Improving inbound logistics at KLM Engine Services

Master Thesis

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Management Summary

Introduction

The *inbound logistics process* encompasses the activities for handling all packages that arrive at KLM Engine Services (ES), such as receiving, (administratively) inspecting, and dispositioning incoming goods. Currently, ES does not measure the performance of the inbound logistics process. However, the management of the logistics department of ES suspects that the inbound logistics process operates inefficiently.

Goals & Methodology

The goals of this research are:

- To analyze the current performance of the inbound logistics process,
- To suggest improvements for the inbound logistics process.

To achieve these goals, we first perform an extensive data analysis to measure the performance of the inbound logistics process. We measure the performance of the process by the average turnaround time of parts. Second, we construct a simulation model to evaluate the performance of several different configurations of the inbound logistics process.

Results – Data analysis

We split the process into four measurement points and measure the turnaround time between these four points using confirmations from several information systems. At each of the four points, a confirmation is placed for every shipment. A confirmation registers information, such as the time, the date, and the state of the shipment. Figure 1 visualizes the measurement points and the confirmations and it shows the mean (μ) and standard deviation (σ) of the turnaround time between the points. In the data analysis, we also measure the turnaround time of the process that takes place directly before the inbound logistics process: the delivery of packages from the KLM Engineering & Maintenance Logistics Centre to ES. In Figure 1, this takes place between placing the DM and TR confirmations. The inbound logistics process takes place between the TR and GR confirmations.

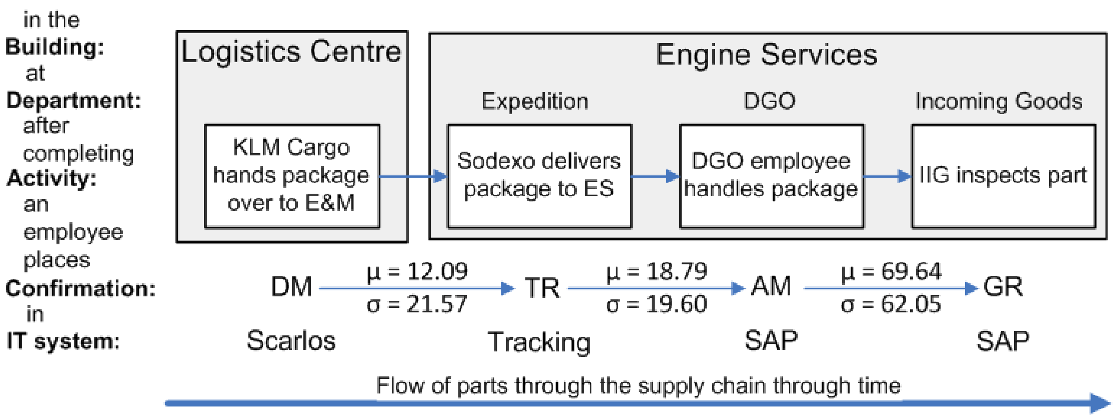


Figure 1: Overview of the turnaround times (hours) between the measurement points.

ES usually measures the performance of a process by the P95 value. P95 stands for the 95th percentile. The target for the inbound logistics process is a P95 value of 48 hours. This target is not reached, since a turnaround time of 48 hours currently lies at the 46th percentile. Furthermore, we conclude that the turnaround time of parts between all four measurement points fluctuates heavily.

Results – Simulation study

With our simulation model, we evaluate the effect of six variables on the performance of the inbound logistics process. These variables are: (1) The schedule of IIGs (Inspector Incoming Goods), (2) The number of DGO employees, (3) The critical buffer size: the size of the Incoming Goods buffer before extra IIG capacity is used, (4) Change in the input of packages and parts to the inbound logistics process, (5) Change in the number of PIGs (Problem Incoming Goods), and (6) Change in the number of emergency requests. Table 1 shows the variables, including the values that we analyzed.

IIG Roster Type	#DGO	Critical buffer size	%Input	%PIG	%Emergency requests
7x2, 7x1, 5x2	1, 2	2, 3, 4, 5	60, 70, 80, 90, 100 110	70, 80, 90, 100	80, 90, 100

Table 1: Experimental settings.

The results of the simulation study show that the 7x1 schedule is the best schedule, because it achieves almost the same turnaround time as the 7x2 schedule, but at considerably lower costs. FIFO decreases the P95 value significantly. By assigning an extra employee to DGO, an 11% lower turnaround time can be achieved at the expense of 0.2% more IIG capacity. Reducing the number of PIGs also leads to substantial performance improvement. Reducing the number of emergency requests has a much smaller effect. The best way to increase the performance of the system is to lower the critical buffer level. Despite the fact that ES needs a buffer to cope with the variability of the system, the current critical buffer level of 5 days is too high. By reducing this level to 2 days, ES can achieve a 46% reduction in the lead time at the expense of 3% more capacity. The increased capacity can be partially compensated by optimizing other experimental factors, such as the number of PIGs. Looking at the effect of changes in the input, we concluded that if a structural change in the input occurs, ES needs to adjust its full-time IIG capacity in order to maintain its current performance.

Recommendations

Based on the results of the simulation study, we recommend the following:

- Schedule IIGs by the 7x1 schedule.
- Parts should be handled by FIFO: eliminate the causes of deviations from the FIFO principle.
- Gradually decrease the critical buffer size to 2 days.
- Invest to decrease the number of PIGs.
- In case the input changes structurally, adjust the IIG capacity.
- Ensure that the team managers fully support the changes, because they play a key role in the acceptance of the changes by the employees.

Preface

With this report of my graduation project at the logistics department of KLM Engine Services, I complete my Master of Science degree in Industrial Engineering and Management at the University of Twente and end my career as a student. My time as a student has been a fantastic experience: I enjoyed almost every day of it, met so many nice people, and gained a lot of knowledge. However, after almost ten years of being a student, I am excited to move to the next step in my life and see what challenges await as a full-time working member of society.

I am very pleased that KLM Engine Services offered me the opportunity to do my graduation project, because it is an inspiring company that offered me the chance to learn and developed myself, both professionally and personally. I gained valuable knowledge on how a company functions in a highly competitive market, but I also got the opportunity to train my personal skills in a challenging business environment.

I would not have been able to finish this assignment without the help of several people, to whom I want to express my gratitude. First, I thank my supervisors from the University of Twente, Martijn Mes and Marco Schutten, for their pleasant support, useful advices, and critical assessments (despite the many hours that it cost me to incorporate these into my report) that altogether made it possible for me to graduate, even within the desired timeframe.

I also thank Jan de Graaff, my supervisor at KLM Engine Services, for his guidance. Jan, I very much enjoyed our talks, not only about my assignment, but also about KLM and the valuable advice that you have given me for my professional career.

Every day that I arrived at my workplace, there was always a good story, a laugh, and a nice atmosphere waiting for me. Sunny Ramkhewan and Elwin Booman, I thank you for that and for your tremendous help with my project.

I thank the wonderful people from the logistics department that I could always turn to for help, especially the team managers and the incoming goods inspectors. Also, I thank the people from other departments of KLM that I interviewed, in particular Martijn Wennekes and Ino Sohl, for helping me with my data analysis.

Last, but certainly not least, I thank my parents, sisters, grandmother, friends, and my wife Jalin for their unlimited moral support that pulled me through my setbacks, and for restoring my faith in a good ending. It is great to know that I can always depend on you.

Maarten Klaassen

August 2012

Table of Contents

1. Introduction

This chapter introduces the research field of this graduation project at the logistics department of KLM Engine Services. We describe the motivation for starting this research and explain the structure of this report. We start by sketching the background of KLM Engine Services and its logistics department in Section 1.1. Section 1.2 then discusses the problem statement and Section 1.3 introduces the research goal. Section 1.4 presents the research questions, research methodology, and the structure of the report.

1.1 Background

KLM Engine Services (ES) is the business unit of KLM that provides maintenance, repair, and overhaul services on aircraft engines of both KLM and other airlines. The logistics department of ES is responsible for:

- The storage and retrieval of spare parts from the warehouse of ES,
- Internal transport of parts between the departments of ES,
- Outbound logistics: handling the outbound flow of goods from ES,
- Inbound logistics: handling the inbound flow of goods to ES.

The *inbound logistics process* is the subject of this research. It encompasses the activities for handling the inbound flow at ES, such as receiving, (administratively) inspecting, and dispositioning incoming goods. The inbound flow consists of all packages that arrive from external parties or other KLM maintenance units, mostly via the KLM E&M Logistics Centre (90%). These packages contain for example parts (external repairs, new parts, etc.) and equipment that are used within the engine repair process of ES, or office supplies.

When a package is delivered to ES, it is received by an employee at the logistical department *Expedition*. The employee sorts the package based on whether its contents require an incoming goods inspection. A part or equipment requires an incoming goods inspection if it will be used in the engine repair process at ES. Goods that do not require an inspection are for instance office supplies or parts that ES needs to repair for another KLM maintenance unit or an external client. These packages are moved directly to other departments in ES.

Packages with parts that require inspection are moved to the logistical department *Decentralized Goods receipt* (*DGO*). At DGO, an employee checks the contents of the package, registers the acceptance of the package, and moves the package to the logistical department *Incoming Goods* for visual and administrative inspection.

At Incoming Goods, the parts in the package and the paperwork are administratively inspected (e.g. certificates) by an inspector incoming goods. He also performs a visual inspection to detect any clear damage due to for example transport. As a final step, he determines further routing through ES. In case the part successfully passes these inspections, it either goes to stock, directly to the shop for technical inspection, or directly to the department *Assembly Preparation*. Parts that do not pass these inspections are moved to the quarantine area. Chapter 2 gives a more detailed description of the activities involved with inbound logistics.

1.2 Problem statement

The management of the logistics department of ES suspects that the current process for handling the inbound flow is inefficient. The main reason for this suspicion is that very little is known about the performance of the inbound logistics process. The logistics department of ES does not analyze the performance of the inbound logistics process. The most important performance indicator of this process is the turnaround time of parts and packages. The main target for inbound logistics, set by the management of ES, is that 95% of the parts that successfully passed all inspections should have a turnaround time of at most 48 hours over the entire inbound logistics process. So 95% of the parts should be inspected within 48 hours after their arrival at ES. Although there is no exact information on the current turnaround time, it is clear that this goal is currently not reached.

Packages are being tracked through the whole repair process by several information systems (*SAP* at ES and vendors, *Tracking* at KLM E&M Logistics Centre, and *Scarlos* at KLM Cargo and other couriers in the supply chain). This means that there is a lot of historical data available in these information systems on for instance the location and delivery times of packages. From this historical data, a lot of information could be gathered and used to measure the performance of the inbound logistics process and to improve the inbound logistics process at ES.

1.3 Research goal

From the above problem statement, we derive the following main research question:

> ***What is the performance of the inbound logistics process at the logistics department of KLM Engine Services and how can it be improved in terms of turnaround time and cost savings, using historical data from the information systems?***

So the goal of this research is to identify the current performance of the inbound logistics process and to suggest improvements for the inbound logistics process. These improvements are not limited to financial gains, but also for instance improvements in turnaround time.

1.4 Research questions

In this section, we present the research questions. These questions determine the structure of the research and finally lead to answering the main research question as stated in Section 1.3. We present every research question with a clarification of the question, the chapter in which we answer it, and a brief explanation of the method we use to answer the question.

1. How does the current inbound logistics process at the logistics department of Engine Services work?

The first step in this research is the identification of the current situation at the logistics department of ES. An identification of the activities in the current inbound logistics process is required before being able to analyze and improve it. We answer this question in Chapter 2. We gather the information from interviews with several employees at ES and its logistics department, internal reports, and by joining employees of the logistics department during their work. Not only does joining these employees during their work give insight in how the process works, it also gives the opportunity to discover issues in the process.

2. What is known in literature about organizing a process such as the incoming logistics process?

For answering this question, we look at available literature. By answering the first research question, we have identified and characterized what type of organization the logistics department of ES is. We use this result to describe what is known in literature about the possible ways of arranging a process similar to the inbound logistics process at the logistics department of ES. This literature review is the subject of Chapter 3.

3. How can the performance of the inbound logistics process be measured and what is its current performance?

The first goal of this question is to make the performance of the inbound logistics process measurable. To achieve this, we identify the key performance indicators of the process. Then, we perform a data analysis, based on historical data from the various information systems at ES, to determine the performance of the inbound logistics process. We discuss the identification of the key performance indicators and the data analysis in Chapter 4.

4. What is a good simulation model of the inbound logistics process for evaluating the effect of changes to the process on the performance of the process?

Since the inbound logistics process is too complex to analyze numerically, we use *simulation*. Simulation is a tool that can be used to evaluate systems that cannot be evaluated analytically (Law & Kelton, 2000). Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies (…) for the operation of the system (Shannon, 1975).

To evaluate the influence of changes to the process on the performance of the process, we introduce the decision variables of the inbound logistics process and construct experiments with these variables. An experiment is a unique realization of the set of decision variables, so that each experiment represents a distinct way of arranging the inbound logistics process; a distinct configuration of the process. We use the simulation model to evaluate the expected performance of the process in each of these configurations.

Chapter 5 discusses the design of the simulation model and the design of the experiments that we perform with the model.

5. To which benefits will the changes lead and what issues need to be taken into account during implementation of the suggested changes?

In Chapter 6, we present the results of the simulation study: the expected performance of the different configurations. We also reflect on these results to determine which changes to the inbound logistics process are most favorable to implement at ES. Since the effectiveness of the changes that we suggest depends on the way they are implemented, we also elaborate on the implementation process.

After answering the research questions, we close with a conclusion in Chapter 8.

In this research, we follow the seven steps that Law (2003) suggests to take in a simulation study. These seven steps are displayed in the first column of Figure 1.1. Figure 1.1 shows the structure of this report by linking the seven steps of the simulation study to the chapters and our research questions. The second column connects the steps to the chapter numbers in which the steps are taken, including the main subject(s) of each chapter. The last column shows the research questions and in which chapter these questions are answered.

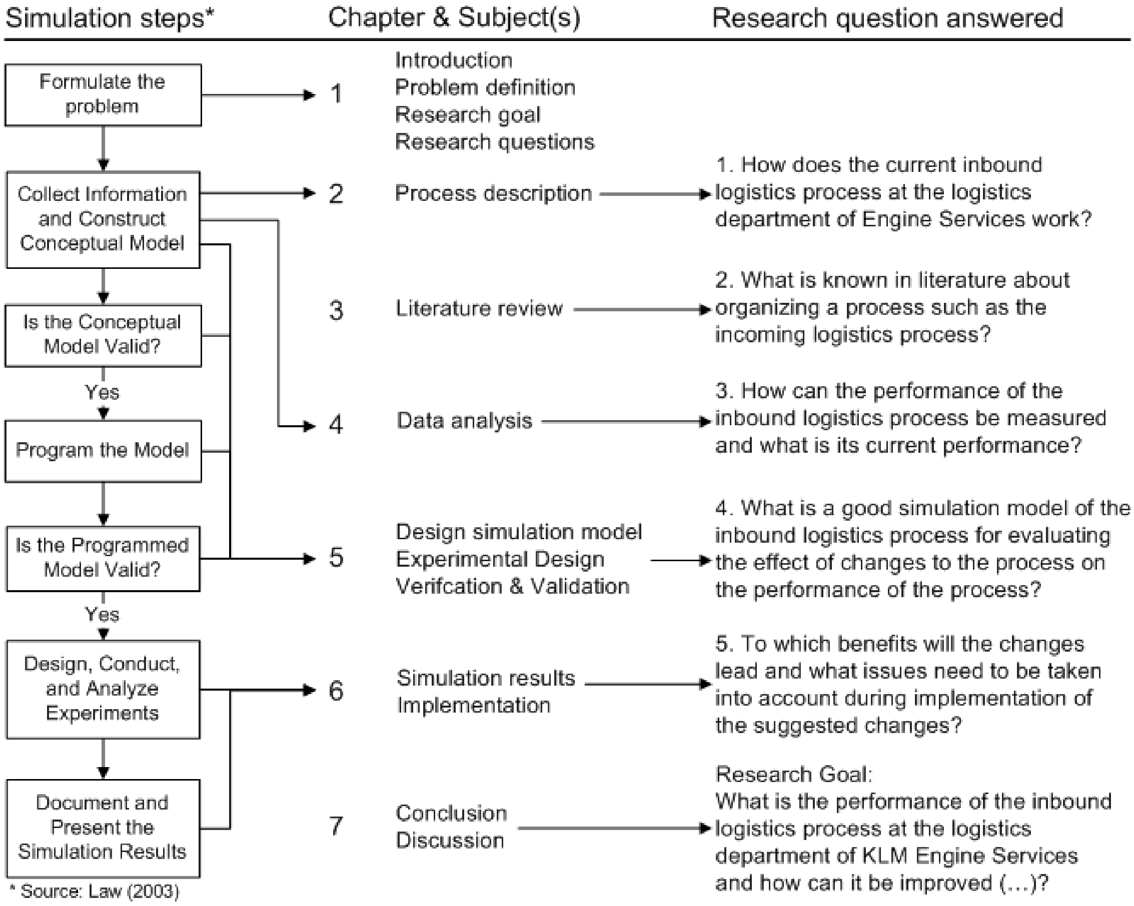


Figure 1.1: The structure of this report.

2. Analysis of the inbound logistics process

This chapter describes the activities, actors, and parties that are involved with the inbound logistics process at the logistics department of ES. We start by sketching the background of the company KLM and more specifically ES in Section 2.1. Section 2.2 explains some important terminology. Section 2.3 gives insight in the supply chain that parts go through before arriving at ES. Section 2.4 describes the activities that take place in the inbound logistics process and Section 2.5 explains how the scheduling of personnel at the logistical departments DGO and Incoming Goods is performed. Section 2.6 gives a summary of this chapter and concludes it.

2.1 Company background

This section introduces the company KLM, its business unit KLM Engine Services (ES), and the logistics department of ES. First, Sections 2.1.1 and 2.1.2 discuss the company KLM and the division of KLM that ES belongs to, Engineering & Maintenance. Second, Section 2.1.3 explains the structure of ES and its logistics department.

2.1.1 KLM Royal Dutch Airlines

KLM Royal Dutch Airlines was founded in 1919. It is the core of the KLM Group, which further consists of KLM Cityhopper, Transavia, and Martinair. The KLM Group is part of the Air France KLM Group. This group is the result of the merger of Air France Industries and KLM Royal Dutch Airlines in May 2004. Both Air France and KLM Royal Dutch Airlines still operate under their original brand names.

KLM is the largest airline in the Netherlands and the oldest airline in the world still operating under its original name. It carries about 23 million passengers and half a million tons of freight annually (KLM Annual report ’10-’11). KLM has three core businesses: the largest one is Passenger Transportation, followed by the Cargo division, and Engineering & Maintenance (E&M). In this research, we focus on E&M, which we discuss in the next section.

2.1.2 KLM Engineering & Maintenance

KLM E&M carries out maintenance, repair, and overhaul on aircrafts, engines and components of the fleet of both internal clients (Air France KLM Group) and external clients (other airlines). Approximately 5,000 employees work at E&M. E&M offers a wide portfolio of activities that are provided by the three business units: Aircraft Maintenance, Component Services, and Engine Services (ES).

Aircraft Maintenance is the smallest business unit. Its activities are *Line Maintenance* and *Base Maintenance*. Line Maintenance is unscheduled maintenance on aircrafts that are in service, either on-site or in a hangar. Base Maintenance is scheduled and more thorough maintenance; it takes place in a hangar on aircrafts that are out of service. About 80% of the aircrafts in maintenance at Aircraft Maintenance come from internal clients, for instance KLM and Transavia.com.

The supply of serviceable components to both internal and external customers is the responsibility of Component Services. Component Services delivers repair & overhaul services for components, maintains the warehouse of spare parts, and provides the internal transportation of components at Schiphol between the maintenance units of the three business units of E&M, and the E&M Logistics Centre. The main customer of Component Services is Aircraft Maintenance.

The third business unit of E&M is Engine Services. We discuss ES in Section 2.1.3.

2.1.3 KLM Engine Services

ES is the business unit within KLM E&M that provides maintenance, repair, and overhaul services on four types of aircraft engines that are all produced by General Electric. For more information about these engines types, see Appendix C. Approximately 250 engines are repaired every year of which 40% are engines from members and partners of the Air France KLM Group and 60% come from third party clients (Castro et al., 2010). The turnover of Engine Services was 450 million Euros in 2010 and the amount of labour hours is about 900 FTEs.

Stages

Engines in the repair process of ES follow a four stage program that takes 60 to 63 days. In stage 0 (at most 3 days), the engine is received and a thorough inspection follows that defines the work scope of the engine. In stage 1 (12 days), the engine is completely disassembled: first into modules, then into assies (sub-modules), and finally into parts. An engine consists of approximately 10,000 parts. See Appendix F for an example of the structure of an engine.

After the disassembly of the engine, the parts are inspected by employees of the department *Parts & Disposition*. They determine whether a part is still serviceable or requires a repair or replacement. The repair and replacement of parts takes place in stage 2, which is the most time-consuming stage: 33 to 35 days. Repairs take place either internally or externally, depending on whether ES has the ability to repair an item itself, and whether ES has a contract with a vendor such as General Electric that obliges ES to let this vendor perform the repair. Replacement items come either from stock in the ES warehouse or directly from external vendors via the inbound logistics process; hence, the inbound logistics process is part of stage 2. After all parts are declared serviceable, a final conformity check takes place in the department Assembly Preparation before the engine enters stage 3, the assembly of the engine. This stage takes 12 to 13 days. Figure 2.1 displays the main activities that take place in every stage.

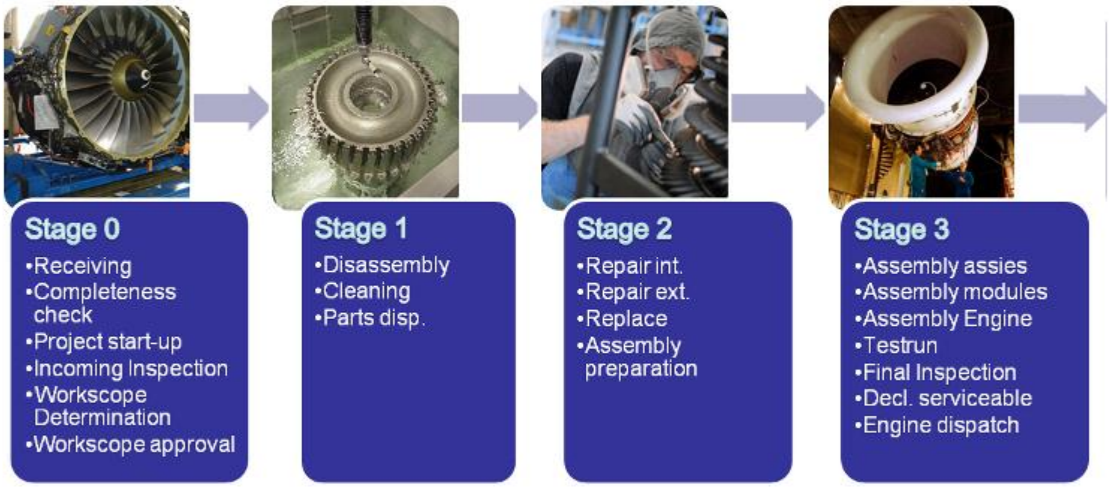


Figure 2.1: Overview of the four stages.

Figure 2.2 displays a map of the Engine Shop of KLM Engine Services. In the centre of the map, there is the central assembly hall. The shaded areas represent the various repair and assembly stations, and the Parts & Disposition department. The hall has 12,200 square meters floor area and is 11 meters in height. On the top of the map is the department Assembly Preparation. The logistics department and its main logistical sub-departments are in the top left corner of the map.

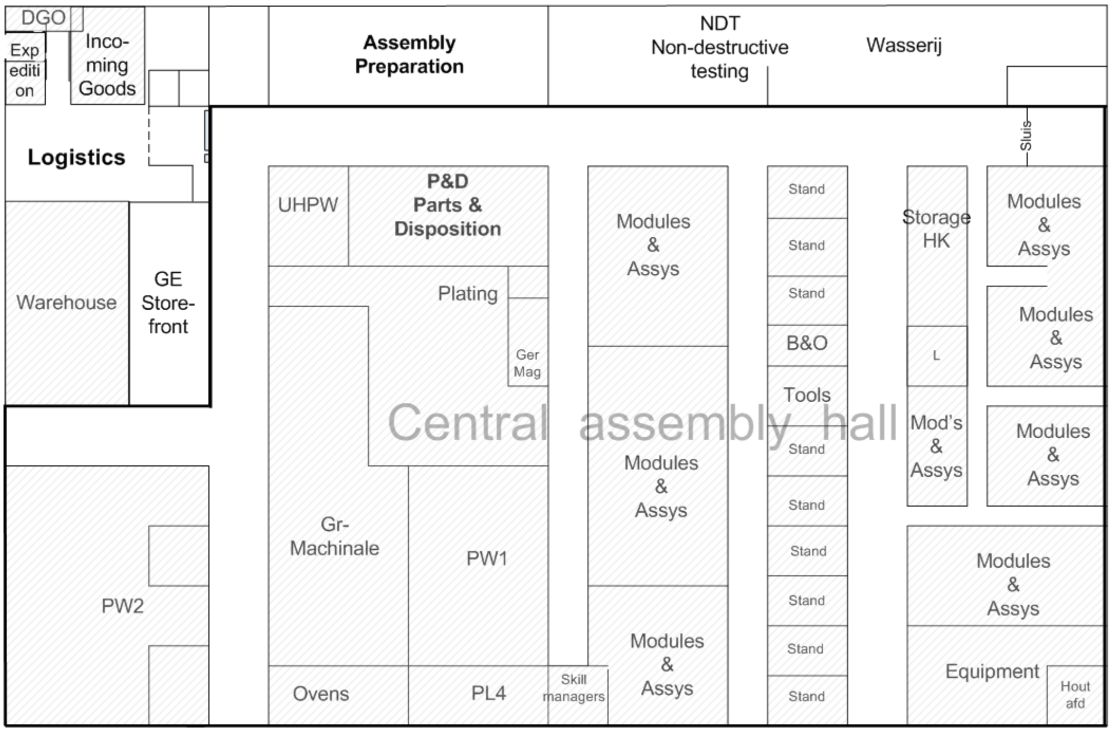


Figure 2.2: Map of the central assembly hall and the logistics department.

2.2 Terminology

Before going into the details of the inbound logistics process at the logistics department of ES, we first elaborate on some important terminology. Although the treatment of these phenomena a priori may seem premature, it is necessary to improve the readability of the rest of this chapter.

2.2.1 Purchase Order

Every part (repaired, new, or second-hand, see Section 2.2.5) that is delivered at ES for usage in the engine repair process, belongs to a *Purchase Order* (PO). A PO is created by the department of ES that orders the product. A PO is registered in *SAP*, the ERP system used by ES. It serves as the identification by which an order is followed, both physically and financially. The PO is created at the start of a purchase or external repair process. A PO can contain multiple types of parts and of each of these types there can be multiple units. In case of a repair, a PO usually contains just one type of part. To be able to distinguish between the different types of parts on a PO, every type of part has its own *item number* on the PO.

Once all parts included in a PO have arrived at ES and successfully passed the incoming goods inspection, the PO is closed and the financial settlement is concluded. Take for example a part that needs to be repaired. After disassembly of the engine, all parts are technically inspected by the Parts & Disposition department. If an inspector decides that the part requires an external repair, he creates an order for the repair and SAP automatically creates a PO. Then the part is transported to the logistical department Expedition, where the part is packaged, the airway bill for the shipment gets prepared, and finally the shipment is sent out to the vendor.

Throughout the whole process, several confirmations are placed in the information systems (SAP, Tracking, and Scarlos) based on this PO number. So the routing of the PO is tracked and ES can follow where the PO is. Once the repair is finished, the vendor sends the part back to ES using the same PO number. When the part arrives back at ES and successfully passes the incoming goods inspection, it receives a *Goods Received* (*GR*) *confirmation* in SAP. At this time the financial process starts: the costs for the repair are included on the bill of the owner of the engine and the vendor gets paid in case all parts of the PO have received a GR confirmation in SAP. If a vendor is unable to deliver all parts of a PO in one instance, it delivers the parts of the PO in multiple instances by partial deliveries.

2.2.2 Characteristics of a part

Every type of part has a unique *part number*, by which it is internationally known. Some part types are *serialized*, which means that every specific item of that part type has a *serial number* next to the part number. A serialized part is followed through its entire lifecycle and every repair or overhaul is registered. A life-limited part is always serialized, because the time and number of cycles since the item was new and the time since the last overhaul are registered during the lifecycle of every unique part.

Every part is registered separately in SAP, whether it is serialized or not. This allows ES to follow every unique part and to link all the paperwork (e.g. certificates and test reports) to that part.

2.2.3 Service bulletin

A *service bulletin* is an instruction for a repair or inspection to be performed on a certain part. The original manufacturer of the part publishes the bulletin and provides it to its customers. The service bulletin is issued to correct or improve the functionality of the concerning part. It comes with a priority level, which indicates the urgency of the bulletin and the degree by which the performance of the part is improved. The highest priority level requires immediate execution of the service bulletin. After the instruction of the service bulletin is performed on a part, the paperwork of the part is updated.

2.2.4 Certificate

All parts used at ES must have a *certificate*. A certificate contains information, such as the part and serial number, the name of the vendor, the production date, the maintenance, repair, and overhaul history of the part, and the service bulletins that have been performed. A certificate is a proof of quality for the concerned part given out by a national aviation authority, such as the American FAA or the European EASA. When an aerospace manufacturer produces its parts in line with safety regulations set by the national aviation authority in question, this authority provides a license to the manufacturer that allows the manufacturer to deliver parts with certificates of this national aviation authority. Such licenses are not only used for manufacturers of aerospace parts, but also for maintenance, repair, and overhaul companies, such as ES. ES currently has licences of several aviation authorities, including: FAA, EASA, CAAC (China), and CAA (United Kingdom). The country where the owner of the part is located, determines what license the part requires, not the country the manufacturer is situated in. Only parts that have a validly filled certificate of the right national aviation authority can be used in aerospace. Appendix E shows an example of a filled EASA certificate.

2.2.5 Employees at logistics department of ES

There are three kinds of operational employees at the logistics department of ES. The *general warehouse personnel* performs all operational tasks except incoming goods inspection, for example receiving packages, storing parts in the warehouse, picking orders from the warehouse, or preparing shipments for external repairs. All members of the general warehouse personnel are trained to be flexible all-round warehouse employees, so they can perform all these tasks. Despite their all-round training, however, most general warehouse employees have gotten accustomed to just one of these tasks and are no longer capable to perform the other tasks.

Incoming goods inspection may only be done by people who are licensed to work as an *inspector incoming goods* (IIG). The IIGs are the second group of operational employees. They are members of the general warehouse personnel who received special training that allows them to perform incoming goods inspections.

The third group of employees is the *System Check Group*. These employees can perform all operational tasks. They solve all problems that occur in any process at the logistics department and handle all non-standard cases. They can also perform incoming goods inspection, in case for example extra capacity is needed.

2.2.6 Part categories

There are three categories of parts to distinguish: *new*, *repaired*, and *second-hand parts*. Not only within ES, but rather in the whole airline industry, this is a very important distinction. The reasons for this strict distinction are twofold. First, in terms of economic valuation, there is a huge difference; even if an overhauled part outperforms a similar non-overhauled, but new part, it is still valued lower than the inferior new part. Second, clients usually specifically demand the use of either new, repaired, or second-hand parts for the maintenance of their engines.

This distinction is also clearly visible in several areas within ES. For example, at the Incoming Goods department, there are dedicated IIGs for both new parts and repaired parts. The routing through ES after inspection also differs per part category. In the warehouse and in SAP, there is a very strict separation between new parts and repaired or second-hand parts. Another example is the supply chains of each of these parts. These are considerably different as will become clear in Section 2.3. The same holds for the procedures for ordering parts.

2.3 Supply Chain

This section elaborates on the supply chain that parts go through before arriving at ES. Starting at the final destination, ES, we move upwards through the supply chain and discuss the different links involved. First, we discuss the E&M Logistics Centre in Section 2.3.1. Then, based on the country of origin of the shipment (either domestic or non-domestic), we explain the rest of the supply chain in Section 2.3.2. Section 2.3.3 discusses the difference per part category (new or repair).

2.3.1 E&M Logistics Centre

With the exception of some minor shipments such as office supplies, all shipments ordered by any business unit of E&M, such as ES, will first be sent to the E&M *Logistics Centre* (*LC*). The LC is situated at the area called Schiphol-Oost. At the LC, packages are sorted and sent to the right maintenance unit (hangars, Engine Services, etc.) by a truck of the internal courier company, Sodexo. These trucks deliver to each of the maintenance units at Schiphol-Oost several times a day according to a fixed schedule. Sodexo also provides internal E&M transportation: the transport between the maintenance units on Schiphol-Oost and picking up packages that should be sent out to external vendors. These packages are then delivered at the LC and sorted before being sent out to the vendor.

Figure 2.3 shows the lay-out of a part of Schiphol-Oost. The part surrounded by the bold lines is the *Technisch Areaal*. It is a secured area, which is only accessible by KLM employees and other authorized persons. Here all the major maintenance units of KLM E&M at Schiphol are situated, including ES and several major hangars. The LC lies directly to the left of the Technisch Areaal.

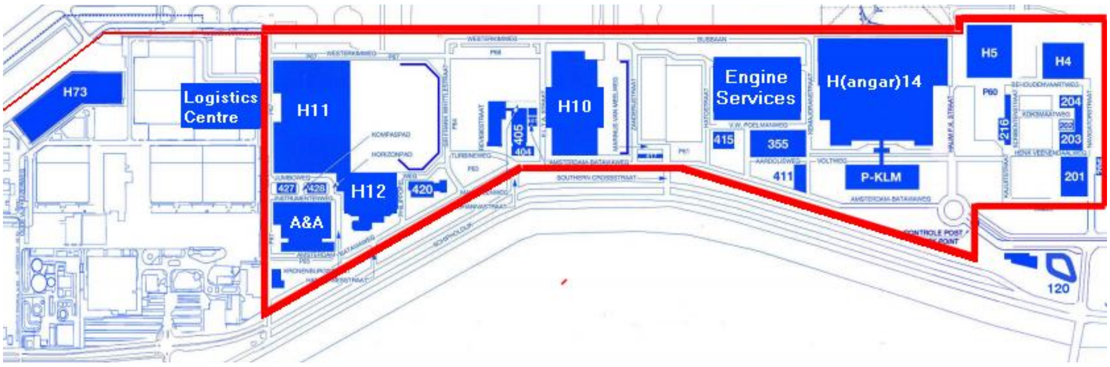


Figure 2.3: Map of Schiphol-Oost Technisch Areaal.

2.3.2 Country of Origin

The country of origin of the package determines the lay-out of the supply chain before the LC. In case of domestic shipment, the part is always delivered via the road by trucks, either with a courier or directly from the vendor. Non-domestic shipments go through several more steps. Usually, transport is done via airplanes. In this case, a vendor sends the part with a courier to a nearby airport. Here, the part is handed over to a cargo company (this can either be KLM Cargo or another freight carrier), which ships the parts to Schiphol. At Schiphol, the part is cleared by customs and handed over to KLM Cargo located at Schiphol Centre. Finally, the shipment is transported to the LC. Non-domestic shipments can also arrive via the road. For these shipments, a special Cargo desk is present in the LC. Here, customs can be cleared, which improves turnaround time. Figure 2.4 displays the links in the supply chain for packages that are sent from both domestic and non-domestic vendors. Figure 2.5 shows a map of Schiphol including the location of the Technisch Areaal and Schiphol Centre, where KLM Cargo is situated.

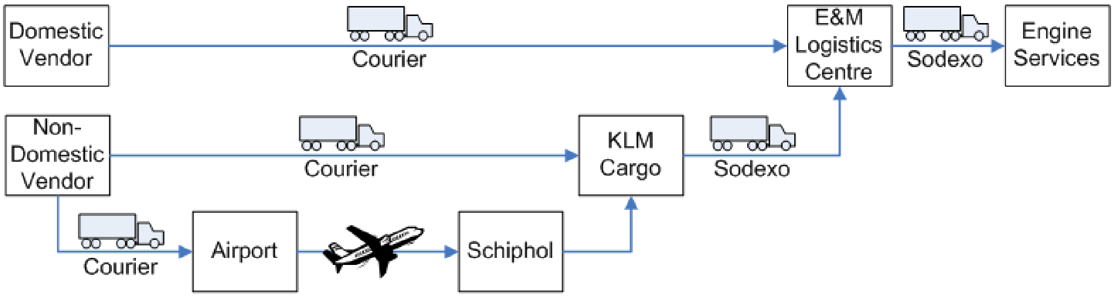


Figure 2.4: Supply chain links of packages coming from both domestic and non-domestic vendors.

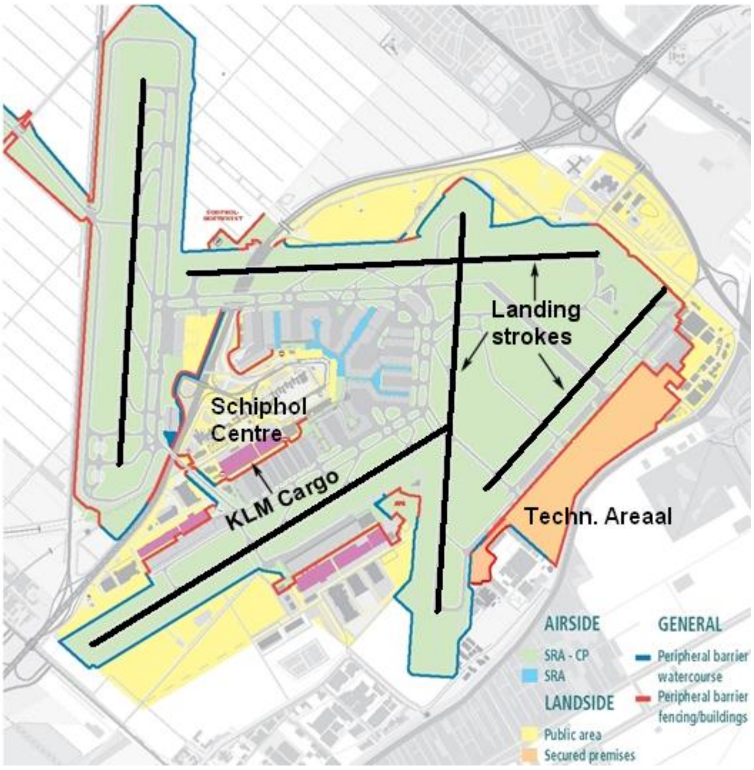


Figure 2.5: Map of Schiphol.

2.3.3 Part Category

Apart from the country of origin of the shipment, the part category (new or repair) is the other main factor that influences the steps a part goes through. The steps described above apply for both new and repaired parts, but repaired parts first need to be sent to the repair vendor. Basically, a repaired part that is sent to the vendor goes through the above described supply chain in the exact opposite way. First, it goes from Engine Services to the Logistics Centre. Then, depending on the country where the vendor is situated, it either goes directly to the vendor by road or via KLM Cargo and other links in the supply chain to the vendor.

2.4 Process description

The packages that arrive at ES and require an inspection go through three logistic stages. First, the package is dropped off at ES at Expedition (Section 2.4.1), then it goes to DGO (Section 2.4.2), and finally it goes to Incoming Goods (Section 2.4.3) for an administrative and visual inspection. Packages and parts that do not successfully pass these inspections go into quarantine (Section 2.4.4). Section 2.4.5 explains why the inbound logistics process is designed in the current manner. Since this section is quite extensive, we briefly conclude it in Section 2.4.6.

While reading this section, it is important to keep the following definitions in mind. A part is a single item as used in engines. A package refers to an actual box as sent by a vendor to ES. A package contains one or more parts. A package may contain parts of more than one PO, but the parts of a PO can also be delivered in more than one package, even at a different date.

2.4.1 Receiving incoming goods

The process of receiving packages at the Expedition department is designed to facilitate proper receiving of the delivered packages and dispositioning to either DGO (see Section 2.4.2) or departments in the engine shop. These tasks are performed by the DGO employee, who is a member of the general warehouse personnel.

Packages are being delivered at ES several times a day by the E&M delivery service. Packages mostly come via the E&M Logistics Centre (LC), but they can also come from another maintenance unit for internal repairs. Every package that has been dropped off at Expedition is accepted if it has no transportation damage. Damaged packages are rejected and returned to the driver. The driver places a delivery notification in *Tracking* (an Air France KLM information system used by the LC for tracking and tracing packages) upon acceptance.

The final step is the determination of the routing within ES. Some packages do not require an incoming goods inspection and are sent directly to the shop. The majority does require an inspection and is moved to the DGO buffer room. Packages that do not require inspection at Incoming Goods are for example office supplies and parts destined for the department Parts & Component Repair. This department performs repairs for external clients and other KLM maintenance units.

Figure 2.6 displays the process of receiving packages in a flowchart. The diamond shapes represent a decision that the DGO employee needs to take. The rectangles represent an activity that an employee has to perform. The oval shapes with outgoing arrows are events that initiate the process, while the ovals with incoming arrows briefly describe what happens after the process at Expedition ends.

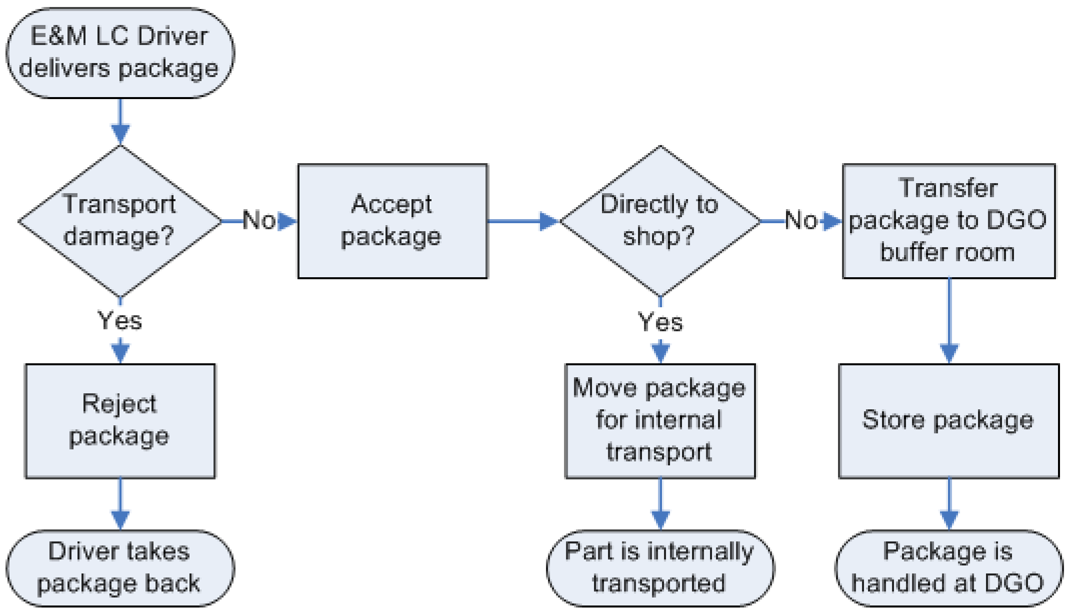


Figure 2.6: Flowchart of arriving packages at the Expedition department of ES.

2.4.2 DGO

The purpose of the DGO (Decentralized GOods Receipt) department is to confirm that the contents of the package are sent correctly, to register the time and date of acceptance of the package by Engine Services, and to prepare the package for incoming goods inspection. The responsibility for the package is officially transferred from the LC to ES after acceptance at DGO, because acceptance implies ES has received the package in the right state. Responsibility for the package is an important issue in case a discrepancy occurs, for instance when the package is missing.

When the DGO employee is not involved in receiving goods at the Expedition department, his activities take place at DGO. Packages need to be called in via SAP through placing an *AM confirmation* (Accepted at Maintenance unit, which is ES). This confirmation can only be placed if the package has been cleared by customs through a *CR* (*Customs Release*) notice in SAP. In case this CR notice is not available, the DGO employee contacts KLM Cargo to request the CR to be placed.

After the AM confirmation is placed, the DGO employee prints a label with the time and date of the AM confirmation and places it on the package. Then he opens the package and briefly inspects the package and its contents for any clear damage. He also checks whether the number of parts match the bill of lading. If he discovers damage or a mismatch of the contents with the bill of lading, an inspector incoming goods creates a quarantine notification for the package and moves the package to the quarantine area. We discuss the quarantine area in Section 2.4.4.

The final step is to decide whether the package needs to go through incoming goods inspection (see Section 2.4.3) or should be moved to another destination. The DGO employee places the packages for incoming goods inspection in the buffer of the Incoming Goods department according to the FIFO principle using the AM labels. He places the other packages in the internal transportation cars.

Figure 2.7 displays this process. For an explanation of the symbols in the figure, see Section 2.4.1.

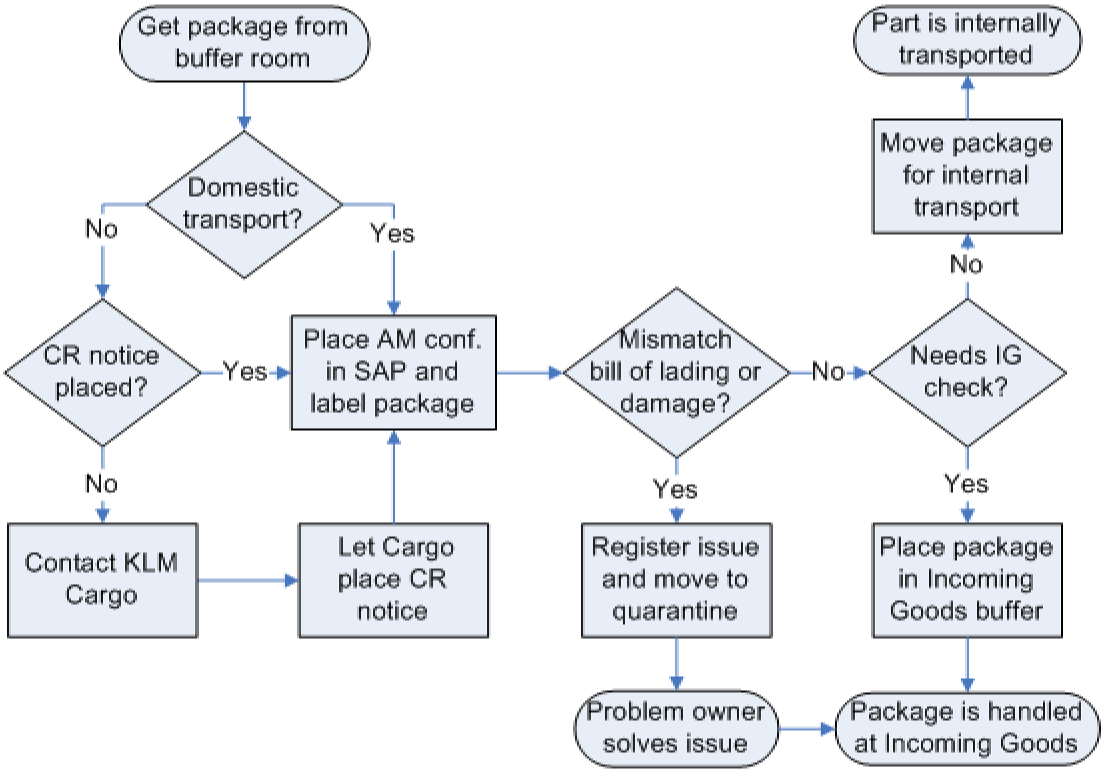


Figure 2.7: Flowchart of DGO.

2.4.3 Incoming Goods

The purpose of incoming goods inspection is *quality assurance*: to guarantee that every part that is used in any process within ES meets the quality requirements as demanded by aviation authorities. An incoming goods inspection verifies that the items have been sent without damage, the administrative elements have been filled in correctly, and the item is delivered in compliance with what was requested on the Purchase Order. A technical inspection is not part of the incoming goods inspection.

At the Incoming Goods department, the unit changes from packages to parts. All parts from a package need to be inspected piece by piece by an *Inspector Incoming Goods* (*IIG*), although some minor parts, such as nuts, may be inspected by bulk. An incoming goods inspection roughly consists of four steps: a visual inspection, an administrative inspection, the placement of an inspection confirmation in SAP, and finally further internal routing of the part. The tasks that need to be performed in these four steps may differ per part category (new, repaired, or second-hand) and the kind of shipment (engine part, tools, equipment, internal routing, and drop shipment). The remainder of this section explains the incoming goods inspection step by step.

Visual inspection

An inspector takes a package with one or more parts from the buffer according to FIFO principle. However, the FIFO principle is often not followed. The main reason for not following FIFO is the *cherry picking* by IIGs. An IIG who is cherry picking deliberately pick parts that are easier to inspect rather than following FIFO. Another exception to the FIFO rule is the emergency request, which we discuss further on in this section. Also, since repair and new parts have separate buffers, FIFO only applies per part category (new or repair).

During the visual inspection, the IIG checks every part for damage. This is not a technical inspection, but rather a thorough visual inspection to discover any damage of the part. The visual inspection is similar for all part categories.

Administrative inspection

The administrative inspection consists of checking whether the certificates are correctly filled in and whether the information on the certificates is in compliance with data stored in SAP and on the physical product. The IIG checks whether the received part(s) match with what was requested by comparing the parts and paperwork to data in the PO. Then the IIG checks the validity of the certificates. He checks whether the right certificates are sent and whether they are filled correctly. Certificates need to be filled according to strict guidelines set by the national aviation authority in question (see Section 2.2.4). These guidelines prescribe the exact way in which a certificate should be filled. This differs per part type. The inspection of certificates of new parts typically requires the least time, because there is no history of repairs that needs to be filled in as is the case with repaired parts. In case of a repaired part, the IIG needs to check whether the repair is performed by the vendor as requested on the PO by looking at the certificate and the information incised on the part. After the administrative check, new serialized parts require an additional step, which is the creation of an *equipment number* in SAP. The equipment number is used to track the part.

GR confirmation

After both the visual and administrative inspection have been successfully completed, the IIG places a *GR* (*Goods Received*) *confirmation* for the part in SAP. This confirmation indicates that the part meets all requirements. Any part used in ES, whether it is stored in the warehouse or dedicated to a project, must have received a GR confirmation. The GR confirmation is also critical in the financial process: a vendor will not get paid until all parts in the PO have received a GR confirmation. In case the IIG notices an unconformity during any of the inspections, he registers a quarantine notification and moves the part to the quarantine area. We discuss the quarantine process in Section 2.4.4.

After placing the GR confirmation, SAP automatically generates a transportation slip based on the information entered by the department that placed the PO. The transportation slip indicates the further routing of the part through ES. The IIG places the part in the right transportation car for internal transport to the right department.

Disposition

After incoming goods inspection, parts go to several locations. Parts that are supposed to be used for an active project (an engine currently in maintenance at ES) go to the Assembly Preparation department, where all the parts of an active project are stored together until they are all serviceable and the engine can be assembled. Externally repaired parts always belong to an active project, since only parts that come from a disassembled engine are sent to external vendors for repairs.

Externally repaired parts must return to the engine where they came from. An exception to this is when an *exchange* has taken place. This means that the original part that came from the engine is replaced by another part of the same type. An exchange is performed when the part that was supposed to be placed in a certain engine got delayed in the repair process. To prevent delay for the entire engine, the part is exchanged.

New parts and second-hand purchased parts can also belong to a certain project and therefore go to Assembly Preparation, but may as well be purchased for stock. In this case the part goes to the warehouse, where it is stored. In the warehouse, there is a strict separation of storage locations, both physically and in SAP, for new parts and repaired or second-hand parts (even if the second-hand part has never been used).

Second-hand parts

Second-hand parts are either purchased for an engine project or for stock. There are two main reasons for purchasing second-hand parts. First, the second-hand market is the main source for parts of old engine types that are in the decline stage of the product life cycle, such as the CF6-50 engine. Often, new parts are no longer produced for this engine type. Since the availability of some of these parts solely depends on the second-hand market, some parts are not only purchased for active projects, but also for stock. Second, some customers specifically request second-hand parts to minimize costs.

Second-hand parts lead to a lot of quarantine cases, because the process for ordering second-hand items is rather complicated and SAP is not designed properly for dealing with second-hand parts at incoming goods inspection.

Internal route

The third disposition option of a part after incoming goods inspection is an internal route. A part requires an internal route if it needs an additional treatment before it can be used. This is for example a technical inspection after an external repair, a quality inspection of a second-hand purchased part, or an extra coating of a (new) part. The internal route is indicated on the transportation slip. After a part has been on an internal route, it returns to Incoming Goods. Since the part is already visually and administratively inspected and has received a GR confirmation, it only requires a manual transfer in SAP to its final storage location as indicated on the transportation slip. This is either the warehouse or Assembly Preparation.

Other deliveries

Apart from the three part categories (new, repair, and second-hand), there are two other types of deliveries that require specific handling: *FHMI parts* and *drop shipment parts*. We briefly explain what these parts are and why they require different handling. FHMI is the product group that consists of all the tools and equipment used in maintenance and repair activities, for example screwdrivers, tape, and sealing wire. The vast majority of these items do not require incoming goods inspection, but some special FHMI parts do require incoming goods inspection as described above, because they have a certificate, which requires inspection. A drop shipment is a delivery of part(s) directly to ES by a customer. These parts should either be put on the engine of that customer or go into the customers stock in the ES warehouse. Drop shipment parts go through visual and administrative inspection as any other parts, but they do not receive a GR confirmation since they are not property of KLM. To be able to follow the part after the inspections, the IIG registers the part in SAP.

Emergency request

Sometimes parts are directly needed elsewhere in the shop, for example because the engine where the part belongs to is already in the assembly process. In such cases, the part may be picked from the Incoming Goods buffer and goes immediately through incoming goods inspection. The most accurate information to determine the location of the part is the date of the AM confirmation in SAP. Although the buffer should be constructed by FIFO based on AM date, it is often difficult to locate the part, because the exact location of parts in the buffer is not stored.

2.4.4 Quarantine

If a package or part has failed either the DGO or incoming goods inspection, an IIG creates a *PIG* (*Problem Incoming Goods*) notification in the PIG database and moves the package to the *quarantine area*. Information such as the vendor, part#, PO#, and serial#, is entered in a PIG, together with the cause of the problem (for example a serial# mismatch, damage) and a precise description of the problem.

The responsibility of solving the PIG does not lie with the IIG, but with the *problem owners*. Every PIG has one or more problem owners. These problem owners are selected by the IIG who creates the PIG. The IIG selects the problem owner based on several factors, such as the root of the problem or the person who created the PO. A problem holder can be a department (for example Engineering or Planning) or more specifically a member of that department.

To solve PIGs, every (possible) problem owner looks into the PIG database several times a day. When he notices a PIG of which he is the problem owner, he comes to the quarantine area to solve the PIG. This can be on any time of the day. Even though the problem owner should solve the PIG himself, he often turns to an IIG for assistance. In case the problem owner does not start solving a PIG, an IIG initiates the solving procedure, even though the IIG is not responsible for the PIG: the problem owner is. The time an IIG spends on solving a PIG is at the expense of the time the IIG can spend on performing regular incoming goods inspections. So solving PIGs degrades the performance of the inbound logistics process, despite that the logistics department of ES is not responsible for solving these PIGs.

Once a PIG is solved, the package or part is moved back to the Incoming Goods buffer and is handled according to normal incoming goods inspection procedures, as described in Section 2.4.3.

Figure 2.8 displays the entire process of incoming goods inspection.

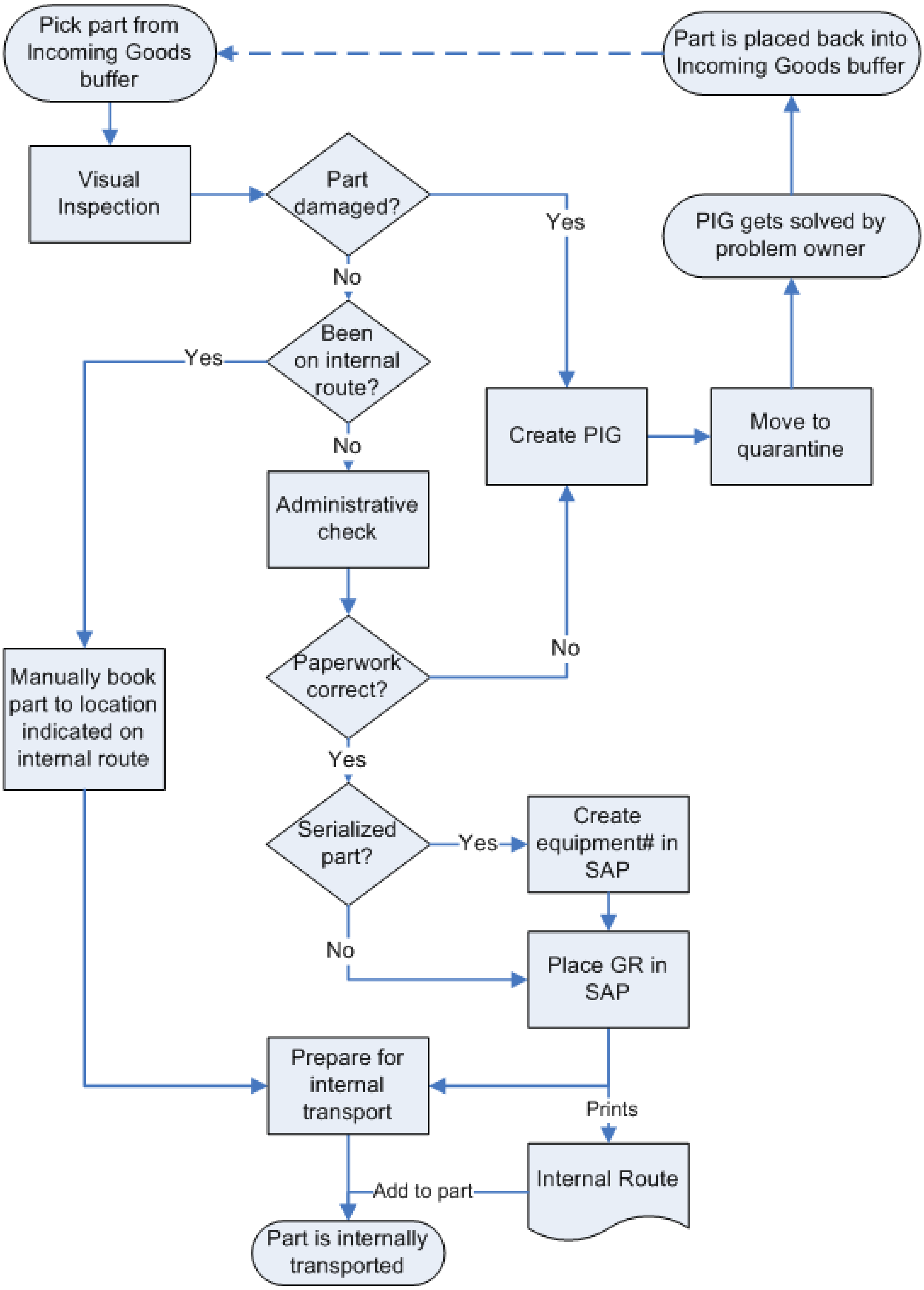


Figure 2.8: Flowchart of incoming goods inspection.

2.4.5 Design of process lay-out

The inbound logistics process, as described in this section, is designed in a similar way as other engine maintenance and repair companies, of which some, such as General Electric, served as an example. KLM practices the business philosophy of *Lean Six Sigma*, a synergy between *Lean Manufacturing* and *Six Sigma*, in organizing its business processes (see Section 3.2). To make the inbound logistics process more 'lean', the management of ES organized a *Kaizen* event in early 2007 to improve the performance of the inbound logistics process. During a Kaizen event, which takes one or more days, a whole department fully focuses on improving processes. The goal of the Kaizen event for inbound logistics was to redesign the inbound logistics process to create a smooth flow of parts through the entire inbound logistics process by reducing the buffers at Expedition and DGO to a minimum level. To achieve this, the DGO department was redesigned. Two general warehouse employees were assigned to DGO at all time and two desks allowed them to quickly inspect the packages and prepare the parts for incoming goods inspection. Another result of the Kaizen event is a method to solve quarantine issues (PIGs): the *roll call*. A roll call is a multi-disciplinary meeting in which IIGs and problem owners meet daily on fixed times to solve all PIGs as soon as possible, but within at most 72 hours of the creation of the PIG.

Although the current lay-out is still based on the results of this Kaizen event, the main results of this event are no longer used. The logistical departments (Expedition, DGO and Incoming Goods) are still situated at the same place, but due to several factors, such as a shortage of personnel, there is just one instead of two employees working at DGO, who is at the same time responsible for internal transport. There is no longer a smooth flow through the process since the buffer at DGO usually is substantial. Also, roll calls are no longer performed, which has lead to an increasing number of parts in the quarantine area, because PIGs are not being solved.

2.4.6 Conclusion

We gave an overview of the activities involved with inbound logistics. The design of the inbound logistics process is similar to the design of other engine maintenance and repair companies. There are the three stages that packages go through, before being transported further into ES. Packages are delivered from the Logistics Centre.

Packages are first received by a DGO employee and checked for transportation damage. Then the DGO employee checks whether the shipment matches the airway bill, and prepares the parts from the package for the final stage, the incoming goods inspection. This inspection consists of visual and administrative checks. Parts that successfully pass the inspection are moved to their destination in ES. Parts that fail inspection in any of the three stages are moved into the quarantine area, from where the respective problem owner should solve the issue.

Figure 2.9 visualizes the flow of packages and parts through the physical areas of inbound logistics and the employees involved with the process. All flows of goods are included in the figure, with the exception of some minor part flows, such as parts that have returned from inside the shop after an internal route. The width of an arrow designates the amount of parts flowing through the arrow. For a map of the entire logistics department, of which Figure 2.9 is a part, see Appendix D.

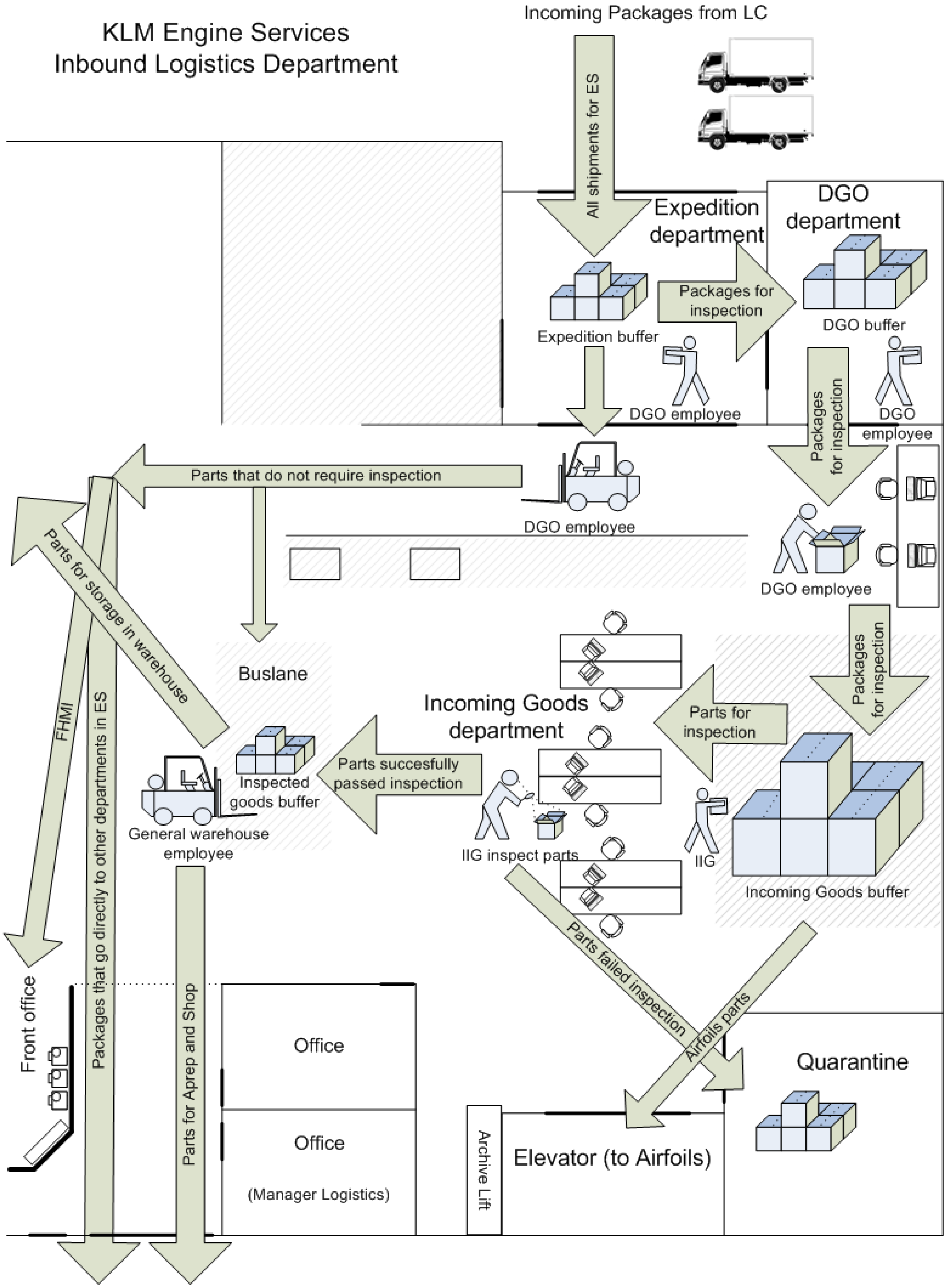


Figure 2.9: Map of inbounds logistics at the logistics department of ES.

2.5 Scheduling

To achieve lower personnel costs, the management of ES has experimented with three different scheduling methods for IIGs. In this section, we discuss the scheduling of personnel at the logistics department of ES and specifically the scheduling of IIGs. In Section 2.5.1, we explain the original schedule, the 7x2 schedule. Section 2.5.2 explains what ES wants to gain by introducing new schedules. Then we discuss the two new schedules: the 5x2 schedule in Section 2.5.3 and the 7x1 schedule in Section 2.5.4. In Chapter 5, we evaluate the performance of the inbound logistics process for these three schedules.

2.5.1 Original schedule: 7x2

There are two groups of personnel involved in the inbound logistics (see Section 2.2.5): the general warehouse personnel and the IIGs. A member of the general warehouse personnel is assigned to DGO, while the IIGs are assigned to incoming goods inspection. There are three teams, the A, B, and C-team, over which the two groups of personnel are divided. Each team consists of a group of general warehouse employees and a group of IIGs.

At the logistics department, scheduling is based on a 7x2 schedule. Operations run seven days a week, because the logistics department provides parts to the engine shop, where operations run seven days a week. Every day is split into two periods, a day shift (from 7:10 to 15:40) and an evening shift (from 15:30 to 0:00). So a week can be seen as fourteen periods: seven days of each two periods. During each shift, an entire team is working, while the other two teams are not. The assignment of the teams to shifts goes according to a fixed three-weekly rotating schedule, as shown in Table 2.1.

Week #	Week 1							Week 2							Week 3						
Day	**M**	**T**	**W**	**T**	**F**	**S**	**S**	**M**	**T**	**W**	**T**	**F**	**S**	**S**	**M**	**T**	**W**	**T**	**F**	**S**	**S**
Day shift	A	A	A	B	B	B	B	C	C	C	A	A	A	A	B	B	B	C	C	C	C
Evening shift	B	C	C	C	A	A	A	A	B	B	B	C	C	C	C	A	A	A	B	B	B

Table 2.1: Schedule for the assignment of crews to shifts

Each team has its own team manager. He is, among other tasks, responsible for the assignment of general warehouse personnel to the various tasks, such as DGO and order picking. Available IIGs are assigned to incoming goods inspection. Only in case of a shortage of available general warehouse personnel or a surplus of IIGs, the team manager decides to assign an IIG to a general warehouse task.

Every shift, one person is working full time at DGO. Every team has only one or two people who work at DGO, even though any member of the general warehouse personnel should be able to work at the DGO department. This reduces flexibility in case this DGO employee is absent. If necessary, a second employee may be assigned during the day to assist at DGO.

At the Incoming Goods department, there are two groups of inspectors, each dedicated to inspect one of the part categories: one group only handles repair parts, while the other handles new parts and the FHMI parts that require inspection. Drop shipment parts (see Section 2.4.3) are handled by all inspectors. The reason for this distinction is that repair parts always belong to a running project, which means these could have higher priority than new parts, of which about 80% goes directly into stock. Every team contains five or six full-time IIGs, but also a few general warehouse employees and System Check Group members, who can be employed as IIG in case of a shortage of IIGs.

2.5.2 Introduction of new schedules

From November 2011, the management of ES started experiments with the scheduling of IIGs. The reasons for experimenting with new schedules are twofold. First, the management presumes lower productivity during the weekends. Second, management believes that the higher costs for employing people in the weekend does not outweigh the reduced lead time. Since the general warehouse personnel also has employees with an IIG license, critical parts needed in the engine shop can still be inspected during the weekends, even with few or no IIGs present.

To compensate the employees for working during the weekend, ES rewards extra hours for the time worked, which are added to the monthly salary. Table 2.2 shows per roster type the number of extra hours ES needs to pay its employees per month for working during the weekends.

Roster type	#hours extra salary per employee per month	#employees	total #hours extra per month
7x2 (regular)	34	17	578
7x1 (new)	10	12	120
5x2 (new)	0	12	0

Table 2.2: Extra hours per roster type.

Next to saving costs by employing fewer employees during the weekend, there have been two other changes. The first change is that the management of ES decreased the number of IIGs from on average 17 during the regular 7x2 roster to 12 during the new schedules. We discuss the consequences of the decline in the number of IIGs in Chapter 4, the data analysis. Second, several measures have been taken that encourage working by the FIFO methodology, such as merging the separate buffers for new and repair parts and storing parts on movables racks. These racks are sorted by date and time of the AM confirmations of the parts on the rack, creating a clearer organized buffer. This leads to a decrease in the search time for emergency requests, because parts can be found more easily in the clearer organized buffer.

2.5.3 New schedule: 5x2

In November 2011, a pilot for an experimental schedule started. This schedule splits the scheduling of general warehouse personnel and IIGs. The general warehouse personnel is still scheduled according to the regular 7x2 schedule. The IIGs are now divided over two teams, the X and Y team (although officially still being part of their old team). There is no longer work done during the weekends, which means the roster changed from a 7x2 to a 5x2 schedule. The schedule for assigning teams to the shifts is a fixed biweekly rotating schedule. A team works during an entire week on the same shift every weekday and in the following week on the other shift. Both teams have five full-time IIGs and one IIG in training, who is estimated to reach 50% of the productivity of a regular IIG. Before the pilot started, the number of IIGs was on average seventeen; an exact number cannot be given, since the total number of IIGs fluctuated over the year. If we compare this to the total number of IIGs during the pilot started, the total number of IIGs decreased by about five.

2.5.4 New schedule: 7x1

The third schedule, which started in May 2012, is called the 7x1 schedule. The 7x1 schedule comes down to two shifts on each weekday and one shift (the day shift) on both Saturday and Sunday. In the weekend shifts, the number of IIGs is limited to just 2 IIGs. The management of the logistics department of ES intends to permanently use the 7x1 schedule for IIGs.

2.6 Conclusion

This chapter explained the steps engine parts go through in both the inbound logistics process at the logistics department of KLM Engine Service and the supply chain. It also dealt with the scheduling of personnel.

All parts that arrive at ES come from the E&M Logistics Centre and are delivered by the internal courier service of KLM E&M. These trucks deliver multiple times a day according to a fixed schedule. The links of the supply chain that parts go through before arriving at the LC depend on two factors: the country of origin of the vendor, and whether or not the part is a repair item. Domestic shipments arrive via road directly from the vendor. Non-domestic packages come via KLM Cargo.

Inside ES, packages pass three departments. First, a package is received at the Expedition department. Second, the package is moved to DGO, where a general warehouse employee unpacks the package, checks whether the contents match the airway bill, and prepares it for the final stage, incoming goods inspection. Here, the parts are visually and administratively inspected. Parts that fail inspection go to the quarantine area. Quarantine issues need to be solved by their respective problem owner, usually another departments of ES, depending on the nature of the issue. In all these departments, the priority rule for package or part selection is first in, first out (FIFO). However, FIFO is often not followed due to several reasons, such as cherry picking.

There are two groups of personnel at the logistics department. The first group is the general warehouse personnel. They may be employed at all logistic activities, including DGO, but except incoming goods inspection. The second group, the Inspectors Incoming Goods, are general warehouse employees with a license to perform incoming goods inspection. These two groups of employees are divided over three teams. A day is split into a day and evening shift. To every shift one of the three teams is assigned. In the regular schedule, the 7x2 schedule, both groups of employees work seven days a week. To save costs, different scheduling methods for the IIGs have been applied with less IIGs working during the weekends.

3. Literature review

This chapter introduces the reader to some literature that is related to this research. Section 3.1 discusses literature on turnaround time reduction. In Section 3.2, we discuss literature on the business philosophy of KLM: Lean Six Sigma. Section 3.3 describes simulation, which is the tool we use in this research to model the inbound logistics process and to evaluate the proposed interventions to improve the process.

3.1 Turnaround time reduction

In this section, we discuss literature on the reduction of turnaround time. We start with discussing flexible flow shops in Section 3.1.1. Section 3.1.2 elaborates on dispatching rules. In Section 3.1.3, we describe workload control rules. Lean Manufacturing and Six Sigma also provide tools and practices to reduce the turnaround time. We discuss these concepts in more detail in Section 3.2.

3.1.1 Flexible flow shop

A *job shop* is a model of a process in which jobs consists of a number of operations that need to be performed on different machines (Pinedo, 2005). The inbound logistics process can be seen as a special case of the job shop: a *flexible flow shop*. In a flexible flow shop, jobs visit a number of workcenters that are placed in series. Each workcenter consists of a number of identical machines in parallel (Pinedo, 2005). All jobs follow the same sequence of workcenters, although some jobs may bypass a workcenter when they do not require processing there. In the case of the inbound logistics process, the jobs are the packages and parts, the workcenters are the three logistical departments and the quarantine area (which jobs often bypass), and the machines are the employees handling the parts.

The goal of a job shop scheduling problem is to schedule the operations of the jobs in a way that minimizes the objective(s), such as the average turnaround time or the number of late orders. There is a vast amount of extensions to the classical job-shop problem. For instance, parts are processed in batches (Shen & Buscher, 2012), machines require set-up times (Allahverdi et al., 2008), jobs do not have a fixed processing order through the machines (Zhu & Wilhelm, 2006), or there are multiple optimization objectives (Xia & Wu, 2005). Each of these problems has specific characteristics. Due to the distinct characteristics, there are also numerous approaches to solve job shop scheduling problems.

Solving job shop scheduling problems is very difficult, because job-shop scheduling problems are NP-hard (Garey et al., 1976). This means that computation time grows exponentially with the number of jobs *n.* This difficulty has motivated a number of solution methods, including optimizing methods (such as branch and bound or dynamic programming), heuristics (such as tabu search or simulation), and hybrids (methods that combine optimizing method solvers with a heuristic). Each approach has unique characteristics that make it suitable for application to specific problems (Zhu & Wilhelm, 2006).

3.1.2 Dispatching

Dispatching rules prescribe which job should be loaded on a machine in case this machine becomes free (Holthaus & Rajendran, 1997). ES, for instance, has FIFO as its main dispatching rule. Dispatching rules can be based on several aspects, such as the time jobs have been in the process (for instance FIFO), the processing time of the jobs (for instance SPT, shortest processing time first), or the due-date of the jobs (for instance EDD, earliest due-date first).

The appropriate dispatching rule for a process depends on the objective (Philipoom, 2000). ES, for instance, uses FIFO as its main dispatching rule. FIFO generally performs poorly on flow time characteristics in dispatching studies. However, FIFO has good performance on criteria such as *maximum flow time* (Philipoom, 2000). Since ES strives to minimize the P95 value, which is a measure of the maximum flow time, FIFO seems a suitable choice for ES. To minimize the average flow time of all parts, processing time rules are most suitable (Jayamohan & Rajendran, 2000). When customer service is an important criterion, dispatching rules based on the due date usually perform well, since they focus on avoiding tardiness (Philipoom, 2000).

There is no single rule that performs well on all objectives. SPT, for instance, generally performs very well on minimizing the average flow time and minimizing the number of tardy jobs, but performs poorly on the maximum flow time and variance. Combining multiple dispatching rules with different objectives can lead to better performance results on these objectives (Holthaus & Rajendran, 1997).

3.1.3 Workload control

By applying *Workload Control (WLC) rules*, the amount of work that is released to the work floor is controlled. WLC protects the work floor from external dynamics and uncertainties by creating a separate pool of unreleased jobs. The purpose of WLC rules is to control the turnaround times by limiting the work-in-progress (WIP) on the work floor (Soepenberg et al., 2012). Empirical investigations show that WLC rules can reduce the total time in the system by 40–50% (Bertrand and Van Ooijen, 2002). Hopp and Spearman (2004) argue that an explicit limit on WIP allows increased productivity, such as CONWIP (Constant WIP).

There are various *Order Review and Release (ORR)* strategies to control the workload. In Section 2.4.3, we elaborated on cherry picking, which is the main cause that often FIFO is not followed by the employees in the inbound logistics process. Philipoom & Fry (1999) performed a case study on how to prevent job selection not based on formal job priority. They found that with the controlled release of jobs into the shop using an ORR strategy, the operations managers can enforce job priorities and herewith improve performance. The effect of a lack of following dispatching rules is much smaller using ORR, because the amount of jobs on the work floor is limited (Thürer et al., 2011).

We refer to the extensive literature reviews on WLC by Fredendall et al. (2010) and Thürer et al. (2011) for more information about WLC (rules).

3.2 Lean Six Sigma

KLM practices the business philosophy *Lean Six Sigma*, which is a synergy between *Lean Manufacturing* and *Six Sigma*, in its business processes, including the inbound logistics process. In this section, we discuss these two concepts, their principles, and the synergy between the two philosophies. In Section 3.2.1, we elaborate on Lean Manufacturing. Section 3.2.2 discusses Six Sigma. Section 3.2.3 describes the synergy of these two concepts into Lean Six Sigma.

3.2.1 Lean Manufacturing

Lean Manufacturing, or Lean Production, is generally described from two points of view, either “from a philosophical perspective related to guiding principles and overarching goals, or from the practical perspective of a set of management practices, tools, or techniques that can be observed directly” (Shah & Ward, 2007). In this section, we elaborate on the concept of Lean Manufacturing based on these two points of view.

Philosophy perspective

Due to confusion caused by the two abstraction levels and the broad span of the concept, there exist many definitions and views in literature on Lean Manufacturing. To clarify the confusion surrounding the term Lean Manufacturing, Shah & Ward (2007) conducted an extensive literature review on Lean Manufacturing. They propose the following definition to capture the many facets of Lean Manufacturing:

> *Lean production is an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability.*

Although there is ambiguity in literature on the definition of Lean Manufacturing, its goal is more clearly established. A company that adopts Lean Manufacturing strives to eliminate non-value adding activities, or *waste*, in order to maximize the value for the customer. The Lean Manufacturing philosophy focuses on avoiding the seven cardinal types of waste (Ohno, 1988):

1. Transportation: unnecessary transport of parts under production.
2. Inventory: stacks of parts waiting to be completed or finished products waiting to be shipped.
3. Motion: unnecessary movement of people working on products.
4. Waiting: unnecessary waiting by people to begin the next step.
5. Over-processing the product with extra steps.
6. Over-production of products not needed.
7. Defects in the product.

Practical perspective

Womack & Jones (1996) defined five principles that are fundamental to Lean Manufacturing. These principles are: specify value, identify the value stream, make the value-creating steps flow, transform processes into pull, and pursue perfection through continuous improvement of the processes. To achieve the goal of Lean Manufacturing (the elimination of waste) by these principles, many practices exist.

As with the definition of lean, there is no consensus in literature on which practices belong to Lean Manufacturing. However, Cua et al. (2001) and Shah & Ward (2008) state that there is general agreement within literature that there are four main aspects of Lean Manufacturing, in which practices are often bundled: quality management, pull production, preventive maintenance, and human resource management. Concrete examples of these practices are just-in-time production, turnaround time reduction techniques, maintenance optimization, and lot size reductions. The purpose of all these practices is to identify and remove some form of waste.

To apply these practices, several tools, methods, and techniques have been developed. Examples of these tools are (Hopp & Spearman, 2004, Akbulut-Bailey et al., 2012): *value stream mapping* (to identify the value stream and the wastes in the stream), *5S* (a method to create a cleaner working environment), and *the visual factory* (making the process clearly visible to everyone).

To successfully implement Lean Manufacturing, employees need to be encouraged to *directly* contribute to improving the process.

3.2.2 Six Sigma

As with Lean Manufacturing, descriptions of Six Sigma also range from a business philosophy for improvement to a bundle of practices (Linderman et al., 2003, Schroeder et al. 2008). The focus in Six Sigma lies on identifying sources of *variability* and reducing these. It is a methodology for variability reduction rather than a general strategy for improvement, such as Lean Manufacturing (Hopp & Spearman, 2004). The name Six Sigma stems from the original principle, as developed by Motorola, that the failure rate should be defined as all parts that are outside the specification limit of six standard deviations (sigma) from the mean. This means that there may be at most 1 defect per 3.4 million parts.

A clear definition of the concept is not available in literature. Therefore, Schroeder et al. (2008) conducted an extensive literature study to define Six Sigma. We explain the concept and its elements based on the definition of Schroeder et al. (2008). They define it as follows:

> *Six Sigma is an organized, parallel-meso structure to reduce variation in organizational processes by using improvement specialists, a structured method, and performance metrics with the aim of achieving strategic objectives.*

First, we see that the definition highlights the focus of the reduction of variation. The *parallel-meso structure* refers to the special Six Sigma teams that operate outside an organization's normal way of operating. These teams are led by full-time *improvement specialists,* called *Black Belts.* Black Belts are trained in the Six Sigma method and are solely focused on improving the organization. Typically, they lead multiple projects simultaneously. Other members of the teams are Green Belts, who are part-time member.

The *structured method* of Six Sigma includes five steps known as Define, Measure, Analyze, Improve, and Control (DMAIC). This method is aimed at systematically finding the root of a problem by employing standard quality tools such as a cause-effect charts and statistical process control. The DMAIC method is based on the

PDCA (Plan, Do, Check, Act) model, but it puts more emphasis on integrating specific tools and involving different organizational members.

Six Sigma uses a variety of metrics to measure the benefits and performance of the Six Sigma method. The *performance metrics* can either be customer-oriented or financial. This distinction clearly underscores the focus on both financial and non-financial (customer-related) results, which is at the root of the Six Sigma philosophy. The customer-oriented metrics, such as critical-to-quality metrics, are aimed at identifying and measuring the customer needs. The financial metrics are aimed at measuring and monitoring the benefits of the projects.

A successful integration of the Six Sigma philosophy involves a learning organization that strives for continuous improvement. It requires companywide commitment and training everyone in the company in DMAIC, the concept, and the tools. This is a systematic, ongoing process (Wiklund & Wiklund, 2002).

3.2.3 Synergy

Shah et al. (2008) compare the Lean Manufacturing and Six Sigma philosophies to determine the use of the business philosophy of *Lean Six Sigma*, which combines the principles and practices of Lean Manufacturing and Six Sigma. They conclude that most researchers agree that there are more commonalities between Lean and Six Sigma tools and practices than differences. The most significant overlap is in the area of quality management: quality management practices are included in defining, describing, and measuring both Lean Manufacturing and Six Sigma. Even so, there are also differences. For instance, while Lean Manufacturing requires workers in the process to directly improve it, Six Sigma deploys change through the parallel organizations structure.

The philosophies are complementary on some important aspects. For example, most practices and tools of Lean Manufacturing focus on the elimination of obvious waste, such as excessive buffers and work-in-progress, long set-up times, inefficient transport, and rework that can be avoided. While it is clearly very important to eliminate this kind of waste, it should be noted that the elimination of this kind of waste has always been common practice in organizations. Lean Manufacturing also aims to address indirect waste, which is mostly caused by *variability* (Hopp & Spearman, 2004). Since Six Sigma is a variability reduction method, it connects perfectly with Lean Manufacturing.

3.2.4 Lean Six Sigma in the inbound logistics process

We have already encountered elements of Lean Six Sigma, such as the Kaizen event (see Section 2.4.5) in the report. This section discusses other principles and techniques of Lean Six Sigma that are relevant to the inbound logistics process.

KLM strives to reduce variability and to create a stable turnaround time in all its processes. This is one of the fundamentals of the Lean Six Sigma concept. To focus on a steady turnaround time, performance measurement at KLM is often not based on the mean, but rather on the *P95 measure*. P95 stands for the 95%-percentile, which is the value below which 95% of all observations fall. With the P95 measure, companies are forced to reduce the span of turnaround times, rather than focussing on the average. By identifying the extreme values and solving the issues that causes these extreme values, companies reduce the span and create a more stable and reliable process.

The objective of Lean Six Sigma is to maximize the value to the customer. We measure the value of the inbound logistics process by the turnaround time of parts. To increase the value of the inbound logistics process, we must identify and remove waste and decrease the variability in the process. Examples of waste in the inbound logistics process are the parts that need to go into quarantine, IIGs searching for emergency requests, and the buffers. Sources of variability are for instance not using FIFO and the highly volatile arrival process.

3.3 Simulation

Most real-world systems are too complex to allow realistic models to be evaluated analytically (Law & Kelton, 2000). This is also the case for the inbound logistics process at ES. The main cause of the complexity of the inbound logistics process is the volatility in several key factors in the process, such as input demand, inspection times, and available personnel. Models of complex systems, such as the inbound logistics process of ES, can be studied by means of simulation (Law & Kelton, 2000). Simulation is the process of designing a model of a system and conducting experiments with this model for the purpose either of understanding the behavior of the system or evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system (Shannon, 1975).

Simulation is complementary to several business process improvement approaches, such as Lean Six Sigma; it can be used to assess the potential improvements that can be made to the system (Fowler & Rose, 2004). Simulation is one of the few tools capable of measuring financial indicators, operational indicators and customer satisfaction indicators in the same analysis (Ferrin et al., 2005).

Adams et al. (1999) give several examples of how simulation could be used within the lean manufacturing strategy, such as identifying problems in manufacturing, ranking the various opportunities for process improvement, or predicting the impact of accepted improvements before implementation.

Standridge & Marvel (2006) identify five reasons for using simulation to enhance the Lean process:

1. Variation must be addressed, both random and structural.
2. Data must be fully analyzed to help understand the random nature of system behavior.
3. The interaction between system components must be assessed.
4. The future state must be validated before it is implemented to minimize or eliminate the period of trial and error adjustments.
5. Alternatives to the future state must be systematically identified and considered.

In Section 1.4 we introduced the approach we use in this research for our simulation study: the seven steps that compose a typical sound simulation study (Law & Kelton, 2003). Following these steps is not a sequential process. It requires checking the validity of previous steps before proceeding to the next step. Figure 3.1 shows this iterative process. For more information about simulation and the details about each step, we refer to Law & Kelton (2000).

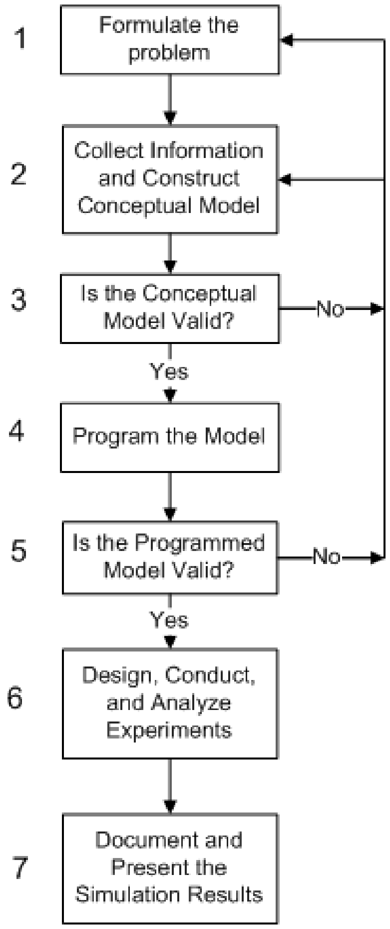


Figure 3.1: Seven step approach for conducting a simulation study.

4. Data analysis

In this chapter, we describe the results from the data analysis. We perform this analysis to describe the performance of the inbound logistics process and to gather data we need for our simulation model (see Chapter 5). We gather and analyze data from the period running from November 1, 2010 to October 31, 2011. We choose this period, because it is the most recent period in which the original IIG schedule was used (see Section 2.5). Since there might be seasonal effects, we choose a period of 12 months to capture all the seasons.

We start this chapter by discussing the turnaround time of parts and packages in Section 4.1. In Section 4.2 we discuss the arrival process of parts at ES. Section 4.3 elaborates on the handling times of various tasks in the inbound logistics process. In Section 4.4, we compare the different scheduling methods. Section 4.5 concludes this chapter.

4.1 Turnaround time

The *turnaround time* of a part is the time it takes for a part to go through the inbound logistics process. In this section, we start with discussing the methodology we use to determine the turnaround time in Section 4.1.1. In Section 4.1.2, we describe how shipments can be tracked using confirmations in information systems. Section 4.1.3 discusses how we filter the data. Section 4.1.4 presents the results of measuring the turnaround times. In Section 4.1.5, we discuss the measurement of the stability of the turnaround times in the inbound logistics process.

4.1.1 Methodology

In Section 1.2, we established that the key performance indicator of the inbound logistics process is the turnaround time of a part from the moment it arrives at ES until it successfully completed incoming goods inspection. To be able to measure the performance of the entire inbound logistics process in more detail, we divide the process into four sections. Each section represents a different point in the supply chain, both inside and outside ES, at which during a specific activity a *confirmation* is placed for each part or package in any of the three information systems: SAP, Tracking, and Scarlos. A confirmation contains information, such as the date and time of the confirmation, the PO and item number, the person placing the confirmation, the state of the shipment, and the vendor. Based on the date and time of each of these confirmations, we determine the turnaround time of a part or package between each of these sections in the supply chain. This gives us a better insight in the performance of the process than when we would only consider the total turnaround time.

Figure 4.1 visualizes our method for measuring the turnaround times by showing the time, place, activity, and confirmation that belong to each of the four sections. For every confirmation, it shows:

- the *building* in which the confirmation is placed (the two shaded rectangles),
- the *department* in this building (this only applies within ES),
- the *activity* in which the confirmation is placed *after* the activity is completed (the four rectangles in the building areas),
- the *information system* in which the confirmation is placed.

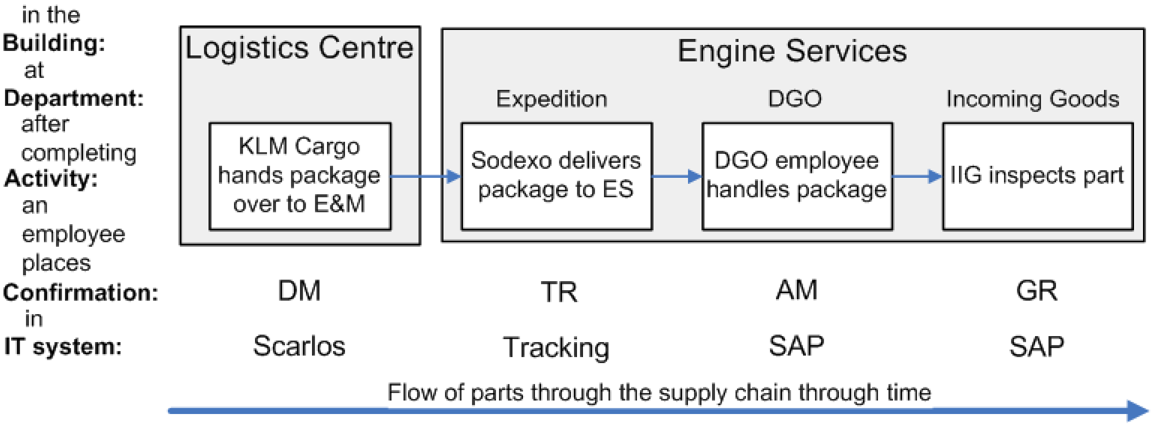


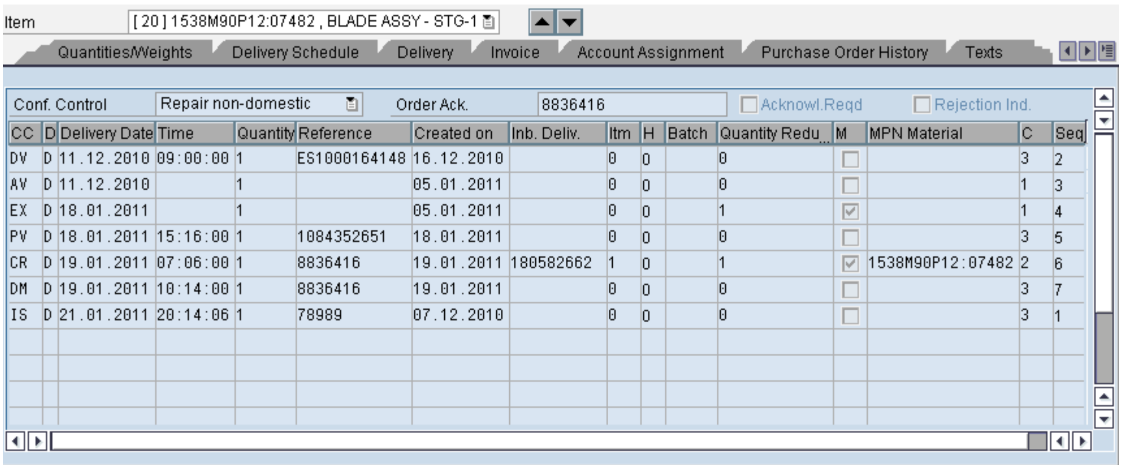
Figure 4.1: Overview of the measurement points in the supply chain.

To indicate the turnaround time between two activities, we use the matching confirmations of these activities. For example, TR-AM indicates the turnaround time of a part between the TR and AM confirmation: the time between the completion of the delivery of a package at ES (TR) and the moment of completion of handling the package at DGO (AM). In this remainder of this chapter, we use this notation to indicate a time interval between two confirmations.

In Section 4.1.2, we explain in detail how the placement of confirmations works and how we determine the turnaround time based on confirmations.

4.1.2 Tracing shipments by IT confirmations

POs are followed through the entire supply chain by the placement of confirmations in the several information systems that are used (SAP, Tracking, and Scarlos). Several parties in the supply chain place these confirmations. These parties include Engine Services itself, but most confirmations are placed by vendors, couriers, and other divisions and units of KLM, such as KLM Cargo and the LC. Figure 4.2 shows an example of the confirmations placed in SAP for an item of a PO. This item, a blade, has been repaired externally (in Singapore).


Item [20] 1538M90P12:07482 , BLADE ASSY - STG-1

Quantities/Weights | Delivery Schedule | Delivery | Invoice | Account Assignment | Purchase Order History | Texts

Conf. Control: Repair non-domestic — Order Ack.: 8836416 — Acknowl.Reqd — Rejection Ind.

CC	D	Delivery Date	Time	Quantity	Reference	Created on	Inb. Deliv.	Itm	H	Batch	Quantity Redu...	M	MPN Material	C	Seq
DV	D	11.12.2010	09:00:00	1	ES1000164148	16.12.2010		0	0		0	☐		3	2
AV	D	11.12.2010		1		05.01.2011		0	0		0	☐		1	3
EX	D	18.01.2011		1		05.01.2011		0	0		1	☑		1	4
PV	D	18.01.2011	15:16:00	1	1084352651	18.01.2011		0	0		0	☐		3	5
CR	D	19.01.2011	07:06:00	1	8836416	19.01.2011	180582662	1	0		1	☑	1538M90P12:07482	2	6
DM	D	19.01.2011	10:14:00	1	8836416	19.01.2011		0	0		0	☐		3	7
IS	D	21.01.2011	20:14:06	1	78989	07.12.2010		0	0		0	☐		3	1

Figure 4.2: Example of confirmations placed on a PO.

In the example of Figure 4.2, the first confirmation was placed by the courier: the DV (Delivered at Vendor) confirmation. Then the vendor placed an AV (Accepted by Vendor) confirmation to confirm it received the package. Then, when the vendor finished the repair, it placed an EX (Ex-works) confirmation. The courier placed a PV (Picked up at Vendor) confirmation upon picking up the package with the repaired part. Next was the CR (Customs Release) note, which means the package is cleared by customs. Finally, the DM (Delivered at Maintenance Unit) confirmation was placed when KLM Cargo handed over the package to the LC. The last confirmation in this example, IS, indicates the execution of an interface between SAP and Scarlos to exchange information.

The confirmations described above are not only very useful for tracking separate purchase orders, but also for data analysis on large data sets, for example measuring the time between the several links in the supply chain. This is what we want to achieve with the measurement points from Figure 4.1. SAP allows extensive options for data analysis on these confirmations.

Unfortunately, there are many issues that trouble data analysis based on confirmations. The first issue is that several confirmations, such as the CR, can be placed from several locations. Since the location differs per package and cannot be determined by looking at the data, it is not possible to determine where the package was in the supply chain at the time of the confirmation. Second, confirmations are often omitted, because the placement of most confirmations is not required at all time. This leads to a lot of missing data. Third, the data stored in the confirmation, such as date and time, may be incorrect, because the confirmations are usually not placed instantly, but rather later through an interface, or even manually. There is also no consistency among the various couriers and vendors in the way confirmations are filled. So to be able to use a confirmation in our data analysis, these issues either need to be addressed, or should not apply to the confirmations we use.

We continue this section with discussing the four confirmations we use in our data analysis: the DM, TR, AM, and GR confirmations. In the remainder of this chapter, we omit the word confirmation when we refer to these four confirmations.

GR

After the incoming goods inspection has been successfully completed, an IIG places a GR for the part in SAP (see Section 2.4.3). A GR is obligatory and is always placed at the same location: the Incoming Goods department. Without this confirmation, a part may not be used in any engine, because it has not been confirmed that the part meets the quality standards. Since the GR is the most reliable confirmation, we use the GR as the base of our analysis. The rough data set that we retrieve from SAP consists of 51,828 GRs. We remove the GRs placed at the Airfoils department and the duplicate entries in SAP. This results in a data set of 31,610 GRs placed at the logistics department of ES between November 2010 and October 2011.

As mentioned in Section 2.4.4, parts that have failed the incoming goods inspection, go into the quarantine area. These parts stay here until the PIG has been solved by its problem owner. The turnaround time of PIG parts increases while they are in quarantine, because these parts have not yet received a GR. So the performance of the inbound logistics process decreases, while the cause of it is beyond the control of the logistics department of ES. Therefore, we do not consider parts that went through quarantine in the performance measurement of the inbound logistics process. From the 31,610 GRs in our data set, 1,783 have been in quarantine (see Section 4.3.2).

For every part that has received a GR between November 2010 and October 2011, we search for the matching confirmations (AM, TR, DM) and determine the turnaround time between each of the links as follows. We export data from the three information systems to MS Excel. We create an identifier for every part by merging its PO number with its item number (see Section 2.2.1). Some of these identifiers are not unique due to partial deliveries (see Section 2.2.1). In these cases, we manually alter the identifiers to create unique identifiers. Then, by using these unique identifiers, we gather the time and date of each confirmation for every part. The time difference between two confirmations for a part is the time the part took to move between two links: the turnaround time.

AM

One of the major difficulties in the data analysis is the retrieval of 'Accepted at ES' (AM) confirmation data. This confirmation is placed at DGO after the DGO employee has handled a package to confirm that ES has properly received the package (see Section 2.4.2). There are two ways of storing an 'Accepted at ES' confirmation in SAP. SAP has the functionality to store an AM for a PO in the same manner as other confirmations. However, we find that in 95% of the cases this functionality is not used. This is due to limitations in SAP on the number of different confirmations that can be placed on a PO. Instead, the 'Accepted at ES' is stored as text in the *TrnsIDcode* field, which is part of the *Shipment form* in the *header* of the *inbound delivery number* that belongs to the Customs Release (CR) confirmation for the PO. This text is automatically filled by SAP in the Shipment form when the DGO employee confirms ES has received the package. The time and date are also filled in the Shipment form. See Appendix G for an example of the Shipment form with an 'Accepted at ES' confirmation placed in it.

Only in about 2% of the cases, an 'Accepted at ES' confirmation is stored as a proper AM confirmation in SAP. This only applies to some domestic shipments, because these do not have a CR confirmation (since domestic shipments do not have to be cleared by customs). In all other cases, either the Shipment form is used or the AM confirmation is omitted. Out of the 31,610 parts that received a GR confirmation, 27,523 (88.3%) received an AM confirmation via the Shipment form, 691 (2.2%) had a proper AM confirmation, and 2,996 (9.5%) had neither of these confirmations.

Due to the cumbersome manner of using the Shipment form to place an AM, it is not possible to directly retrieve AMs with a matching PO and item number from SAP. To connect a PO and item number with a Shipment form, we use an intermediate step. We retrieve two data sets from SAP: all the filled Shipment forms and all CR confirmations placed between November 2010 and October 2011. The data set with the Shipment forms contains the AMs, while the CR confirmations come with a PO and item number. Both data sets contain an inbound delivery number, which is a unique number in SAP given to every package that arrives at ES. We merge the two data sets in MS Excel by matching the inbound delivery number from both data sets, resulting in one data set with PO and item numbers connected with the time and date of their AMs.

In the remainder of this report, we refer to either way of placing an ‘Accepted at ES’ confirmation in SAP by the term AM confirmation, because the distinction is only relevant when retrieving the data from SAP.

TR

The contents of this section are based on interviews with Leo Vennik, Project Manager at the LC, and Martijn Wennekes, Logistics Project Leader at the LC.

The TR is placed in Tracking by an employee of Sodexo after he has dropped a package at ES to confirm that the package has successfully been delivered (see Section 2.4.1). We face several difficulties that trouble a reliable analysis of the data from Tracking. The most important issue is the incompatibility between SAP and Tracking data. When Tracking was introduced in 2008, it was supposed to be integrated into all maintenance units of E&M, including ES. ES, however, decided not to adopt Tracking into its processes, because ES finds SAP sufficient for tracking parts. Since ES does not use Tracking, functionality to allow ES to follow parts in Tracking has not been developed. The purpose of Tracking is to allow the LC to follow packages through the process, not the parts inside the package. Every package is stored as one single entry in Tracking and receives just one number, by which the package is known in Tracking. So packages that contain multiple parts are also stored by a single entry number. All other parts in the package remain unknown in Tracking. The number by which a package is stored in Tracking is either the PO and item number from one of the parts inside the package, or the Air Waybill number of the entire package. Furthermore, the item number is very often omitted and information is stored incorrectly, because the majority of the entries are entered manually and none of the fields are obligatory. Due to all these issues, we can only match 8,292 (26.2%) TRs to the 31,610 GRs.

DM

The DM is placed in the LC when KLM Cargo delivers the package at the LC. The LC, which is part of E&M, is the intermediary for all shipments sent to any of the business units of E&M (see Section 2.3.1): all packages go via the LC before being delivered at the right business unit. This means that packages at the LC are already in possession of E&M, but not yet present at the right business unit, such as ES. So the delivery time between the LC and ES extends the turnaround time of all parts delivered to ES. Because the delivery time between the LC and ES is an internal (E&M) factor, it is relevant for ES to know what the turnaround time of packages between the LC and ES is. However, the delivery from the LC to ES is not part of the inbound logistics process, so it cannot be directly influenced by the management of the logistics department of ES. Therefore we only determine the turnaround time of parts between the LC and ES in this data analysis, but we will not consider this factor in our simulation model in Chapter 5.

The DM is a ‘Prove of Delivery’ confirmation placed in Scarlos, which gets translated through an automatic interface into a DM in SAP. The DM is a standard SAP confirmation, such as the ones we see in the example of Figure 4.2. This means the DM is directly connected to a PO and item number. Out of the 31,610 GRs in our data set, we found 24,892 (78.7%) parts with a DM and 6,718 (21.3%) without a DM.

4.1.3 Outlier detection

With the data set of confirmations (DM, TR, AM, and GR) and the method we described in Section 4.1.2, we calculate the turnaround times of all parts between the four measurement points. The resulting turnaround times, which we discuss in Section 4.1.4, show several potential *outliers*. Barnett & Lewis (1994) define an outlier as an observation that appears to be inconsistent with the rest of that set of data. Anomalies in our data set are caused by several factors, such as IT-system errors, human errors, and errors due to connecting data from different IT systems. We need to correct the data by identifying and removing the outliers, before we can analyze the data. Negative turnaround times are obvious outliers, so we remove the DM, TR, and AM confirmations leading to negative turnaround times. Since GRs are the most reliable confirmations (see Section 4.1.2), we did not remove these.

We also notice several potential outliers with remarkably large turnaround times. Both formal and informal tests exist for the identification of outliers in univariate data. Formal testing requires a test statistic, which usually assumes some well-behaving distribution, on the basis of which the extremes are possibly declared outliers. Most of the test statistics are designed to identify a single univariate outlier or an outlier pair using a normal distribution (Barnett & Lewis, 1994, Laurikkala et al., 2000). Informal tests do not require the use of a theoretical distribution. They use various location and scale parameters based on the sample data to construct an interval to identify outliers. Values that lie outside this interval are considered as outliers (Seo, 2006).

Formal tests are not suitable for determining outliers in our data for two reasons. First, the distribution of all the turnaround and arrival times in this research is (heavily) skewed to the right and therefore we cannot assume normality. Second, we cannot fit a theoretical probability distribution to the data. Using *EasyFit* statistical software, we tested the fit of over fifty continuous probability distributions with the Kolmogorov-Smirnoff, Anderson Darling, and Chi-square tests. The fit of all distributions was rejected, even if we only allow a very small probability of 1% (so $\alpha = 0.01$) for a Type I error, which is to falsely reject the hypothesis that the data follows the tested distribution. Therefore, we must use an informal outlier identification method.

The *classical boxplot* (Tukey, 1977) is one of the most frequently used informal outlier detection methods (Hubert & Vandervieren, 2008). In this method, all values that lie outside the interval [Q1 − 1.5 IQR; Q3 + 1.5 IQR] are considered as outlier, where Q1 is the *first quartile*, Q3 the *third quartile*, and IQR = Q3 − Q1 the *inter-quartile range*. However, many regular observations will exceed the boundaries of the interval in heavily skewed data sets, such as our data set, and will unrightfully be labeled as outlier. This is the case with most commonly used outlier detection methods (Hubert & Vandervieren, 2008). Therefore, we must use an outlier detection method that takes into account the skewness of the data.

Seo (2006) compared several informal outlier identification methods. He concluded that the *adjusted boxplot method* (Hubert & Vandervieren, 2008) works best with heavily skewed data. The adjusted boxplot method is designed specifically for outlier detection in skewed data sets. It is a variant of the classic box plot method, but it determines the cut-off values based on the *medcouple (MC)* (Brys et al., 2003). The medcouple is a measure for the skewness of the data. In the adjusted boxplot method, an observation is considered as an outlier if it lies below the lower boundary $Q1 - 1.5 * IQR * e^{-4 * MC}$ or above the upper boundary $Q3 + 1.5 * IQR * e^{3 * MC}$.

We use the adjusted boxplot for outlier detection in our data set. For the calculation of the medcouple and an example of the adjusted boxplot compared to the classical boxplot, see Appendix H.

4.1.4 Results

In this section, we present the results of the analysis of the turnaround times between the four measurement points and their confirmations: DM, TR, AM, and GR (see Figure 4.1).

DM-TR

Table 4.1 displays the summary statistics of the turnaround times between DM and TR (DM-TR).

N (# parts)	6,634
Mean turnaround time (hours)	16.28
Standard deviation	74.30
Skewness	26.03
Q1	1.95
Median	3.06
Q3	10.99
Q3-Q1	9.04
Medcouple	0.75
Outlier if greater than	138.82

Table 4.1: Summary statistics of DM-TR, including outliers.

Before we analyze the data, we remove the outliers (see Section 4.1.3). Using the adjusted boxplot method, we find that 138.82 hours is the upper boundary of the adjusted boxplot, so we consider all turnaround times above 138.82 hours as an outlier and we remove these observations from the data set. Table 4.2 shows the summary statistics of this filtered data set. If we compare the summary statistics of Table 4.1 and Table 4.2, we see that by removing the outliers (only 1.2% of the observations), the average turnaround time decreases by 25.7%, the standard deviation by 71.0%, and the skewness by 89.2%. These large decreases show that the removal of outliers is necessary in order to give a correct view of the data.

N (# parts)	6,554
Mean turnaround time (hours)	12.09
Standard deviation	21.57
Skewness	2.82
Q1	1.94
Median	3.03
Q3	9.17
Q3-Q1	7.23

Table 4.2: Summary statistics of DM-TR, outliers removed.

Figure 4.3 shows the distribution of the turnaround times after we have removed the outliers. The horizontal axis shows the turnaround time in hours, while the vertical axis shows the cumulative fraction of parts that were delivered within a certain amount of time. Since there are no observations in the interval [125, 138.82], we do not display this part in the graph. Figure 4.3 gives a clear overview of the high amount of parts with a high turnaround time. The majority of the parts (67.3%) receives a TR within 5 hours after the DM, but 32.7% of the parts have turnaround times quite evenly divided over the broad range between 5 hours and 125 hours. So even after the removal of the outliers from the data, there is still a large number of parts with high turnaround times. The average turnaround time, 12.09 hours, is highly influenced by these high turnaround times, since it lies even above the third quartile value of 9.17 hours (see Table 4.2).

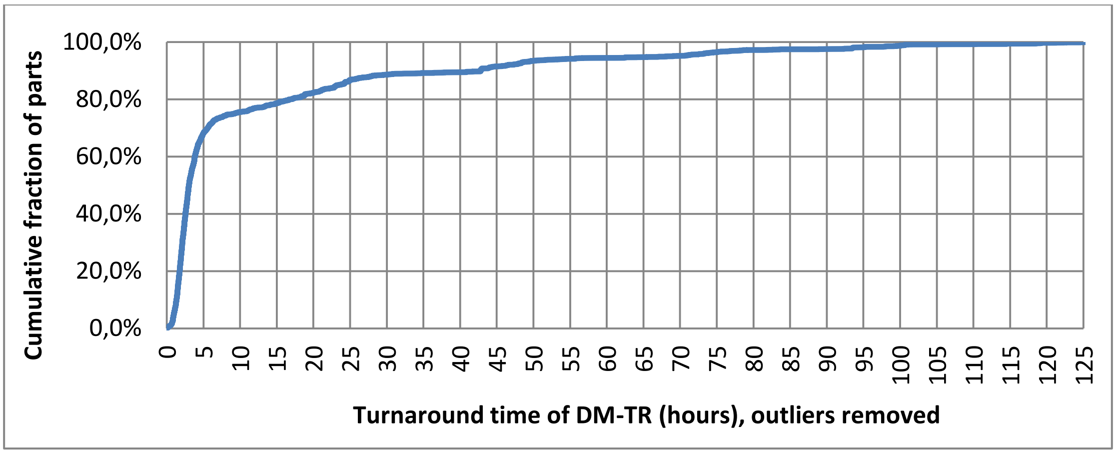


Figure 4.3: Distribution of the turnaround time of DM-TR (N = 6,554), outliers removed.

Figure 4.4 shows the turnaround times of DM-TR by the frequency of parts per hour. It shows the high number of parts that receive a TR within 5 hours after the DM, as we have also seen in Figure 4.3. However, it shows more clearly that there is steady number of parts in each of the turnaround time bins above 10 hours. This causes the distribution of the turnaround time to be heavily skewed to the right, as we already mentioned in Section 4.1.3. The relatively high skewness of the data (see Table 4.2) also supports this conclusion. This indicates that the process faces difficulties in delivering a stable turnaround time for all parts.

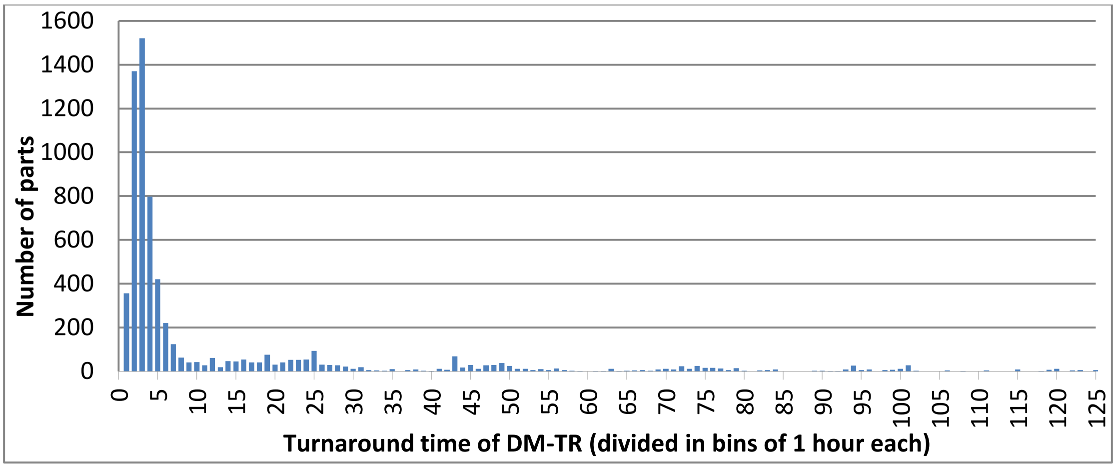


Figure 4.4: Frequency of turnaround time of DM-TR per hour (N = 6,554).

TR-AM

The next step in the supply chain takes place between TR and AM (TR-AM). This is the first part of the inbound logistics process. First, we remove the outliers with the adjusted boxplot method. The upper boundary of the adjusted boxplot is 98.04 hours. This leads to labeling 4.6% of the 7,363 observations as an outlier. This is a high number of outliers. We established in Section 4.1.2 that the data from Tracking, the TR, is unreliable. However, the DM-TR data also relies on TRs, while this data has a lower fraction of outliers (1.2%). To explain this difference, we compare the outliers of both data sets. We find that the majority of the parts that we consider an outlier in the TR-AM data (78.8%) has a *negative* DM-TR. We have already removed these observations from the DM-TR data set, because it indicates that the TR has been placed earlier than the DM. This finding confirms that these TRs are indeed incorrect observations, so we rightfully consider a relatively high fraction of observations of TR-AM as outliers that should be removed from the data set. Table 4.3 shows the summary statistics of TR-AM without the outliers. Figure 4.5 shows the distribution of the turnaround times of TR-AM in hours without the outliers.

N (# parts)	7,023
Mean turnaround time (hours)	18.79
Standard deviation	19.60
Skewness	1.58
Q1	3.83
Median	13.25
Q3	25.70
Q3-Q1	21.87

Table 4.3: Summary statistics of TR-AM, outliers removed.

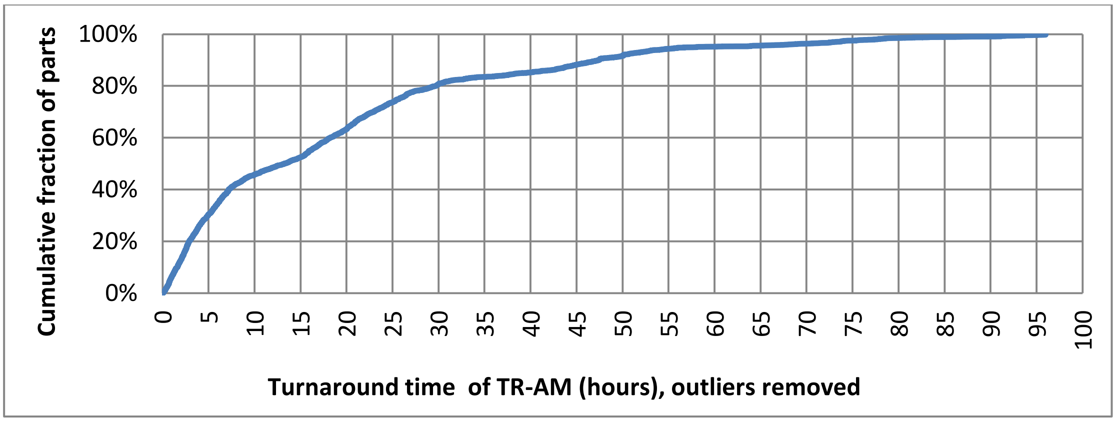


Figure 4.5: Distribution of the turnaround time of TR-AM (N = 7,023), outliers removed.

In Figure 4.5, we notice three small bumps in the graph, occurring around 10 hours, 34 hours, and 58 hours. A bump in this kind of graph might show that there is a common disturbance that leads to a decline of the turnaround time. The gaps of approximately 24 hours between the three bumps suggest that the cause is a daily event. This is indeed the case, because the bumps are caused by the idle time during the night. If we subtract the idle time from the turnaround time, the bumps should disappear. Figure 4.6 confirms this by showing the graph of the turnaround times with the nightly idle time subtracted.

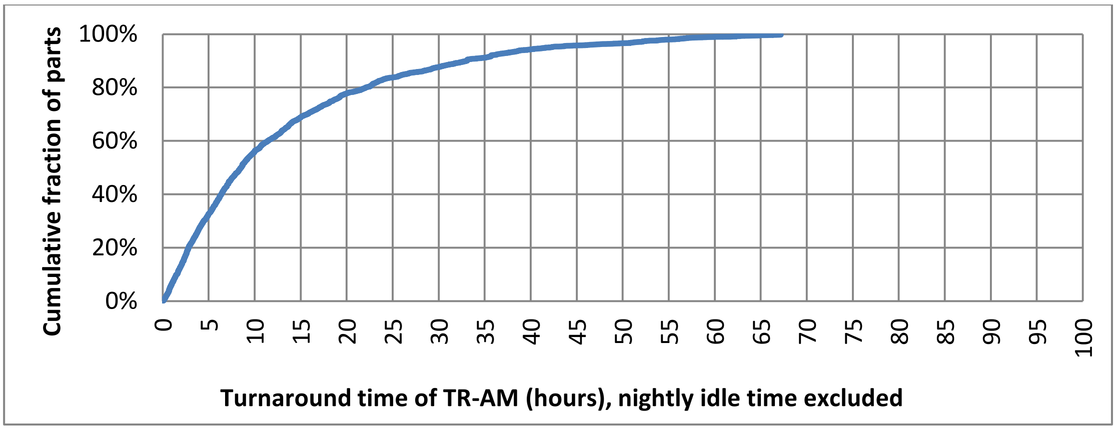


Figure 4.6: Distribution of the turnaround time of TR-AM, nightly idle time excluded.

If we compare the smoothness of the graph of TR-AM with the graphs of DM-TR, we see that the process of TR-AM is more stable. Except for the nightly idle time, Figure 4.5 shows a smooth line, while Figure 4.3 and Figure 4.4 show many peaks. These peaks are a strong indicator of disturbances in the process, such as packages being lost or a lack of FIFO. However, the TR-AM data is still skewed to the right, given the positive skewness (see Table 4.3) and the fact that 61.1% of the parts have a turnaround time below the mean. This indicates that the TR-AM process also faces difficulties in delivering a stable process, although less than the DM-TR process.

AM-GR

The final step we consider is the turnaround time between AM and GR (AM-GR). This is the last step in the inbound logistics process. As mentioned in Section 4.1.2, we do not consider the turnaround time between AM-GR of parts that went through quarantine for performance measurement of the inbound logistics process. Therefore we remove the quarantine parts from the data set. We also remove the outliers from the data. From the 27,109 observations, we identified 1.1% as outlier with the adjusted boxplot method. This results in a filtered data set of 26,812 items. Table 4.4 shows the summary statistics of the filtered data. Figure 4.7 shows the distribution of the turnaround times over the parts in the filtered data set. As was the case with the TR-AM data, the nightly idle time also causes kinks in the graph for AM-GR. The turnaround time of 60.2% of the parts is lower than the mean and, similar to the DM-TR and TR-AM data, this data set is also skewed to the right. This indicates that this process also faces difficulties to deliver a stable average turnaround time.

N	26,812
Mean turnaround time (hours)	69.64
Standard deviation	62.05
Skewness	1.85
Q1	24.17
Median	51.91
Q3	97.23
Q3-Q1	73.06

Table 4.4: Summary statistics of AM-GR.

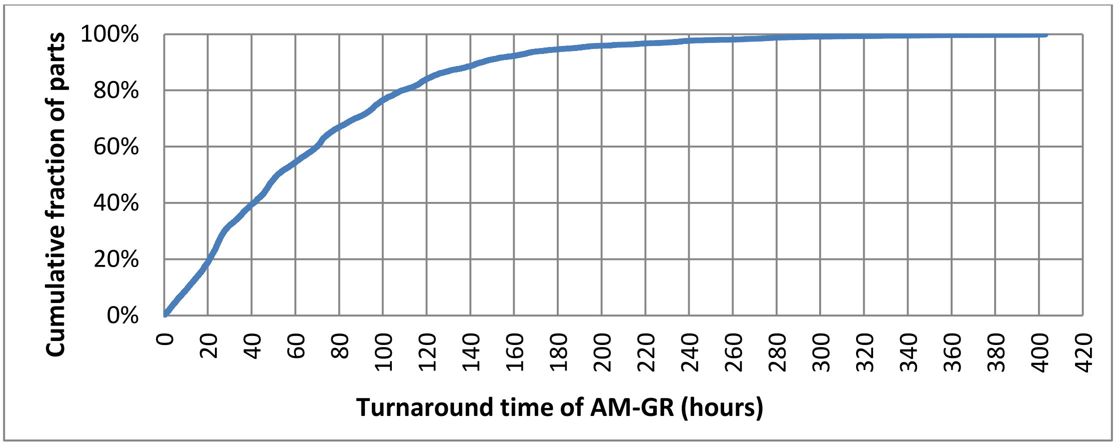


Figure 4.7: Turnaround times of AM-GR (N = 26,812) after removing outliers.

4.1.5 Stability of the turnaround time of in the inbound logistics process

ES measures the performance of its processes with the P95 measure, which is a Lean Six Sigma tool (see Section 3.2.4). At the logistics department of ES, the main target for the performance of the inbound logistics process is that 95% of the parts should be inspected within 48 hours after their arrival at ES. This means 95% of the parts should have a turnaround time from TR to GR of at most 48 hours. Currently, this only applies to 45.8% of the parts, so this goal is not reached.

As part of the Lean Six Sigma philosophy, ES strives to achieve a stable turnaround time in its processes for all parts (see Section 3.2.4). However, a stable turnaround time is not realised in any of the three sub-processes (DM-TR, TR-AM, and AM-GR) discussed in this section. Based on interviews with several stakeholders within the logistics department of ES, we concluded that the main cause for this instability in the inbound logistics process is *cherry picking*. Cherry picking refers to employees deliberately selecting easier parts or packages to handle and avoiding the harder ones, rather than sticking to FIFO. This leads to longer turnaround times for the parts and packages that are often avoided. For TR-AM, we found a second important cause of the broad span in the turnaround times, namely the peak in the input that occurs during parts of the week. We discuss this in Section 4.2. The identification of the reasons for the instability of DM- TR lies beyond the scope of this research, because this part of the supply chain is not part of the inbound logistics process and cannot be changed by ES.

While the P95 measure is the most commonly used measure at KLM, we have chosen to measure the turnaround time in this section by the mean value over all parts. The P95 value is measured in the outer region of the span of turnaround times. Due to the high number of possible anomalies in our data, our representation of the span of turnaround times is not reliable enough to measure the P95 value. Hence, the mean is a more robust measure than P95, because its value is based on the turnaround times of all parts rather than only the parts with a high turnaround time.

4.2 Arrival Process

In this section, we discuss the arrival process of parts to the logistics department of ES. All packages that arrive at the logistics department of ES are scanned. This scan is stored as the TR confirmation. As we have seen in Section 4.1.2, we can only connect a TR to a GR for 26.2% of the parts. The main reason for this low number of usable TRs is the incompatibility between the way data is stored in Tracking and SAP (see Section 4.1.2). However, the Tracking data is very reliable for determining the number of *packages* delivered to ES, because approximately 99% of all packages delivered by Sodexo are scanned and registered in Tracking (Martijn Wennekes, 2012). So despite that the majority of these data entries cannot be matched to SAP data on the part level, it gives a complete overview of the amount of packages that are delivered to ES.

Figure 4.8 displays the average fraction of packages delivered to ES at every day of the week, and during every hour of the day. Each bar is a stacked chart. A block in one of the bars represents the relative volume (compared to the average weekly total volume) that is delivered on average in the specific hour of that day. During the night (between 0:00 and 7:00 AM), no deliveries are made. Figure 4.8 shows that most packages arrive at ES on Thursdays and Fridays. The lowest amount of packages is delivered during the weekend. During a day, most packages arrive between 12:00 and 17:00. Appendix I presents the data we use to create Figure 4.8.

The Tracking data shows us the dispersion over the week of the deliveries to ES, but it does not show the amount of packages that require incoming goods inspection. To calculate the amount of packages that went to DGO (and Incoming Goods) after arriving at ES, we use the AM data. SAP does not store data on packages. When a DGO employee places an AM confirmation on a package, SAP stores this as an AM confirmation on all the parts inside the package, but it does not store it for the package itself. So we cannot retrieve the amount of packages handled during any period of time directly from SAP. However, all the parts that were in a package have the exact same time and date of the AM. This AM is also unique, because a DGO employee can place just one AM at a time. So we calculate the number of packages by counting the number of unique date/time occurrences of AM. The 26,812 AMs in our data set contain 11,257 unique AMs. This means that on average one package contains 2.38 parts for incoming goods inspection.

Figure 4.9 shows the average number of packages that are handled at DGO per day of the week. If we compare this figure to the distribution of the arrival of packages in Figure 4.8, we notice a clear difference in the weekend. The amount of packages arriving at ES during a weekend day is less than half of the amount arriving during a weekday, but the amount of packages handled at DGO on a weekend day is among the highest amounts of the week. Since the DGO department does not have enough capacity to handle all packages arriving at Thursdays and Fridays on the same day, the DGO employee handles these parts during the weekend. Due to this, the turnaround time of TR-AM increases and the span becomes wider.

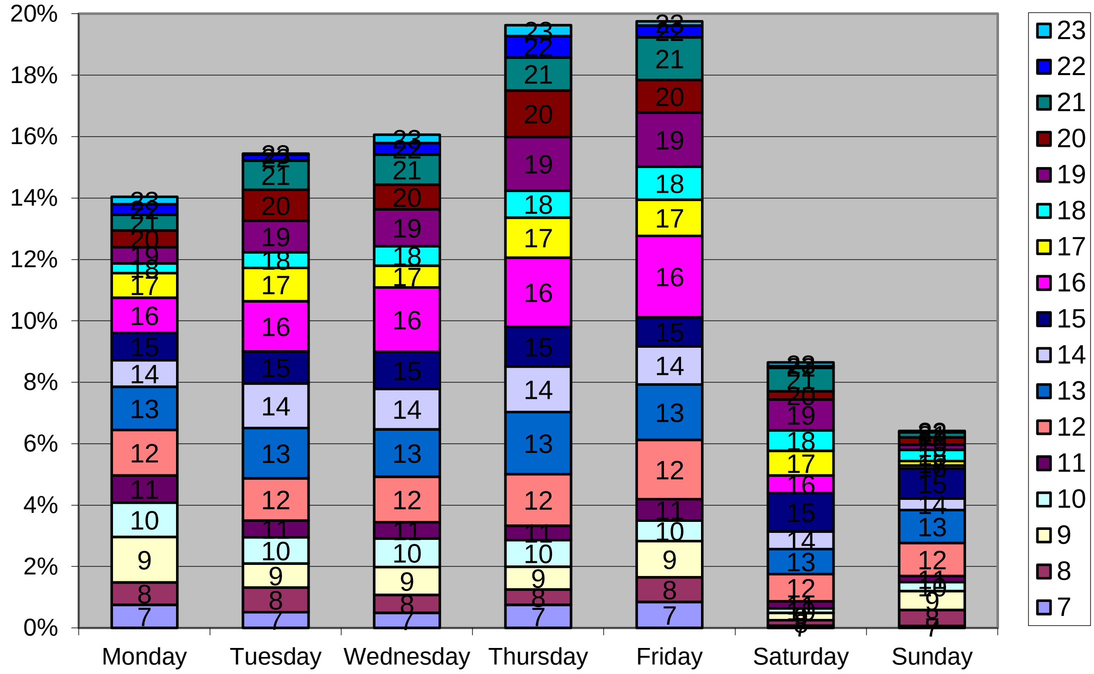


Figure 4.8: Average fraction of deliveries made to ES during every hour of every day.

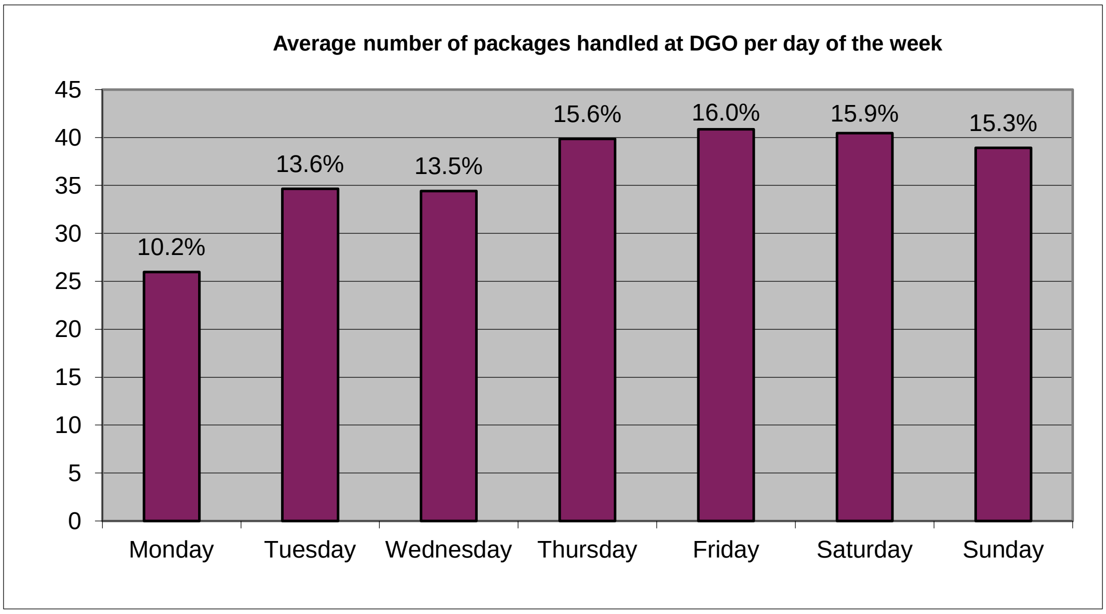


Figure 4.9: Number and fraction of packages handled at DGO per day of the week.

Table 4.5 shows the values for the number of deliveries per day, based on historical data from Tracking and SAP. Appendix I gives a more detailed description of the arrivals by showing the distribution of the number of parts in every package.

Number of deliveries	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Average	7.15	8.25	8.08	8.96	9.08	4.78	3.6
Standard deviation	2.22	2.20	1.77	1.97	2.02	1.50	1.58

Table 4.5: Number of deliveries to ES by Sodexo per day.

4.3 Handling times

In this section, we discuss the *handling time* of DGO employees and IIGs for each of their tasks. This includes the time they spend on handling packages at DGO, inspecting parts at Incoming Goods, solving PIGs, and searching for emergency requests. Section 4.3.1 elaborates on the time an employee needs to come to an AM or GR confirmation. In Section 4.3.2, we describe the time is spent on solving PIGs. Section 4.3.3 discusses the time IIGs spend on searching for emergency requests.

4.3.1 Production rates

To determine the number of parts or packages an employee handles, we calculate the *production rate* of both IIGs and DGO employees. We define the production rate as the number of parts or packages an average employee handles per amount of working time. We exclude idle time due to breaks, the transfer between two shifts, and cleaning at the end of each shift. We do not exclude other idle time during a shift, such as toilet breaks, because we have insufficient data to quantify this idle time.

We cannot retrieve production rates directly from an information system, because there is no information system that registers the time and date an inspection is started and finished. An inspection is finished when a confirmation is placed, but the start of the inspection is not stored. We cannot use the time and date of the previous confirmation as the starting point, because several IIGs inspect multiple parts at the same time before confirming these in SAP. So to calculate the production rates, we determine the total number of confirmations between November 2010 and October 2011, and the total amount of time spent by the employees on placing these confirmations. Then we calculate the production rates by dividing these two values. In the remainder of this section, we elaborate on how we determine these values.

Based on the AM and GR data from SAP that we gained in this chapter (see Section 4.1.2), we determine the total amount of AMs and GRs that were placed between November 2010 and October 2011.

To calculate the amount of time employees worked, we use data from *MPS* (Maintenance Planning Shift). MPS is the information system that ES uses to keep track of the presence and absence of every employee. We calculate the *effective working time* by subtracting the idle time from the hours that the employees were present. Idle time includes breaks, cleaning time, and the time needed to transfer between the day and night shift. During a shift, which takes 8.5 hours, an employee has a total of 1 hour of breaks. We estimate the total time required for cleaning and transferring between two shifts at 20 minutes based on interviews with DGO employees and IIGs. Due to this idle time at the end of each shift, new inspections are not started after 35 minutes before the end of a shift. The value we gain after taking into account these factors is the effective working time. To calculate the production rates for placing a GR, we also subtract the time IIGs spend on the two major disturbances in the process: solving PIGs (see Section 2.4.4) and searching for emergency requests (see Section 2.4.3). In Section 4.3.2 and Section 4.3.3, we elaborate on the handling time of PIGs and emergency requests respectively.

By dividing the total amount of working hours spent on GRs and AMs by the number of GRs and AMs, we gained the production rates of IIGs and DGO employees respectively. We find that the average inspection time leading to one GR confirmation is 29 minutes. Handling a package at DGO takes on average 14 minutes. Due to the rather rough method of determining the average turnaround time, we cannot determine the volatility in the handling time based on the data. Therefore we interview all IIGs and DGO employees to estimate the volatility of the handling time for placing a GR and AM. From these interviews, we conclude that the distribution of both handling times is skewed to the right and has a quite low variability.

4.3.2 PIGs

PIGs (Problem Incoming Goods) are an important disturbance in the inbound logistics process, because solving PIGs decreases the amount of parts an IIG can inspect; the time an IIG spends on solving the PIG is at the expense of inspecting regular parts. If an IIG discovers an issue during the inspection of a part, he creates a PIG (see Section 2.4.4) in the PIG database. This takes 10 minutes per PIG. The PIG database stores information about the PIG, such as the PO and item number, the issue, and when it is solved. The PIG database shows that the number of PIGs entered and solved between November 2010 and October 2011 is 1,783. This also includes parts that ended up more than once in the PIG database. Table 4.6 shows the distribution of the frequency by which parts went into the quarantine.

# Times PIG	Frequency	#PIG entries
1	1,489	1,489
2	117	234
3	14	42
4	2	8
5	2	10
Total		**1,783**

Table 4.6: Number of PIGs.

There is no data available in information systems, such as SAP or the PIG database, on the solving time of PIGs. Due to time limitations and the high variability of the time for solving PIGs, we do not measure the PIG solving time. Instead, we interview the IIGs who are responsible for solving PIGs to estimate the average value and the variability of the handling time of PIGs. We take the average value of their individual estimates to calculate values. Based on the interviews, we conclude that the average inspection time is 42 minutes. The distribution of the PIG handling time is skewed to the right and has a high variability. The minimum time to solve a PIG is 10 minutes, while it can take up to 80 minutes to solve a PIG. In some exceptional cases, it can even take over 2 hours. The most common time required for solving a PIG is 37 minutes. Solving PIGs takes 9.2% of the total effective working time. Table 4.7 shows a summary of the data on solving PIGs.

Time to create PIG (minutes)	10
Minimum solve time (minutes)	10
Maximum solve time (minutes)	80
Most likely solve time (minutes)	37
Mean solve time (minutes)	42
#PIGs per year	1,783
% of effective work time	9.2%

Table 4.7: Summary of PIG solving data.

4.3.3 Emergency requests

Searching for emergency requests is a disturbance of the inbound logistics process. The number of emergency requests depends on the current shift. Emergency requests are triggered by employees of other departments in ES, such as Planning. Employees of these departments mostly work during the day shift on a weekday. The number of emergency requests during a day shift on a weekday is on average one above the amount of days work in the Incoming Goods buffer. Given that the average amount of work in the Incoming Goods buffer is four days, the number of emergency requests per year during a weekday is (4+1) * 260 = 1300. Emergency requests also occur during the dayshift in a weekend with an average of 0.5 per day. Emergency requests during a night shift barely occur; this number is negligible. Table 4.8 summarizes these results.

# Emergency Requests	Value
Per weekday during day shift	#days work in buffer
Per weekend during day shift	0.5
Per night shift	0
Average per year	1,325
% of effective work time	3.8%

Table 4.8: Number of emergency requests.

As with the solving time of PIGs discussed in Section 4.3.2, there is also no data available in information systems to determine the handling time of emergency requests. Therefore, we use the same method, interviewing IIGs, to determine the average value and variability of the time to search for an emergency request. Table 4.9 shows the results of these interviews.

Search Time	Time (minutes)
Minimum	5
Maximum	45
Most likely	22.5
Average	24

Table 4.9: Search times for emergency requests.

4.4 Comparison of IIG rosters

In Section 2.5, we introduced the three rosters for scheduling IIGs; the regular 7x2 roster and two new rosters, 5x2 and 7x1. The main reason for experimenting with these new schedules is to save costs by employing less IIGs during the weekend. However, with the introduction of the new schedules, there are also changes in the way of working: measures have been taken by the management of the logistics department of ES to encourage working according to the FIFO principle. Also the number of employees decreased from 17 to 12. This is a decline of almost 30% in the amount of IIGs. The management of the logistics department of ES believes that despite this considerable decline, it can still achieve the at least the same average and P95 turnaround time for the inbound logistics process. In this section, we analyze the consequence of this decline based on the available capacity. We discuss the consequence on the turnaround time in Chapter 6, where we present the results of the simulation model.

Table 4.10 shows the number of employees that were available per shift during each of the schedules. Since the number of employees varied during the regular schedule, we indicate the number of employees as a value between 5 and 6 per shift. This is also the average number of employees per shift. The average number of employees per shift during the new schedules is 4.3 (6 employees per shift * 10 shifts / 14 shifts per week).

		Number of IIGs per shift per day						
Roster type	**Shift**	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
7x2 (regular)	Day	5-6	5-6	5-6	5-6	5-6	5-6	5-6
	Night	5-6	5-6	5-6	5-6	5-6	5-6	5-6
7x1 (new)	Day	4	6	6	6	4	2	2
	Night	6	6	6	6	6	0	0
5x2 (new)	Day	6	6	6	6	6	0	0
	Night	6	6	6	6	6	0	0

Table 4.10: The number of IIGs per shift per day per roster type.

Table 4.10 does not take into account the absence of employees, due to for example sickness and days off. It shows the availability of employees in case they would be present on all 260 workdays a year. Using the MPS data, we find that an employee is absent on 63 of the 260 workdays. This means that the presence rate is 75.8%. If we multiply the average number of employees per shift with the presence rate, we find that on average 4.55 IIGs were present during the regular schedule and 3.26 during the new schedules.

So we see that during the regular schedule, the IIG capacity was considerably higher than during the new schedules. However, management still believes that the same performance can be achieved with the new schedules, because there was an overcapacity of IIGs during the regular schedule. This overcapacity was dealt with by multitasking of the IIGs; in case of sufficient IIG capacity during a shift, IIGs were employed at other logistical departments, such as DGO and the warehouse. On average 1.28 IIGs per shift worked at other tasks at the logistics department of ES, while 3.27 IIGs performed incoming goods inspections.

So the actual number of IIGs performing incoming goods inspection, 3.27, is about equal to the number of IIGs in the new schedules, 3.26. This clarifies how the same performance can be achieved with the new schedules, while there is a decline of 30% in the number of IIGs.

Table 4.11 summarizes the results of this section.

Roster type	**#IIGs per shift**	**#IIGs present per shift**	**#as IIG**
7x2 (regular)	6	4,55	3,27
7x1 (new)	4,3	3,26	3,26
5x2 (new)	4,3	3,26	3,26

Table 4.11: Number of IIGs per shift.

4.5 Conclusion

In this chapter, we analyzed data to determine the performance of the inbound logistics process and gather data for our simulation model (see Chapter 5). To determine the turnaround time of the inbound logistics process, which is the key performance indicator, we split the process into four measurement points. When a part leaves a measurement point, the time and date of the departure from this measurement point is registered in an information system. Based on the time difference between two measurement points, we determined the turnaround time for all parts between each of these four measurement points.

Figure 4.10 visualizes these measurement points and shows the mean and standard deviation of the turnaround time between these measurement points.

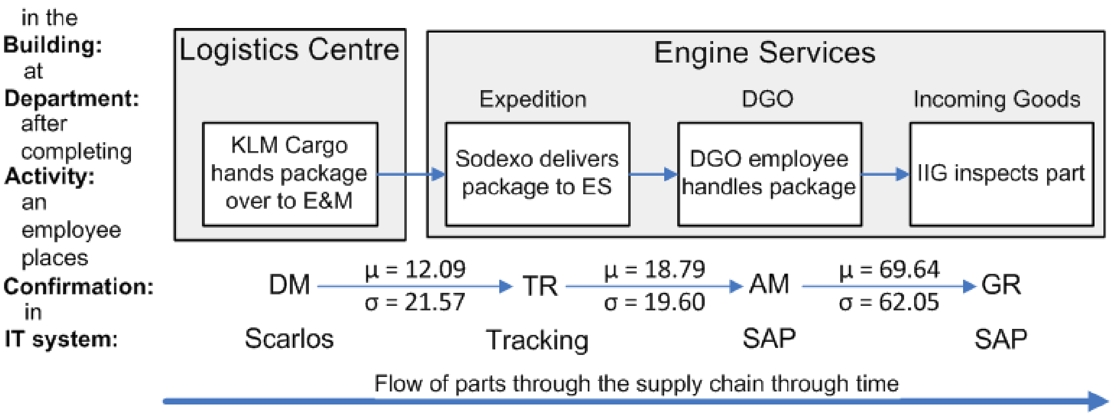


Figure 4.10: Overview of turnaround times (hours) between the measurement points.

There are two important conclusions we can draw from the analysis on the turnaround time of the inbound logistics process. First, the inbound logistics process underperforms, because the average value and the P95 value of the turnaround times are higher than the goals set by the management of ES. Second, the inbound logistics process faces difficulties in delivering a stable turnaround time for all parts between all four measurement points. This conclusion is supported by the high coefficient of variation and skewness, as we see in Table 4.12. Table 4.12 summarizes the most important results of turnaround time measurement.

	DM-TR	TR-AM	AM-GR	Total
Mean turnaround time (hours)	12.09	18.79	69.64	**100.53**
Standard deviation	21.57	19.60	62.05	
Coefficient of variation	1.78	1.04	0.89	
Skewness	2.82	1.58	1.85	
Q1	1.94	3.83	24.17	
Median	3.03	13.25	51.91	**68.19**
Q3	9.17	25.70	97.23	

Table 4.12: Summary statistics of all three sub-processes.

Analysis of the arrival process showed that most packages arrive on Thursday and Friday, while during the weekend the fewest number of packages arrive. DGO handles most packages on the day they arrive, but a part of the peak arrivals from Thursday and Friday is handled during the weekend.

In the analysis of the handling time for the various tasks of IIGs and DGO employees, we encountered that there is no data available on the time an employee needs to perform a task. Therefore, we estimated the handling times by comparing data from SAP and MPS, and by interviewing the IIGs and DGO employees.

With the introduction of a new schedule for IIGs, the management of ES wants to save costs. In the new schedules, the number of IIGs has decreased by 30%. The remaining capacity could still be sufficient to handle all parts, because there was an overcapacity of IIGs during the regular schedule.

5. Simulation Model

In this chapter, we describe the steps taken to design the simulation model of the inbound logistics process at ES. We will use this simulation model to analyze alternative configurations of the current inbound logistics process. Section 5.1 gives an overview of the model and we explain how we modelled the inbound logistics process. Section 5.2 shows how we implemented the simulation model into simulation software. In Section 5.3, we discuss the experimental design. Section 5.4 presents the simulation setup for our experiments. Section 5.5 describes how we ensure the validity of the simulation model. Section 5.6 concludes this chapter.

5.1 Conceptual model design

In this section, we discuss the design of the simulation model of the inbound logistics process. Section 5.1.1 briefly discusses how parts and packages flow through the simulation model. Section 5.1.2 elaborates on the assumptions we make in modeling the inbound logistics process. Section 5.1.3 explains how we handle the variability of the inbound logistics process in our simulation model.

5.1.1 Flow of parts through the model

As mentioned earlier, we create a simulation model to analyze the inbound logistics process. Figure 5.1 shows the flow of packages and parts in our simulation model.

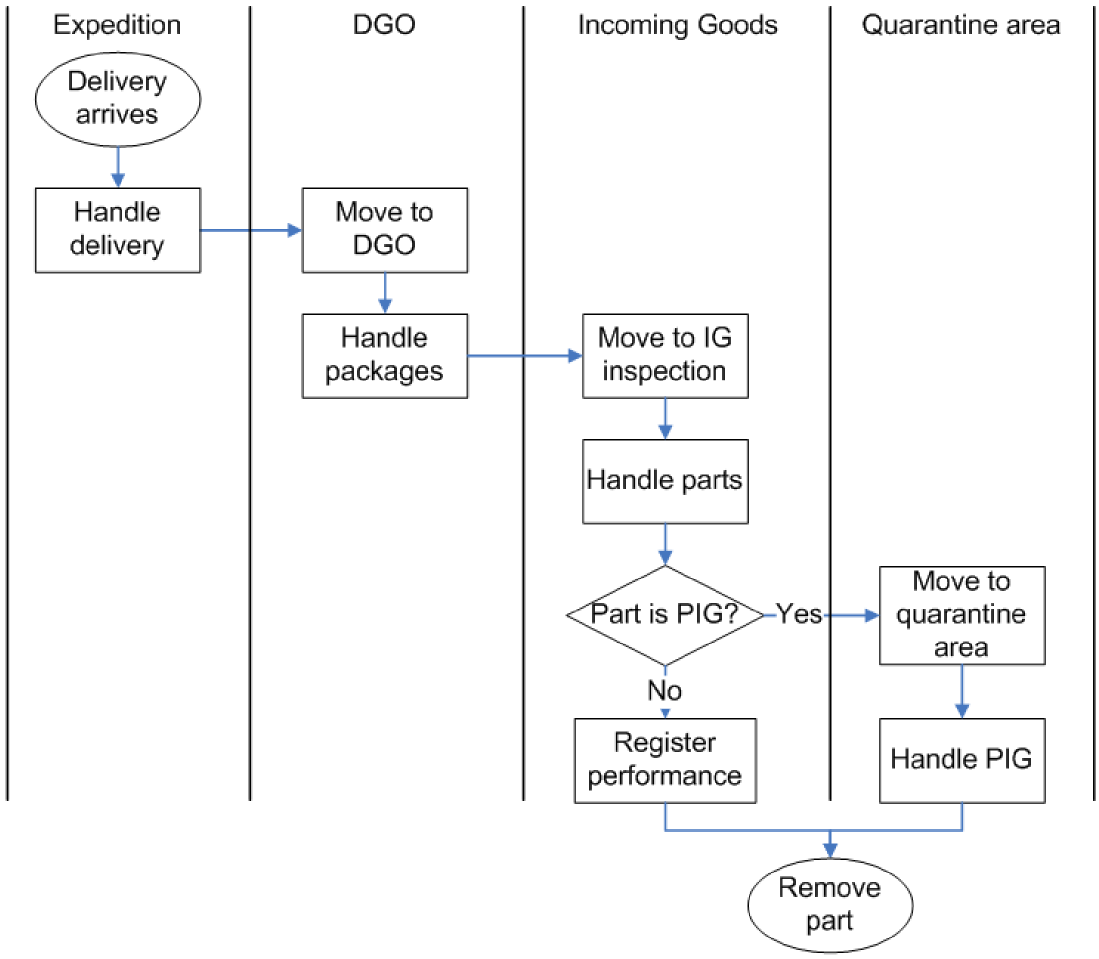


Figure 5.1: The flow of parts through the inbound logistics process in the simulation model.

Figure 5.1 can be seen as a concise representation of Figure 2.9 and the process description of Chapter 2, because we bundled the consecutive steps taken on a package at for instance DGO as one activity: 'handling a package'. Also, we do not specify the destination of a part that leaves the process, because this is not relevant for the simulation model. Furthermore, we do not model all package and part flows in accordance with the process description. Since the purpose of the simulation model is to measure the performance of the inbound logistics, we may change our representation of the actual process as long as it does not jeopardize accurate performance measurement. This is common practice in a simulation study. In Section 5.1.2, we justify all cases in which our model is not in accordance with the situation as given in the process description of Chapter 2.

Figure 5.1 shows the three main logistical departments that parts go through and the quarantine area. Each of these departments has its own buffer. The output is placed in the buffer of the next department, where it remains until it is handled by an employee. After storing the statistics of the output of the Incoming Goods department and the quarantine area, the output is removed from simulation model. Packages and parts remain most of their time inside a buffer, either at Expedition, DGO, Incoming Goods, or the Quarantine area, and will only be moved from here when an employee retrieves it from this buffer. Due to this lack of continuous flow, we interpret the three departments of the inbound logistics process as a line of three consecutive queuing systems, each with an arrival distribution, processing time, servers (the employees), and a buffer. While various queuing systems of this type can be analyzed numerically, we cannot do this for the inbound logistics process due to the complex characteristics that the system possesses, such as random occurrence of emergency requests or a DGO employee being the 'server' in two departments. Section 5.1.3 explains all causes of complexity in the inbound logistics process and explains how we model these in the simulation model.

5.1.2 Assumptions

In this section, we discuss the assumptions that we make for our simulation model to represent aspects of the inbound logistics process that we cannot model exactly as in the actual situation. We first present the assumptions and we elaborate on these assumptions in the remainder of this section:

- The scope of the simulation model is the inbound logistics process
- FIFO handling of parts and packages
- Each employee handles at most one part at a time
- Shifts do not overlap
- The buffer of the Expedition department has priority over the DGO buffer
- Unlimited buffer size at all departments
- 1 IIG per day shift per weekday for solving PIGs
- Parts go at most once into quarantine
- Inspection times of PIGs decrease after the PIG is solved
- No overtime
- No different priorities between parts at the Incoming Goods department
- Faster handling of emergency requests in the new schedules

The scope of the simulation model is the inbound logistics process

In the data analysis, we discussed the performance of the inbound logistics process and of the delivery of packages from the LC to ES. The delivery from the LC to ES is not part of the responsibilities of ES, so this process cannot be directly influenced by the management of the logistics department of ES. Therefore, we do not consider these deliveries. We only consider the activities that take place in the inbound logistics area at ES. This means the delivery of packages at ES is the starting point of our model, so the delivery from the LC to ES lies outside our scope.

FIFO handling of parts and packages

In our simulation model, we assume parts and packages are processed by FIFO order in both the regular 7x2 schedule and the new 5x2 and 7x1 schedules (see Section 2.5), despite that FIFO is not strictly followed, especially not during the regular schedule. We assume FIFO handling of parts for two reasons. First, we cannot model the dynamics that cause the process to deviate from the FIFO principle, because we have insufficient data. Second, it is the way the inbound logistics process is designed and it is the goal of ES to establish a perfect FIFO process. So by assuming FIFO handling in our simulation model, we give a representation of the actual process by simulating the desired situation.

Each employee handles at most one part at a time

In the simulation model, each employee handles at most one part at a time. IIGs sometimes prefer to inspect multiple parts from the same package simultaneously. Since simultaneous inspections do not influence the average inspection time, but are rather for convenience of the IIG, we assume that one at a time inspections are a good representation of the actual situation.

Shifts do not overlap

In the actual situation, the day shift runs from 7:10 to 15:40 and the night shift runs from 15:30 to 0:00. The 10 minute overlap is meant for the transfer between the two shifts. In this overlap, there are no inspections performed by IIGs from both shifts, because the last part of every shift is idle time for cleaning and transferring between shifts (see Section 4.3.1). This means inspections of both shifts do not interfere, so for modelling convenience we assume that the shifts do not overlap by letting the day shift run from 7:00 to 15:30.

The buffer of the Expedition department has priority over the DGO buffer

A DGO employee works in both DGO and the Expedition department. The policy at ES is that the buffer at Expedition should be handled immediately. Despite that this policy is not strictly followed by DGO employees, we do implement the policy in our simulation model; the handling of packages that arrive at ES has higher priority over handling packages at DGO.

Unlimited buffer size

The size of the buffers at the logistical departments Expedition, DGO, and Incoming Goods is limited. The buffer of the Expedition department is the smallest. However, since this buffer is emptied immediately, the size of this buffer is not an issue, so we assume unlimited capacity. The buffer at the DGO department seldom reaches its maximum capacity. In this case, a team manager temporarily assigns an extra employee to DGO. Since this occurs seldom and has no consequence for the storage of packages, we assume unlimited buffer size at DGO. The buffer of Incoming Goods has not reached its maximum capacity during the period of our data analysis. However, if the buffer at the Incoming Goods department reaches its maximum capacity, the same conditions apply as with the buffer of the DGO department. Therefore we also assume unlimited size for the buffer at the Incoming Goods department.

PIG solving capacity

Currently, there is usually one IIG per day shift on a weekday working on solving PIGs. However, this number sometimes differs due to for instance absence of IIGs specialized in solving PIGs or a team manager deciding the capacity is needed elsewhere. Since there is no clear definition of these decision rules, we do not model these. Therefore, we assume the number of IIGs working on solving PIGs is fixed to the average value: one IIG per day shift on a weekday.

Parts go at most once into quarantine

During the year, 1,783 PIGs have been registered in the PIG database. As shown in Table 4.6, a fraction of these entries in the database concerns the same part going into quarantine more than once. In our simulation model, we assume parts go at most once into quarantine. This is a valid assumption, because we do not measure the turnaround time of parts that go into quarantine. For performance measurement, it is only important to measure the amount of time IIGs spend on solving PIGs; it makes no difference if the IIG spends time on solving PIGs of two different parts or two PIGs of the same part. Therefore we set the probability for a part to become a PIG at 1,783 / 31,610 = 5.6%, so on average 1,783 PIGs need to be solved per year.

Inspection times of PIGs decrease after the PIG is solved

While an IIG solves a PIG, he also performs parts of the tasks that belong to a regular incoming goods inspection. To account for this, we must reduce the inspection time of a part after the PIG has been solved. Based on interviews with IIGs, we assume that the inspection time decreases with 20%.

No overtime

In our data analysis in Chapter 4, we excluded the work done in overtime and the time employees spent on the work in overtime. In our simulation model, we do not consider overtime either. Due to variability in the handling time, it may occur that an employee is still handling a part when a shift ends. In case a second shift follows on that day, we assume the inspection is continued by an employee of the next shift. In case no other shift follows, the employee finishes the inspection. This leads to a small amount of overtime, which we register in the simulation model.

No different priorities between parts at the Incoming Goods department

During the regular schedule, there were two separate buffers at the Incoming Goods department: one for repair parts and one for other parts. The reason for having two buffers was that repair parts always belong to a current project (see Section 2.4.3). Parts belonging to a current project should have priority over parts that go into the warehouse. However, other parts, such as new and second-hand parts, can also belong to a project. Therefore, it cannot be determined by the part category what part should have priority over another part. Therefore, there was barely any priority given to the repaired parts buffer.

In our simulation model, we assume that all parts are handled as if they have the same priority. We make this assumption for three reasons. First, during the new schedules, the management of ES decided to dispense the two categories (see Section 2.5.2). So for the two new schedules, having no priority is the most realistic representation. Second, as we mentioned, there was barely any priority difference given during the regular schedule. Third, we do not have data to confirm there is a different turnaround time for repair parts compared to other parts.

Faster handling of emergency requests during the new schedules

With the introduction of the new schedules, 5x2 and 7x1, the buffer of the Incoming Goods department was reorganized (see Section 2.5.2); parts are stored by date and time of their AM confirmation on movable racks. Due to these movable racks, the buffer has become more clearly organized than during the regular schedule, 7x2. This leads to a decrease in the time an IIG needs to search for an emergency request. Based on interviews with IIGs, we assume that the search time for an emergency request has decreased with 25%.

5.1.3 Dealing with variability

In this section, we elaborate on the way we handle the variability in the inbound logistics process in our simulation model. The variability of several sub-processes of the inbound logistics process, such as the arrival of parts, is the main reason why we use simulation as a tool to analyze the performance of the inbound logistics process. We will discuss the following topics:

- Arrival process
- Handling time at Expedition
- Inspection time at DGO and Incoming Goods
- Handling time of PIGs
- Search time for emergency requests
- Number of emergency requests
- Number of full time IIGs present
- Duration of breaks

Arrival process

To model the arrival process in the simulation model, we use four probability distributions that each describe an element of the arrival process. These elements are: the number of deliveries per day of the week, the time during the day that a delivery arrives, the number of packages per delivery, and the number of parts per package. Although there is a small correlation between these factors, we assume that their distributions are not correlated, because we do not have sufficient data to correctly model these correlations. Also, since the correlation is rather small, we suspect that a slightly more accurate representation of the actual situation does not outweigh the increase of the complexity of our model.

To model the number of deliveries per day of the week, we use a *rounded* Normal distribution; a Normal distribution from which the values drawn are rounded to integers with a minimum of 0. Rounding all values below 0 to 0 does not jeopardize the validity of our representation of the actual process, because with our parameters (see Table 4.5) the probability of incorrect rounding to 0 (values < -0.5) is at most 0.4%. The mean and standard deviation differ per day of the week as we have seen in Section 4.2. We use the means μ and standard deviations σ from Table 4.5 as the parameters for the rounded Normal distribution. We calculate the fit of the data to this rounded Normal distribution with the Chi-Square Test with α = 0.05. In Appendix J, we show the calculation of the value of the test statistic for Mondays as an example. Since our test statistic $\chi^2 \approx 3.468$ is smaller than the critical value $\chi^2_{6,0.95} = 12.59$, we do not reject the assumption that the data follows a rounded Normal distribution. Chi-square tests for the other days of the week show the same result. Figure 5.2 visualizes the fit of the number of deliveries on Mondays with the rounded Normal distribution in a histogram.

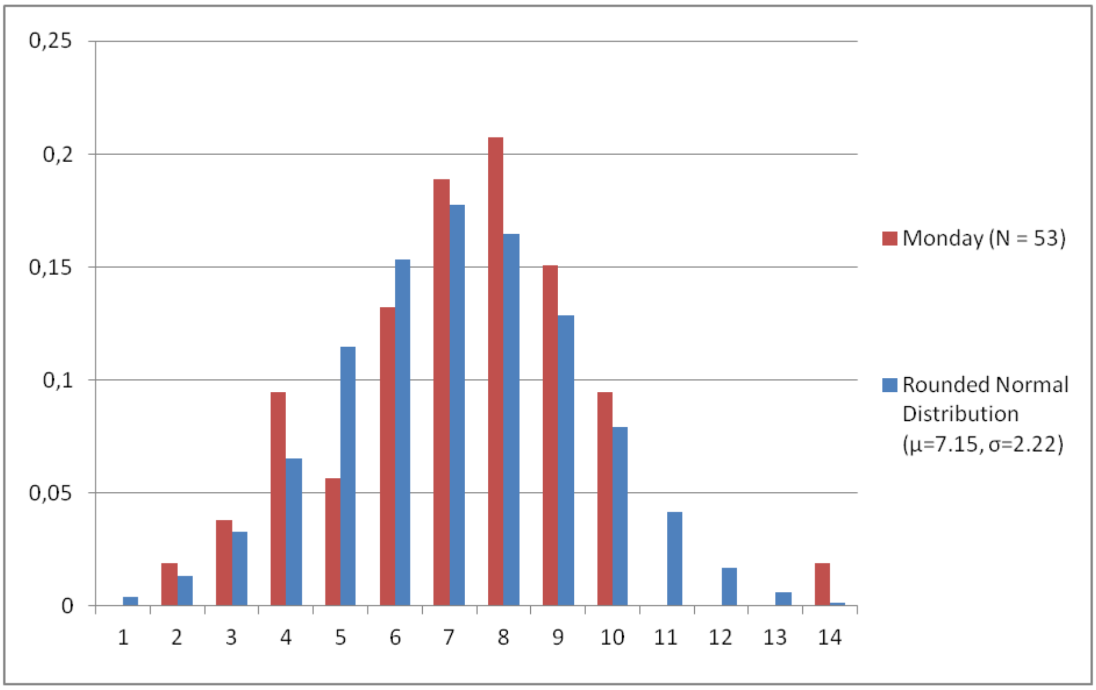


Figure 5.2: Histogram of the fraction of the number of arrivals on Monday based on the data and the normal distribution fitted to the data.

We model the number of packages in every delivery by a rounded Normal distribution with μ = 5.1 and σ = 0.91. These values are based on data from SAP and Tracking. We model the time during the day a delivery arrives by an empirical distribution based on Tracking data. We choose this distribution, because there is no theoretical distribution that fit to the data. We draw the number of parts per package from an empirical distribution as well. Appendix I presents both these empirical distributions.

Handling time at Expedition

Every package that arrives at ES is handled by the DGO employee. This takes on average 4 minutes per package. He selects out the packages with parts that require inspection and moves these to DGO. This applies to 2/3rd of all the packages that arrive at ES. He moves the other packages, 1/3rd of all packages, to the right place for internal transport. We have insufficient data to model the arrival process of the one-third of the packages with parts that do not require inspection. Therefore, instead of modeling the arrival of such packages, we use another method to account for the time the DGO employee spends on handling these packages. We increase the handling time per package in our simulation model with 50%, from 4 to 6 minutes, since for every 2 packages that arrive at ES and go to DGO, on average 1 other package arrives. This ensures the total amount of time a DGO employee spends on handling packages at Expedition is equal to the actual situation.

We model the handling time of a package at the Expedition department with a Normal distribution, with a mean $\mu = 6$ minutes (the average handling time), and the standard deviation $\sigma = 1$ minute. The handling time slightly differs per package, so we assume low variability in the handling time. A process with low variability has a coefficient of variation smaller than 0.75 (Hopp & Spearman, 2001). Since the coefficient of variation is $\mu/\sigma = 1/6 \approx 0.17 < 0.75$, our parameters are a valid choice to model the low variability.

Handling times at DGO and Incoming Goods

The data of the handling times at DGO and Incoming Goods is insufficient to be able to calculate the variance and probability distribution of the handling times (see Section 4.3.1). Based on interviews with the IIGs, we found that the distributions of the package and part handling times at DGO and Incoming Goods respectively are skewed to the right with low variability. Low variability means the coefficient of variation is at most 0.75. Since the Gamma distribution with $\alpha \geq 2$ satisfies both conditions (right skewness and low variability), we use a Gamma distribution with $\alpha = 2$ to model the handling times. Since both handling times have a minimum greater than zero, we need to add a location parameter γ for the minimum handling time to the probability distribution of the handling times. So the distribution of the handling times at packages at DGO and parts at Incoming Goods is given by: γ + Gamma(α,β). Based on the interviews with DGO employees and IIGs, we determine that the minimum time to handle a package at DGO is 8 minutes and to perform an inspection at IIG at 19 minutes. Since the average value μ of the Gamma(α,β) distribution is calculated by $\alpha * \beta$, the value of $\beta = \mu / \alpha$. Table 5.1 presents the values of the parameters of the distribution of the inspection times.

Times (minutes)	DGO	IIG
Average handling time ($\mu = \alpha*\beta + \gamma$)	14	29
Minimum handling time (γ)	8	15
α (Gamma(α,β) parameter)	2	2
β (Gamma(α,β) parameter)	3	7

Table 5.1: Parameters to describe the distribution of handling times.

Handling time of PIGs

To determine the distribution of the PIG solving time, we use the *triangular approach*. Law & Kelton (2000) mention that in case no system data is available, the triangular approach can be followed. In this approach, experts are asked for an estimate of the minimum (a), maximum (b), and most likely (c) time to perform a task. The values a, b, and c are parameters of the Triangular distribution. We use this triangular distribution to describe the probability distribution of the PIG solving time. A disadvantage of the Triangular distribution is that it assumes a strict minimum and maximum, while this is often not the case. However, a minimum does apply for the time to solve PIGs. The minimum time is the time required to register a solved PIG in the PIG database.

We estimate the values of the parameters a, b, and c of the triangular distribution in Section 4.3.2 by interviewing the IIGs responsible for solving PIGs. Solving a PIG takes at least 10 minutes. The maximum is 80 minutes and the most likely value is 37 minutes. Figure 5.3 shows the probability distribution of the PIG solving time.

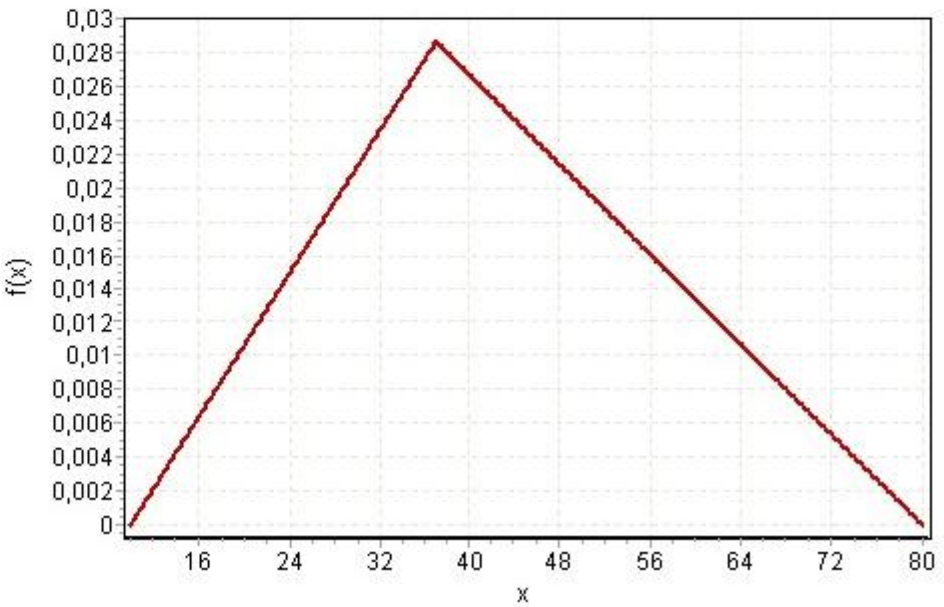


Figure 5.3: Probability distribution of the PIG solving time (in minutes).

Search time for emergency requests

To determine the distribution of the search time for an emergency request, we also use the triangular approach. The same condition apply as with the handling time of PIGs: no system data is available and due to time limitations we cannot measure the time to search for emergency requests. In Section 4.3.3, we found that the parameters of the Triangular distribution are as follows: the minimum search time is 5 minutes, the maximum is 45 minutes, and the most likely search time is 22.5 minutes.

Number of emergency requests

In Section 4.3.3, we determined the average number of emergency requests. This number differs per shift. During a day shift on a weekday, this number is on average equal to the number of days of WIP in the buffer of the Incoming Goods department. The variability in the number of emergency is low to moderate, so we assume that the coefficient of variation should be at most equal to one. To model the variability in the number of emergency requests, we draw the number of emergency requests on a weekday from a Normal distribution with the mean μ being the number of days of WIP and the standard deviation σ = 1 (based on interviews with the team managers). The average number of emergency requests during a day shift in the weekend is 0.5. We have no data on the variability of the number of emergency requests during a day shift in the weekend, so we assume the probability of 0 emergency requests is 0.5

and 1 emergency request is also 0.5. Since the number of emergency requests during a night shift is negligible, we assume no emergency requests occur during a night shift. The emergency requests randomly arrive during the day.

Number of full time IIGs present

The number of full time IIGs that are present depends on two factors: the roster type and the *absence rate*. The roster type is a decision variable (see Section 5.3.2), so we do not model this as a naturally changing variable. However, the active roster type does influence the way we determine the absence rate, which is a naturally changing variable.

Three rosters have recently been used for scheduling the IIGs (see Section 2.5 and Section 4.4). During the regular 7x2 schedule, there was an overcapacity of IIGs. On average there were 17 IIGs, while approximately 12 were working as IIG. Due to this overcapacity, the team managers had a great amount of flexibility to employ a constant amount of IIGs to maintain a stable buffer size. We model this flexibility by having either 3 or 4 employees per shift as IIG with an average of 3.27, as we established in Section 4.4.

During the other two schedules, 5x2 and 7x1, there is no overcapacity of employees, so there is no flexibility in the number of full time IIGs present per shift. It depends on how many employees are absent. The probability of a single employee being absent is 0.242, so we draw the number of present IIGs during a shift from a Binomial(n,p) distribution with n being the value from Table 4.10 (The number of IIGs per shift per day per roster type) for the current shift and p = 1 - 0.242 = 0.758.

Number of extra IIGs

A team manager may assign a member of the System Check Group to incoming goods inspection in case extra capacity is required. To prevent jeopardizing the continuity of the work of the System Check Group, a maximum of 1 applies. Whether a team manager decides to assign an extra IIG to incoming goods inspection depends on the number of days WIP in the buffer of Incoming Goods. By interviewing the three team managers, we determined the probability of assigning an extra IIG as shown in Table 5.2.

Number of days WIP in Incoming Goods buffer	0-4	5	6	7	8	≥ 9
Probability to assign an extra IIG	0	0.2	0.4	0.6	0.8	1

Table 5.2: Distribution of the probability that a team manager assigns an extra IIG.

Duration of breaks

During a workday, there are five breaks; two short breaks and one long break during the day shift and two long breaks during a night shift. A short break takes on average 15 minutes, the long breaks 30 minutes. The duration of these breaks is not fixed. To model the variability in these breaks, we use a Uniform(a,b) distribution with the lower (a) and upper (b) boundaries being 5 minutes below and above the average duration of a break.

5.2 Simulation model implementation

In this section, we briefly present the actual simulation model that we create based on the conceptual model design of Section 5.1. We design the simulation model with the simulation software package *Tecnomatix Plant Simulation*. Figure 5.4 displays the main window of the simulation model.

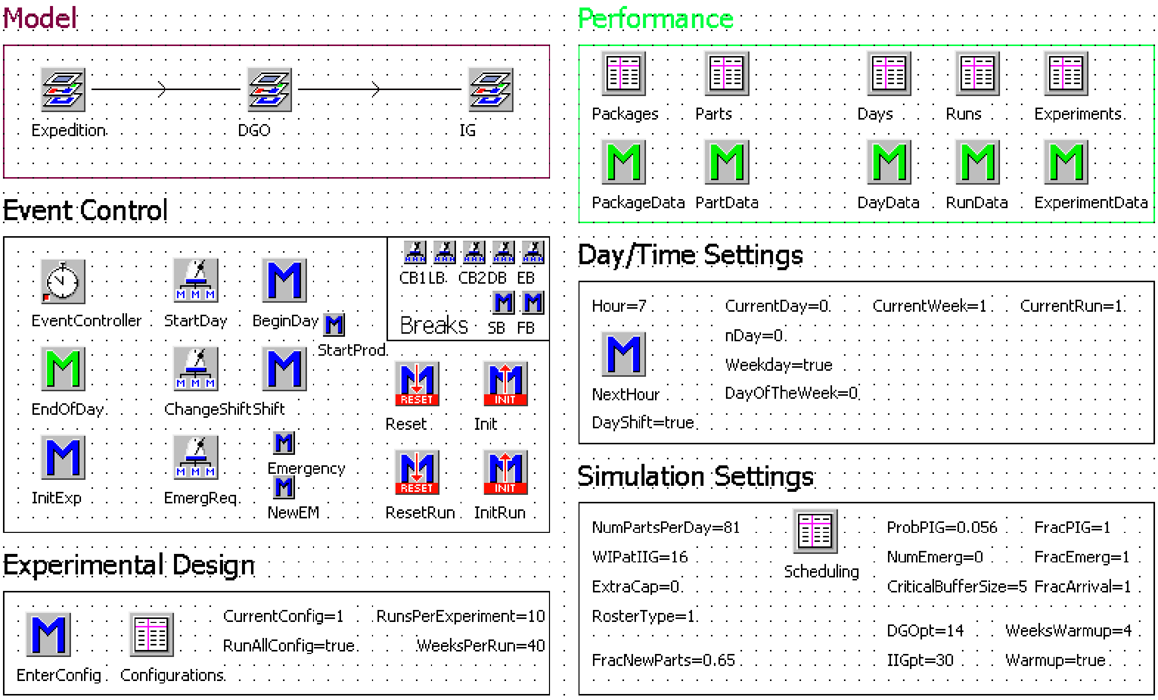


Figure 5.4: Screenshot of the main window of the simulation model.

The main window is a *frame*. A frame contains several elements, such as methods with programming code, tables with input data, variables, or sub-frames. These sub-frames also contain (some of) these elements. Figure 5.4 shows that the main window consists of six areas. We briefly introduce these areas.

The top left area, the *Model* area, is the actual model through which the packages and parts flow. It contains three sub-frames that each represent one of the three departments of the logistics department of ES: Expedition, DGO, and Incoming Goods (including the quarantine area). These sub-frames contain several elements to model these departments, such as blocks that represent the work stations and buffers or methods with programming code to control the flow of packages and parts through these blocks. Appendix K shows the sub-frames of these three departments.

The *Event Control* area generates all events that occur through time. The EventController is the clock of the system. When an event occurs, a method (the elements in the model with the M) is executed that generates the activities that happen after the event. For example at the start of the working day (every day at 7 AM), the method BeginDay is executed.

The *Experimental Design* area contains settings of the current experiment, such as the number of runs, the scheduling policy, and the input. Other settings are in the *Simulation Settings* area.

The *Day/Time Settings* area contains several parameters that keep track of the time in the simulation run. These parameters are continuously updated during a simulation run.

The performance measurement is done in the *Performance* area. Here, all the data of a simulation run is stored and exported to Excel for further analysis.

5.3 Experimental Design

The purpose of the simulation model is to conduct experiments to analyze the influence of changes in decision variables on the performance of the inbound logistics process. In this section, we discuss the design of these experiments. First, Section 5.3.1 introduces the performance indicators we use to measure the performance. In Section 5.3.2, we elaborate on the decision variables; the experimental factors of which we want to analyze the influence on the performance. We formulate the experiments in Section 5.3.3.

5.3.1 Performance indicators

In this section, we discuss the two performance indicators that we use to measure the performance of the inbound logistics process: the turnaround time of parts and packages and the number of employees employed in the inbound logistics process.

Turnaround time

As we mentioned in Section 1.2 and Section 4.1, the most important performance indicator is the turnaround time of parts through the entire inbound logistics process. In the simulation model, we measure the turnaround time by the both the mean and P95 value. In the data analysis, we did not measure the P95 value, because our data is not reliable enough to correctly model the span of turnaround times (see Section 4.1.5). An accurate representation of the span of turnaround times is required to measure the P95 value, because the P95 value is measured in the outer regions of this span. The main cause for a broad span of turnaround times is that employees deviate from the FIFO principle by cherry picking. However, since we assume FIFO handling in our simulation model (see Section 5.1.2), the model gives an accurate representation of the span of turnaround times and therefore we can accurately estimate the P95 value in our simulation model.

Number of employees

The second performance indicator is the number of employees that are present. The number of employees is a measure for the costs. It is a key factor in the determination of the performance of the process; employing more personnel most likely improves the turnaround time, but it also has a negative impact on the costs. So to determine the performance of the configurations of the process that we analyze with the simulation model, we have to make a trade-off between the personnel costs in terms of the number of employees employed, and the turnaround time.

5.3.2 Experimental Factors

In this section, we introduce the six experimental factors of which we want to analyze the influence on the performance indicators. We introduce the factors and explain what values of the factor we analyze with the simulation model.

IIG schedule

Three rosters have recently been used for scheduling the IIGs (see Section 2.5 and Section 4.4). These schedules are the regular schedule, 7x2, and the new schedules, 5x2 and 7x1. We use the simulation model to determine the performance of the inbound logistics process with the three schedules. The experimental factor IIG scheduling is a *qualitative* experimental factor, because the difference between the IIG schedules is not just in numerical factors, such as the number of IIGs, but also for instance in the way that the capacity of IIGs is utilized by the team managers. Our other five experimental factors are *quantitative*, because they only assume numerical values. Table 5.3 summarizes the differences between the three schedules in the simulation model.

	Roster type		
Aspect	**7x2 (regular)**	**7x1 (new)**	**5x2 (new)**
#IIGs	17	12	12
Overcapacity	yes	no	no
Capacity in weekend	full	limited	none
FIFO handling	yes	yes	yes
Buffer clearly organized?	no	yes	yes

Table 5.3: Differences between the three IIG schedules.

For more information on these differences, see Section 2.5 and Section 4.4. In Section 5.1.2 and Section 5.1.3, we elaborate on how we represent the qualitative aspects of the IIG scheduling in our simulation model.

DGO scheduling

A DGO employee works at two logistical departments: Expedition and DGO. Currently, there is one member of the general warehouse personnel working at DGO per shift. However, the inbound logistics process has been designed with two members of the general warehouse personnel working at DGO (see Section 2.4.5). We investigate the performance of both options with the simulation model. Since the DGO employee is a member of the general warehouse personnel, we assume that during the idle time, the DGO employees perform other tasks at the logistics department of ES. This means the extra DGO employee does not imply that extra employee has to be hired. The two DGO employees option rather reflects a more flexible utilization of the general warehouse personnel.

Extra IIGs

Next to the IIGs and the general warehouse personnel, the third group of operational personnel at the logistics department of ES is the System Check Group (see Section 2.2.5). Most members of the System Check Group are licensed to perform incoming goods inspection. In case extra IIG capacity is required at the Incoming Goods department, the management of the logistics department of ES decides to use members of the System Check Group as IIG. In the current situation, extra IIG capacity is utilized from the moment the *critical buffer size* is 5 days. This means that the buffer of the Incoming Goods department contains parts that have been in the buffer for 5 days (see Table 5.2). With the simulation model, we investigate what the influence is of lowering the critical buffer size. In other words: we investigate the influence of utilizing the extra IIG capacity before the amount of work has reached 5 days. The options we investigate are a critical buffer size of 2, 3, 4, and 5 days.

Reducing the critical buffer size is an example of a workload control (WLC) rule (see Section 3.1.3). Most WLC rules assume that the amount of jobs in the system is controlled by not releasing new jobs into the system until the WIP has dropped below a certain level. At ES, the amount of jobs in the system is controlled by temporarily adding extra IIG capacity to the system once the buffer has reached the level of 5 days WIP. We assume a maximum extra capacity of one IIG.

Change in the number of packages arriving at ES

In 2012, ES faces a decline in the number of engines to repair due to the economic crisis. Consequently, the input to the inbound logistics process (the number of packages and parts that arrive at ES) declines as well. Therefore we investigate how the inbound logistics process performs with a change in the input. With the simulation model, we test the performance when the input is 60%, 70%, 80%, 90%, 100%, and 110% compared to the input during the period we performed the data analysis on (November 2010 to October 2011).

Change in the number of PIGs

PIGs cause disturbances in the inbound logistics process (see Section 2.4.4). While PIGs are neither caused by the logistics department of ES, nor their responsibility, it does decrease the productivity of the IIGs and the performance of the inbound logistics process. Interviews with several employees of ES showed that processes, both at ES and at vendors, can be improved to prevent PIGs from occurring. The design of these possible process improvements is outside the scope of this research. However, with the simulation model, we show what the influence is on the performance of the inbound logistics process when the number of PIGs declines with 10%, 20%, and 30% compared to the current situation. This shows what the possible gains are of improving processes in order to decrease the number of PIGs.

Change in the number of emergency requests

During the interviews we held with several employees of the logistics department of ES, we noticed that several emergency requests are not urgent enough to be qualified as such. Since emergency requests require IIGs to search for the parts, it decreases their productivity. The employees estimate that approximately 20% of the emergency requests are not urgent enough to be labeled as emergency request. Therefore we investigate with the simulation model what the influence of the performance is if the number of emergency requests declines with 10% and 20%.

5.3.3 Experiments

In Section 5.3.2, we introduced the experimental factors and the different values, or *levels*, they can assume. If we assign a level to each of these experimental factors, we form an *experiment*. In this section, we discuss the experiments we perform with our simulation model.

Since the IIG schedule is the main experimental factor, we first determine the effect of the IIG schedules: 7x2, 7x1, and 5x2. Table 5.4 shows the design of the three experiments. All other experimental factors are equal to the *original setting*. The original setting refers to the situation in which the experimental factors are at the same level as during the time from which we took our data set for the data analysis in Chapter 4 (November 2010 to October 2011). We refer to the IIG scheduling by *Roster Type*, because it is a qualitative experimental factor representing more than just the number of IIGs (see Section 5.3.2).

IIG Roster Type	#DGO	Critical buffer size	%Input	%PIG	%Emergency requests
7x2 (regular)	1	5	100	100	100
7x1 (new)	1	5	100	100	100
5x2 (new)	1	5	100	100	100

Table 5.4: Experiments to compare the different IIG schedules with the original setting.

The IIG schedule is one of our six experimental factors. To determine the effect of each of the other experimental factors individually, we perform the experiments as presented in Table 5.5. For each experimental factor, we analyze the influence in both the original setting (in which the 7x2 roster is active) and the original setting with the 7x1 schedule. This leads to 28 experiments.

We do not consider the 5x2 schedule in the experiments of Table 5.5, because it is unlikely that this schedule will be adopted in the near future. Since both new schedules have a considerable impact on the salary of the IIGs, the management of ES made a concession to the IIGs by deciding not to implement the schedule that has the highest impact on the salary of IIGs: the 5x2 schedule.

IIG Roster Type	#DGO	Critical buffer size	%Input	%PIG	%Emergency requests	# Exp
7x2, 7x1	2	5	100	100	100	2
7x2, 7x1	1	2,3,4	100	100	100	6
7x2, 7x1	1	5	60,70,80,90,110	100	100	10
7x2, 7x1	1	5	100	70,80,90	100	6
7x2, 7x1	1	5	100	100	80,90	4

Table 5.5: Experiments to determine the effect of the individual experimental factors.

In the experiments of Table 5.5, we change the five quantitative experimental factors one at a time to determine their *individual* effect. However, we also want to determine what the *combined* effects of the experimental factors are. This means that the effect of one experimental factor depends on the value of another experimental factor. For instance, the effect of the number of emergency requests may interact with the employment of extra IIGs, because both factors depend on the buffer size.

To determine the combined effect of the experimental factors, we need to construct experiments in which we combine different values for the experimental factors. If we want to simulate all possible combinations, a *full factorial design*, we have to perform 2 (7x1 or 7x2 roster) * 2 (1 or 2 DGO employees) * 4 (Critical buffer size) * 6 (%Input) * 4 (%PIG) * 3 (%Emergency Requests) = 1152 experiments. This is an extensive amount of experiments. Therefore we do not use the full factorial design. Instead, we use a *2^k factorial design*.

In the 2^k factorial design, we pick two values for all $k=6$ experimental factors: a 'low' and 'high' value. We then simulate all $2^6=64$ possible factor-level combinations. Table 5.6 shows the experiments we need to perform using the 2^k factorial design. Since 12 of the experiments as described in Table 5.4 and Table 5.5 are also part of the experiments in the 2^k factorial design, the factorial design leads to 64 - 12 = 52 more experiments. The total number of experiments we perform is 52 (Table 5.6**)** + 28 (Table 5.4) + 3 (Table 5.4) = 83.

IIG Roster Type	#DGO	Critical buffer size	%Input	%PIG	%Emergency requests	#Experiments
7x2, 7x1	1, 2	2, 5	60, 100	70, 100	80, 100	64

Table 5.6: Experiments to perform in the 2^k factorial design.

5.4 Simulation setup

In this section, we discuss the simulation setup. In Section 5.4.1, we specify the warm-up period. Section 5.4.2 discusses the run length. Section 5.4.3 elaborates on the number of runs we perform per experiment. We do not determine the simulation setup of each of our 83 experiment separately. Since the three experiments of Table 5.4 reflect (one of) the most critical factor-level combinations of the process, we assume the simulation setup for these experiments suffices for all experiments. We determine the simulation setup using the output of the performance indicator with the highest variability, because this is the most critical performance indicator for a reliable analysis of the output. The output of the number of employees is the most stable, so we use the output of the turnaround time.

5.4.1 Warm-up period

To determine the performance of the process, we should only measure the performance when the process is in its *steady state*: the state in which the performance of the process is not influenced by initial conditions, such as an empty system. Therefore we should start measuring the performance after the *warm-up period.* The warm-up period is the group of observations from the beginning of the simulation that depend on the initial conditions. To shorten the warm-up period, we create an initial state in which the system is not empty. We assume the initial work in progress is equal to the average work in progress.

We express the warm-up period in a number of weeks, because the behaviour of the system differs per day of the week, so we must ensure that all seven days of the week occur an equal amount of times. For determining the warm-up period, we use the graphical method of Welch, see Appendix L. We estimate the warm-up period to be 2 weeks.

5.4.2 Run length

Our simulation is a non-terminating simulation, because there is no natural event that causes the simulation to terminate. Therefore we need to specify the length of each run. We choose the run length to be a number of weeks, because the behaviour of the system depends on the day of the week. Therefore we must ensure that all days of the week occur in equal amount. Law & Kelton (2000) state that the run length should be much larger than the warm-up period. Since we have chosen a warm-up period of 2 weeks, any run length above 10 weeks suffices for this condition. However, the run length should also be large enough to allow infrequent events to occur a reasonable number of times. Since the system is highly variable, there are many of such events. Therefore we choose a run length that is much larger than the warm-up period, but at the same time not too large, so it does not lead to an excessive execution time of the simulation model. We use a run length of 30 weeks.

5.4.3 Number of runs

To be able to give a reliable estimate of the performance of the system, we need to perform multiple runs of the same experiment. We calculated the number of runs required using the sequential procedure as described by Law & Kelton, 2000. This procedure is described in Appendix M. The number of runs for our experiments is 60. Given the run length of 30 weeks, every experiment consists of 60 * 30 = 1800 weeks, which is quite much. The reason that our experiments require such a high number of weeks is that the average turnaround time varies heavily between runs. Apparently, the variability of the process has a big impact on the performance of the process.

5.5 Verification and Validation

Verification is concerned with determining whether the model assumptions have been correctly translated into a computer program; in other words, debugging the simulation computer program. *Validation* is the process of determining whether a simulation model is an accurate representation of the system (Law & Kelton, 2000). These two concepts are closely related. It is important that we verify and validate our model, to ensure that it works correctly, so we can perform a valuable analysis with our simulation model. By justifying the assumptions that we make and the way we deal with variability of the system in Section 5.1, we have already discussed several important efforts to verify and validate our model. However, we also use several other techniques to verify and validate the model.

We construct the model gradually. This means we start with a lowly detailed simulation model and gradually increase the complexity by adding elements to the model. During each step, we debug the model. By gradually building the model, we verify that each step is modelled correctly.

Another important technique that we use is stepping through the model while it runs. We watched the animation of the model to check whether the flow of parts goes as expected. Also, we change the settings of input parameters and methods during a simulation run to see whether the model responds in the way we expect. For instance, when we increase the handling time of a package at the Expedition department during a simulation run, we check whether packages remain longer in the DGO buffer.

Furthermore, we check whether we have correctly modelled the complex sources of variability by comparing the output of the model to the results of the data analysis. For instance, the arrival process is the most complex source of variability; we use four different probability distributions to describe this process. The simulation model produces in the original setting on average 36.4 packages per day and 86.5 parts per day. If we compare this to the results of the data analysis (36.4 packages and 86.6

parts per day), we see that these numbers closely resemble the values of the simulation model. Therefore, we conclude that we have correctly modelled the arrival process. We perform similar checks for the handling times of DGO employees and IIGs, the number of emergency requests, and the number of PIGs.

As a final step, we validate our simulation model through *results validation*: we compare the output data of the simulation model run in the original setting (see Section 5.3.3) with the results of the data analysis. Since the simulation model in the original setting is the representation of the situation during the period of the data analysis, the simulation model should produce results that closely resemble the results of the data analysis. We use the output of the two performance indicators, the average turnaround time and the number of IIGs, for results validation. Data analysis showed that the average turnaround time is 88.43 hours and on average 3.27 full-time IIGs work per shift. In the simulation model, the average turnaround time is 88.90 hours and on average 3.27 full-time IIGs work per shift. Since these values closely resemble the actual situation, we conclude that our simulation model is valid.

5.6 Conclusion

This chapter described the design of the simulation model. We made the following assumptions:

- FIFO handling of parts and packages
- Employees handle one part at a time
- Shifts do not overlap
- Expedition department buffer has the highest priority
- Unlimited buffer size at all departments
- 1 IIG per day shift per weekday for solving PIGs.
- Parts go at most once into quarantine
- Inspection time of PIGs decreases after the PIG is solved
- No overtime
- No different priorities between parts
- Faster handling of emergency requests in the new schedules

We also introduced the probability distributions we use to model events with natural variability. Table 5.7 gives an overview of these distributions.

Process / activity	Distribution	Parameters
# deliveries per day	Rounded Normal(μ,σ)	see Table 4.5
# packages per delivery	Empirical	see Appendix I
# parts per package	Rounded Normal(μ,σ)	μ= 6, σ= 1
time of delivery	Empirical	see Appendix I
handling time per package at Expedition (minutes)	Normal(μ,σ)	μ= 6, σ= 1
handling time per package at DGO (minutes)	γ + Gamma(α,β)	α= 2, β= 3, γ= 8
handling time per part at Incoming Goods (minutes)	γ + Gamma(α,β)	α= 2, β= 7, γ= 15
handling time per PIG (minutes)	Triangular(a,b,c)	a= 10, b= 80, c= 37
handling time per emergency request (minutes)	Triangular(a,b,c)	a= 5, b= 45, c= 22.5
# Emergency request during a weekday day shift	Rounded Normal(μ,σ)	μ= WIP(days), σ= 1
# Emergency request during a weekend day shift	Rounded Uniform(a,b)	a=0, b=1
# Emergency request during a night shift	None	0

# full time IIGs present (in 7x2 roster)	Rounded Uniform(a,b)	a= 2.77, b= 3.77
# full time IIGs present (in 5x2 or 7x1 roster)	Binomial(n,p)	n= max #IIG, p= 0.758
# extra IIGs	Bernoulli(p)	see Table 5.2
Duration of short breaks	Uniform(a,b)	a= 10, b= 20
Duration of long breaks	Uniform(a,b)	a= 25, b= 35

Table 5.7: Overview of all probability distribution.

Next, we introduced the two performance indicators that we use to measure the performance of the inbound logistics process. The most important one is the turnaround time of parts. We measure both the average and P95 value of the turnaround time. The second performance indicator is the number of employees employed. The number of employees is a measure for the costs. So to determine the performance of the configurations of the process that we analyze with the simulation model, we have to make a trade-off between the personnel costs in terms of the number of employees employed, and the turnaround time.

The experimental factors are the variables that we change in our model to determine their effect on the performance of the system. Table 5.8 shows the 6 experimental factors, including the values, or levels, of the factors that we will analyze. By assigning a level to each of the experimental factors, we create an experiment. We designed 83 different experiments to perform with our simulation model.

IIG Roster Type	#DGO	Critical buffer size	%Input	%PIG	%Emergency requests	#Experiments
7x2, 7x1, 5x2	1, 2	2, 3, 4, 5	60, 70, 80, 90, 100 110	70, 80, 90, 100	80, 90, 100	83

Table 5.8: The experimental factors and the levels we simulate.

We also introduced the simulation setup. We determined the warm-up period using the graphical method of Welch, selected a run length, and calculated the required number of runs using the sequential procedure. Table 5.9 shows the results.

Warm-up period	2 weeks
Run length	30 weeks
Number of runs	60

Table 5.9: Simulation settings.

To ensure whether the simulation model works properly, we verified and validated our model using various techniques, such as results validation, a gradual model design, and extensive debugging.

6. Results

In this chapter, we present and analyze the results of the simulation study. We perform the experiments that we designed in Chapter 5. The experiments are divided into three groups of experiments. The first group contains the experiments to analyze the individual effect of the experimental factor IIG schedule. The IIG schedule is a separate group of experiments, because it is the most important experimental factor (see Section 5.3.3. We discuss the results of this category in Section 6.1. The second group consists on the experiments to analyze the individual effect of the other experimental factors. Section 6.2 presents the results of these experiments. In Section 6.3, we discuss the results of the third group of experiments: those to test the combined effect of the different factors. Section 6.4 elaborates on the implementation process. Section 6.5 concludes this chapter.

Besides presenting the numerical results, we also elaborate on the results and discuss the qualitative aspects and practical implications of the proposed system configurations.

6.1 IIG schedule

To test the individual effect of the experimental factor IIG scheduling, we constructed three experiments in Section 5.3.3 in which only the IIG scheduling changes, while the other five experimental factors are in the original setting. Table 6.1 shows the results of the three experiments, measured by the two key performance indicators (see Section 5.3.1). The capacity (#IIGs per shift) includes both the number full-time IIGs that were present and the number of extra IIGs.

	Turnaround time (hours)		Capacity
Experiment	**Average**	**P95**	**# IIGs per shift**
7x2 in original setting	88.9	158.71	3.32
7x1 in original setting	89.8	164.76	3.31
5x2 in original setting	93.4	169.04	3.31

Table 6.1: Results of the IIG scheduling experiments.

We notice several differences between the three schedules. The 7x2 seems to perform best on turnaround time, but it requires a slightly higher capacity. To determine whether the differences between the test results are significant, we perform a *t-test.* With a t-test, we construct a confidence interval for the difference between two outputs. In this chapter, we test all differences with a t-test. By default, we do not address significance, unless the difference is not significant or the difference is small, but still significant.

The differences between the three schedules on the #IIGs per shift appear not to be significant. The differences in turnaround time between the 5x2 schedule and the other two schedules are both for the average and P95 significant. So the 5x2 schedule is outperformed by the other two schedules. The difference between the 7x2 and 7x1 schedule is only significant for the P95 value. Due to a lower capacity of IIGs during the weekend in the 7x1 schedule, the spread of turnaround time broadens, which causes a higher P95 value. However, we must keep in mind that the P95 value for the 7x2 schedule as determined by our simulation does *not* represent the actual situation. It represents the (desired) situation in which parts are handled by the FIFO principle. Hence, we cannot state that the *actual* 7x2 schedule achieves a significantly lower P95 value. We can only conclude that the 7x2 schedule in which parts are handled on a FIFO basis achieves a significantly lower P95 value than the 7x1 schedule. However, if we compare the P95 values of the 7x1 and 7x2 schedule (with FIFO part handling) with the P95 value of the *actual* 7x2 process (>200 hours), we see that FIFO clearly improves the P95 value.

Based on these numerical results, we conclude that the 7x2 (with FIFO part handling) is the best schedule, because it performs either as good as or better than the other two schedules on all performance indicators. This is what we expected based on to the comparison we made in Section 4.4. We concluded that the average number of full-time IIGs per shift is approximately equal in the three schedules, but the regular schedule allows more flexibility in the number of available IIGs due to an overcapacity. On the other hand, the new schedules have a reduction of the search time for emergency requests due to more clearly organized buffers, but this does not outweigh the reduced flexibility.

A comparison of the three schedules solely based on the numerical results from our simulation study is not sufficient to determine which schedule is the best schedule for ES to adopt. As Section 2.5.2 and Table 2.2 show, an important factor that we did not consider in our simulation study is the saving of personnel costs due to less weekend shifts. While the 7x2 schedule performs significantly better (3.8%) on the P95 value of the turnaround time, the personnel costs for this schedule are higher. In the 7x2 schedule, each full-time IIG receives a fee worth 34 hours of labour for working during the weekend. In the 7x1 schedule this number decreases to 10 hours. This is a substantial saving. Given that the difference between the two schedules in terms of turnaround time is small, while the cost savings are substantial, we conclude that the 7x1 schedule is the most favourable schedule.

6.2 Individual effects of experimental factors

In Section 6.1, we discussed the individual effect of the experimental factor IIG schedule. In this section, we discuss the individual effects of the other experimental factors. We perform the experiments for the individual effect of the factors using both the 7x2 schedule and the 7x1 schedule. The results show that the effects of other experimental factors are very much alike in both schedules. Therefore, by default, we show the results of only one schedule, the 7x1 schedule. We use the 7x1 schedule, because this is the most favorable schedule (see Section 6.1) and will most likely be adopted by ES. Only in case that the results of the 7x2 schedule show a different effect, we show both results.

Section 6.2.1 discusses the effect of employing an extra DGO employee. Section 6.2.2 elaborates on the effect of changing the critical buffer size. In Section 6.2.3, we analyze the influence of a change in the input. Section 6.2.4 and Section 6.2.5 discuss the effect of a reduction in the number of PIGs and emergency requests respectively.

6.2.1 Number of DGO employees

We test two levels of the number of DGO employees. The first level is 1 full-time DGO employee, which corresponds to the current situation. The second level is 2 DGO employees multi-tasking. Since the general warehouse personnel is trained for multiple tasks in the logistics department of ES, we assume that these two DGO employees are both current members of the general warehouse personnel. Since they can perform other tasks in the logistics department during the idle time, there are no extra personnel costs involved.

Data analysis showed that the turnaround time at the DGO department is much lower (at most 25%) than the time a part stays in the Incoming Goods buffer. Hence, the total turnaround time is barely influenced by the DGO department and therefore we do not expect the total lead time to change much due to an extra DGO employee. However, the simulation results, displayed in Table 6.2, show an unexpected effect.

	Turnaround time (hours)		Capacity
Experiment	Average	P95	# IIGs per shift
7x2 - 1 DGO	88.9	158.71	3.315
7x2 - 2 DGO	79.0	148.45	3.323
7x1 - 1 DGO	89.8	164.76	3.308
7x1 - 2 DGO	77.6	151.25	3.311

Table 6.2: Results of the experiments for the number of DGO employees.

We notice a substantial decrease in the total turnaround time. We identify two reasons for this decrease. The first reason is the increase in the buffer size of the Incoming Goods department. Since more parts are in this buffer, the critical buffer size is reached sooner. This leads to employing more extra IIGs. This effect is supported by the small, but significant increase in the #IIGs per shift, as shown in Table 6.2. The second reason is that due to the extra capacity, the DGO department can handle the peak of arrivals on Thursday and Friday much faster, which decreases the probability that the Incoming Goods department becomes idle. The differences between the two schedules with 2 DGO employees are not significant.

Apart from the substantial decrease in turnaround time, ES can achieve another advantage by employing two DGO employees. Currently, ES does not know whether it has received a package until the AM confirmation has been placed, because ES does not use Tracking. The simulation results show that with 2 DGO employees, the average handling time at DGO decreases from 18.8 to 1.6 hours. This gives ES more control over its process, because it is almost at all time aware of what packages and parts it has received.

By assigning two members of the general warehouse personnel to DGO, we achieve an 11% lower turnaround time at the expense of 0.2% of extra IIGs. However, our assumption that multi-tasking does not deteriorate the productiveness of other tasks of the DGO employees may not hold in practice, because it requires an extensive amount of flexibility in the tasks. For example, when a delivery arrives, our model assumes the employee can temporarily suspend its tasks and continue later on, without any loss of time.

6.2.2 Critical buffer size

The critical buffer size is the size of the buffer, measured in the number of days of work in progress, from which extra IIG capacity may be employed by a team manager to prevent the buffer from growing too large. The current policy is a critical buffer size of 5 days. To analyze the effect of lowering the critical buffer size, we performed experiments for three lower levels: 2, 3, and 4 days. Table 6.3 shows the results, including the percentage of time the Incoming Goods department has at least 1 idle IIG due to an empty buffer. Figure 6.1 displays the average turnaround time for all levels in both the 7x1 and 7x2 schedule.

	Turnaround time (hours)		Capacity	
Critical Buffer Size	Average	P95	# IIGs per shift	Incoming Goods Idle
5 days	89.8	164.76	3.31	0.0%
4 days	75.6	141.85	3.32	0.1%
3 days	62.7	120.22	3.34	0.2%
2 days	48.7	97.85	3.40	0.5%

Table 6.3: Results of the experiments for the critical buffer size with the 7x1 schedule.

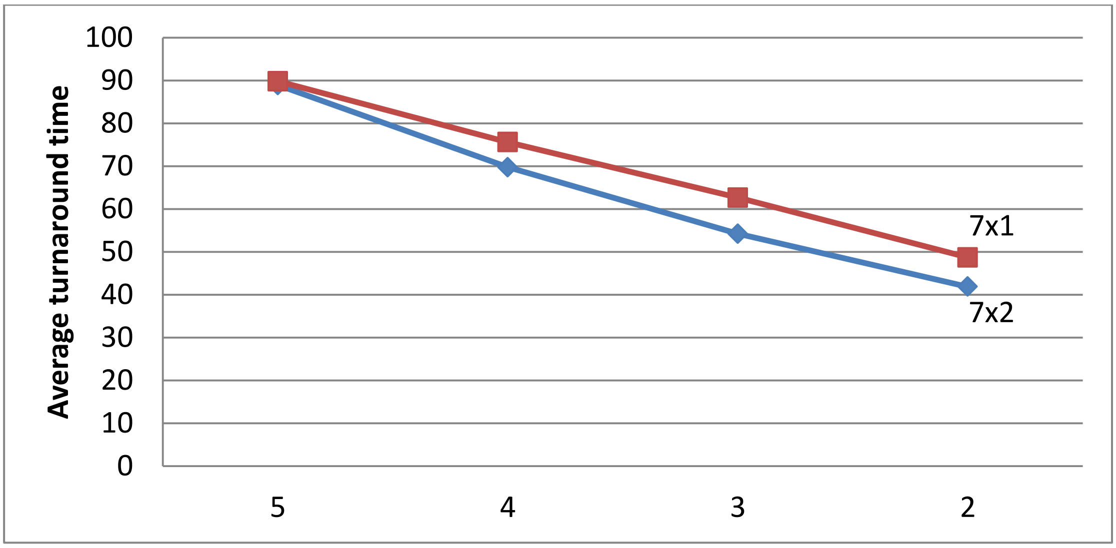


Figure 6.1: Average turnaround times for the critical buffer size level in 7x2 and 7x1 schedule.

The results show a massive effect. By decreasing the critical buffer size to either 2, 3, or 4 days, a decrease in the average and P95 turnaround time of at least 16% per level at the expense of at most 2% more personnel can be achieved. The effect of lowering the critical buffer size has the largest effect in the 7x2 schedule due to the fact that more IIGs can be employed in the weekend.

Based on these results, we conclude that the current level for the critical buffer size is too large. Since the inbound logistics process is highly variable, it does require a buffer to cope with the variability. However, a buffer of five days is clearly too large. To shorten the turnaround time, only a small amount of extra capacity is required. This seems worth the investment.

6.2.3 Change in input

The amount of parts arriving to ES changes continuously due to the volatile industry. For instance, during the economic crisis, the input declined to 60% of the amount as it was during the period of our data analysis. To determine the effect of a change in the input, we performed experiments with the following levels for the input: 60%, 70%, 80%, 90%, 100%, and 110%. Table 6.4 and Figure 6.2 show the results.

	Turnaround time (hours)		Capacity	
Input	Average	P95	# IIGs per shift	Incoming Goods Idle
110%	178.2	269.95	3.61	0.0%
100%	89.8	164.76	3.31	0.0%
90%	36.7	88.70	3.25	1.8%
80%	19.1	59.47	3.25	4.2%
70%	12.1	45.77	3.25	7.0%
60%	8.4	38.04	3.25	10.6%

Table 6.4: Results of the experiments for the change in input with the 7x1 schedule.

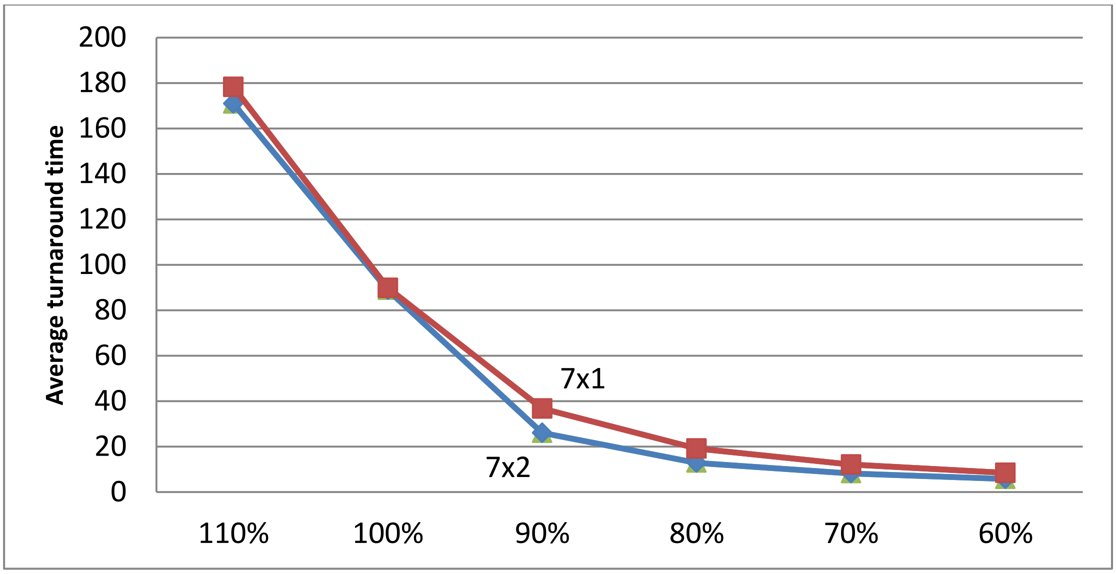


Figure 6.2: Average turnaround time in 7x1 and 7x2 for various input levels.

The results show that the process is highly sensitive to *structural* changes in the input; variability in terms of temporary changes is accounted for in the model by the various probability distributions. If the input increases by 10%, the system can barely manage. An extra IIG is always needed, causing a 9% increase in the number of IIGs per shift. The average turnaround time becomes twice as large. On the other hand, if the input decreases with 10%, the system can easily cope with the input. Extra IIGs are no longer needed and the buffers are empty in 1.8% of the time.

Since the simulation model registers such a high amount of idle time for a low input, we perform an additional experiment to test the performance if the number of employees decreases. We select the scenario where the number of employees decreases from 12 to 10. This is a decrease of 17% in the number of full-time IIGs, so we consider input levels of the same magnitude: 90%, 85%, and 80%. Table 6.5 shows the results of these simulations.

	Turnaround time (hours)		Capacity
Input	Average	P95	# IIGs per shift
90%	156.17	235.48	2.95
85%	118.70	202.05	2.80
80%	64.38	132.55	2.72

Table 6.5: Results for different inputs with 10 IIGs in a 7x1 schedule.

In the experiments of Table 6.5, we also notice a high sensitivity of the performance to a change in the input: it easily leads to a mismatched capacity. In case a structural change in the input occurs of more than 5%, ES needs to adjust its capacity.

6.2.4 Change in number of PIGs

Next, we look at the effect of decreasing disturbances. The most important disturbance to the inbound logistics process is the time IIGs spend on solving PIGs. This takes 9.2% of their time. Table 6.6 shows the results of the experiments to determine the effect of reducing the number of PIGs.

	Turnaround time (hours)		Capacity
%PIG	Average	P95	# IIGs per shift
100%	89.8	164.76	3.31
90%	84.4	155.61	3.30
80%	79.1	147.71	3.29
70%	74.5	143.06	3.28

Table 6.6: Results of the experiments for the change in the number of PIGs.

We see that every 10% decline in the number of PIGs reduces the required capacity by 0.01 per shift and the average turnaround time by approximately 5 hours. As we mentioned before, the design of the measures that need to be taken to accomplish a decrease in the number of PIGs are outside the scope of this research.

6.2.5 Change in number of emergency requests

The second major disturbance to the inbound logistics process is searching for emergency requests. We investigate the effect of a decline in the number of emergency requests as well.

	Turnaround time (hours)		Capacity
%Emergency requests	Average	P95	# IIGs per shift
100%	89.8	164.76	3.31
90%	89.5	163.55	3.31
80%	87.7	160.67	3.30

Table 6.7: Results of the experiments for the number of emergency requests.

There is no significant difference between 90% and 100% level. However, a decrease to 80% does show a significant decrease in the average and P95 turnaround time and the capacity. The effect of decreasing the number of emergency requests is quite small, especially if we compare it to the effect of reducing the number of PIGs. So to reduce the influence of disturbances on the inbound logistics process, ES should rather try to reduce the number of PIGs.

6.3 Combined effect between experimental factors

To determine the combined effect of experimental factors, we performed 52 additional experiments to the experiments we already performed using the 2^k factorial design (see Section 5.3.3). We select a lowest and highest value for all 6 experimental factors and perform all possible factor-level combinations. We do not elaborate on all these experiments here. Instead, we only discuss the results that add to the analyses of Section 6.1 and Section 6.2.

Compensating for an increased input

As we have seen in Section 6.2, the performance of the inbound logistics process is very sensitive to changes in the input of the system. We concluded from the analysis that a change in the input should be compensated by the capacity. So in case the input increases with 10%, ES needs to employ more full-time IIGs. However, we established that there are also other experimental factors that significantly influence the turnaround time. To see whether ES can use these experimental factors to cope with a 10% increase in the input, we perform the experiment in which we have the input at the most negative level, 110%. We set the number of DGO employees (2), the reduction of the number of PIGs (70%), and the number of emergency requests (80%) at the most positive levels. The experiment shows that the average turnaround time decreases from 178 hours to 131 hours, but this is still much higher than the original 89.8 hours. The required capacity also decreases: from 3.71 IIGs per shift to 3.55, which is still much higher than the original 3.31 IIGs per shift. We conclude that these measures are capable of compensating partially for an increase in the input.

Compensating additional required capacity

The best way to increase the turnaround time is to reduce the critical buffer level. However, this goes at the expense of the capacity. Therefore, we investigate what measures we can take to compensate for the additional required capacity. We will look into the combined effect of lowering the critical buffer level to 2 with three other experimental factors at their most favorable level: the number of DGO employees (2), the number of PIGs (70%), and the number of emergency requests (80%). Table 6.8 shows the results.

Experiment	Critical buffer level	DGO	%PIG	%Emergency requests	#IIG per shift
1	2	1	70	80	3.37
2	2	1	70	100	3.37
3	2	1	100	80	3.40
4	2	2	70	80	3.34
5	2	2	70	100	3.34
6	2	2	100	80	3.37
Original 7x1	5	1	100	100	3.31

Table 6.8: Experiments to compensate for additional capacity.

Again, we see that the effect of reducing the number of emergency requests is very limited: the differences between experiment 1 and 2, and between 4 and 5 are not significant. The other differences are significant, including the difference with the original number of IIGs per shift. In other words, none of these configurations could compensate the increase in the required number of IIGs per shift due to adopting a critical buffer level of two days.

6.4 Implementation

In this section, we discuss issues that might occur in implementing the changes to the inbound logistics process and present the steps to take to implement the changes. In Section 6.4.1, we discuss possible sources of resistance to change. Section 6.4.2 elaborates on the important role of team managers during and after the implementation process. In Section 6.4.3, we present the steps to implement the changes.

6.4.1 Resistance to change

Our recommendations are mostly in line with common Lean Six Sigma practices. For instance, decreasing the number of PIGs is a good example of eliminating waste. Shah & Ward (2003) investigated the implementation process of lean practices into an organization. They found that in a strongly unionized environment, such as KLM, the implementation of changing work force rules is considerably more difficult than in non-unionized organizations. The fact that the 5x2 schedule will most likely be not adopted shows this is indeed the case at KLM. Some of our recommendations, such as reducing the critical buffer size and adopting FIFO part handling, involve changing the work force rules. Another important factor that influences the implementation process of lean practices is the age of the organization: Shah & Ward (2003) state that older organizations are less likely to implement lean practices due to resistance to change and liability of newness. Considering these findings, ES should expect difficulties when implementing these changes.

In order to overcome the difficulties during the implementation process caused by changes to the work force rules, ES should also implement the changes that do not require a change in the work force rules, such as decreasing the number of emergency requests and PIGs. Employees benefit from these changes, because they spend less time on handling disturbances to the process, but it does not influence their activities. ES needs to communicate a total package of advantages and disadvantages to its employees; employees need to understand the benefits of the changes to both ES and themselves.

6.4.2 Team managers

The team managers are very important in the implementation and acceptance of changes to the work force rules. For instance, to lower the critical buffer size, they need to monitor the buffer and decide when an extra IIG should work at the Incoming Goods department. They need to change their previous decision rule.

Some changes to the work force rules, such as FIFO part handling, do not directly involve decisions to be made by the team managers. However, they play an important role in controlling whether these changes rules are applied by the operational employees, because they are directly responsible for controlling the tasks that the operational employees perform. For instance, IIGs must handle parts by the FIFO principle. However, it is the responsibility of the team managers to control the behavior of the employees. Team managers must ensure that the employees perform their activities correctly.

So the acceptance of FIFO part handling, a lower critical buffer size, and a flexible use of DGO employees greatly depends on the team managers. Therefore, the management of ES must ensure the team managers fully support the changes.

In section 3.1, we described that an order review and release strategy can be used to prevent cherry picking and enforce job selection on formal job priority, such as FIFO. With the introduction of the new schedules at ES, movable racks have been introduced to organize the buffer (see Section 2.5.2). With these racks, the team managers can enforce IIGs to only pick parts from racks that are selected by the team managers based on FIFO.

6.4.3 Implementation steps

Not all changes can be implemented immediately and simultaneously. Therefore, we recommend taking the following steps to implement the changes.

1. Immediately start lowering the critical buffer size.
Since this change is the easiest to implement and has the biggest effect, we recommend implementing this change first. As stated in Section 6.4.2, the commitment of the team managers is crucial to the success of lowering the critical buffer size. We recommend lowering the critical buffer size gradually in order to allow everyone adapt to the new situation and prevent resistance to change as much as possible (see Section 6.4.1).

2. Encourage multi-tasking of the general warehouse personnel.
All members of the general warehouse personnel are trained to perform all operational tasks, such as DGO. However, most employees have lost this ability due to focusing solely on one specific task. The results show that more flexibility at the DGO department leads to a significant improvement in the turnaround time.

3. Encourage other departments to review their emergency request policy.
Although the effect of reducing the number of emergency requests is limited, the costs of lowering the amount of emergency requests are negligible. This is because it solely consists of efforts by the management of the logistics department of ES to communicate to other departments in ES to review their emergency request policy.

4. Invest in decreasing the number of PIGs.
This is the most costly and time-consuming change, but the results show that it will lead to substantial improvement of the turnaround time. Reducing the number of PIGs requires investments in several departments of ES, such as planning and purchasing, but also the logistics department responsible for sending parts for repairs to vendors. However, all these departments will profit from the reduction in the number of PIGs.

6.5 Conclusion

In this chapter, we presented and analyzed the results of the experiments we performed with the simulation model.

First, we discussed the effect of the three IIG scheduling methods. The 5x2 schedule is outperformed by both the 7x2 and 7x1 schedule. The 7x2 schedule slightly outperforms the 7x1 schedule on turnaround time, but this does not outweigh the much higher costs. Therefore, we concluded that the 7x1 schedule is the best schedule.

Next, we determined the individual effects of the other experimental factors. By assigning an extra employee to DGO, an 11% lower turnaround time can be achieved at the expense of 0.2% more IIG capacity. Reducing the number of PIGs also leads to substantial performance improvement. Reducing the number of emergency requests has a much smaller effect.

The best way to increase the performance of the system is to lower the critical buffer level. Despite that ES needs a buffer to cope with the variability of the system, the current critical buffer level of 5 days is too high. By reducing this level to 2 days, ES can achieve a 46% reduction in the lead time at the expense of just 3% more capacity. The increased capacity can be partially compensated by optimizing other experimental factors, such as the number of PIGs.

Looking at the effect of changes in the input, we concluded that if a structural change in the input occurs, ES needs to adjust its full-time IIG capacity in order to maintain its current performance. Compensating by means of adding an extra DGO employee and reducing the number of PIGs and emergency requests has limited effect.

We also looked into issues that might occur due to the implementation of the changes. There are two important issues that ES needs to take into account during, but also after the implementation process. These issues are: the possible resistance to changes that influence the way employees need to work, such as FIFO part handling, and the key role that the team managers have in the implementation and acceptance of the changes. We recommend starting the implementation process with gradually lowering the critical buffer size.

7. Conclusions & recommendations

This chapter concludes this report. We present the most important findings of this research and give recommendations based on the findings. Section 7.1 summarizes the research and the steps we have taken to answer the research questions. In Section 0, we present suggestions for further research.

7.1 Conclusion

We performed this research for the management of the logistics department of ES with the following goal:

> *To determine the current performance of the inbound logistics process and to suggest alternatives to improve the performance of the inbound logistics process.*

To achieve this goal, we constructed five research questions. In this section, we summarize our research by discussing our answers to the five research questions.

1. How does the current inbound logistics process at the logistics department of Engine Services work?

At Es, incoming goods go through three logistical departments: Expedition, DGO, and Incoming Goods. A DGO employee works at both the Expedition and DGO department. At Expedition, the DGO employee checks the packages for transportation damage and sorts the packages based on their destination in ES. If a package contains parts that require inspection, he moves the package to the DGO department. At the DGO department, the DGO employee checks whether the shipment contains the right parts, he registers the acceptance of the package in an information system, and he prepares the parts in the package for the final stage, the incoming goods inspection. The incoming goods inspection is performed by an IIG. The inspection consists of visual and administrative checks. Parts that successfully pass the inspection are moved to their destination in ES. Parts that fail inspection in any of the three stages are moved into the quarantine area, from where the respective problem owner should solve the issue. Operations run seven days a week during two shifts per day. However, the management of ES wants to reduce the personnel costs by adopting a new schedule that decreases the amount of shifts during the weekend.

2. What is known in literature about organizing a process such as the incoming logistics process?

To answer this question, we first identified the inbound logistics process as a flow shop. To reduce the turnaround time in a flow shop, we discussed two techniques: dispatching rules and workload control. Dispatching rules prescribe which part should be handled by an employee that becomes available. ES uses the dispatching rule FIFO, which generally performs poorly on the average flow time, but performs well on minimizing the maximum flow time of parts, which is the objective of ES. Workload control rules control the amount of work that is released to the work floor. They can significantly improve the turnaround time and limit the effect of deviations from the dispatching rules. Second, we discussed the business philosophy of KLM, Lean Six Sigma. The key principles of Lean Six Sigma are to eliminate waste and to reduce variability in the process. Third, we discussed simulation, which is the tool we use to answer research question 4 and 5. Since literature on both Lean Six Sigma and job-shop scheduling recommend the use of simulation, we concluded that simulation is a suitable tool for evaluating various configurations of the inbound logistics process.

3. How can the performance of the inbound logistics process be measured and what is its current performance?

We performed a data analysis to answer this research question. The key performance indicator of the inbound logistics process is the turnaround time. To determine the turnaround time of the inbound logistics process, we first split the process into four measurement points. Then, we determined the average turnaround time of parts between these measurement points based on confirmations placed for all parts in several information systems. Figure 7.1 visualizes these measurement points and shows the mean (μ) and standard deviation (σ) of the turnaround time between these measurement points. Currently, the inbound logistics process currently underperforms, because the turnaround times as shown in Figure 7.1 are higher than the goals set by the management of ES. Furthermore, the turnaround time for all parts between all four measurement points is instable due to employees disregarding the FIFO dispatching policy and the highly variable arrival process.

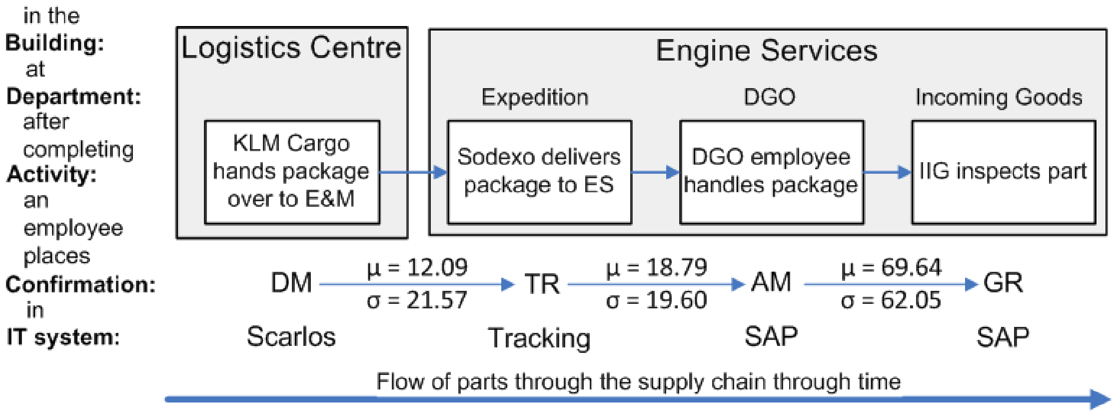


Figure 7.1: Overview of turnaround times between the measurement points.

4. What is a good simulation model of the inbound logistics process for evaluating the effect of changes to the process on the performance of the process?

To evaluate the performance of the inbound logistics process in several different configurations, we constructed a simulation model. We used simulation, because the inbound logistics process is too complex to analyze numerically. We measured the performance with two performance indicators: the turnaround time and the number of IIGs that are present. We introduced six experimental factors to model changes to the inbound logistics process. These experimental factors are:

- The schedule of IIGs
- The number of DGO employees
- The size of the Incoming Goods buffer before extra IIG capacity is used
- Change in the input of packages and parts to the inbound logistics process
- Change in the number of PIGs
- Change in the number of emergency requests.

Table 7.1 shows the experimental factors, including the levels that we analyzed. By assigning a level to each of the experimental factors, we created experiments. We created 83 distinct experiments; every experiment is a distinct representation of a configuration of the actual inbound logistics process.

IIG Roster Type	#DGO	Critical buffer size	%Input	%PIG	%Emergency requests	#Experiments
7x2, 7x1, 5x2	1, 2	2, 3, 4, 5	60, 70, 80, 90, 100 110	70, 80, 90, 100	80, 90, 100	83

Table 7.1: The experimental factors and the levels we simulate.

5. To which benefits will the changes lead and what issues need to be taken into account during implementation of the suggested changes?

The final step in the research was to run the 83 experiments in the simulation model and analyze the results. Our main findings are:

- The 5x2 schedule is outperformed by both the 7x2 and 7x1 schedule. The 7x2 schedule slightly outperforms the 7x1 schedule on turnaround time, but this does not outweigh the much higher costs. Therefore, we concluded that the 7x1 schedule is the best schedule.
- FIFO decreases the P95 value significantly.
- By assigning an extra employee to DGO, an 11% lower turnaround time can be achieved at the expense of 0.2% more IIG capacity.
- Reducing the number of PIGs leads to substantial performance improvement.
- Reducing the number of emergency requests has a much smaller effect.
- The best way to increase the performance of the system is to lower the critical buffer level. Despite that ES needs a buffer to cope with the variability of the system, the current critical buffer level of 5 days is too high. By reducing this level to 2 days, ES can achieve a 46% reduction in the lead time at the expense of just 3% more capacity. The increased capacity can be partially compensated by optimizing other experimental factors, such as the number of PIGs.
- If a structural change in the input occurs, ES needs to adjust its full-time IIG capacity in order to maintain its current performance. Compensating by means of adding an extra DGO employee and reducing the number of PIGs and emergency requests has limited effect.
- Issues that need to be taken into account during and after the implementation are the possible resistance to changes that influence the way employees need to work, such as FIFO part handling, and the key role that the team managers have in the implementation and acceptance of the changes.

7.2 Suggestions for further research

In this research, we limited ourselves to considering only three schedules. It is very likely that neither of these schedules is optimal. With our simulation model, various other IIG scheduling techniques can be evaluated. Although the 7x1 schedule is an improvement compared to the original 7x2 schedule, we recommend researching other scheduling techniques to further optimize the IIG scheduling.

Since ES strives to minimize the maximum flow time of parts, the choice for FIFO as the dispatching rule is reasonable. However, literature shows that FIFO is not optimal (Holthaus & Rajendran, 1997). Also, some parts have higher priorities than others, because they belong to a running project, while other parts are ordered to place in the warehouse. These parts have a lower priority. By applying different part priorities, ES could reduce the number of tardy parts and also reduce the number of emergency request. Therefore, we recommend to research whether changing the dispatching rule can lead to improved results.

The simulation model has been designed, validated, and verified based on the original setting. However, the current situation is very different from the original setting. For instance, ES faces a considerable decrease in the input; the input is currently (August 2012) 65% of the input compared to the original setting. Also, the current schedule is the 7x1 schedule. Since the 7x1 schedule has been used in the last 6 months, we recommend verifying and validating the simulation model by comparing the results of the simulation model with the historical data of the last 6 months.

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Interviews

See Appendix B

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Appendix A Abbreviations

DGO: Decentralized GOods Receipt (logistical department)

EASA: European Aviation Safety Agency (European aviation authority)

E&M: Engineering & Maintenance

ES: KLM Engine Services

FAA: Federal Aviation Administration (United States aviation authority)

IIG: Inspector Incoming Goods

LC: Logistics Centre (of KLM E&M)

PO: Purchase Order (identification number in SAP of an order)

SAP: ERP-system used at ES

Scarlos: Information system used at KLM Cargo to track parts and packages

Tracking: Information system used at the Logistics Centre of KLM to track packages

SAP confirmations

AM: Accepted at MU (=ES)

AV: Accepted by Vendor

CR: Customs Release Note

DM: Delivered at MU (=LC)

Ex: Ex works Vendor

GR: Goods Received

PV: Picked up at Vendor

TR: Tracking, delivered at ES

Appendix B Summary of interviews

Table B.1 presents an overview of the interviews we held with several experts on different areas within KLM to gain information. With every interviewed person, we mention his role within KLM and the main subject(s) of the interview(s).

Role	Name(s)	Subject(s)
Inspector Incoming Goods (IIG)	M. Ahmed I.K. Autar M. van Dijk H.G. Jager A. Kasiemkhan A. Knoppel F.W.J. Nuijens O.C.J. Matthijsen R.M.F. Nabibaks A.M. Ricardo Sousa M.S. Thakoersingh M.A. Windhorst A. Yildiz G.C.P. v.d. Zwaan	Activities of incoming goods inspection Design of the inbound logistics process Inspection time Issues in the inbound logistics process Search time for emergency requests Time to create and solve PIGs
DGO Employee	A. Kool H. Poublon H.M. Ramlakhan	Tasks of DGO employee Handling time at Expedition Handling time at DGO
Team Manager Logistics	J.E. van der Horn R. Keizer H. Ramoul	Design of the inbound logistics process Scheduling Critical buffer size Number of emergency requests
Key-user SAP WMS	E. Booman	Various, main subjects: Data analysis (GR, AM, and DM data) SAP Design of inbound logistics process
Support Group Employee	B. Ramkhewan	Various, main subject: MPS
Manager Stage 2	J.A. de Graaff	Various, main: Scheduling (IIG Roster Types)
Manager Logistics	A. Doeser	Various
Project Leader Logistics at the Logistics Centre	M.F.P. Wennekes	Data analysis: TR data. Process design at the LC
Project Manager at the LC	L. Vennik	Process design at the LC
Project Leader Logistics	A. Hermans	Various, main: Process design at ES
System Check Group	R. Tognetti	Various, main: SAP
MPS Service Employee	G. Hey	MPS data
Supply Chain Analyst	I.L.N.J. Sohl	Data analysis: AM and DM data
Projectmanager Logistics	F. Bakkenist	Data analysis
Supply Chain Analyst Engine Control Officer	N. Dalmulder	Planning at ES Supply chain of repair and new parts
Senior Project Manager at KLM Cargo	J.N. Kraus	Process design at KLM Cargo
Information Engineer	A.T. Scheick	Handling times and production rates
ex-Manager Logistics	W. Broekhuizen	Design of the inbound logistics process

Table B.1: Overview of the interviews.

Appendix C Engine Types

KLM ES provides maintenance, repair, and overhaul services on four types of engines. All these engines are developed by General Electric. Three of these engines are members of the CF6 family. These engines are used on wide-body planes, for example the Airbus A300 and A330, the Boeing 747 and 767, and the McDonnell Douglas MD-11. The oldest CF6 engine that is repaired at ES is the CF6-50, which is currently in the late decline phase of the product life cycle. The CF6-80C2 is an improved version of the CF6-50. Despite its age of over thirty years the CF6-80C2 is still a commonly used engine in the maturity stage of its life cycle. This type has the most shop visits at Engine Services. The latest version of the CF6 is the CF6-80E, which is currently in the growth stage of the product life cycle. The fourth engine type that ES handles is the CFM56-7, the latest version in the CFM series. This engine is mainly used on Airbus A330 planes. This engine is also in the growth stage and has the second most shop visits at ES. Figure C.1 shows the four engine types including the number of shop visits to KLM ES in 2010-2011.

Figure C.1: The engine types at ES and the number of shop visits (SVs) in 2010-2011.

Appendix D Map of the logistics department of ES

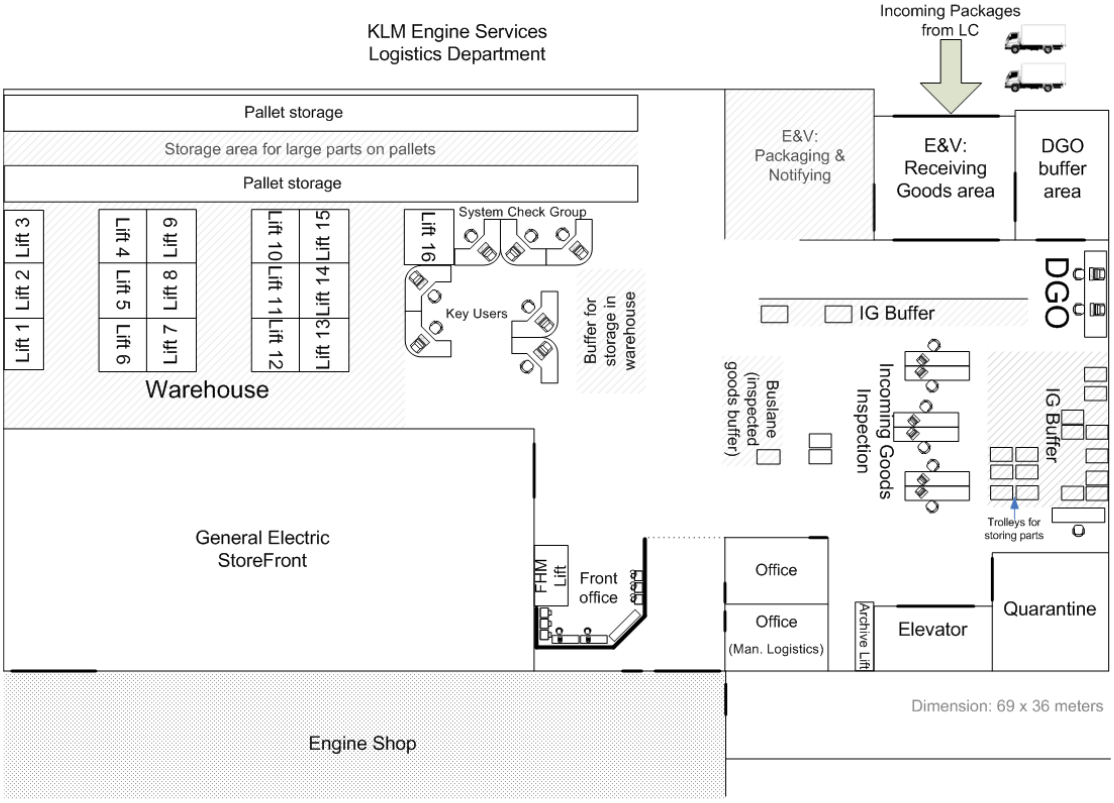

Figure D.1: Detailed map of the logistics department of ES.

Appendix E Certificate

1. DIRECTION GENERALE DE L'AVIATION CIVILE FRANCE

2. **AUTHORISED RELEASE CERTIFICAT**
Certificat libératoire autorisé
EASA FORM 1
Formulaire 1 de l'EASA

3. Form Tracking Number / ***N° de repère du Formulaire***
N° 729575

4. Organisation Name and Address / ***Nom et Adresse de l'organisme***
CRMA Aero repair
C.R.M.A.
14, Av. Gay-Lussac - Z.A de la Clef de Saint Pierre 78990 ELANCOURT

5. Work Order / Contract / Invoice / ***Bon de commande / Contrat / facture***
30855580
OR CRMA : **LC12210101**

6. Item / Item	7. Description / Description	8. Part No / N° de pièce	9. Qty / Qté	10. Serial N° / N° série	11. Status / Work Etat / Travaux
10	**LPT Rotating air seal stage 2**	**338-111-603-0**	**1**	**DA476485-J**	**OVERHAULED**

12. Remarks / ***Remarques***

OVERHAULED according to CFMI CFM56-7B ESM 72-54-06 revision 44 dated 15/07/2015
Rep001, Rep002 and Rep004 applied.
CSN: 14924 TSN 40635

No applicable AD/CN or mandatory S/B on this part in our field of work

The civil aeronautical product has been maintained in accordance with US Federal Aviation Regulations under FAA certificate n° CNF6912C .

13a. Certifies that the items identified above where manufactured in conformity to :
Certifie que les éléments identifiés ci-dessus ont été fabriqués conformément aux :
☐ approved design data and are in condition for safe operation
données de conception approuvées et sont en état de fonctionner en toute sécurité
☐ non-approved design data specified in block 12
données de conception non approuvées spécifiées dans la case 12

14a. ☒ Part - 145.A.50 Release to Service
Approbation pour remise en service selon Partie 145.A.50
☒ Other regulation specified in block 12
Autre règlementation précisée en case 12

Certifies that unless otherwise specified in block 12, the work identified in block 11 and described in block 12, was accomplished in accordance with Part-145 and in respect to that work the items are considered ready for release to service.
Certifie que, sauf indication contraire spécifiée en case 12, les travaux identifiés en case 11 et décrits en case 12 on été réalisés conformément à la partie 145 et qu'au vu de ces travaux, la (les) pièce(s) est (sont) considérée(s) prête(s) à la remise en service.

13b. Authorised Signature / *Signature autorisée*

13c. Approval / Authorisation Number / ***Numéro d'agrément / d'autorisation***

14b. Authorised Signature / ***Signature autorisée***
C.R.M.A. 44

14c. Certificate / Approval Ref. No / ***N° de certificat / d'agrément*** **FR.145.028**

3d. Name / ***Nom***

13e.Date (dd mmm yyyy) / ***Date (jj mmm aaaa)***

14d. Name / ***Nom*** ARCHIMBAUD P

14e. Date (dd mmm yyyy) / ***Date (jj mmm aaaa)*** 06 MAR 2012

USER/INSTALLER RESPONSABILITIES *Responsabilités de l'utilisateur/installateur*

This certificate does not automatically constitute authority to install the item(s).
Ce document ne constitue pas forcément l'autorisation d'installer l'(es) item(s)

Where the user/installer performs work in accordance with regulations of an airworthiness authority different than the airworthiness authority specified in block 1 it is essential that the user/installer ensures that his/her airworthiness authority accepts items from the airworthiness authority specified in block 1.
Quand l'utilisateur/installateur travaille selon les réglementations d'une autorité de navigabilité différente de l'autorité de navigabilité mentionnée dans la case 1, il est essentiel que l'utilisateur/installateur s'assure que son autorité de navigabilité accepte les items libérés par l'autorité de navigabilité mentionnée dans la case 1.

Statements in blocks 13a and 14a do not constitute installation certification. In all cases aircraft maintenance records must contain an installation certification issued in accordance with the national regulations by the user/installer before the aircraft may be flown.
Les indications portées en cases 13a et 14a ne constituent pas une certification de montage. Dans tous les cas le dossier d'entretien de l'aéronef doit contenir une certification d'installation délivrée conformément aux règlements nationaux par l'utilisateur/installateur avant que l'aéronef puisse voler.

EASA Form 1 - Issue 2 / Formulaire 1 de l'EASA - Edition 2

Figure E.1: Example of an EASA certificate for an overhauled part.

Appendix F Engine structure overview

Figure F.1 and Figure F.2 show an example from SAP of an engine and all its elements: modules, sub-modules, and part types. SAP displays the engine and its elements in a tree structure. To indicate that an element is a sub-element of a higher level in the hierarchy, it is situated below and on the right of the higher level element and connected with a line. In this example, the top level is the number of the engine in SAP, 455438. It is the most left situated entry indicating it is the highest level in the hierarchy. The second level is the actual engine repair project. This engine consists of 40 modules and 4 part types; the third level in the hierarchy. The 4 part types are displayed directly below the engine with the quantity of the part type on the right of the parts. The 40 modules each consist of several sub-modules. In the example of Figure F.1 and Figure F.2, one of the modules is expanded; it shows the 23 sub-modules of module the *Fan Frame, Stator and IGB assembly*. From these 23 sub-modules, we expanded the *Fan Stator Assembly* sub-module, which consists of 12 part types and 1 module that has 1 part type.

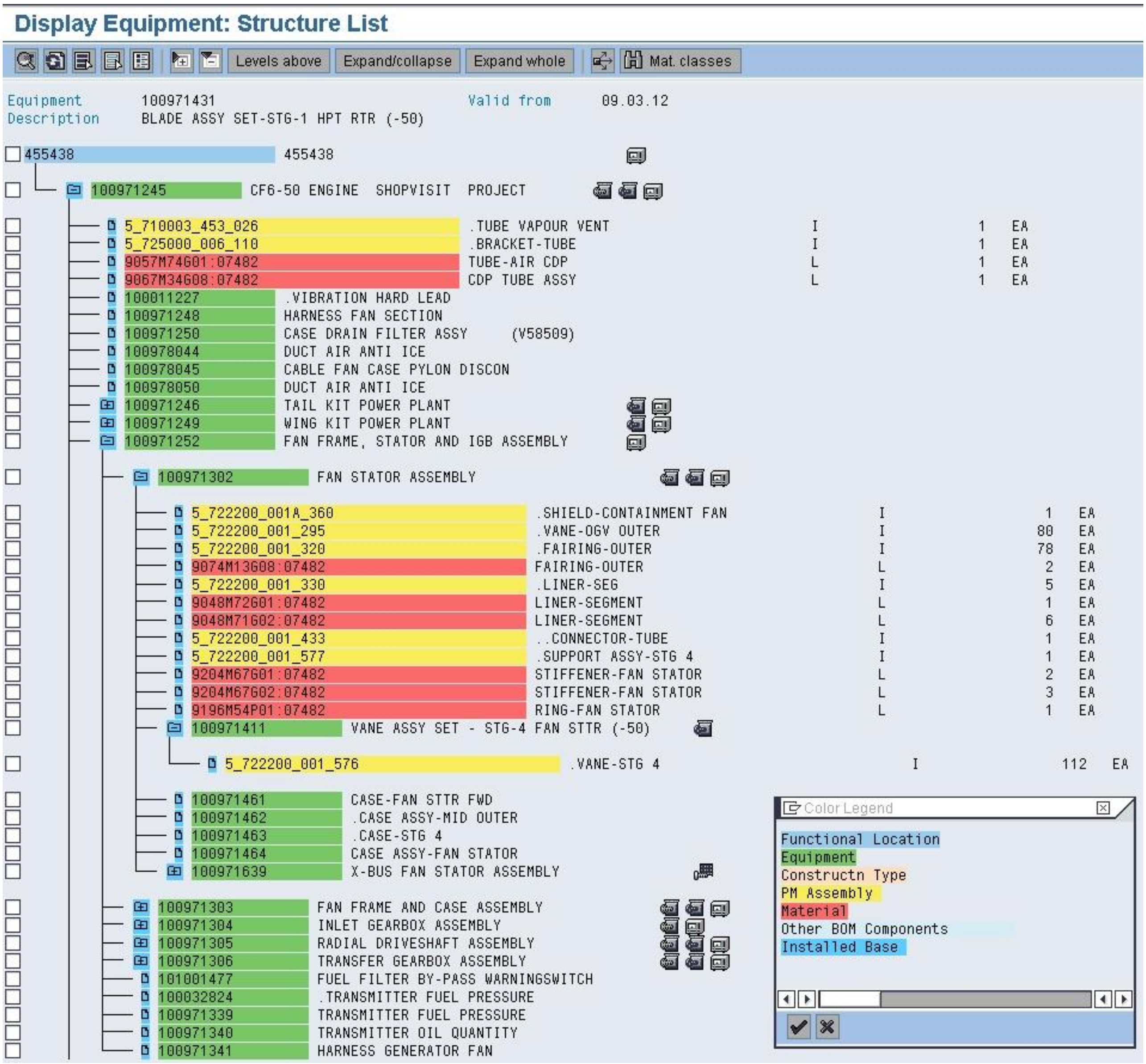

Figure F.1: Example of an engine structure in SAP (continues in Figure F.2).

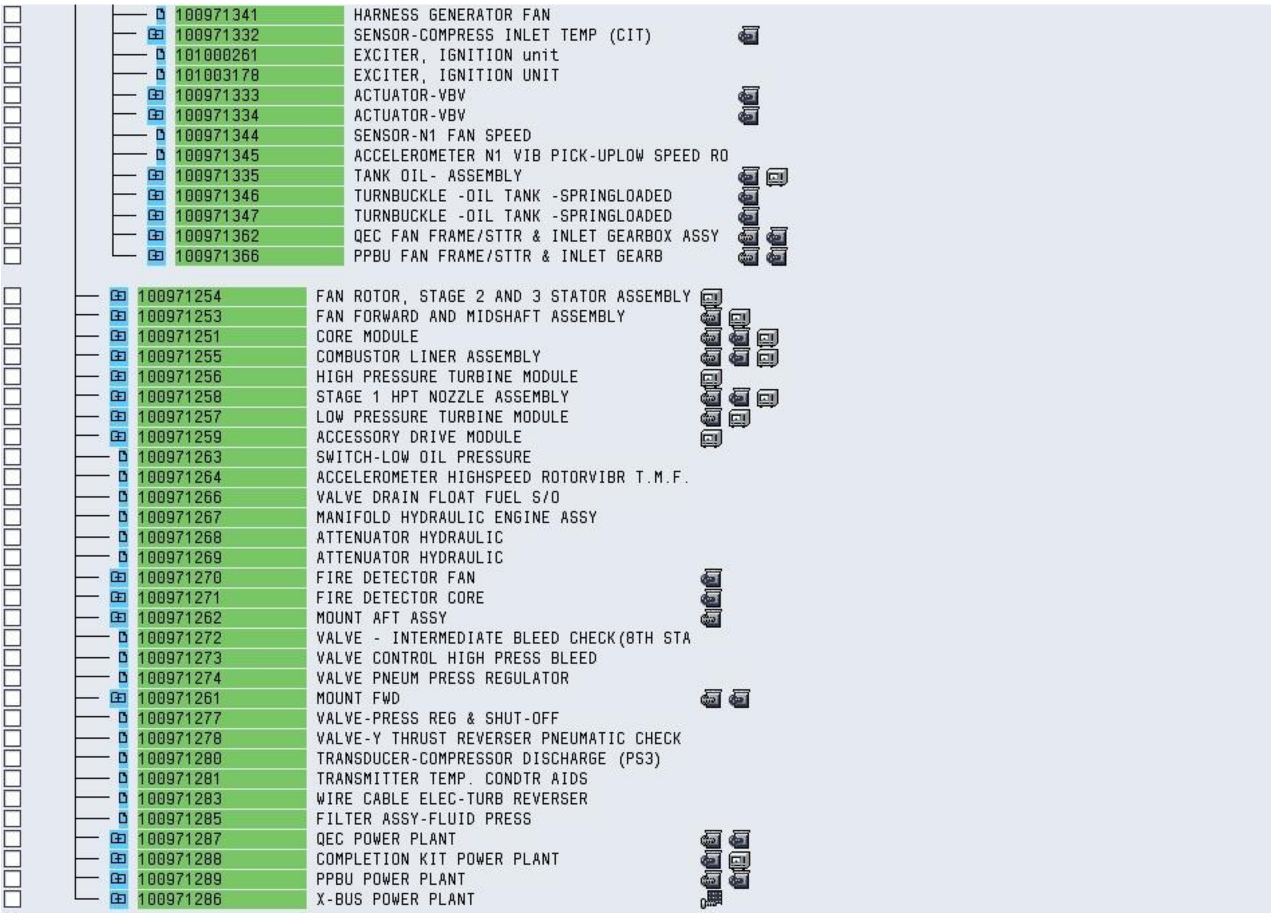

Figure F.2: Example of an engine structure in SAP (continued from Figure F.1).

Appendix G Shipment form with AM confirmation

The AM confirmation in SAP is usually placed in text fields of the Shipment form in the header of the inbound delivery number that belongs to a CR confirmation (see Section 4.1.2).

Figure G.1 shows an example of an AM confirmation placed in the Shipment form. The date and time of the confirmation are stored in the TransPlanngDate field, while the actual confirmation 'Accepted at ES' is stored in the TrnsIDCode field.

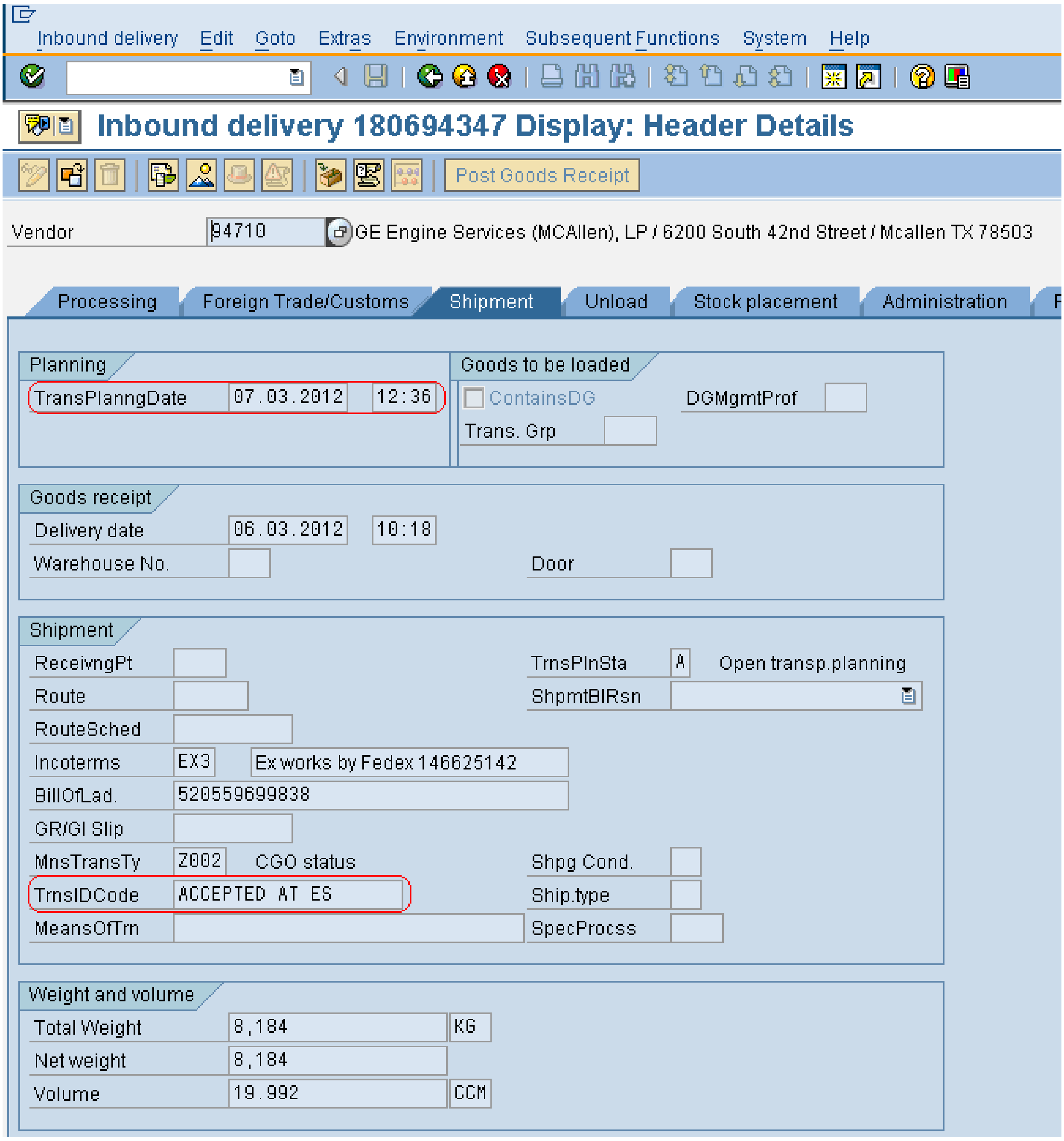

Figure G.1: Example of an AM confirmation placed in the Shipment form.

Appendix H Calculation of the medcouple

In this appendix, we explain how to calculate the medcouple for a data set and how to construct an adjusted boxplot, based on Brys et al. (2003).

Given a data set with *n* observations $X_n = \{x_1, x_2, \ldots, x_n\}$. We sort X_n such that: $x_1 \leq x_2 \leq \ldots \leq x_n$. Let m_n be the median of X_n. Then the medcouple (MC) is given by:

$$MC = \underset{x_i \leq m_n \leq x_j}{\text{median}} \; h(x_i, x_j)$$

Where for all $x_j \neq x_i$, the function $h(x_i,x_j)$ is given by: $h(x_i, x_j) = \frac{(x_j - m_n) - (m_n - x_i)}{x_j - x_i}$

So the function $h(x_i,x_j)$ measures the (standardized) difference between the distances of x_i and x_j to the median. Its value is positive if x_j lies further from the median than x_i, negative if x_i does, and 0 in the symmetric case where $x_j - m_n = m_n - x_i$.

Table H.1 shows how to calculate the lower and upper boundaries of the adjusted boxplot. Values that lie outside the interval between the lower boundary and upper boundary are considered as outlier. Note that in case MC = 0, the boundaries are equal to the boundaries of the classical boxplot.

MC	Skewed	Lower boundary of adjusted boxplot	Upper boundary of adjusted boxplot
> 0	To the right	$Q1 - 1.5 * IQR * e^{-4*MC}$	$Q3 + 1.5 * IQR * e^{3*MC}$
< 0	To the left	$Q1 - 1.5 * IQR * e^{-3*MC}$	$Q3 + 1.5 * IQR * e^{4*MC}$
0	Symmetrical	$Q1 - 1.5 * IQR$	$Q3 + 1.5 * IQR$

Table H.1: Values of the lower and upper boundary of the adjusted boxplot.

Figure H.1 shows an example from Hubert et al. (2007) of a classical boxplot and an adjusted boxplot for the same data set. The figure shows that the upper boundary of the classical boxplot lies too low, so several observations lie outside the boundaries of the boxplot and are unrightfully considered as an outlier. The adjusted boxplot clearly gives a better representation of the upper boundary.

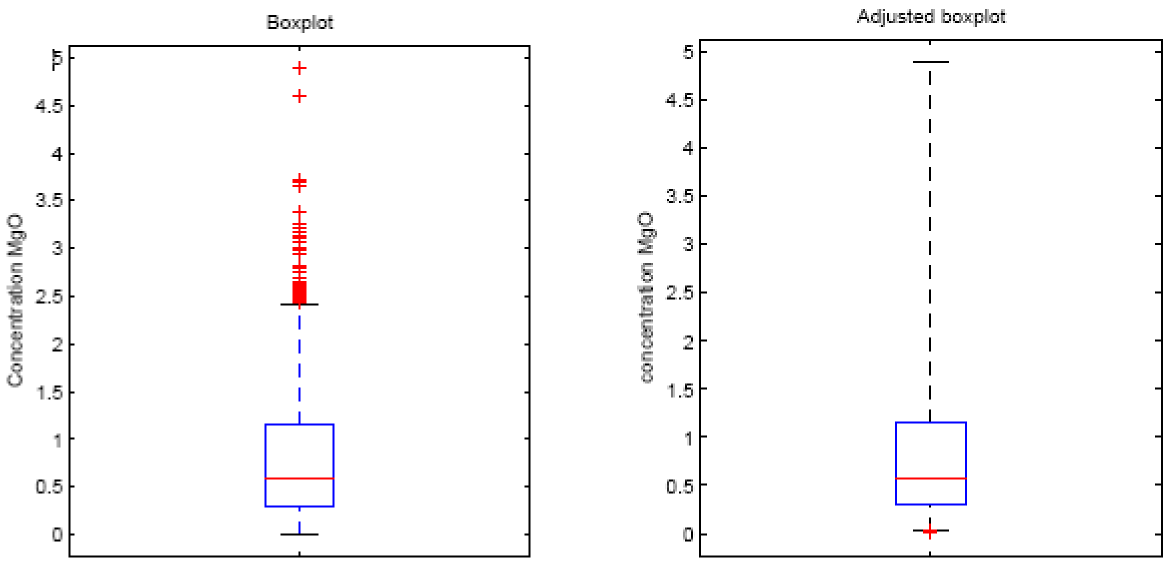

Figure H.1: Example of a classical boxplot and an adjusted boxplot for the same data set of MgO concentrations (source: Hubert et al., 2007).

Appendix I Empirical distributions of the arrival process

Table I.1 and Table I.2 show empirical distributions that we use in the simulation model.

#parts in box	1	2	3	4	5	6	7	8	9	10
Probability	66.3%	12.3%	6.0%	3.6%	2.4%	2.0%	1.4%	1.0%	0.7%	0.7%
#parts in box	11	12	13	14	15	16	17	18	19	20
Probability	0.5%	0.6%	0.4%	0.3%	0.0%	0.2%	0.2%	0.2%	0.2%	0.1%

Table I.1: Empirical Probability Distribution for the number of parts per package.

Hour of the Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
7	5%	4%	4%	5%	4%	1%	1%
8	5%	4%	2%	2%	4%	3%	8%
9	6%	3%	3%	2%	4%	6%	8%
10	6%	4%	5%	5%	3%	3%	5%
11	5%	3%	3%	3%	3%	4%	4%
12	9%	9%	9%	7%	9%	11%	15%
13	9%	10%	11%	9%	10%	10%	14%
14	7%	9%	8%	7%	8%	7%	6%
15	6%	7%	7%	8%	6%	11%	12%
16	9%	11%	12%	10%	11%	7%	3%
17	8%	8%	6%	8%	6%	9%	2%
18	4%	4%	5%	5%	6%	6%	5%
19	6%	8%	8%	7%	7%	10%	4%
20	4%	7%	6%	7%	6%	4%	4%
21	8%	7%	7%	8%	7%	5%	5%
22	3%	3%	2%	3%	3%	2%	0%
23	2%	0%	2%	2%	1%	2%	1%

Table I.2: Probability per hour per day of a delivery arriving at ES.

Appendix J Fitting the arrival distribution with a χ^2-test

To calculate the fit of the number of deliveries to ES per day with a Normal distribution with the values rounded up to integers, we use the Chi-square test. With this test, we calculate the *test statistic* χ^2 based on the data and compare this to the *critical value*. If the test statistic lies below the critical value, we do not reject the assumption that the data fits the probability distribution. The critical value is drawn from the chi-square distribution based on the degrees of freedom

As an example, we show how we test the fit of the data from Mondays to the rounded Normal distribution with μ = 7.15 and σ = 2.22; the average and standard deviation of the number of deliveries to ES on Mondays. Table J.1 shows the calculation of the test statistic:

$$\chi^2 = \sum_{j=1}^{k} \frac{(N_j - n * p_j)^{\,2}}{n * p_j} = \sum_{j=1}^{7} \frac{(N_j - 53 * p_j)^{\,2}}{53 * p_j} = 3.468$$

with:

N_j : # of observed values in interval j (j = 1, 2, …, k)

n : total # of observed values (= 53)

p_j : # expected values in interval j (given the rounded Normal(7.15,2.22) distribution)

j	Frequency = N_j	Expected Probability = p_j	n * p(j)	$(N_j - n * p_j)^2$	$\frac{(N_j - n * p_j)^{\,2}}{n * p_j}$
1	8	≤ 4	0.116	6.171	0.542
2	3	5	0.115	6.069	1.552
3	7	6	0.154	8.138	0.159
4	10	7	0.177	9.406	0.037
5	11	8	0.164	8.717	0.598
6	8	9	0.128	6.810	0.208
7	6	≥ 10	0.145	7.690	0.371
n	**53**				**χ^2 = 3.468**

Table J.1: Calculation of the χ^2 test statistic.

We have k=7 intervals, so the degrees of freedom is 7-1=6. The significance level α=0.05, so the critical value is $\chi^2_{6,\ 0.95}$ = 12.59. Since our test statistic χ^2 = 3.468 is smaller than the critical value, we do not reject the assumption that the arrival data is distributed by a rounded Normal(7.15,2.22) distribution.

Appendix K Sub-frames of the simulation model

Figure K.1, Figure K.2, and Figure K.3 display the sub-frames of the simulation model that represent the three logistical departments.

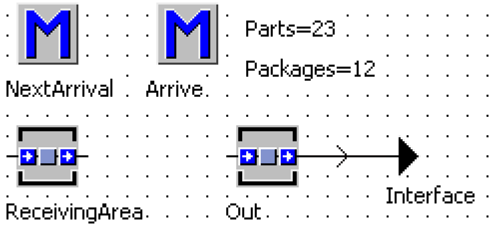

Figure K.1: Screenshot of the Expedition department in the simulation model.

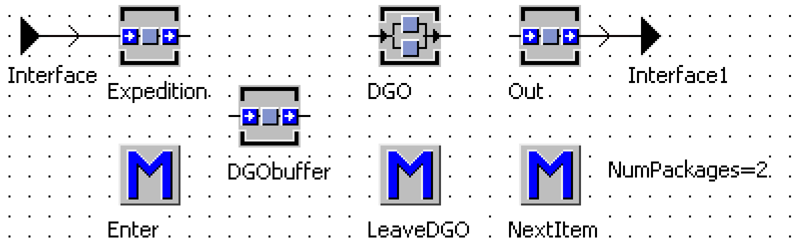

Figure K.2: Screenshot of the DGO department in the simulation model.

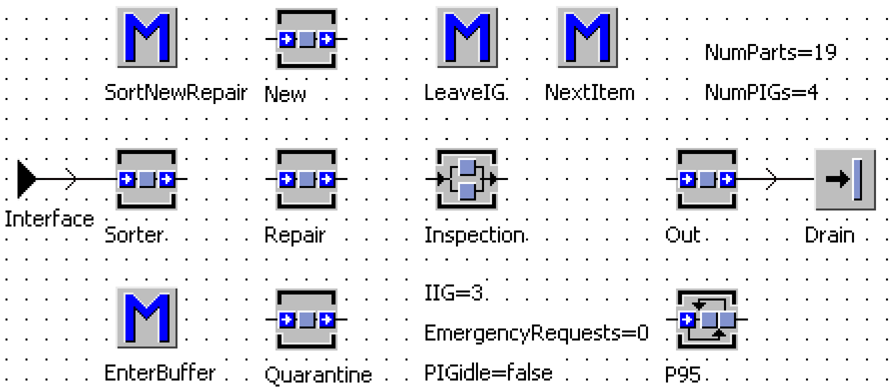

Figure K.3: Screenshot of the Incoming Goods department in the simulation model.

Figure K.4 shows a screenshot of the Incoming Goods department during a simulation run. It shows where the parts are in the Incoming Goods department. For instance, there are two parts in quarantine and the 6 IIGs are each inspecting 1 part.

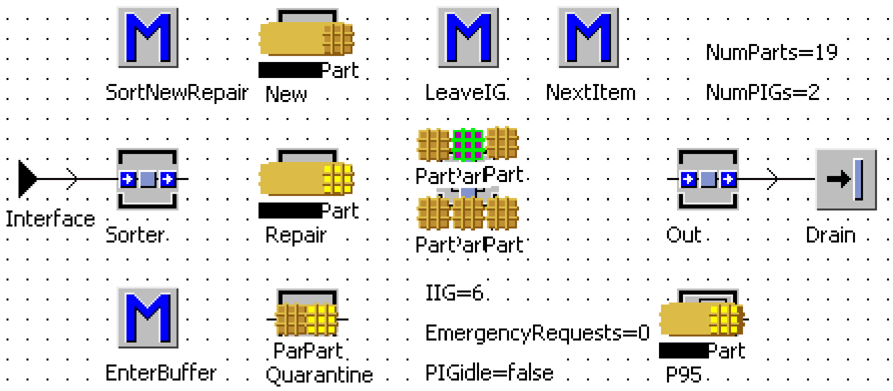

Figure K.4: Screenshot of the Incoming Goods department during a simulation run.

Appendix L Warm-up period

To determine an adequate warm-up period, we used the graphical method of Welch as described in Law & Kelton (2000). This method consists of four steps:

1. Make $n \geq 5$ replications of the simulation, each with length m (m is large). Y_{ji} is the *i*th observation from the *j*th replication (i = 1, 2, …, m; j = 1, 2, …, n)
2. Calculate the mean over the *i*th observation over n runs:
   $\overline{Y_i} = \sum_{j=1}^{n} Y_{ji} / n$ for i = 1, 2, …, m
3. Calculate the moving average $\overline{Y_i}(w)$, where w is the window. ($w \leq m/4$)
4. Plot the moving averages and choose the observation h beyond which the output seems stable. The observations before h form the warm-up period.

We did not perform Welch method for all our experiments due to time limitations. However, we selected the experiments in which the levels of the experimental factors seem most critical for the system, so we assume that the warm-up period for these experiments suffices for all experiments. Figure L.1 shows the graph we used to determine the warm-up period for the system in the original setting. The x-axis shows the number of the part. The y-axis shows the turnaround time in minutes.

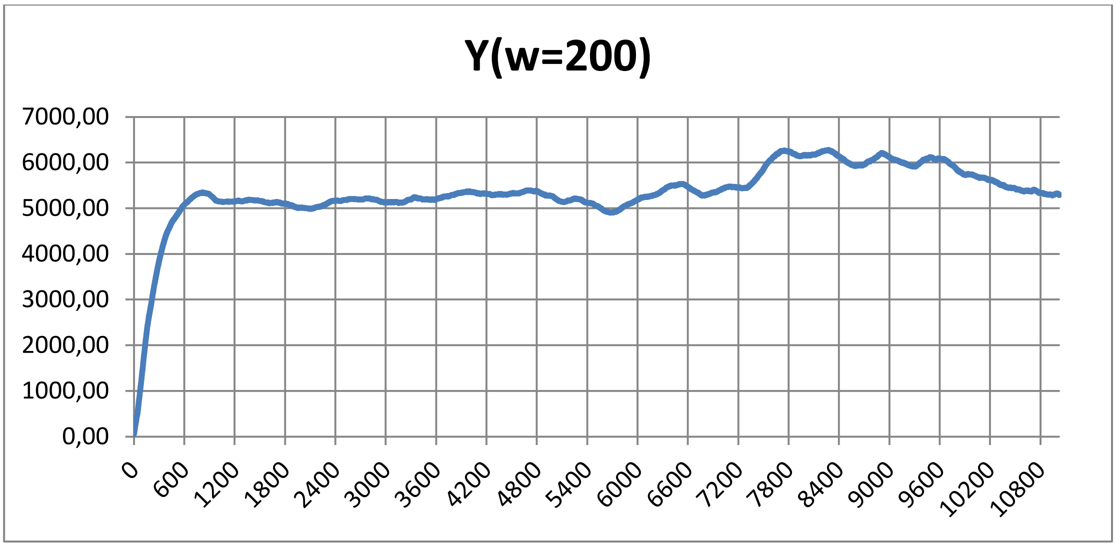

Figure L.1: Graph of the moving averages of the turnaround time of parts.

We performed n = 10 runs, each of length m = 20 weeks. We tested several values for the window. For w = 200, the graph became reasonably smooth. From approximately the 1100th part, the output seems to be stable. On average approximately 600 parts are inspected per week, so we estimate the warm-up period to be 2 weeks (= 1200 parts).

Appendix M Number of Runs

To determine the required number of runs for each experiment to ensure we can make a reliable estimate of the performance, we perform the sequential procedure as described in Law & Kelton (2000). We briefly explain the steps of this method.

First, we choose the desired relative error γ and calculate the matching corrected target value γ' = γ / (1+γ). (we choose γ = 0.1, so γ' = 0.091). Also, we choose α = 0.05. Then we follow the following steps:

1. Make $n_0 \geq 2$ replications of the system and set $n = n_0$.
2. Calculate the sample mean $\overline{X_n}$, the sample variance S_n^2, and the confidence interval half-width $\delta(n,\alpha) = t_{n-1,1-\alpha} * \sqrt{S_n^2 / n}$
3. If $\delta(n,\alpha) / \overline{X_n} \leq \gamma'$, then stop. Current n suffices.
   Else: n = n+1, perform another replication, and go to step 2.

Table M.1 shows the steps we have taken to determine the required number of runs for the system in the original setting. We see that for n ≥ 58, the output matches the requirement of step 3. We chose n = 60 as the required number of runs.

Run	Average turnaround time (min)	Average time over n runs	t-inv	variance	δ(n,α)	δ(n,α) / Average
1	7690,88					
2	6992,92	7341,90	12,71	243571,94	4434,19	0,604
3	6816,35	7166,72	4,30	213854,19	1148,77	0,160
4	7279,22	7194,85	3,18	145733,82	607,45	0,084
5	5109,38	6777,75	2,78	979134,90	1228,64	0,181
6	2882,49	6128,54	2,57	3312157,11	1909,90	0,312
7	6478,40	6178,52	2,45	2777616,80	1541,36	0,249
8	2003,51	5656,64	2,36	4559653,01	1785,18	0,316
9	6731,70	5776,10	2,31	4118113,21	1559,87	0,270
10	6352,36	5833,72	2,26	3693752,59	1374,85	0,236
11	7184,56	5956,53	2,23	3490264,97	1255,09	0,211
12	6263,23	5982,08	2,20	3180807,03	1133,17	0,189
13	8772,09	6196,70	2,18	3514520,74	1132,87	0,183
14	5982,07	6181,37	2,16	3247463,34	1040,49	0,168
15	2859,94	5959,94	2,14	3750961,20	1072,53	0,180
16	2987,25	5774,15	2,13	4053202,09	1072,79	0,186
17	6963,78	5844,13	2,12	3883125,04	1013,17	0,173
18	6213,31	5864,64	2,11	3662278,07	951,66	0,162
19	3368,81	5733,28	2,10	3786669,36	937,91	0,164
20	7290,66	5811,15	2,09	3708642,52	901,29	0,155
21	5429,89	5792,99	2,09	3530132,00	855,25	0,148
22	2703,06	5652,54	2,08	3796014,65	863,84	0,153
23	1546,36	5474,01	2,07	4356541,50	902,59	0,165
24	7384,28	5553,60	2,07	4319174,17	877,57	0,158
25	7259,35	5621,83	2,06	4255591,54	851,53	0,151

26	5804,90	5628,88	2,06	4086656,90	816,52	0,145
27	7893,33	5712,74	2,06	4119393,85	802,89	0,141
28	7238,60	5767,24	2,05	4049975,46	780,35	0,135
29	7442,08	5824,99	2,05	4002061,08	760,96	0,131
30	4952,42	5795,91	2,05	3889438,69	736,42	0,127
31	6862,05	5830,30	2,04	3796457,25	714,70	0,123
32	2808,15	5735,86	2,04	3959409,17	717,41	0,125
33	6672,01	5764,22	2,04	3862234,67	696,85	0,121
34	3214,77	5689,24	2,03	3936365,31	692,26	0,122
35	5744,02	5690,81	2,03	3820675,59	671,45	0,118
36	7431,10	5739,15	2,03	3795642,19	659,19	0,115
37	3796,78	5686,65	2,03	3792174,74	649,28	0,114
38	5896,83	5692,18	2,03	3690846,08	631,47	0,111
39	5903,57	5697,60	2,02	3594864,27	614,62	0,108
40	4512,93	5667,99	2,02	3537774,29	601,54	0,106
41	6228,39	5681,65	2,02	3456989,77	586,87	0,103
42	7671,30	5729,03	2,02	3466927,03	580,23	0,101
43	9051,92	5806,30	2,02	3641163,04	587,25	0,101
44	5185,30	5792,19	2,02	3565249,44	574,06	0,099
45	6948,52	5817,89	2,02	3513934,15	563,18	0,097
46	3333,06	5763,87	2,01	3570072,13	561,10	0,097
47	2253,18	5689,17	2,01	3754693,99	568,93	0,100
48	3621,93	5646,10	2,01	3763837,66	563,34	0,100
49	3675,56	5605,89	2,01	3764669,84	557,31	0,099
50	2982,63	5553,42	2,01	3825469,92	555,86	0,100
51	5637,36	5555,07	2,01	3749098,66	544,58	0,098
52	5253,96	5549,28	2,01	3677330,52	533,87	0,096
53	8137,93	5598,12	2,01	3733048,96	532,56	0,095
54	7481,34	5633,00	2,01	3728290,53	527,03	0,094
55	2732,83	5580,27	2,00	3812174,63	527,83	0,095
56	6635,74	5599,11	2,00	3762755,79	519,48	0,093
57	3956,50	5570,30	2,00	3742900,32	513,33	0,092
58	4412,86	5550,34	2,00	3700333,11	505,79	**0,091**
59	7837,44	5589,10	2,00	3725192,47	502,98	0,090
60	8069,11	5630,44	2,00	3764560,41	501,22	0,089

Table M.1: Sequential procedure for the system in the original setting.