit
Johnson SU	no fit
Laplace	247 (19)
Logistic	436 (19)
LogLogistic	213 (19)
Lognormal	1.11e+003 (19)
Normal	1.11e+003 (19)
Pareto	no fit
Pearson 5	174 (19)
Pearson 6	441 (19)
Power Function	303 (19)
Rayleigh	no fit
Triangular	1.96e+003 (19)
Uniform	2.5e+003 (19)
Weibull	223 (19)

Location C:

Document6: Goodness of Fit

data points	115
estimates	maximum likelihood estimates
accuracy of fit	3.e-004
level of significance	5.e-002

$\chi^2(15) = 25$

summary

distribution	Chi Squared
Beta	127 (15)
Cauchy	117 (15)
Chi Squared	238 (15)
Erlang	102 (15)
Exponential	102 (15)
Extreme Value IA	107 (15)
Extreme Value IB	368 (15)
Gamma	102 (15)
Inverse Gaussian	86.6 (15)
Inverse Weibull	102 (15)
Johnson SB	no fit
Johnson SU	67.1 (15)
Laplace	144 (15)
Logistic	146 (15)
LogLogistic	87.2 (15)
Lognormal	86.3 (15)
Normal	234 (15)
Pareto	no fit
Pearson 5	93. (15)
Pearson 6	181 (15)
Power Function	262 (15)
Rayleigh	no fit
Triangular	383 (15)
Uniform	788 (15)
Weibull	89.7 (15)

Appendix 2: VBA Code

"Dashboard_values" Module:

```
Option Explicit
Sub input_calculations()

Dim num_dhl_orders_city, i, j, zone, num_working_days As Integer

Dim volume, counter, fixed_cost, used_weight, manifested_weight, volumetric_weight, rounded_weight, d1, d2, holding_cost_m2, holding_cost_m3 As Double

Dim Country As String

'Defining number of working days in a year
num_working_days = 253

Sheets("Filtered Data").Range("C2") = num_working_days

'count number of DHL rows for specific location and print it in the Filtered Data and Dashboard sheet
num_dhl_orders_city = Sheets("Filtered Data").Range("E1048576").End(xlUp).Row - 2

Sheets("Filtered Data").Range("C19") = num_dhl_orders_city

Sheets("Dashboard").Range("D47") = num_dhl_orders_city

'Calculating used weight for shipment
For i = 1 To num_dhl_orders_city

    manifested_weight = Sheets("Filtered Data").Range("N2").Offset(i, 0).value

    volumetric_weight = Sheets("Filtered Data").Range("O2").Offset(i, 0).value

    If manifested_weight > volumetric_weight Then

        used_weight = manifested_weight

    Else

        used_weight = volumetric_weight

    End If

    Sheets("Filtered Data").Range("BT2").Offset(i, 0) = used_weight

Next

'Calculate volume for each shipment
For i = 1 To num_dhl_orders_city

    volume = Sheets("Filtered Data").Range("O2").Offset(i, 0).value / 167

    Sheets("Filtered Data").Range("BU2").Offset(i, 0).value = volume
Next
```

```
'Rounding up the used_weight
For i = 1 To num_dhl_orders_city

    d1 = Sheets("Filtered Data").Range("BT2").Offset(i, 0).value

    If d1 > 10 Then

        d2 = Application.WorksheetFunction.RoundUp(d1, 0)

    Else

        d2 = Application.WorksheetFunction.Ceiling(d1, 0.5)

    End If

    Sheets("Filtered Data").Range("BX2").Offset(i, 0) = d2

Next
'Finding correct zone in pricelist for location
For i = 1 To 232

    If Sheets("Filtered Data").Range("AK3") = Sheets("Filtered Data").Range("CA2").Offset(i, 0).value Then

        Country = Sheets("Filtered Data").Range("BZ2").Offset(i, 0).value

    End If

Next

For i = 1 To 232

    If Country = Sheets("Pricelist DHL").Range("AC7").Offset(i, 0).value Then

        zone = Sheets("Pricelist DHL").Range("AD7").Offset(i, 0).value

    End If

Next
'Fixed Cost
For i = 1 To 30

    If Sheets("Pricelist DHL").Range("B29").Offset(0, i).value = "Zone " + zone Then

        fixed_cost = Sheets("Pricelist DHL").Range("B30").Offset(0, i).value

    End If

Next

'Printing in Filtered Data
Sheets("Filtered Data").Range("B2") = zone

Sheets("Filtered Data").Range("C6") = fixed_cost

'Calculating the cost
For i = 1 To num_dhl_orders_city

    d1 = Sheets("Filtered Data").Range("BX2").Offset(i, 0).value

    d2 = Application.WorksheetFunction.VLookup(d1, Sheets("Pricelist DHL").Range("A30:Z439"), Sheets("Filtered Data").Range("B2") + 2, True)

    Sheets("Filtered Data").Range("BY2").Offset(i, 0) = d2

Next
```

```
'Creating bins and calculating frequency in each bin for the weights and calculating its probability
Sheets("Filtered Data").Range("CB2") = "Bins"
Sheets("Filtered Data").Range("CC2") = "Weight Frequency"
Sheets("Filtered Data").Range("CD2") = "Weight Probability"
Sheets("Filtered Data").Range("CE2") = "Actual variable cost for bin"
Sheets("Filtered Data").Range("CF2") = "Expected variable cost c"

counter = 0

For i = 1 To 410

    Sheets("Filtered Data").Range("CC2").Offset(i, 0).value = 0

Next

For i = 1 To 20

    counter = counter + 0.5

    Sheets("Filtered Data").Range("CB2").Offset(i, 0) = counter

Next

For i = 1 To 390

    counter = counter + 1

    Sheets("Filtered Data").Range("CB22").Offset(i, 0) = counter

Next

For i = 1 To num_dhl_orders_city

    For j = 1 To 410

        If Sheets("Filtered Data").Range("BT2").Offset(i, 0) <= Sheets("Filtered Data").Range("CB2").Offset(j, 0).value Then

            Sheets("Filtered Data").Range("CC2").Offset(j, 0).value = Sheets("Filtered Data").Range("CC2").Offset(j, 0).value + 1

            j = 410

        End If

    Next

Next

For i = 1 To 410

    Sheets("Filtered Data").Range("CD2").Offset(i, 0).value = Sheets("Filtered Data").Range("CC2").Offset(i, 0).value / num_dhl_orders_city

Next

'Acutal variable cost for bin
For i = 1 To 410

    d1 = Sheets("Filtered Data").Range("CB2").Offset(i, 0).value

    d2 = Application.WorksheetFunction.VLookup(d1, Sheets("Pricelist DHL").Range("A30:Z439"), Sheets("Filtered Data").Range("B2") + 2, True) -
     Application.WorksheetFunction.Index(Sheets("Pricelist DHL").Range("C19:Z19"), 0, Sheets("Filtered Data").Range("B2"))

    Sheets("Filtered Data").Range("CE2").Offset(i, 0) = d2

Next
```

```
'Expected variable cost c
For i = 1 To 410

    Sheets("Filtered Data").Range("CF2").Offset(i, 0).value = Sheets("Filtered Data").Range("CD2").Offset(i, 0).value *
     * Sheets("Filtered Data").Range("CE2").Offset(i, 0).value

Next

Sheets("Filtered Data").Range("C7") = Application.WorksheetFunction.Sum(Sheets("Filtered Data").Range("CF3:CF412"))

'****************************************************************************************
'****************************************************************************************

'Empirical distribution calculations for volume

'Clear bins, 0.02 steps
For i = 1 To 500

    Sheets("Filtered Data").Range("CN2").Offset(i, 0).value = 0

Next

'Printing bins with increased size of 0.02
Sheets("Filtered Data").Range("CN3").value = 0.02

For i = 1 To 500

    Sheets("Filtered Data").Range("CN3").Offset(i, 0).value = Sheets("Filtered Data").Range("CN3").Offset(i - 1, 0).value + 0.02

Next i

'Volume frequency
For i = 1 To 500

    Sheets("Filtered Data").Range("CO2").Offset(i, 0).value = 0

Next

For i = 1 To num_dhl_orders_city

    For j = 1 To 500

        If Sheets("Filtered Data").Range("BU2").Offset(i, 0) <= Sheets("Filtered Data").Range("CN2").Offset(j, 0).value Then

            Sheets("Filtered Data").Range("CO2").Offset(j, 0).value = Sheets("Filtered Data").Range("CO2").Offset(j, 0).value + 1

            j = 500

        End If

    Next j

Next i

'Bin Mean
For i = 1 To 500

    Sheets("Filtered Data").Range("CR2").Offset(i, 0).value = Sheets("Filtered Data").Range("CN2").Offset(i, 0).value - 0.01

Next

'New probabilty
For i = 1 To 500

    Sheets("Filtered Data").Range("CP2").Offset(i, 0).value = Sheets("Filtered Data").Range("CO2").Offset(i, 0).value / num_dhl_orders_city

Next

'Expected volume for bin
For i = 1 To 500

    Sheets("Filtered Data").Range("CQ2").Offset(i, 0).value = Sheets("Filtered Data").Range("CR2").Offset(i, 0).value *
     * Sheets("Filtered Data").Range("CP2").Offset(i, 0).value

Next

'E[v]
Sheets("Filtered Data").Range("C14") = Application.WorksheetFunction.Sum(Sheets("Filtered Data").Range("CQ3:CQ503"))
```

```
'*******************************************************************************************
'*******************************************************************************************

'Calculates Lambda for the location
Sheets("Filtered Data").Range("D2") = num_dhl_orders_city / num_working_days

Sheets("Filtered Data").Range("D2") = Application.WorksheetFunction.Round(Sheets("Filtered Data").Range("D2"), 3)

'Estimated annual cost for the location
Sheets("Filtered Data").Range("C8") = (Sheets("Filtered Data").Range("C6").value + Sheets("Filtered Data").Range("C7").value) *
* Sheets("Filtered Data").Range("C2").value * Sheets("Filtered Data").Range("D2").value

'Actual annual cost
Sheets("Filtered Data").Range("C9") = Application.WorksheetFunction.Sum(Sheets("Filtered Data").Range("BY2:BY10000"))

'******************************************************************************************
'******************************************************************************************

'Holding cost /m3*days
holding_cost_m2 = 100

holding_cost_m3 = (holding_cost_m2 * 0.45 * 0.9) / (1.15 * 20)

Sheets("Filtered Data").Range("C13") = holding_cost_m3

Sheets("Filtered Data").Range("C13") = Application.WorksheetFunction.Round(Sheets("Filtered Data").Range("C13"), 2)

'E[w]
Sheets("Filtered Data").Range("C15") = Sheets("Filtered Data").Range("C13") * Sheets("Filtered Data").Range("C14")

'Storage box space
Sheets("Filtered Data").Range("C16") = 0.9 * 0.45 * 0.45

'Expected weight for bin
For i = 1 To 410

    Sheets("Filtered Data").Range("CG2").Offset(i, 0).value = Sheets("Filtered Data").Range("CB2").Offset(i, 0).value *
     * Sheets("Filtered Data").Range("CD2").Offset(i, 0).value

Next

'E[weight]
Sheets("Filtered Data").Range("C20") = Application.WorksheetFunction.Sum(Sheets("Filtered Data").Range("CG3:CG412"))

'*******************************************************************************************
'*******************************************************************************************

'Volume Trend for the location
For i = 1 To 12

    Sheets("Filtered Data").Range("CM2").Offset(i, 0) = 0

Next

For i = 1 To num_dhl_orders_city

    For j = 1 To 12

        If Sheets("Filtered Data").Range("G2").Offset(i, 0) = j Then

            Sheets("Filtered Data").Range("CM2").Offset(j, 0) = Sheets("Filtered Data").Range("CM2").Offset(j, 0) + 1

            j = 12

        End If

    Next

Next

End Sub
```

```
'Registers input variables for location from Filtered Data sheet and prints them in the Dashboard sheet
Sub dashboard_input()

Dim lambda, c, K, w, h, exp_vol, exp_weight, annual_cost  As Double

K = Sheets("Filtered Data").Range("C6").value
c = Sheets("Filtered Data").Range("C7").value
lambda = Sheets("Filtered Data").Range("D2").value
w = Sheets("Filtered Data").Range("C15").value
h = Sheets("Filtered Data").Range("C13").value
exp_vol = Sheets("Filtered Data").Range("C14").value
exp_weight = Sheets("Filtered Data").Range("C20").value
annual_cost = Sheets("Filtered Data").Range("C8").value

Sheets("Dashboard").Range("D39").value = lambda
Sheets("Dashboard").Range("D32").value = c
Sheets("Dashboard").Range("D38").value = K
Sheets("Dashboard").Range("D33").value = w
Sheets("Dashboard").Range("D37").value = h
Sheets("Dashboard").Range("D49").value = exp_vol
Sheets("Dashboard").Range("D48").value = exp_weight
Sheets("Dashboard").Range("D50").value = annual_cost

End Sub
```

“Filter_Data” Module:

```
Option Explicit
```

```
'Filters the data based on the location
Sub filteringDHLdata()

Dim Data As Excel.Worksheet
Set Data = Worksheets("Data")
Dim City, City2 As String

'Defines the location input cell as D28 in the Dashboard sheet
City = Sheets("Dashboard").Range("D20").value
City2 = UCase(City)

Dim num_DHL_orders, tot_Categories, num_orders_city, num_dhl_orders_city As Long

'Clear cells in Filtered Data
Sheets("Filtered Data").Range("E3:BY10000").ClearContents
Sheets("Filtered Data").Range("CB3:CJ10000").ClearContents

'count number of DHL rows in the Data sheet
num_DHL_orders = Sheets("Data").Range("A1048576").End(xlUp).Row - 2

'count number of DHL columns in the Data sheet
tot_Categories = Data.Cells(2, Columns.Count).End(xlToLeft).Column
```

```
'*****************************************************************************************************

'Prints all data about a location in the Filtered Data sheet
Dim counter, j, i As Long

counter = 1

For j = 1 To tot_Categories

    Sheets("Filtered Data").Range("E2").Offset(0, j).value = Sheets("Data").Range("A2").Offset(0, j).value

Next

For i = 1 To num_DHL_orders

    If Sheets("Data").Range("F2").Offset(i, 0).value <> "ECONOMY SELECT" Then

        If Sheets("Data").Range("BO2").Offset(i, 0).value = City2 Then

            For j = 1 To tot_Categories

                Sheets("Filtered Data").Range("E2").Offset(counter, j - 1).value = Sheets("Data").Range("A2").Offset(i, j - 1).value

            Next

        counter = counter + 1

        End If

    End If

Next

'Format cells in column E as long date format
Sheets("Filtered Data").Range("E3:E10000").NumberFormat = "yyyy-mm-dd"

'count number of DHL rows for specific order
num_dhl_orders_city = Sheets("Filtered Data").Range("E1048576").End(xlUp).Row - 2

'Calculates the volume
Sheets("Filtered Data").Range("BU2") = "Volume"

For i = 1 To num_dhl_orders_city

    Sheets("Filtered Data").Range("BU2").Offset(i, 0) = Sheets("Filtered Data").Range("O2").Offset(i, 0).value / 167

Next


End Sub
```

“Main” Module:

```
Sub Button1_Click()
'-------------------------------------'
'Main function which calls sub-modules
'-------------------------------------'

'Filter and sort data
Call filteringDHLdata

'Caclulate and print relevant variables from filtered data
Call input_calculations

'Assign input data and print on dashboard
Call dashboard_input

'Calculates Long-Run Average Cost based on input values
Call Gmatrix(Sheets("Dashboard").Range("D38").value, Sheets("Dashboard").Range("D32").value, Sheets("Dashboard").Range("D33").value,
                                                                          Sheets("Dashboard").Range("D39").value)
'Calculate potential cost savings
Call cost_savings_T

'Print message
Call End_Msgbox

End Sub
```

“Message_box” Module:

```
Option Explicit

'This sub shows a message box when the run is over,
'so the user analyzing a location knows when the run is finished

Sub End_Msgbox()

'Display "successful run" message box
VBA.Interaction.MsgBox Excel.Application.UserName & ", your run of the programme was successful!", , "Consolidation shipping analysis"

End Sub
```

“Original_formula_module” Module:

```
Option Explicit

'-------------------------------------------------------------------------------------------------------------'

'   All formulas () are reffering to Mutlu, Fatih, S I. la Çetinkaya, and James H. Bookbinder.
'   "An analytical model for computing the optimal time-and-quantity-based policy for consolidated shipments."
'   Iie Transactions 42.5 (2010): 367-377.

'-------------------------------------------------------------------------------------------------------------'


'* Poisson PDF              (Error-checked)

Function poissonPDF(n, T, lamda) As Double

poissonPDF = (Exp(-lamda * T) * (lamda * T) ^ n) / Application.WorksheetFunction.Fact(n)

End Function
```

```
'* Poisson CDF              (Error-checked)

Function poissonCDF(x, T, lamda) As Double

Dim n As Long
Dim answer As Double


    For n = 0 To x

        answer = answer + poissonPDF(n, T, lamda)

    Next

poissonCDF = answer

End Function
```

```
'* Complementary poisson CDF       (Error-checked)

Function complementpoissonCDF(x, T, lamda) As Double

Dim n As Long
Dim answer As Double

answer = 1 - poissonCDF(x, T, lamda)

complementpoissonCDF = answer

End Function
```

```
'* Erlang probability function (2)           (NOT USED in Model)

Function erlangPDF(T, i, lamda) As Double


    erlangPDF = lamda * ((lamda * T) ^ (i - 1)) * ((Exp(-lamda * T)) / (Application.WorksheetFunction.Fact(i - 1)))

End Function
```

```
'* Expected Cycle length (4)                 (Error-checked)

Function expectedCycleLength(q, T, lamda) As Double


    expectedCycleLength = (1 / lamda) + ((q / lamda) * complementpoissonCDF(q, T, lamda)) + (T * (poissonCDF(q - 1, T, lamda)))

End Function
```

```
'* Expected Shipment Cost E(Cs)    (5)          (Error-checked)

Function expectedShipmentCost(K, c, q, T, lamda) As Double

    expectedShipmentCost = K + c * ((1 + (q * complementpoissonCDF(q, T, lamda))) + (lamda * T * poissonCDF(q - 1, T, lamda)))

End Function
```

```
'* Expected waiting cost (14)              (Error-checked)

Function expectedWaitingCost(w, q, T, lamda) As Double

    If (T > Sheets("Dashboard").Range("D21").value) Then

        If (Sheets("Dashboard").Range("D23").value = "Linear") Then
            w = w + (Sheets("Dashboard").Range("D22").value)

        Else

          w = w + (Sheets("Dashboard").Range("D22").value * (T - Sheets("Dashboard").Range("D21").value))

        End If

    End If

    expectedWaitingCost = w * (((q / lamda) * complementpoissonCDF(q, T, lamda)) + (T * poissonCDF(q - 1, T, lamda)) + (((q - 1) / 2) *
   (q / lamda) * complementpoissonCDF(q, T, lamda)) + (T / 2) * sumFunc(q - 1, T, lamda))
End Function
```

```
'* Sum function for eq 14.                  (Error-checked)

Function sumFunc(x, T, lamda) As Double

Dim i As Long
Dim value As Double

value = 0

    For i = 0 To x - 1
        value = value + i * poissonPDF(i, T, lamda)
    Next

sumFunc = value

End Function
```

```
'* Expected cycle cost i.e. waiting cost + shipment cost    (Error-checked)
Function expectedCycleCost(K, c, w, q, T, lamda) As Double

    expectedCycleCost = expectedShipmentCost(K, c, q, T, lamda) + expectedWaitingCost(w, q, T, lamda)

End Function
```

```
'* Expected long run average cost G   (15)                       (Error-checked)

Function expectedCost(K, c, w, q, T, lamda) As Double

    expectedCost = expectedCycleCost(K, c, w, q, T, lamda) / expectedCycleLength(q, T, lamda)

End Function
```

```
'****************************************************** FOR ILLUSTRATION ****************

' Caclulates and prints Long-Run Average Cost heatmap in Dashboard for different q and T

Sub Gmatrix(K, c, w, lambda)

    Dim Matrix(0 To 30, 0 To 30) As Variant

    Dim i, j As Long
    Dim min_value As Double

    For i = 0 To 30
        For j = 0 To 30

            Matrix(i, j) = expectedCost(K, c, w, i, j, lambda)

        Next j

        w = Sheets("Dashboard").Range("D33").value


    Next i

    For i = 0 To 30
        For j = 0 To 30

            Sheets("Dashboard").Range("G96").Offset(i, j).value = Matrix(i, j)

        Next j
    Next i

   'Plot: min value, opt q & T, E[cycle time] for T=2 and T=opt
   min_value = 10000000

    For i = 0 To 30
        For j = 0 To 30
            If (min_value >= Sheets("Dashboard").Range("G96").Offset(i, j).value) Then

                min_value = Sheets("Dashboard").Range("G96").Offset(i, j).value
                Sheets("Dashboard").Range("D34").value = j
                Sheets("Dashboard").Range("D35").value = i

            End If

        Next j
    Next i

    Sheets("Dashboard").Range("D36").value = min_value
    Sheets("Dashboard").Range("D40").value = expectedCycleLength(Sheets("Dashboard").Range("D35").value, Sheets("Dashboard").Range("D34'
    Sheets("Dashboard").Range("D41").value = expectedCycleLength(Sheets("Dashboard").Range("I128").value, 2, Sheets("Dashboard").Range('
                                                                                  .value, Sheets("Dashboard").Range("D39").value)
Erase Matrix                                                                      )39").value)

End Sub
```

```
' Print Long-Run average cost for different T in "Sensitivity_Analysis" sheet.
Sub analysis_print(K, c, w, optQ, i, lamda)

Dim answer As Double

answer = expectedCost(K, c, w, optQ, i, lamda)

Sheets("Sensitivity_Analysis").Range("C30").Offset(i, 0).value = answer

End Sub
```

“Sensitivity_analysis” Module:

```
Option Explicit

'Calculates cost savings
Sub cost_savings_T()

Dim i As Long
Dim K, c, w, optQ, optT, lamda, cycletime As Double

'Assig Values
K = Sheets("Dashboard").Range("D38").value
c = Sheets("Dashboard").Range("D32").value
w = Sheets("Dashboard").Range("D33").value
lamda = Sheets("Dashboard").Range("D39").value

'Caclulate optQ and E[L] and print in "Sensitivity_Analysis" sheet
    For i = 0 To 30
        optQ = Sheets("Dashboard").Range("G128").Offset(0, i).value
        cycletime = expectedCycleLength(optQ, Sheets("Sensitivity_Analysis").Range("A30").Offset(i, 0).value, lamda)

        Sheets("Sensitivity_Analysis").Range("B30").Offset(i, 0).value = optQ
        Sheets("Sensitivity_Analysis").Range("D30").Offset(i, 0).value = cycletime
        Call analysis_print(K, c, w, optQ, i, lamda)

    Next i


End Sub
```

Appendix 3: Long-Run Average Cost

Location A:

Q \ T	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577	577
1	577	523	518	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517	517
2	577	509	500	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498	498
3	577	505	492	489	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488
4	577	503	488	484	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482	482
5	577	503	487	481	479	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478	478
6	577	502	486	480	477	476	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475	475
7	577	502	486	479	476	474	473	473	473	473	473	473	473	473	473	473	473	473	473	473	473	473	473	473	473	473	473	473	473	473	473
8	577	502	485	478	475	473	472	472	472	472	471	471	471	471	471	471	471	471	471	471	471	471	471	471	471	471	471	471	471	471	471
9	577	502	485	478	474	472	471	471	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470
10	577	502	485	478	474	472	470	470	469	469	469	469	469	469	469	469	469	469	469	469	469	469	469	469	469	469	469	469	469	469	469
11	577	502	485	478	474	471	470	469	469	469	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468
12	577	502	485	478	474	471	470	469	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468	468
13	577	502	485	478	474	471	469	468	468	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467
14	577	502	485	478	474	471	469	468	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467	467
15	577	502	485	478	474	471	469	468	467	467	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466
16	577	502	485	478	474	471	469	468	467	467	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466
17	577	502	485	478	474	471	469	468	467	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466	466
18	577	502	485	478	474	471	469	468	467	466	466	466	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465
19	577	502	485	478	474	471	469	468	467	466	466	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465
20	577	502	485	478	474	471	469	468	467	466	466	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465
21	577	502	485	478	474	471	469	468	467	466	466	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465	465
22	577	502	485	478	474	471	469	468	467	466	466	465	465	465	465	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464
23	577	502	485	478	474	471	469	468	467	466	466	465	465	465	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464
24	577	502	485	478	474	471	469	468	467	466	466	465	465	465	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464
25	577	502	485	478	474	471	469	468	467	466	466	465	465	465	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464
26	577	502	485	478	474	471	469	468	467	466	466	465	465	465	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464
27	577	502	485	478	474	471	469	468	467	466	466	465	465	465	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464
28	577	502	485	478	474	471	469	468	467	466	466	465	465	465	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464
29	577	502	485	478	474	471	469	468	467	466	466	465	465	465	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464
30	577	502	485	478	474	471	469	468	467	466	466	465	465	465	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464	464
Min G	576,8	502,4	485,4	477,9	473,7	471,1	469,3	468,0	467,0	466,2	465,7	465,2	464,8	464,5	464,3	464,1	463,9	463,8	463,7	463,7	463,7	463,7	463,7	463,7	463,7	463,7	463,7	463,7	463,7	463,7	463,7
Opt Q	0	11	13	15	16	17	18	20	21	22	23	24	26	27	28	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30

Location B:

Q \ T	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247	247
1	247	228	223	221	220	220	220	219	219	219	219	219	219	219	219	219	219	219	219	219	219	219	219	219	219	219	219	219	219	219	219
2	247	224	217	214	212	211	211	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210
3	247	224	215	211	208	207	207	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206	206
4	247	224	214	210	207	205	204	204	203	203	203	203	203	203	203	203	203	203	203	203	203	203	203	203	203	203	203	203	203	203	203
5	247	224	214	209	206	204	203	202	202	202	201	201	201	201	201	201	201	201	201	201	201	201	201	201	201	201	201	201	201	201	201
6	247	224	214	209	206	204	203	202	201	201	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
7	247	224	214	209	206	204	202	201	201	200	200	199	199	199	199	199	199	199	199	199	199	199	199	199	199	199	199	199	199	199	199
8	247	224	214	209	206	204	202	201	200	200	199	199	199	199	198	198	198	198	198	198	198	198	198	198	198	198	198	198	198	198	198
9	247	224	214	209	206	204	202	201	200	199	199	199	198	198	198	198	198	198	198	198	198	198	198	198	198	198	198	198	198	198	198
10	247	224	214	209	206	204	202	201	200	199	199	198	198	198	198	197	197	197	197	197	197	197	197	197	197	197	197	197	197	197	197
11	247	224	214	209	206	204	202	201	200	199	199	198	198	198	197	197	197	197	197	197	197	197	197	197	197	197	197	197	197	197	197
12	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	197	197	197	197	197	197	197	197	197	197	197	197	197	197
13	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	197	197	196	196	196	196	196	196	196	196	196	196	196	196
14	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	197	196	196	196	196	196	196	196	196	196	196	196	196	196
15	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	196	196	196	196	196	196
16	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	196	196	196	196	196	196
17	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	196	196	196	196	196	196
18	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	196	196	196	196	195	195
19	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	196	195	195	195	195	195
20	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	195	195	195	195	195	195
21	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	195	195	195	195	195	195
22	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	195	195	195	195	195	195
23	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	195	195	195	195	195	195
24	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	195	195	195	195	195	195
25	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	195	195	195	195	195	195
26	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	195	195	195	195	195	195
27	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	195	195	195	195	195	195
28	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	195	195	195	195	195	195
29	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	195	195	195	195	195	195
30	247	224	214	209	206	204	202	201	200	199	199	198	198	197	197	197	197	196	196	196	196	196	196	196	196	196	195	195	195	195	195
Min G	247,1	223,6	214,1	209,0	205,8	203,6	202,1	200,9	200,0	199,2	198,6	198,1	197,7	197,4	197,1	196,8	196,6	196,4	196,2	196,1	195,9	195,8	195,7	195,6	195,5	195,5	195,4	195,3	195,3	195,2	195,2
Opt Q	0	8	10	11	11	12	12	13	14	14	15	15	16	16	17	17	18	18	19	19	20	21	21	22	22	23	23	24	24	25	25

Location C:

Q \ T	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101
1	101	93	90	88	87	87	86	86	86	86	86	86	86	86	86	86
2	101	92	87	85	83	82	82	81	81	81	81	81	81	81	81	81
3	101	91	87	84	82	81	80	79	79	79	78	78	78	78	78	78
4	101	91	86	83	81	80	79	78	78	78	77	77	77	77	77	77
5	101	91	86	83	81	80	79	78	77	77	77	76	76	76	76	76
6	101	91	86	83	81	80	79	78	77	77	76	76	76	76	75	75
7	101	91	86	83	81	80	79	78	77	77	76	76	75	75	75	75
8	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	75
9	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	75
10	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
11	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
12	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
13	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
14	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
15	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
16	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
17	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
18	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
19	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
20	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
21	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
22	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
23	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
24	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
25	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
26	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
27	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
28	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
29	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
30	101	91	86	83	81	80	79	78	77	76	76	76	75	75	75	74
Min G	101,1	91,4	86,4	83,3	81,2	79,7	78,6	77,7	77,0	76,4	76,0	75,6	75,2	74,9	74,7	74,4
OptQ	0	7	8	9	10	10	10	11	11	12	12	12	13	13	13	14

Q \ T	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0	101	101	101	101	101	101	101	101	101	101	101	101	101	101	101
1	86	86	86	86	86	86	86	86	86	86	86	86	86	86	86
2	81	81	81	81	81	81	81	81	81	81	81	81	81	81	81
3	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78
4	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77
5	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76
6	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75
7	75	75	75	75	74	74	74	74	74	74	74	74	74	74	74
8	75	74	74	74	74	74	74	74	74	74	74	74	74	74	74
9	74	74	74	74	74	74	74	74	74	74	74	74	74	74	74
10	74	74	74	74	74	74	74	74	74	74	73	73	73	73	73
11	74	74	74	74	74	74	74	73	73	73	73	73	73	73	73
12	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
13	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
14	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
15	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
16	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
17	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
18	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
19	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
20	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
21	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
22	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
23	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
24	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
25	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
26	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
27	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
28	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
29	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
30	74	74	74	74	74	74	73	73	73	73	73	73	73	73	73
Min G	74,2	74,1	73,9	73,8	73,6	73,5	73,4	73,3	73,2	73,2	73,1	73,0	73,0	72,9	72,8
OptQ	14	14	15	15	15	15	16	16	16	17	17	17	18	18	18