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Steering life cycle costs in the early design phase

by
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Abstract

This master thesis project describes and models the relationships between life cycle costs and technical system availability for capital goods, and material handling systems in particular. Innovative in this research is that it integrates decisions in the system design phase with decisions in the operational and maintenance phase. The resulting model provides insight in the trade-offs between these decisions in terms of costs, and therefore can evaluate different alternatives.
An applied model has been developed for baggage handling systems, which can be applied to any given system design.

Preface

This master thesis is the final work of my study Industrial Engineering and Innovation Sciences. I have executed this master-thesis at the department of Operations Planning Accounting and Control in the area of service logistics and at Vanderlande Industries.

From the University of Technology Eindhoven I would like to thank Tarkan Tan for his supervision during my master. I have really enjoyed our cooperation and the helpful support that he provided during the project. Since the topic I have worked on is quite innovative for practice and literature, therefore I worked closely with Kurtulus Öner, AIO at Eindhoven University of Technology. I would like to thank him for the time and effort he put in our discussion sessions. Finally, I would also like to thank Geert-Jan van Houtum, my second supervisor for his feedback on my presentations and reports.

At Vanderlande Industries I would first of all want to thank my first supervisor Radj Bachoe. I have very much appreciated our discussions and all the effort he put into our project. Furthermore I would like to thank Jeroen Goes and Maarten Broekman for their input and feedback on my presentations.

Finally I would like to thank my family and friends for supporting me during my study period. Thanks to you all I have really enjoyed this period!

Rutger Vlasblom
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Executive summary

This report is the result of a Master-thesis project at Vanderlande Industries (VI). VI is an internationally operating company with extensive knowledge and experience in the design and implementation of innovative, automated solutions for material handling systems. The company is divided in four business units; Distribution, Express Parcel, Baggage Handling and Service. The results of this project are generalizable to all the business units, but have a detailed focus on the business units Baggage Handling and Service.

A current trend in the material handling branch is that the demand for life cycle costs (LCC) analysis is increasing. This results in the tendency of original equipment manufacturers becoming responsible for system performance and LCC. Anticipation by these original equipment manufacturers is required in order to provide their customers competitive advantage in terms of lowest LCC and high system performance.

The difficulty with LCC minimization is that multiple disciplines like sales, system design, R&D and service are involved. Commercial issues like lowest system acquisition price and highest technical system availability (AT) can cause conflicting issues when minimizing LCC. For example, the impact of system design decisions in the early sales phase will affect the maintenance costs during the operational phase. Therefore, insights in the effects of decisions at the related disciplines should be made visible and taken into account for LCC calculations. Moreover, system design decisions determine a large part of the AT. In general it can be stated that LCC are largely determined by the requirements on AT. Therefore an insight into the relationships between LCC and AT is strongly desired.

The research assignment developed in this study is stated as:

Develop a calculation model that determines the relationship between technical system availability and life-cycle costs. Based on this model, build a tool which supports VI in the sales phase on evaluating the availability and life cycle costs of a given system design using mean time between failure (MTBF) and mean down time (MDT) on section level.

The goal in this study is not to find the optimal values for the decision variables of the model in order to minimize the LCC. In stead this study establishes and models the relationship between the decision variables and LCC and AT. This approach has lead to the following action plan:

- Determine the current LCC methodology and the LCC focus of this model
- Determine the decision variables that should be incorporated in this model
- Construct a calculation model that incorporates the relationships of LCC and AT
- Build a tool that provides insight in the effects of the decision variables on LCC and AT

The current LCC methodology has well covered the important cost elements and the cost structure of LCC of material handling systems. The next steps should be to determine the potential trade-off relationships between the costs and to develop a methodology to evaluate these trade-off relationships.

In order to determine the decision variables that should be incorporated in this model, it is determined which factors influence AT. Before defining these factors it is important to have consistency about how AT is defined in this study:
A system is technically available when it can meet the throughput where VI and its customer agreed on. A system is unavailable when due to technical failure the system can not meet the throughput where VI and its customer have agreed on.

The interest of customers of BHS in AT is mainly influenced by the high costs related to downtime of the system. Therefore they require a high level of AT. This high level can be obtained in two ways;

1. by increasing the MTBF of the system
2. by decreasing the MDT of the system.

This study has determined seven decision variables that affect the MTBF and MDT of a material handling system.

It appeared that not all of the relationships between the decision variables and the MTBF and MDT could be obtained from practice. For some variables as realistic as possible assumption had to be made in order to establish a suitable relationship. Other variables were considered to be constant in this study. Of the seven decision variables, the four most relevant have been incorporated;

- sections (affects MTBF)
- level of redundancy (affects MTBF)
- level of preventive maintenance actions (affects MTBF)
- spare part inventory levels (affects MDT)

The other three decision variables were assumed to be constant;

- level of modifications and retrofits (affects MTBF)
- level of training and maintainability (affects MDT)
- service contract type (affects MDT)

Changing the decision variables in order to influence the technical availability level requires investments. To identify which investments lead to lower LCC, it is essential to determine the relationship between investments and the decision variable. To determine these relationships multiple data-analyses have been conducted at a reference site in order to obtain reliable data. Furthermore a relationship has been established between the availability of the system and the expected number of delayed bags (down time costs). Moreover, the other parts of LCC of BHS are considered as constants in this model, and determined by the current methodologies of VI.

Based on these variable and constant relationships a mathematical model has been developed and translated into a tool that provides insight in the effect of the decision variables. The model is qualitatively validated by justification of all decisions and assumptions made in this study. A sensitivity analysis has tested the robustness of the model and provided insight in the sensitivity of the modeled relationships. An actual project has been evaluated by comparing different system designs, different conveyors lengths, different inspection frequencies, different spare part levels and possible reductions in MTTR. The main results of this evaluation are:

- Investments in increasing designed capacity and in technical system availability can earn it self back by savings on downtime costs.
- Extra spare part investments in comparison to the current policy did not provide substantial higher AT. Reducing the spare part levels has a negative impact on AT, and leads to higher LCC. This means that due to the downtime cost function an optimum can be found between spare part levels and minimized LCC.
- The replacement of long conveyors by multiple shorter conveyors increases the LCC and AT, due to the increasing amount of critical components in the system.

Furthermore main general conclusions of this research are:

- The model is generalizable and can be applied to other segments (distribution and express parcel) as well. Of course these applications would require other input variables, however these can be obtained in a similar way as for BHS.
- Special attention has been paid to create an intuitive tool, which uses information that is well known within VI. It uses the basics of the sandglass model (appendix B) with section level as lowest workable level. Furthermore a fit within current business processes has been created, and it is well prepared for future changes in the current business processes.
- Instead of LCC calculations on stock keeping unit (SKU) level (element and material level) delay time for spare parts is aggregated to section level, which prevents too detailed analysis in an early project phase.

Finally the main recommendations to improve the model are as follows:

- Since the data at the reference site is tracked over a relative short time-span the distributions for failure rates on section level and spare part level could not be obtained. Therefore the MTBF figures used in this study are based on the best estimates possible. It is recommended to replicate these measurements in the future in order to obtain more reliable failure distributions.
- The analyzed data is based on one reference site and not replicated in order to validate the data to other reference sites. A recommendation would be to replicate this data at different reference sites to increase reliability of the input parameters of the model.
- In this study the effect of inspections on the MTBF of is considered to follow a linear relationship. In reality it can be assumed that the relationship will behave more like a concave relationship. Further research on these relationships between different maintenance frequencies and the MTBF is highly recommended.
- For the expected number of delayed bags (an important indicator for down time costs) holds that system dependency is not taken into account, while this factor will most probably will affect the down time costs as well. Therefore it also highly recommended replicating the same analysis at other reference sites.

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Introduction

In the past few years the customer demand for life cycle cost (LCC) analysis for material handling systems has increased. The downward pressure on prices has led to a situation where customers of material handling systems want to focus on their core competences. Therefore the responsibility of system performance and LCC is put more and more into the hands of the original equipment manufacturer (Kim, Cohen, Netessine 2007).

Vanderlande Industries (VI) developed a lot of knowledge regarding the LCC of material handling systems. They have experienced an increasing trend in the demand for LCC analysis in combination with system performance (system availability). Therefore VI wants to position the current LCC support to a level, where it can offer its customers systems that provide competitive advantage in terms of lowest LCC and high system performance.

This Master thesis project aims at developing a model, which supports in steering LCC costs and system performance in the initial phase of a project, by focusing on the design of the system. This research consists of two preliminary studies that have been conducted before the start of this project. Chapter 1 is a combination of these preliminary studies.

Chapter 1 combines the practical insights obtained and quantitative data analysis with literature related to the area of LCC and system performance. This has resulted in a clear insight in the branch developments and in a problem statement. Based on these insights a research assignment has been developed to steer this project into the right direction. This report consists of four more chapters of which an outline is given at the end of the first chapter.

1 Company description and research assignment

This chapter consists of three sections; in the first section a company description is presented, and in the second section it describes the path toward the developed research assignment for this project. Finally the third section elaborates on the demarcation of this study.

1.1 Company description

The company description consists of four subsections; it starts with a general overview of the company in subsection 1.1.1 and continues with the business units of interest for this specific study in subsection 1.1.2. In subsection 1.1.3 the departments related to the topics of this study are described. This section concludes with the problem background and states the problem definition in subsection 1.1.4.

1.1.1 History and company profile

Vanderlande Industries (VI) was founded in 1949 from a small company by E. van der Lande, whose primary business was service and repair of machines for the textile industry. Nowadays, VI has evolved to an internationally operating company with extensive knowledge and experience in the design and implementation of innovative, automated solutions for material handling in distribution facilities, e-fulfillment centers sorting facilities of express parcels, production facilities and baggage handling systems. VI implements material handling systems of all sizes, ranging from many local sorting depots, airports and distribution centers to the world's largest facilities.

The mission of VI is: "*To support our customers worldwide in significantly improving their competitive position by designing, implementing and servicing automated material handling systems.*" Translating this mission into the current business strategy generates a net sales around 600 million euros a year (Annual report, 2008).

The emphasis within VI is on close partnership with the customer, extending from initial analysis of the underlying business processes through total life-cycle support. To achieve this, VI possesses core competences in all the relevant disciplines, ranging from system design and engineering, through supply chain management and manufacturing, to information and communication technology, system integration, project management and customer services. Vanderlande Industries is a global player with a presence in all key regions of the world. It operates locally through customer centers in many countries handling all key business functions and maintaining direct contacts with customers.

1.1.2 Company structure

In essence the company is divided into four different business units; Distribution, Baggage Handling, Express Parcel, and Service. The study described in this report is executed in the area of Baggage Handling and Service, therefore below a brief description of these business units is given:

Baggage Handling
VI designs, builds and services Baggage Handling Systems (BHS) for airports of all sizes. These solutions combine operational effectiveness (low rates of mishandled bags), short connection times and high conveyability. Based on proven technology, in-depth business knowledge and industry best-practices, they deliver high availability, reliability and low costs per handled bag.

Service
The business unit Service recently emerged within VI's structure due to the rising interest of customers to buy maintenance service for their systems. VI provides all the required service facilities through the operational lifetime of customer systems. The most important performance criteria for this business unit are productivity, reliability and system availability.

Although this research model focused on these two business units, the same general model can be applied to Distribution and Express Parcel. However detailed model descriptions require system specific input parameters.

1.1.3 Departments of interest

For each business unit holds generally that the business processes are as depicted in figure 1.1. It presents how new products are developed, exposed and sold to the customers. As described before the study object will be the BHS and Service business unit, within these business units the system engineering department, service and the sales engineering department are of specific interest.

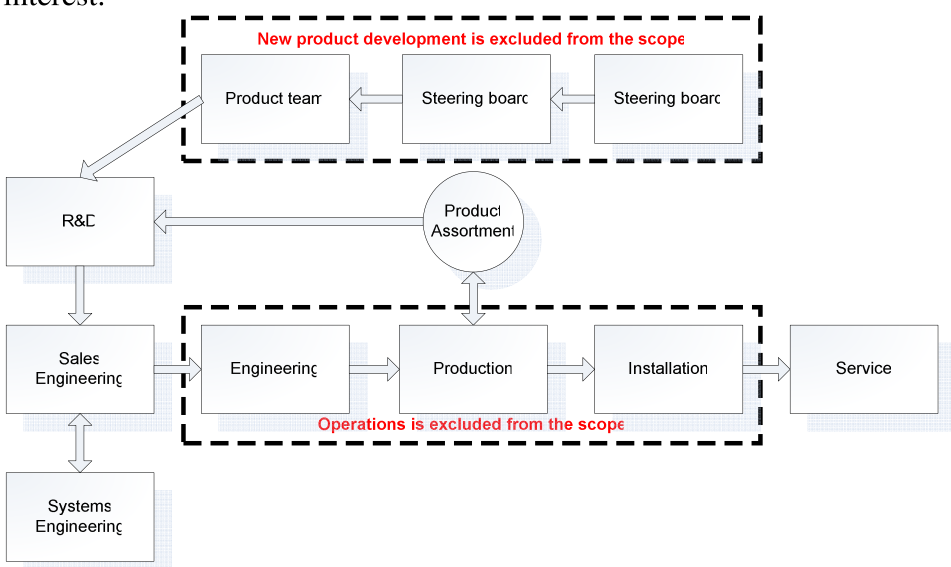

Figure 1.1: Global overview of VI's business process

Research and development
One of the critical success factors is the continuous development of new products. Market needs are ventilated by the steering board and translated into functional and technical requirements by product teams. Based these functional and technical specifications, the R&D department develops

new products that form the building blocks for VI's systems. In this study only a selected group of BHS products and their characteristics are used from the R&D department.

Sales engineering
The sales department determines in cooperation with the customer the specifications of the new system of the customer. Using the building blocks (sections) from the product assortment provided by R&D the sales engineers start building a system. In this proposal phase the degree of influence on the system design is quite large.

Systems engineering
The systems department can support the sales engineers in the design and equipment selection phase of the system. This support exists of capacity and availability studies executed by systems simulation. Pricing support is done by systems proposal verification and pricing. Quotations contain a fixed price, project planning and project scope. Also the system performance, in terms of capacity, commercial and delivery conditions, penalty clauses, accepted error level, noise level and method of performance measurement, are specified. Life cycle considerations could also be included upon request, although not every sales project requires LCC the demand is increasing.

Operations
When systems are definite and sold to the customer, engineers produce and install all the equipment. Although all main decisions on the system design have been made in the sales phase, it can occur that on-site the system design can be made more efficient or has to be adjusted. These adjustments can be done but in a limited fashion. All activities executed in the operations department are considered to be out of the scope of this study.

Service
As mentioned before another important department in the process and in this study is the service department. After the system is installed and considered to be fully operational the system needs to be maintained in order to prevent failures during operation. Service is done on a contract basis, ranging from a helpdesk telephone service to on-site maintenance teams. Maintenance functions will be evaluated on aspects as costs, failure rates, down times (availability). Although in this phase the influence on the system design and LCC are limited, system maintenance is executed as efficient as possible. Furthermore the expertise of service is also represented in product teams where new products are designed, such that serviceability is high and the amount of downtime is minimized.

1.1.4 Background and problem definition

Since quite some years VI developed a lot of knowledge regarding LCC of their systems. Currently the demand for LCC analysis in combination with system performance of material handling systems is increasing. Therefore there is a need to lift the current LCC support to a next level. Support can also be found in literature, where Kim et al (2007) state that performance-based contracting, an approach frequently used in capital intensive industries such as aerospace, is replacing traditional service procurement practices.

Background

This subsection describes the current situation with respect to the development and trends in the material handling branch. Five of these aspects will be discussed in detail.

Increasing demand for LCC analysis
A rising trend in material handling systems is the increasing interest in the total life-cycle costs of a system. Ever more customers require a detailed insight into these life-cycle costs. The current analysis to provide system specific LCC is mainly based on experience-figures, which have not been validated in practice. Furthermore LCC analysis is expected to become a standard deliverable and a competitive advantage.

Emergence of performance based contracts
Contracts that focus on performance of material handling systems are becoming more and more important. The system performance is generally measured by availability of the entire system during operation time. In various capital good industries, penalty costs (downtime costs) are charged in case the agreed availability levels are not met, while a specific reward payment can be received in case the system performed better than agreed on.

Importance of service
In the last 5 years multiple cost break-down studies have been conducted on LCC of VI's BHS at different airports (van Putten (2002), Hoefkens (2005) and Franssen (2006)). These cost break-down structures all stressed the large contribution of service costs in LCC. Currently it is estimated that yearly service costs are 5% of the initial project investment. Furthermore to stress the importance of service, VI mentions service in their mission statement as a competitive advantage for the customer.

Lack of central LCC model
Currently when system engineering supports in developing a LCC analysis it requires input from all related departments and combine these in order to come to a rough LCC calculation. When these departments try to minimize their costs or provide alternatives, it is currently not very transparent to see the effect on the LCC.

No integrated availability calculation
Availability studies are executed by the systems simulation department. This calculation method uses fixed failure and repair figures which are based on test figures obtained in the equipment test center of VI. Beside the fact that there are many doubts about the accuracy of these figures they are also set fixed and therefore independent of maintenance policy and spare part policy.

Problem definition

Based on the described situation, with respect to the development and trends in the material handling branch, the following problem definition is defined:

Although VI has a lot of knowledge and expertise in the area of life cycle costing, there is a large need for a central calculation model that provides quantified insight in the relationship between system availability and life-cycle costs.

In order to solve this problem it is important to carefully state a research assignment. The next section provides a brief description of the path towards this research assignment.

1.2 Research assignment

In order to come from the problem definition to this research assignment a desk research has been conducted in order to explore previous research and literature within this area. Figure 1.2 visualizes the path of converging to the research assignment. First two important researches done at VI in the area of LCC have been analyzed to find out which areas have already been explored and what is still underdeveloped. Based on these underdeveloped areas a literature review has been conducted to generate a focus in the research assignment.

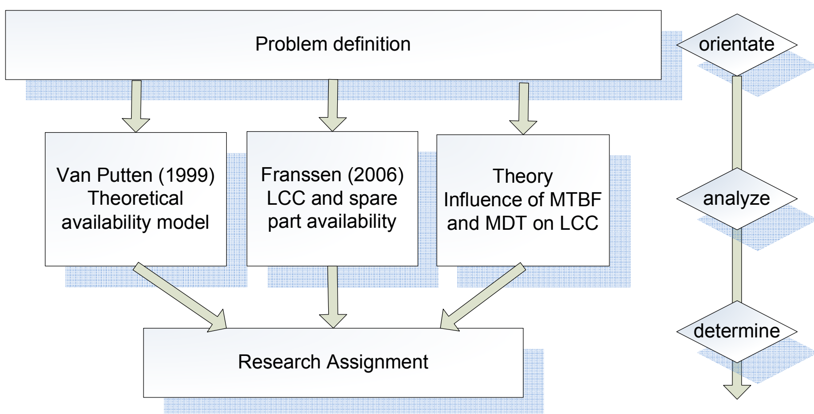

Figure 1.2: determining the central research question and assignment

Previous research at VI

Ever since these trends described in 1.1.4 became visible VI has been working on providing an insight into total LCC. The first research related to life cycle costing was done by van Putten (1999, master thesis project). This research focused on determining a method for life-cycle costing and separately provided insight in models that can determine system availability.
A more recent study on LCC is done by Franssen (2006, master thesis project). He identified the main cost buckets of LCC for a BHS. The main cost buckets that were identified in his research were acquisition costs, maintenance costs, operational costs and down-time costs (see appendix A). An important finding in his research was that it appeared that maintenance and down-time costs together accounted for over 70% of the total LCC of a baggage handling system.
Furthermore Franssen (2006) developed a formula, which consisted of all cost elements of the entire life-cycle of the BHS. Based on this formula he developed a tool that determines the LCC of a specific system. In his calculations he incorporated an optimal spare-part inventory in order to have minimal spare part investments and a high level of spare part availability.

Influence of system's MTBF and MDT on LCC

Previous research has developed quite some insight into the aspects of LCC. An area that is still developing is the influence of the system design on the LCC and availability. According to Dowlatshahi (1992), Barringer and Weber (1996), Elram and Siferd (1998) the majority of the cost drivers are determined and locked up in the design stage, so this stage should receive careful attention. The most important aspect of life-cycle costing in the design phase is the mean time

between failures (MTBF) of the system. On the one hand this plays an important role in the costs of the design phase, increasing the MTBF of the system will also increase the system's acquisition cost (Öner et al, 2008). On the other hand it will also play an essential role in the maintenance costs of the life-cycle, namely lowering the MTBF of the system will lead to higher maintenance costs (in terms of maintenance activities and spare part inventory).
The other important aspect is the time the system is expected to be out of operation when a failure occurs. Although system's MTBF are quite long, the mean down time (MDT) determines the costs of not operating for each system failure. Therefore original equipment manufacturers should make sure these down times are as low as possible. These relationships are of course an interesting issue, because it means that there will be a trade-off point between the MTBF, MDT and the LCC.

This path has lead to the following research assignment:

Develop a calculation model that determines the relationship between technical system availability and life-cycle costs. Based on this model, build a tool which supports VI in the sales phase on evaluating the availability and life cycle costs of a given system design using MTBF and MDT on section level.

1.3 Demarcation

Due to time constraints there is a necessity to narrow down the research scope, this is done in two ways; first of all in terms of modeling relationships and secondly by selecting a study-object that will be analyzed into detail. This section will give an answer and an explanation for the scope of these terms.

1.3.1 Scope of modeling relationships

The section describes how modeling relationships are narrowed down by three decisions; first of all by defining system availability in this study, secondly by determining the related LCC, and thirdly by the level of detail of these relationships.

System availability in this study
In practice system availability consists of two types, namely operational system availability and AT (see figure 1.3). Operational system availability is the part where downtime is caused by operational errors, which cannot be assigned to the components or design of the system. AT is the part where downtime is caused by technical failures in the system, these can be either by system hardware or software failures. This distinction is made in practice in order to allocate failures to either the physical system or the use of the system. Therefore in this calculation method the focus is on AT, and the operational system availability is considered to be constant during the system life cycle in this study.

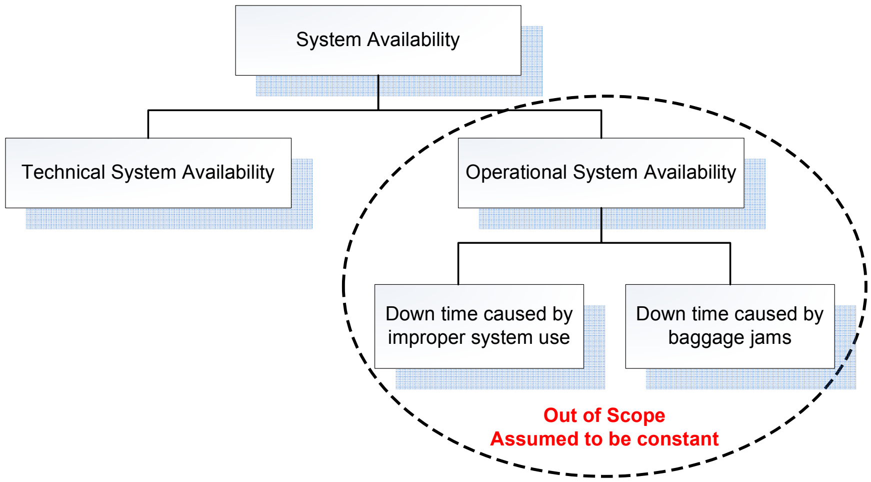

Figure 1.3: System Availability

A detailed break-down of AT is presented in figure 1.4 (Kelly and Harris,1978) applied to VI. This figure gives an overview of the decision variables that influence system availability.

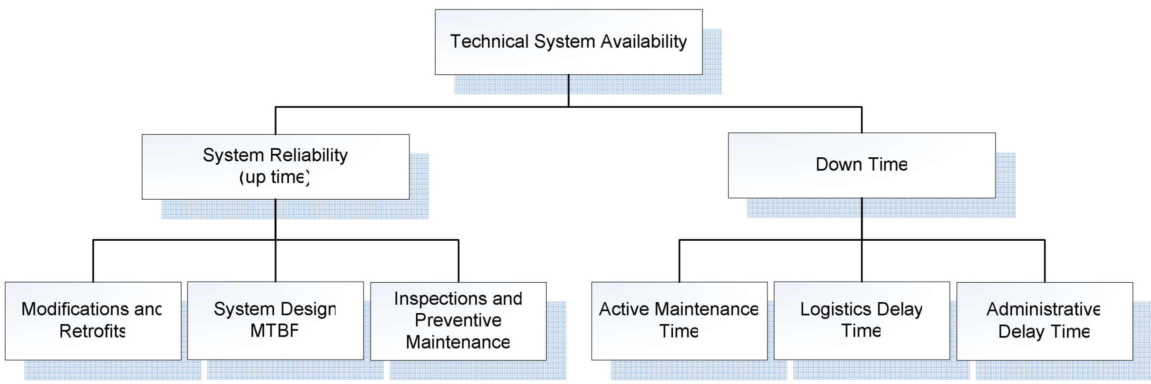

Figure 1.4 Factors that influence system availability (extended version of Kelly and Harris, 1978).

First of all system reliability is largely determined by the system design in terms of the MTBF of the components in the system and the level of redundancy. Secondly system reliability can be extended by inspective and preventive maintenance activities. Finally, and to a less extend system reliability can be influenced in the operational phase by modifications and retrofits. On the other side downtime is influenced by the mean time to repair a technical failure (MTTR). Secondly it is influenced by the availability of spare parts, and finally the downtime is influenced by the response time to a failure.

Related Life cycle costs

As mentioned earlier there have been more studies on LCC conducted, Franssen (2006) has determined the main cost buckets for BHS. As stated in the research assignment the focus of this study is on the LCC that are related to availability. Figure 1.5 shows an overview of the total LCC of a system. The costs in the outer-ring are not related to availability and therefore not considered in this study. The costs in the second ring are related to availability, but since their relation is currently to difficult to determine they have been considered as constants in the model. The costs related to the inner-ring are related to availability and their effects and costs are incorporated in the model. Chapter 2 elaborates on why these LCC are considered in this study.

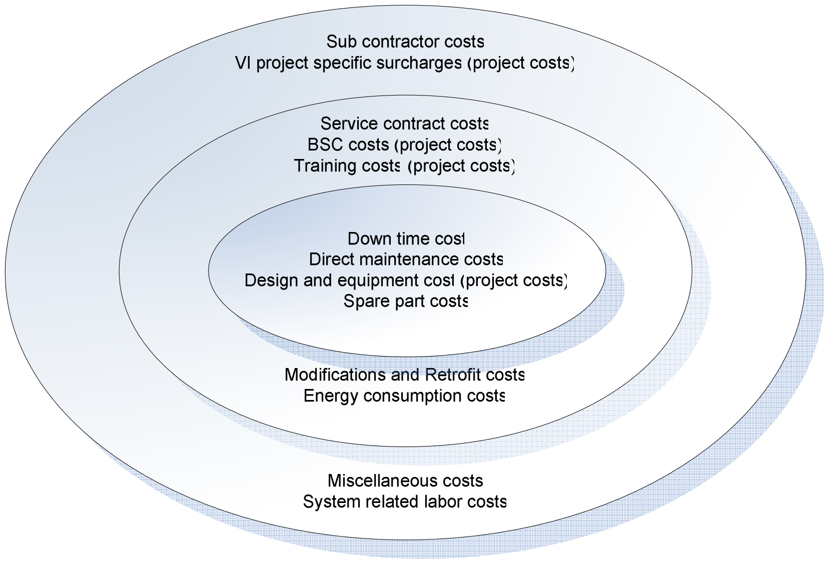

Figure 1.5: Ring-model, VI's total LCC and LCC considered in this study

Level of detail

A sandglass model has been developed, which breaks down an entire material handling system into lower level components (appendix B). The level of MTBF and MDT should be determined in order to have a starting point for an aggregate system availability. By qualitative reasoning together with experts of the design and service department it is decided to set the level of detail on section level. This decision was based on two reasons;

1. It would be too complicated and time-consuming to do data research on a lower level than section level,
2. The need to standardize equipment is increasing and section level is considered to be the lowest workable level which is known throughout the entire organization.

Figure 1.6 provides an example of the level of the system of which the data should be gathered and analyzed. The area level consists of four check in zones and a transport zone. The check in zone consists of two sections (weighing belt and a belt floorveyor), while the transport zone consist of three sections (three belt floorveyors).

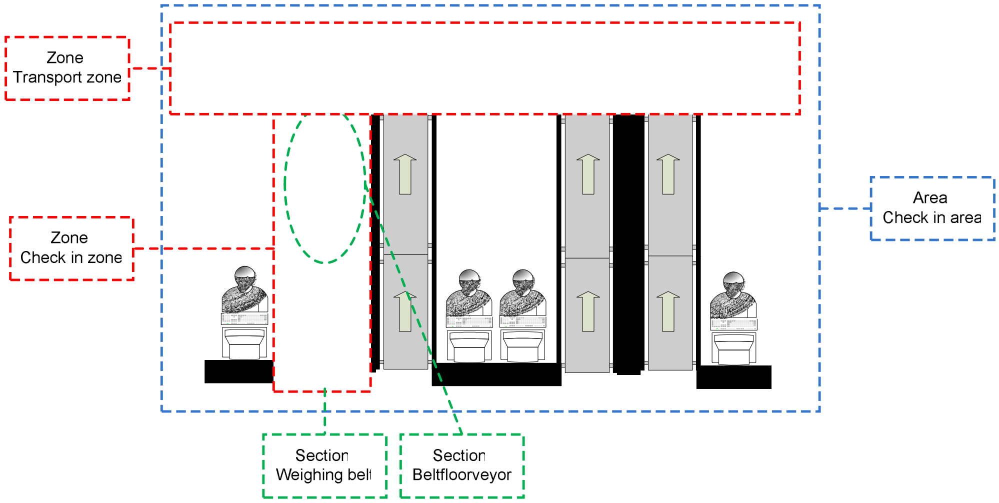

Figure 1.6 Example of a check in area with zones and sections

1.3.2 Scope of study object

Although there are many similarities between the different system types, it is essential to focus on a specific product in order not to get lost in too much information. After some qualitative discussions with experts from the service department it is decided to choose the *baggage handling systems (BHS)*. The argumentation behind this decision has mainly a practical reason; for other product types the logging of maintenance history has never been stored, because in the past there was no interest in using this information. Airline industries are leading in technology and improvements, therefore these kinds of loggings were indeed stored in the past and that makes BHS the best option for data research. Due to time-constraints within the area of BHS it is decided to focus on the *conventional baggage handling equipment*.

1.4 Report outline

This chapter has provided an insight into the problem background, the trends, the problem, the research assignment and the demarcation of this research assignment. Based on the research assignment the report is structured as follows:
Chapter 2 provides a short introduction to LCC calculations, and describes the current LCC methodology. Furthermore, based on an extended model of Kelly and Harris (1978) it describes the LCC focus of this research by determining the most relevant decision variables of technical system availability. The relationships described in chapter 2 are translated into two mathematical models, which are developed and validated in ***Chapter 3***; the first model describes the relationship between the decision variables and AT and the second model between the decision variables and LCC. ***Chapter 4*** elaborates on how an applied version of the model is constructed into a tool, and evaluated by a case study, of an actual project. Furthermore, attention has been paid to the implementation of such a model into the current business processes. Finally, conclusions are presented in ***Chapter 5,*** which will be compared to the problem definition as described in the first chapter.

2 Life cycle costs and system availability

As stated in the previous chapter the demand for LCC analysis of systems is increasing. This chapter describes a definition for LCC and a methodology to perform LCC analysis as described in literature. Furthermore it describes how VI fits within this methodology and what is to be improved. Finally the chapter concludes with the most relevant decision variables that affect LCC and availability that will be used in this study.

2.1 LCC methodology

LCC analysis has been developed by the US Department of Defence in order to minimize the expenses of their purchased equipment (White and Ostwald, 1976). Nowadays the concept is not only used in the military sector, but also in construction and building industry, and in different capital goods industries, because it is of interest of both original equipment manufacturer (OEM) and their customers. A straightforward definition of LCC is given by Blanchard and Fabrycky (1998):

"Life-cycle cost refers to all costs associated with the system as applied to the defined life cycle".

A good methodology to come to a LCC calculation is provided in figure 2.1 by Woodward (1997). The methodology shows in the first step the cost elements of interest which can be seen from the perspective of consumer and of the producer. The second step defines the cost structure to be used, which will result in the potential trade-off relationships. The next step is to determine the mathematical relationship between the costs. The last step is to establish a methodology to evaluate the trade-off points of LCC.

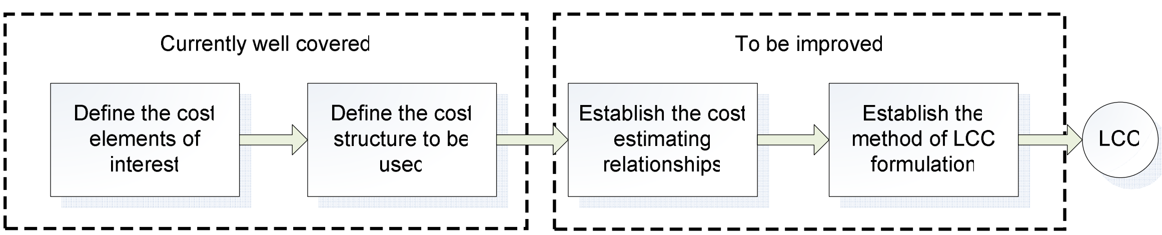

Figure 2.1: Life cycle cost procedure by Woodward (1997)

When this LCC methodology is compared to the current LCC calculation it can be concluded that the first two steps are developed quite well. For the third box counts that relationships between certain costs are not clearly visible for every cost buckets and drivers, and therefore rough estimations are used in LCC calculation. The absence of relationships between important costs results in not having a methodology (the fourth box) to balance cost trade-offs. Therefore this study focuses on establishing the relationships between costs that have not been made visible yet. And it focuses on developing a model, which balances between the cost trade-offs of a system.

2.2 Current LCC analysis

This section describes in 2.2.1 the cost elements that are considered in literature and compares this to the current LCC analysis. Moreover in 2.2.2 provides the cost structure for BHS and 2.2.3 gives an insight in the current method of LCC calculation.

2.2.1 Costs elements

Woodward (1997) identified the following important cost elements when conducting an LCC analysis.

- *Acquisition costs*,
- *Life of the product or system*,
- *Discount rate and inflation*,
- *Operating and Maintenance costs*,
- *Disposal cost*,
- *Information and feedback,*
- *Uncertainty and sensitivity analysis*,

In the current pricing methodology all of these cost elements are taken into account, except for the last two points. Information and feedback is required to test whether the LCC calculations are accurate, due to the short period of data tracking the information for feed back has not been available. For the last point holds that currently the uncertainty, in terms of different inflation and discounting scenarios can be taken into account. But measuring the sensitivity of performance variations and design alternatives is not possible yet.

In addition to the cost elements mentioned, Barringer and Weber (1996) stated that the majority of the cost drivers are determined and locked up in the design stage, so this stage should receive careful attention. Dowlatshahi (1992) lists a number of studies which show that the design of the product determines between 70% and 85% of the LCC of a product. Furthermore Öner et al (2007) have shown by case study that in capital goods industry the amount of down time costs can account up to 48% of total LCC while maintenance cost account for 27%. Therefore as a summary of these studies the main cost buckets for capital good industries are presented in figure 2.2.

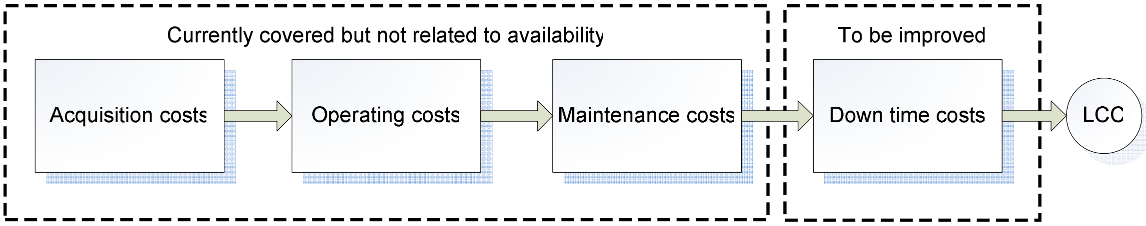

Figure 2.2: Main cost buckets for capital good industries.

These main costs buckets should also be considered for BHS, currently only the first three boxes are estimated in LCC analysis, therefore it is important to get insight into expected down time costs.

2.2.2 Costs structure

As mentioned earlier there have been more studies conducted on LCC, combining the LCC break-down structures of van Putten (2002) and Franssen (2006) leads to the main cost buckets for a typical BHS. Table 2.1 describes these main cost buckets and the sub buckets which form the cost drivers.

Main cost buckets	Sub cost buckets	Described in
Acquisition costs	Project Costs	2.3.1 and 2.3.3
	Initial Spare Part costs	2.3.1
	Sales Charges	2.3.3
Maintenance costs	Labor costs	2.3.1
	Modifications Retrofits costs	2.3.2
	Service contract type costs	2.3.2
	Spare part costs	2.3.1
	Subcontractor costs	2.3.3
	Miscellaneous	
Operating costs	*Labor handling costs*	*Not considered as system costs*
	Facility space costs	*Not considered as system costs*
	Energy consumption costs	2.3.2
	Labor costs (system related)	2.3.3
	Miscellaneous operating costs	
Down time costs	Costs related to technical failures	2.3.1

Table 2.1: LCC at VI

For the customer the operating costs (in terms of handling labor costs) are considered to be the largest part of the total LCC. Labor costs that are to be influenced by the system like employees in the control room and at the manual coding station, are considered system related labor costs and taken into account in the LCC. However, labor handling costs are not influenced by the system, but dependent on desired throughput, and therefore left outside the scope of LCC of a BHS.
Facility space costs are also excluded from the LCC calculations, because occupied facility space is very dependent on the required functionalities. Furthermore customers usually do not have clear insight in the costs per cubic meter, therefore currently customers do not expect facility space costs as part of the LCC.

2.2.3 Current LCC calculation

Currently the LCC calculations are organized in a way that the acquisition costs (the sales and installation phase) are based on a detailed calculation in CAP (the pricing calculation software). The costs in the phases after the installation phase (the service and operating, and disposal phase) are estimations that are mainly based on experience figures. By using the size and travel distances of the system, the number of service engineers per shift is estimated to minimize the response time to failures. Costs for spare parts are estimated as an expected percentage of the total LCC. This expected percentage is based on the LCC analysis of other BHS in the field. Moreover, the operating costs in LCC calculations mainly consist of energy consumption and system related labor costs. Energy costs are calculated by an average kWh consumption per motor in the system, and the system related labor costs are depending on the system requirements. In the current LCC calculations, costs for system downtime (delayed baggage items) are not taken into account. Direct down time costs are mainly determined by the number of baggage items that miss their flight. It has always been difficult to measure the exact number of baggage items that can be attributed to the baggage handling system.

2.3 Decision variables of LCC and AT

As mentioned in the first chapter the aim of this study is to visualize the relationship between LCC and AT. Figure 2.3 is an extended version of an availability model (Kelly and Harris, 1978) applied to VI systems. The figure provides insight in the relationship between LCC and AT.

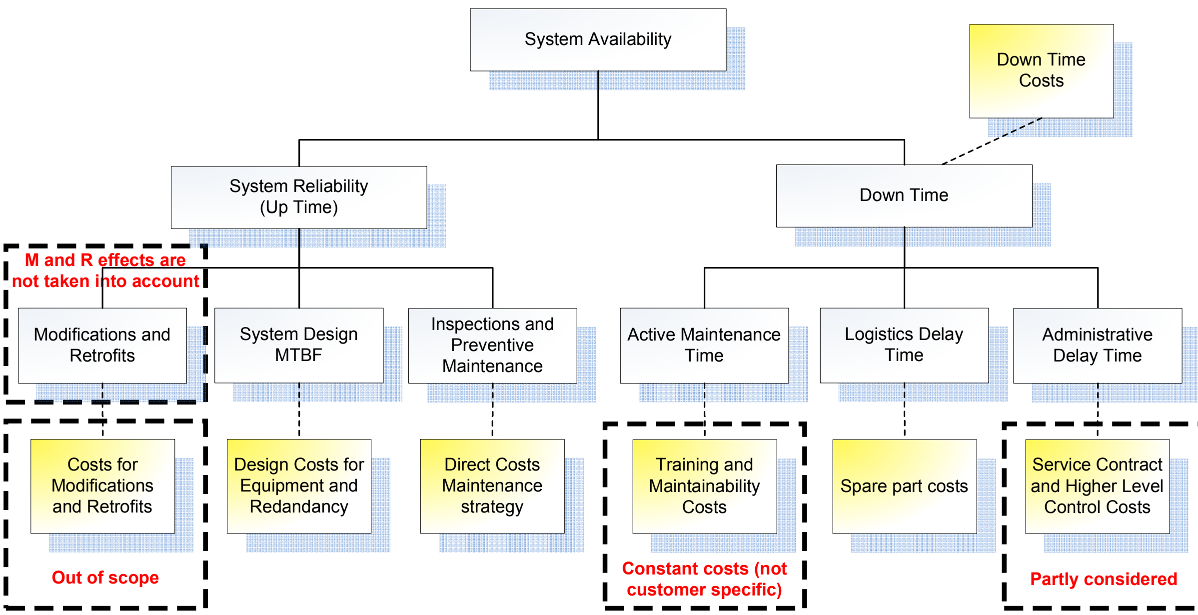

Figure 2.3: Costs related to AT (extended version of Kelly and Harris, 1978).

AT is expressed in the percentage of time that the system is up. The blue boxes below AT are expressed in expected times, which can be affected (prolonged or reduced) by investments in the related yellow boxes.
Moreover this section in general provides an explanation to the costs defined in the ring-model (figure 1.5, subsection 1.3.1). Subsection 2.3.1 describes the incorporated factors that affect LCC and availability of the model. Subsection 2.3.2 describes the factors that hardly affect LCC and availability and therefore incorporated as constants in this model. Finally the costs that are not related to availability are briefly described.

2.3.1 Factors that affect LCC and availability

This subsection describes why equipment and design, maintenance, spare part and down time costs are affecting LCC and availability to a large extent.

Equipment and design costs
As mentioned in chapter 1, the choice for specific sections with a certain MTBF determines a huge part of the system reliability. System reliability on its turn, affects a large part of the LCC of a system. Extending the system reliability is possible by selecting a section with a longer MTBF, but this will most probably result in higher equipment costs. Furthermore the design of a system can influence system reliability as well. This can be done by adding redundant equipment (by-pass lines) to the system. Redundancy requires more equipment and therefore leads to higher equipment costs. Therefore the selection of sections and the level of redundancy form two important decision variables in this study.

Maintenance costs
In order to extend the operational life of the sections in the system a service team influences the level of preventive maintenance. A condition based maintenance strategy is applied by providing periodic inspections. From these inspections possible work-orders will follow that preventively replaces components that are worn-out. Therefore the extending effect the inspection frequency has been incorporated as a decision variable in this model. The effects of the current maintenance policy have been analyzed based on field data. The resulting relationships are described in subsection 3.1.2.

Spare parts costs
From earlier studies (see Franssen 2006) it appeared that the related spare part costs did not form a substantial large percentage of the total LCC (around 4 percent). Still in this study the spare parts are of importance because they influence the mean down time costs to a large extent. Not having spare parts available during a system failure can cause tremendous delays in the operating process and result in down time costs. When spare part costs are considered, a distinction can be made between; the initial investment, the holding costs and the consumption costs. The initial investment is determined at the beginning of the project and implicitly fills the spare part stock levels. These levels should be chosen such that costs are minimized and spare part availability is maximized. The spare part holding costs follow directly from this initial spare part investment. Since stocking can be quite costly due to space consumption (which is expensive at most airports) and depreciation, the holding costs are estimated as a fixed percentage of the total average value stocked per year. For these reasons the spare part stock level is incorporated as a decision variable in this model. The relationships between the spare part investments and AT are described in subsection 3.1.4.

Down time costs
As can be found from figure 2.3 down time is the result of the mean time to repair, the mean logistic delay time and the mean administrative delay time. The effect of technical downtime, in other words technical system unavailability results in operational losses. In the case of baggage handling systems this can result in baggage items that will miss their flight. The costs that are incurred when delayed baggage items miss their flight due to system unavailability are considered to be the down time costs. Subsection 3.2.4 elaborates on how these costs are taken into account in the LCC calculation. Appendix C provides a more detailed insight on how these down time costs have been determined.

2.3.2 Factors that are excluded from this research

Not all of the factors that affect LCC and availability presented in figure 2.3 are taken into account in this study. This subsection elaborates on why costs for modifications and retrofit activities, training and maintainability costs are excluded in this study and how service contract costs, higher level control costs and energy costs are partly taken into account.

Modification and retrofit costs

Modifications have as objective to change the system functionality with an eye to future requirements. This may lead to changes to the system layout, to processes at a system level and to processes at a computer level. Retrofits maintain the system's availability and to ensure that spare parts will continue to be available. Besides this, replacing parts of the automated system to integrate new generations of product may even improve the system's availability, lower the maintenance costs and improve the energy efficiency. Figure 2.3 shows that although modifications and retrofit activities influence system availability and LCC, in this study it is not taken into account. These costs and effects are excluded, because on beforehand it is very difficult to estimate the frequency of these activities and therefore also complicated to estimate the effect on the system uptime and the related costs. An improvement to the current methodology would be to analyze these activities at different reference sites, in order to come up with an expected frequency and effect of modifications and retrofits.

Training and maintainability costs

The mean time to repair can be reduced by training and system maintainability. Training is provided for each system sold, therefore it is reasonable to assume the same learning effect on the MTTR for each system. With regards to maintainability, this becomes a more complex issue when systems are limited to a spacing constraint. In this study it is assumed that systems do not have any spacing constraint and therefore the attention for maintainability is similar for each project. Still, the MTTR of sections is determined by the expected MTTR of the different sections measured by the test center. A step forward for this study would be to research the effect of spacing constraints on the maintainability of BHS and implicitly the effect on system availability.

Service contract type costs

Saving service costs requires predictive insight in the system failures. This predictive insight should be based on well estimated failure distributions of every component in the system. Only when this information is available and reliable, the optimum between preventively replacing components (minimizing the probability of down time) in the system and the number of service engineers on site during operation can be found. VI is currently rethinking their maintenance policy and reorganizing its maintenance registration in order to obtain these failure distributions. It is decided in this study to include the direct maintenance hours for inspections, preventive and corrective maintenance, because this study focuses on visualizing the effect of extra inspection hours on LCC and AT. All indirect maintenance hours are excluded from the LCC calculations in this study. To improve this model the developments that will follow from the improved maintenance policy and accurate failure distributions of components should be incorporated in the future.

Higher and lower level system control costs
The level of system control can range from very little control to tracking and routing decision on higher level. The extent of higher level control usually depends on the complexity of the system and the desires of the customer. Of course a grounded decision on whether or not to adopt higher level control in the system should incorporate a comparison between investments and effect on downtime. Currently information on the effects of higher level control is not available yet and therefore also excluded from this study. For lower level control (which enables central failure detection steered by PLC's) counts that it is incorporated in almost every system. Therefore estimation is used for the failure notification time, which is based on experience figures. The decision to adopt a certain level of higher control in the system is currently based on experiences and customer requirements. The related costs for higher and lower level control will reflect as constant in the equipment costs of the system.

Energy consumption costs
Due to rising energy prices and the rising interest for environmental issues the customer demand for energy consumption forecast calculation is increasing. Investments in energy saving control can not only save energy costs, but it also reduces the hours that the system is running and therefore reduces the wear of the system. Still the effect of energy saving is very much dependent on the system load in terms of utilization rate, the weight and arrival process of baggage items. Therefore only rough estimations for energy costs and effect on system wear can be made. Currently the systems simulation department is improving the calculation method of energy costs, of course this improvement can be added to this model.

2.3.3 Remaining cost buckets

This section discusses the LCC that are not related to AT and that will not be included in this study. These are costs related to subcontractors, project specific costs and sales charges, system operator and control.

Subcontractor costs
Subcontractors can assists in the sales phase for equipment that VI does not provide (e.g. screening machines), and also in the service phase for maintenance on the equipment that VI does not provide. These costs and the related costs are not to be influenced by VI's system.

Project specific and sales charges costs
Each system has its specific project costs in the acquisition phase. Therefore a current accurate pricing methodology is used in order to absorb the costs related to installation of the system, system engineering and production engineering in the form of surcharges to the system's equipment.

System related labor costs
Each designed system requires system operators and controllers. In the case of baggage handling systems these operators are the employees working at the manual coding stations. System controllers are employees that signalize errors in the system due to either technical or operational failures. The number of controllers is very much dependent on the size of the system.

3 Model development

Based on the theoretical model of chapter 2, this chapter describes how the models of system availability and related LCC are build up mathematically. Section 3.1 describes how technical system availability is calculated in this study. Moreover, in section 3.2 the related LCC calculation is described. This chapter concludes with section 3.3 where the decisions in both models are validated.

3.1 Technical system availability (AT) model

As described in chapter 1, availability becomes evermore important in capital good industries. Customers require availability studies for baggage handling, express parcel and distribution systems more often. Especially in the baggage handling sector system availability is judged as an important system performance indicator, and plays an important role in their buying decision. This section consists of five subsections; subsection 3.1.1 describes the current architecture of a material handling system. Subsection 3.1.2 provides the definition of AT and the basic relation with MTBF and MDT. Subsection 3.1.3 elaborates on how to influence the MTBF, while subsection 3.1.4 describes this for the MDT. Finally subsection 3.1.5 describes the calculation model of the technical availability of BHS and its composition.

3.1.1 System architecture

Material handling systems are built up according to the sandglass model (appendix B). In order to calculate LCC and AT for a BHS one first needs to break down the system up to the level of sections. All different sections *j* (e.g. conveyor, belt curve) should be defined. Combinations of sections form a zone *z* (e.g. weighing belt and conveyor form a check in zone). Moreover, multiple zones are incorporated into an area *ar* (e.g. check in zones and transportation zones form a check in area). Process areas are defined as the combination of areas, where a transition (transition from unscreened bags to screened bags) takes place. Process areas denote, how different areas are related to each other, this information can also be obtained from the baggage flow (routing). Therefore the technical system availability for system *s* follows from the relationships between areas.

3.1.2 Definition

Inconsistencies exist about the definition of availability, for this study we define technical system availability and unavailability as follows:

A system is technically available when it can meet the throughput where VI and its customer agreed on. A system is unavailable when due to <u>*technical*</u> *failure the system can not meet the throughput where VI and its customer have agreed on.*

Availability will be expressed in a percentage of time that the system is available in the long run. If the relationship between technical availability and system up and downtime is considered over an infinite horizon, then the following formula holds (Niebel, 1994):

$$AT_j = \frac{MTBF_j}{MTBF_j + MDT_j} \qquad (1)$$

Where AT_j stands for technical system availability for section *j*, $MTBF_j$ represents the mean time between failures of section *j* and MDT_j represents the mean system downtime after a failure of section *j*. Formula *(1)* reflects a steady state calculation of availability, which means that availability will approach that value on the long term. The decision to use a steady state calculation is based on the fact that very little is known about the distribution of the failure rates of the sections in the system. As described in appendix D.3 it was not possible to fit a distribution to the failure rates, due to the limited number of failures in the reliable dataset. An alternative to steady state calculations could be to assume an exponential failure distribution, but since availability is calculated over a systems life time the values will converge to the steady state.

3.1.3 System uptime (MTBF)

The system up time (system reliability) consists of four decision variables; the equipment types, the level of system redundancy, the level of preventive maintenance and the modifications and retrofit activities that are applied to the system. As discussed in section 2.3 this model focuses on section selection, the level of system redundancy, and the level of preventive maintenance policy.

Section selection and the level of system redundancy
The reliability of the system design is built up from the MTBF of the different components used in a system and the redundancy that is incorporated in a system design. Since a lot of information regarding the MTBF of the different sections in a conventional BHS is unknown, a field research has been conducted in order to obtain realistic MTBF figures. Appendix D shows an overview of the data-analysis conducted at a large reference airport, and it presents some of the field MTBF figures with and without the preventive maintenance policy. A similar reasoning counts for adding redundancy to the system, the more redundancy in the system the higher the system up time, but on the other hand redundancy requires more components and more maintenance in the system. Section 3.2 presents an availability calculation method that takes into account the effects of equipment with different MTBF and redundancy. For calculation simplicity it is assumed in this calculation that sections are independent and identically distributed. Furthermore it is assumed different sections also fail independently from each other.

The level of preventive maintenance
Inspections and conditional maintenance can prevent failures occurring during operation and therefore extend component and system reliability (up time). Increasing the frequency of inspections will increase the probability of detecting and preventing possible failures, but on the other hand it will increase the direct maintenance cost. Unfortunately, the data-analysis at the reference site could only provide two points on the relationship between the frequency of inspections and the MTBF figures (see appendix D.4). Since this reference site has a relative high

frequency of inspections it is assumed that the inspection frequency at this site is the maximum and zero inspections is considered as minimum. Moreover in this study it is assumed that for each inspection the probability of detecting a failure is the same, independent of the frequency or time interval of the inspections. This results in formula *2:*

$$MTBF_j(h_j) = MTBF_j + \frac{MTBF_{j,l_j} - MTBF_j}{l_j} \cdot h_j \qquad (2)$$

$MTBF_j(h_j)$ = Mean time between failures of section *j* after inspection frequency h_j (in hours)

$MTBF_j$ = Mean time between failures of section *j* (in hours)

$MTBF_{j,l_j}$ = Mean time between failures of section *j* with inspection frequency *l* measured at the reference site (in hours)

j = corresponds to section *j* (for *j* ϵ 1…J)

l_j = Yearly number of inspections at section *j* done at reference site

h_j = Yearly number of inspections at section *j* in a new system

In reality a concave relationship (see figure 3.1) will probably be more appropriate, because the first inspection will probably have the most positive effect and every next inspection will have less impact. The effects of different types of effect of the inspection frequency has been tested and evaluated in subsection 4.1.4.

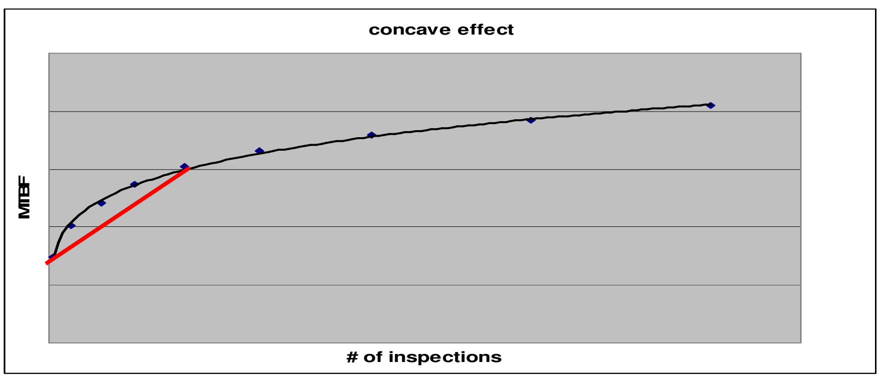

Figure 3.1: Concave effect of the frequency of inspections on the MTBF of sections

An improvement would be to research the effect of their current maintenance policy on the extending effect of the MTBF of all their sections. Another approach could be to apply preventive replacements in their system, based on failure distributions of their different sections.

3.1.4 System downtime (MDT)

The downtime consists of three main elements; namely the mean active maintenance time, mean logistic delay time and mean administrative delay time (formula *3*) each containing its own decision variable. Figure 3.2 presents the downtime of a typical technical failure occurring in the process of a baggage handling system.

$$MDT_j = MTTR_j + MLDT_j(S_{cp,j}) + MADT_j \qquad (3)$$

$MTTR_j$ = Mean time to repair section *j* (in hours)

$MLDT_j(S_{cp,j})$ = Mean logistic delay time for section *j* depending on SKU level $(S_{cp,j})$ (in hours)

$MADT_j$ = Mean administrative delay time for section *j* (in hours)

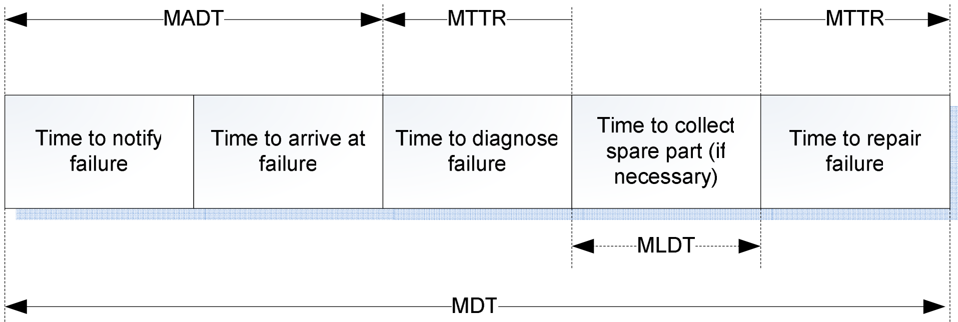

Figure 3.2: Mean down time of a technical failure

Mean time to repair

The mean time to repair (MTTR) is the mean time required to perform corrective maintenance activities. It is the time from the moment the service engineer arrives at the failure until he restarts the system. Because the on-site service team does not keep track of this data, it was not possible to use field figures for the calculations with the MTTR. Therefore the figures available from the test-center were used instead (see appendix D.5).

$MTTR_j$ = expected time to repair section *j* (in hours)

These estimates were measured under testing circumstances and might deviate from the actual repair times in the field. A suggestion would be to combine the information stored for a technical failure in their maintenance database and the actual downtime of the system following from the logging file created in the control room. This provides the opportunity to determine realistic estimates of down time.

Mean logistic delay time

The mean logistic delay time (MLDT) is mainly caused by the travel time from the service engineer to the spare part warehouse at the site, and by spare part availability and the travel time of an emergency transshipment. Having an out of stock during a system failure can cause enormous delay resulting in down time costs. Since this study works with section level it is necessary to know the logistic delay time per section as well. Physical spare parts are stocked on element, material and object level (appendix B), therefore a section is broken up into its most critical parts. For these critical parts physical stock keeping units (SKU's) are stocked. Furthermore it is assumed that each BHS has its own single warehouse on site, which fulfills the demand for replacements. Demand that cannot be fulfilled from this warehouse is fulfilled by the central warehouse (which is assumed never to be out of stock) via an emergency transshipment. To evaluate the mean logistics delay time of a section, formula *4* has been developed:

$$MLDT_j(S_{cp,j}) = TT_j + \sum_{cp=1}^{CP} \frac{m_{cp,j}}{M_j} P_{cp,j}(SO) \cdot TE_{cp,j} \tag{4}$$

TT_j = Expected travel time from the warehouse to the location of the failure for spare part section of type *j* (in hours)
$m_{cp,j}$ = failure rate of SKU's *cp* of section *j* (per hour) (appendix D.7)
M_j = failure rate of section *j* (per hour)
$P_{cp,j}(SO)$ = Probability that SKU *cp* for section *j* is out of stock
$TE_{cp,j}$ = Expected emergency transshipment time of SKU *cp* for section *j* (in hours)
cp = corresponds to SKU *cp* (for *cp* ϵ 1…CP)
$S_{cp,j}$ = The total number of stocked SKU's *cp* according to current spare part policy

To calculate the out of stock probability $P_{cp,j}(SO)$ for a SKU, it is assumed that demand for SKU's follows a Poisson Process with a constant failure rate. This assumption is justified in this case, because although failures can not occur when the system is down, the down times are short and occur rarely in this case. Furthermore although the failure distribution of the equipment might not be exponential there is much equipment running in the system, which means that the assumption can be used for other failure distributions as well.

Based on these assumptions it can be concluded that the number of parts in repair follows an M/G/c/c queue (similar to the Erlang loss system), with c= $S_{cp,j}$ parallel servers, arrival rate $m_{cp,j}$, and mean regular replenishment time $TP_{cp,j}$. For the regular replenishment times it is assumed that distributions between different SKU's and within the same SKU's are independent and identically distributed. This results in formula *5* (van Houtum and Hoen, 2008), which evaluates the fraction of time that a stock-out occurs for a given stock level of SKU *cp*:

$$P_{cp,j}(SO) = \frac{(m_{cp,j} \cdot y_j \cdot TP_{cp,j})^{S_{cp,j}} \cdot \frac{1}{S_{cp,j}!}}{\sum_{k=1}^{S_{cp,j}} (m_{cp,j} \cdot y_j \cdot TP_{cp,j})^k \cdot \frac{1}{k!}} \tag{5}$$

y_j = the number of sections of type *j* in the system (in integer number of sections)
TP_j = preventive maintenance time required for section *j* (in hours)

This study has not as goal to find the optimal spare part level, therefore the current policy is incorporated in this model. This policy determines the number of spare parts based on a fixed percentage of the total parts present in the system and is presented in formula *6*.

$$S_{cp,j} = \max\left(\min\left(S_{cp,j,VI}, S_{cp,j}^{+}\right), S_{cp,j}^{-}\right) \qquad (6)$$

$S_{cp,j,VI}$ = The number of spare parts of section j of spare part type cp calculated by current approximation method (in integer spare parts)

$S_{cp,j}^{-}$ = The minimal fixed stock level of spare parts type cp (in integer spare parts)

$S_{cp,j}^{+}$ = The maximal fixed stock level of spare parts type cp (in integer spare parts)

Based on the failure rates of sections and the expected ratio of spare part usage (obtained from test center data) it is determined what the long term expected delay time is, due to not having spare parts available. This current spare part policy can be improved by the methodologies described by Franssen (2006) and van Sommeren (2007). These methods can also be adopted in this model.

Mean administrative delay time

Mean administrative delay time (MADT) or response time to the problem is the time between the moment of the failure and the moment of alerting a service engineer. Different contract types can be distinguished, the effects of these different contract types are difficult to express in effects on system downtime. Because variables like system size, travel distances within systems, lower level control, quality of engineers, system maintainability and safety precautions are all affecting the response time to a failure. With the current available information it is not possible to include all these effects into a model and calculate a precise response time. Since this business solving problem focuses on baggage handling systems (BHS) it is assumed that the airports require service engineers on site during the operating hours of the system. This assumption enables the model to use an experience figure of VI, which is an estimate for response time from failure to notification and arrival at failure location. The choice whether or not to use VI's labor services is up to the customer, but for calculation simplicity it is assumed that costs for own staff or using VI's staff are similar.

$MADT_j$ = time between failure and service engineer arrives at failure is fixed for every section j.

These expected response times assume a fixed minimal number of service engineers on site. An interesting development will be to determine a relationship between the size of the system (travel distance), the number of service engineers, and the response time to failure. Making these relationships visible it allows for finding trade-off points between the number of service engineers present on site and the amount response time or related down time costs.

3.1.5 Technical system availability (AT) calculation

By knowing how to calculate and influence system uptime and system downtime, building up section availability and system availability can be done. A sandglass model (see appendix B) has been developed, which breaks down an entire system in to subsystems and components and materials. This sandglass model is also used for calculating availability starting at section level, moving up to zone level to area level and finally to system level. Using this sandglass model the

availability calculations from one level to a higher level can be repeated until the level of system availability is reached.
Below follows the system availability calculation in 5 steps. The first two steps can be considered as configuration based on the baggage flow (routing), before the actual calculation starts. The third step determines the availability on zone level, by using the MTBF figures on section level measured in the field. In the fourth step the availability on area level is calculated by using the zone availability calculated in step 3 and the parallel relationships determined in step 1 and 2. Finally in the fifth step availability on system level is calculated by using the same methodology as in step 4 only now using area availability.

Step 1: Based on the agreed system throughput restrictions determine the minimal throughput on area and zone level.

Step 2: Based on the minimal throughput, determine the number of parallel areas or zones required by using the system's routing.

Step 3: Determine availability on zone level by:

$$AT_z = \prod_{j=0}^{J} \left(\frac{MTBF_{j,z}(h_j)}{MTBF_{j,z}(h_j) + MDT_{j,z}} \right) \qquad (7)$$

AT_z = technical availability of zone of type *z* (in percentage)
$MTBF_{j,z}(h_j)$ = Mean time between failures of section *j* in zone *z,* affected by inspection frequency h_j (in hours)
$MDT_{j,z}$ = mean down time of section *j* (in hours)
z = corresponds to zone *z* (for *z* ϵ 1…Z)
NB: sections within a zone are always related sequentially to each other

Step 4: Determine availability on area level by:

4.1 When zones are in parallel: create one aggregate zone availability by:

$$AT_{az} = \sum_{x_{az}}^{n_{az}} \binom{n_{az}}{l_{az}} AT_z^{\,l_{az}} \cdot (1 - AT_z)^{(n_{az} - l_{az})}$$

$$with, x_{az} = \left\lceil \frac{(n_{az} \cdot th_{\max,z}) - q_{az}}{th_{\max,z}} \right\rceil \qquad (8)$$

AT_{az} = Technical availability of aggregate zone *az* (in percentage)
AT_z = Technical availability of zone of type *z* (in percentage)
az = Corresponds to aggregate zone *az* (for *az* ϵ 1…AZ)
n_{az} = Number of zones in parallel in aggregate zone *az*
x_{az} = Minimum number of operating zones required in aggregate zone *az*
$th_{\max,z}$ = Maximum capacity for zone *z* (in bags per hour)
q_{az} = Agreed minimal throughput capacity per aggregate zone *az* (in number of bags)
NB: It is assumed that zones in parallel contain the same availability.

4.2 Compute area availability from normal zone availability and aggregate zone availability by:

$$AT_{ar} = \prod_{az=0}^{AZ} AT_{az,ar} \cdot \prod_{z=0}^{Z} AT_{z,ar} \qquad (9)$$

AT_{ar} = Technical availability of area of type *ar* (in percentage)
$AT_{az,ar}$ = Technical availability of aggregate zone *az* present in system *ar* (in percentage)
$AT_{z,ar}$ = Technical availability of zone *az* present in system *ar* (in percentage)
ar = Corresponds to area *ar* (for *ar* ϵ 1…AR)

Step 5: Repeat step 4 to come from area availability to system availability

Although this methodology does not differ a lot in essence from current availability studies at the simulation department, it uses the sandglass model as a basis for calculations. The availability calculation by these 5 steps requires a substantial amount of time in the configuration steps. But the method is quick in evaluating different designs and equipment types. Still an improvement in terms of time consumption is simulating the availability of a system. Currently systems simulation is working on developing a simulation model that can import a CAD-drawing of a system and determine availability (see section 4.3).

3.2 LCC model

As presented in chapter 2 only those costs are taken into account in this study that have a relationship with AT. For this study the following costs will be described in this chapter; design and equipment costs, maintenance policy costs, spare part costs and down time costs, which results in the general LCC formula (*10*) of this model:

$$LCC_{AT_s} = STC_s + DMC_s + SPC_s + DTC_s \qquad (10)$$

LCC_{AT_s} = Life cycle costs related to technical system availability *AT* of system *s* (in euros)
STC_s = Sales to customer price of system *s* (in euros)
DMC_s = Direct maintenance costs of system *s* (in euros)
SPC_s = Spare part costs of system *s* (in euros)
DTC_s = Down time costs of system *s* (in euros)
s = Corresponds to system *s*

3.2.1 Design and equipment costs

The first cost type that is considered in this study is design and equipment costs. A choice for a different system lay-out by adding parallelism or redundancy will have different design and system costs. Furthermore, decisions on the sections that are used in the system will also affect the equipment costs and system costs. The current pricing method calculates a sales price to customer, which consists of the basic section costs plus a profit margin. And for each section surcharges for the related standard mechanical, electrical, installation, system and production engineering costs are added (see appendix E).

$$STC_s = \sum_{j=1}^{J} STC_j \qquad (11)$$

STC_s = Sales to customer price of system *s* (in euros)

The model uses the outcome of this methodology for the calculation of the total equipment costs, and does not provide an alternative project pricing method.

3.2.2 Maintenance policy costs

In order to extend the operational life of the sections in the system a condition based maintenance strategy is applied by periodic inspections. From these inspections possible work-orders will follow that preventively replaces components that are worn-out. The frequency of inspections is depending on the customer's service engineering capacity. It is assumed that for each inspection the probability of detecting a failure is the same independent of the frequency or time interval of the inspections.

$$DMC_s = INS_s + PM_s + CM_s \qquad (12)$$

INS_s = Total inspection maintenance costs for system *s* (in euros)
PM_s = Total preventive maintenance costs for system of type *s* (in euros)
CM_s = Total corrective maintenance costs for system of type *s* (in euros)

Direct inspection costs
To find the expected total inspection costs the following formula is used:

$$INS_s = \sum_{j=1}^{J} h_j \cdot y_j \cdot TI_j \cdot cd \cdot LC_s \qquad (13)$$

h_j = Yearly number of inspections at section *j* in a new system
y_j = the number of sections of type *j* in the system (in integer number of sections)
TI_j = Inspection time required for section *j* (in hours)
cd = Direct maintenance hour rate (in euros)
LC_s = Life cycle of system *s* (in years)

Formula *13* is used in this report, because currently it is not possible to measure exact inspection time for each section in the system. Therefore this study uses the estimations for inspection time per section determined by the maintenance department at the reference site. It is recommended to register the exact inspection time per section in order to work with more accurate data.

Direct preventive maintenance costs
From these inspections there is a certain probability that a preventive maintenance action will follow. Below the formula for expected preventive maintenance costs is given:

$$PM_s = \sum_{j=1}^{J} \frac{LC_s \cdot yh_s \cdot y_j}{TBI_j} \cdot p(h_j) \cdot h_j \cdot TP_j \cdot cd \qquad (14)$$

$p(h_j)$ = The probability (corresponding to the frequency of inspections h on section j) of preventive maintenance after an inspection

TBI_j = Time between inspections on section j (in hours)

yh_s = yearly operating hours of system s (in hours)

TP_j = preventive maintenance time required for section j (in hours)

Formula *14* is used throughout this model, because it has been possible to measure the probability of preventive maintenance after inspections and the expected time for preventive maintenance. This has been an improvement with respect to the current calculations. Furthermore it uses the assumption that for each inspection the same probability of having a preventive maintenance action occurs. This calculation method can be improved by measuring the effect of their current maintenance policy on the MTBF of all their sections, and incorporate this effect into the model.

Direct corrective maintenance costs
Although inspections can prevent failures during operation, there is also a probability of having failures during operational hours. The direct cost formula of these corrective maintenance actions is described below:

$$CM_s = \sum_{j=1}^{J} \frac{LC_s \cdot yh_s \cdot y_j}{TBI_j} \cdot \left(1 - p(h_j)\right) \cdot h_j \cdot TC_j \cdot cd \qquad (15)$$

TC_j = Corrective maintenance time required for section j (in hours)

The same reasoning as provided for formula *14* holds for formula *15*.

3.2.3 Spare part policy costs

As mentioned in chapter 3.1.4 spare parts form an important factor in the availability level of systems and equipment. There are three types of spare part costs described in this chapter. First of all during the sales phase an initial spare part investment is advised by the service department. During the operational life of the system the customer has to take into account the inventory holding costs for the spare parts and the costs for spare part consumption. The level used in this LCC versus availability study is section level. Spare parts are sold at a lower level than section level, for example it sells the engines and engine parts that form the drive of a section like a conveyor belt. Since the lowest level of equipment in this model is section level an aggregate spare part on section level is created.

$$SPC_s = SI_s + ST_s + SH_s + SU_s \qquad (16)$$

SI_s = The life cycle initial spare part investment for system s (in euros)

ST_s = The life cycle spare part emergency transshipment costs for system s (in euros)

SH_s = The life cycle holding costs for stocking spare parts for system s (in euros)

SU_s = The life cycle spare part usage costs for system *s* (in euros)

Initial spare part investment
Currently the approach to determine the initial spare part investment is based on experience figures. For a given system design the spare parts levels are calculated using a percentage of the total parts present in the system (see appendix G). Furthermore it has a minimum and maximum level incorporated that usually form the boundaries for the selected level. An experienced person judges the levels and in case of long delivery times the levels are adjusted accordingly. Since the calculation method of this study works with spare parts on section level the value of spare parts for a specific section *j* is aggregated. In order to calculate the value of an aggregate section spare part, previous spare part lists and the spare part policy have been analyzed. Below the cost formula for the initial spare part investment costs is given:

$$SI_s = \sum_{j=1}^{J} \sum_{cp=1}^{CP} y_{cp,j} \cdot S_{cp,j} \cdot ci_{cp,j} \qquad (17)$$

$y_{cp,j}$ =The number of SKU's *cp* of section *j* in the system (in integer number of sections)
$S_{cp,j}$ = The total number of stocked SKU's *cp* according to current spare part policy
$ci_{cp,j}$ = The initial spare part cost per critical spare part *cp* of section *j* (in euros)

Formula *17* is used because the goal in this study was not to find the optimal spare part levels, but to explain the effect of spare part levels on AT. Although the initial spare part investment is a relatively small investment (<1%), with respect to the total LCC, methods to optimize spare part levels can be found in van Sommeren (2007) and Franssen (2006).

Emergency spare part transshipment costs
The expected emergency transshipment costs follow from the total expected number of emergency transshipments for all present SKU's *cp* and the costs for an emergency transshipment (formula *18*).

$$ST_s = \sum_{j=1}^{J} \sum_{cp=1}^{CP} y_{cp,j} \cdot m_{cp,j} \cdot P(SO)_{cp,j} \cdot LC_s \cdot yh_s \cdot ct_s \qquad (18)$$

ct_s = emergency transshipment costs for system *s*

With the current spare part policy of VI these expected emergency costs can be considered as very low.

Spare part holding costs
The spare part holding costs are calculated as a yearly percentage of the initial investment. It is assumed that the initial investment reflects the average inventory levels of spare parts. Since inventory is always replenished after consumption the average inventory costs are close to the yearly percentage of the initial investment.

$$SH_s = SI_s \cdot r_s \cdot LC_s \qquad (19)$$

SI_s = The initial spare part investment for system *s* (in euros)
r_s = The yearly percentage paid for SKU's for system *s* (in percentage)
LC_s = Life cycle of system *s* (in years)

Formula *19* is used because it is assumed that spare part stock levels are directly replenished when spare parts are used. Still an exact calculation, where different stock levels are considered due to failure demand during the lead time, will be more exact. But since the failure data is not available on spare part level and the holding costs are relatively small (with respect to the total LCC) it is assumed that this formula is accurate enough.

Spare part usage costs
During the operational life spare parts are required due to equipment failure. Since failure information on spare part level is not available failure information on section level is analyzed each failure on section level is restored by either a system repair or a spare part replacement. These figures are analyzed (see appendix D.6) and averages for spare part costs per section failure are determined. In order to estimate the spare part usage costs during the operational life the following formula is determined:

$$SU_s = \sum_{j=1}^{J} y_j \cdot cu_j \cdot \frac{(LC_s - w_s) \cdot yh_s}{MTBF_j} \qquad (20)$$

cu_j = The expected spare part usage costs per failure on section *j* (in euros)
w_s = agreed warranty period of system *s* (in years)
$MTBF_j$ = Mean time between failures of section *j* (in hours)

Formula *20* calculates the spare part usage cost based on the average yearly spare part costs determined by field measurements. The failure rates of the individual spare parts of a section are not known, but an average cost per section per year can be determined. Therefore the estimation of spare part usage based on field data is an improvement for the current LCC calculations.

3.2.4 Down time costs

Downtime costs at an airport have always been difficult to attribute to a BHS. A form where system downtime directly can be expressed is the number of baggage-items not being loaded to a plane due to; technical or operational problems in the handling process, time scheduling problems or delays in arrival or departure times.
Currently when down time costs were estimated in LCC calculations, they were not a function of the system availability. Therefore it is hard to quantify design related decisions that improve system availability. Franssen (2006) mentioned in his research that delayed baggage items due to system availability should be tracked in order to obtain a relation. In order to establish a function that describes the expected delayed baggage items one first needs to identify all factors that influence the downtime costs. Hopp and Spearman (2008) describe two drivers for queuing time

(comparable to delayed baggage items); variability and utilization rate. Of which they describe utilization rate as the one with the most dramatic effect. For BHS counts that variability is mostly present in arrival time of passengers to the check in desks, because travel times of baggage items is mainly considered to be deterministic. Therefore the following factors that influence the number of delayed baggage items have been identified.

- System throughput
- System capacity
- System availability (technical and operational)
- System dependency

System throughput, in other words the number of baggage items offered to the system, and the designed capacity of the system determine the gross utilization rate of the system. This gross utilization rate is affected by the technical and operational system availability, which results in the net utilization rate. Furthermore there is a qualitative factor that influences the number of delayed baggage items. This factor has to do with the level of system dependency of the customer. When a customer is highly dependent on the system it means that in case of a failure there is no other option than to wait for the repair of the system. When dependency is lower the customer can use alternative ways to transport the goods to the plane in time.
At a reference site figures containing information on the utilization rate, technical and operational availability and the system throughput per day have been obtained and the number of delayed baggage items due to the system. This information is analyzed (see Appendix C) and the following formula for downtime costs will be used during this study:

$$DTC_s = B_s \cdot th_{\max,s} \cdot cm \cdot LC_s \cdot yh \qquad (21)$$

DTC_s = Down time costs of system s (in euros)
B_s = Number of baggage items arriving too late (in number of items/capacity/hour)
$th_{\max,s}$ = Designed maximal hourly capacity of system s (in bags per hour)
cm = Expected costs per missed bag (in euros)
LC_s = Life cycle of system s (in years)
yh_s = Yearly operating hours of system s (in hours)

In order to estimate the expected number of baggage items that will not be loaded on an airplane a trend line is fitted to the data of the reference site (see appendix C). The function of this trend line is presented in formula *21*.

$$B_s = d \cdot e^{g \cdot \frac{th_s}{th_{\max,s} \cdot (TA_s \cdot OA_{,s})}} \qquad (22)$$

AT_s = Technical availability of system s (in percentage)
AO_s = Operational availability of system s, assumed to be constant (in percentage)
th_s = Expected throughput per hour in system s (in number of bags)
d = Constant 1 determined by data-analysis at the reference site (see appendix C)
g = Constant 2 determined by data-analysis at the reference site (see appendix C)

Formula *21* and *22* are used in this study for LCC calculations because currently this is the only method, which is based on field data. Still an important remark needs to be made regarding formula *22*. The data that was analyzed was based on an airport site which was very much dependent on their baggage handling system. This meant that in case of technical or operational system down time there was no other opportunity than to repair the system. For smaller and less complex baggage handling systems this formula will probably give an overrated number of bags that will arrive to late at the airplane. Ideally, the same data analysis should be replicated for systems of different complexity and system dependency in order to estimate the number of missed bags more accurate.

3.2.5 General cost elements

This subsection describes the general cost elements as mentioned in section 2.2.1. First the general life time of the system is described and secondly the discounting and inflation calculation is explained.

System life time (LC_s)

For the system life time a distinction can be made between the economical life and the technical life of the system. Economical life reflects the period a customer wants to use the system and technical life is the period until the system is worn-out. For LCC analysis the economical life is used and it is up to the customer to determine this economical life, in general for BHS this around 15 years.

Discounting and inflation

Discounting is a method where the investment for a future period is adjusted to the time value of money by a discount rate. A discount rate is the percentage of difference between the value of an investment paid in the present and the value of an investment paid in the future. Usually the discounting rate is equal to the rate of return a customer could get on its investment. In LCC analysis it is common to take into account inflation rates for the future period, in order to take some uncertainty into account different rates can be chosen. Formula *23* describes the formula for LCC after discounting and inflation, as can be seen the STC will not be discounted, since this is paid at the start of the project.

$$LCCD_{AT_s} = \left(\frac{LCC_{AT_s} - STC}{LC_s} \right) \sum_{k=1}^{LC_s} \left(\frac{(1+i_s)^k}{(1+IRR_s)^k} \right) + STC \qquad (23)$$

$LCCD_{AT_s}$ = LCC related to technical system availability of system *s* after discounting (in euros)

i_s = Annual inflation rate of system *s* (in percentage)

IRR_s = Internal rate of return of system *s* (in percentage)

3.3 Qualitative model validation

According to van Aken et al (2007) few general discussions on validation techniques are provided in literature. Still the most common type of model validation in literature is comparing the model output to reality. In this study it appeared to be difficult to compare model output to reality, since the model predicts values over 15 to 20 years. LCC information is difficult to collect from customers, because it is not easily shared externally. Therefore this model is not validated quantitative way but in a qualitative way as described by van Aken et al (2007). They describe a research result as valid when it is justified by the way it is generated and discuss three different types of validity, namely construct validity, internal validity and external validity. The model in this study is validated based on these three types of validity.

3.3.1 Construct validity

Construct validity is the extent to which the model measures what it is intended to measure. Figure 2.3 in section 2.3 describes the concepts that are covered in this study, which is based on literature and practice. Chapter 2 describes the model and explains the relations between the concepts and availability and LCC. Argumentation why to include and exclude certain concepts is well though over and discussed with experts. Therefore in general the construct validity is well grounded because concepts are considered in the light of multiple disciplines, namely from the perspective of design, service, simulation and pricing.

3.3.2 Internal Validity

Internal validity concerns the conclusions about the relationships between the concepts in the proposed model. When the model described in chapter 2 is considered the conclusions to be validated concern the concepts of section reliability, maintenance effect, mean active maintenance time, mean logistics delay time, mean administrative delay time and down time.

Section reliability

In order to determine section reliability a field research is conducted as described in appendix D.3. The reasoning behind this data-gathering is based on the existing doubts concerning the current figures used in availability studies. Therefore this methodology is considered to be currently the most accurate approach.

Maintenance effect

The effect of maintenance that is taken into account is a linear relationship between the frequency of preventive maintenance and the extending MTBF. A condition based maintenance policy is used and it is assumed that for each inspection a fixed percentage of failures is prevented. In reality a concave relationship will probably be more appropriate, because the first inspection will probably have the most positive effect and every next inspection will have less impact. But due to the limited available data of different maintenance policies (see appendix D.4) this assumption is used, and results in a linear relationship. Still when a concave relationship is determined in the future the model can be extended with the improvements.

Mean active maintenance time
Mean active maintenance time can be influenced by training and attention for system maintainability. Since these concepts are provided for each system, the MTTR figures used are adopted from the test center and used as a constant factor in the model. Again when in the future new techniques are developed to influence the MTTR these relationships can be inserted in the model.

Mean logistics delay time
Due to limited data no distribution could be plotted to the failure rates of the different equipment types. It is assumed that the demand for spare parts follows a Poisson Process with a constant failure rate. This assumption is justified in this case, because although failures can not occur when the system is down, the down times are short and occur rarely. Furthermore although the failure distribution of the equipment might not be exponential there is much equipment running in the system, which means that the assumption can hold for other distributions as well.

Mean administrative delay time
Mean administrative delay time is mainly influenced by the service contract type and lower level system control. The effect of the service contract type on down time prevention is still difficult to estimate, because every Airport requires an on-site maintenance team, either a VI service team or an own service team. For the level of lower system control counts that for almost all systems the functionality of detecting failures automatically (via SCADA) is provided. These arguments have led to the conclusion to incorporate a constant mean value for the response time to failures.

Down time
In order to establish a relationship between the expected number of delayed bags and the design of the system, the aspects that variables of influence have been analyzed (see appendix C). This analysis resulted in a relationship between operational utilization rate and the delayed bags per designed capacity. Although it was not possible to control for system complexity and customer dependency on the system, still a general formula is established for airports with similar properties.

3.3.3 External validity

External validity focuses on the generalizability of the proposed LCC and AT model. In general in business solving problems the importance of generalizability is less important because the model is applied to a specific business situation. Still generalizability of the model has been an important issue, because in the future the LCC and AT model should be applied to express parcel and distribution systems. The model described in chapter two has a basic framework that fits to all three system types. This thesis has applied the model for BHS, which requires specific BHS input that is different from the other system types. However, when data for the other system types is collected the model can be applied as well.

4 Application

This chapter describes the application of the model developed in chapter 3. In the first section a description of the applied model is given. Moreover, it describes the validation of the applied model and a sensitivity analysis on the model. In the second section describes a case study to give an impression of what kind of insights become possible when the model will be implemented. The third section explains how the model can be developed further and how it fits within the current business processes.

4.1 Applied model

This section describes how the applied version of the model is developed. The first subsection describes the structure of the applied model in terms of the decision variables, input parameters and output values. The second subsection describes input parameters, which can differ for each customer. Finally the chapter concludes with a validation of the relationships in the model, by using extreme values.

4.1.1 Decision variables

The platform used to build this tool is Microsoft Excel (screenshots can be found in appendix J), because this is the most transparent and accessible platform available at VI. Based on the first system design (CAD drawing) developed by the sales department a framework is constructed in MS Excel that determines the relationships between the different system equipment. As described in chapter 1 this study has made use of the Sandglass model (see appendix B) and it actively uses the section level. Before being able to determine system availability based on the five steps calculation method mentioned in chapter 3, one has to determine the availability per section. In order to determine section availability one first needs to determine section MTBF (mean time between failure) and MDT (mean down time). These figures can be influenced by equipment selection, design and service decisions, which are specific for each project. The values for these decision variables follow from VI's or customer policy on:
1. Type of sections in the system
2. Level of system redundancy
3. The frequency of inspections
4. The stock level of spare parts

1. Type of sections in the system
First the selection of sections should be made. For each section a library with specific information is stored in MS Excel. This library contains information on:

- MTBF with no preventive maintenance (in hours)
- Netto MTTR figure (in hours)
- Throughput capacity (bags per hour)
- Probability of finding a failure after inspection
- Inspection time per section
- Preventive maintenance time (per action per section)

- Corrective maintenance time (per action per section)
- Percentage of spare parts used per section
- Spare part usage replacement costs (purchase price per year)
- Spare part costs per item stocked
- Spare part holding cost per year (percentage of average SP stock)
- Spare part lead time
- Expected travel time to system failure (in hours)
- Expected travel time to warehouse (in hours)
- Equipment costs (PCP)
- kWh usage

This information has been collected for 15 conventional baggage handling sections (appendix D.2 elaborates on the methods used and values found).

2. Level of system redundancy
After the selection of sections the system lay-out engineer at the sales department can decide on adding or removing redundancy in the system. This redundancy can take place on zone level, for example in a transportation area one can decide on a second (parallel) transportation zone, but redundancy can also occur at area level or even on system level. By adding redundancy to the system the system becomes more reliable, because the probability of having two parallel zones down is smaller than having one zone down. Adding or removing redundancy should be done manually in the tool by adding or removing parallel relationships between zones, areas or systems.

3. The frequency of inspections
It has appeared from practice that inspections trigger preventive maintenance actions, which prevent the system from failing during operation. Increasing inspections in general will lead to a higher probability of detecting possible failures and taking action to prevent these. The tool also contains the relationship between the frequency of inspections and the extending effect on the MTBF.

4. The stock level of spare parts
The spare part policy on the stock level in the tool can be manually adjusted. The stock level of spare parts is related to the probability of being out of stock when a failure occurs. When the stock level decreases this probability increases and implicitly this means that the probability of emergency spare part transshipment increases.

Based on these decisions availability per section can be determined and therefore availability on system level can be determined by the five step calculation method (as described in chapter 3).

4.1.2 Input parameters

Furthermore some general information needs to be determined for each project, like:
- The system economic life (in general 15 years)
- The number of operating days per year (in general 360 days)
- The number of operating hours per day (in general 12 hours)
- The energy saving factor (in %)

- The kWh price (in €)
- Spare part commission rate (in %)
- Spare part warranty period (in years)
- Costs per baggage item not loaded (in €)
- Costs per direct maintenance hour (in €)
- Expected daily throughput (system specific)
- Designed capacity (system specific)
- Operational availability (in %)
- Expected yearly inflation percentage (country specific)
- Expected yearly discounting rate (project specific)
- Internal rate of return (project specific)

After filling in this information into the tool, the outcome provides the expected LCC and the expected AT of the system.

4.1.3 Validation of the applied model

In order to test whether the relationships in the applied model are constructed as in the model described in chapter 3, the model is tested with extreme values. The applied model is considered valid when after inserting extreme values, the outcome corresponds with the expected behavior. A basic design is used for validation. This section will not explain the outcomes into detail, but focuses on testing the expected behavior in general. All effects of the four decision variables mentioned in subsection 4.1.1 of the applied model are validated. For all tables hold, that the values are expressed in a percentage change with respect to the basic (100%) situation.

Type of sections in the system
The applied model has the opportunity two choose between three alternative conveyors with different characteristics; namely long conveyors (>10 meter), middle size conveyors (around between 3 and 10 meter) and short conveyors (< 3 meter). When a designed system with 100 sequential long conveyors is replaced by the same length in 300 sequential short conveyors it is expected that equipment and maintenance costs will increase due to more components in the system and for the same reason AT will decrease.

Conveyor type	Long	Short	Measured	Expected
Nr of conveyors	100	300	Up	Up
Equipment costs	100%	112%	Up	Up
Maintenance costs	100%	128%	Up	Up
Technical availability	98,93%	-2%	Down	Down

Table 4.1: validity check for different sections in the system

As can be seen in table 4.1 the validity check for different section in the system corresponds with the expected outcome as described above.

Level of system redundancy
The applied model can distinguish between the level of redundancy in the system. When a designed redundant system with 20 parallel zones is replaced by a redundant system with 100

parallel zones it is expected that equipment and maintenance costs will increase due to more components in the system but AT will increase due to more redundant zones.

Redundant level	Low	High	Measured	Expected
Nr of conveyors	20	100	Up	Up
Equipment costs	100%	388%	Up	Up
Maintenance costs	100%	263%	Up	Up
Technical availability	99,70%	0,29%	Up	Up

Table 4.2: validity check for different levels of redundancy in the system

As can be seen in table 4.2 the validity check for different levels of redundancy in the system corresponds with the expected outcome as described above.

The frequency of inspections

When the effect of the frequency of inspections is validated it is expected that the more inspections done the higher the maintenance costs will be and the higher the AT will be. As described before, relation between the frequency of inspections and the MTBF of a section is interpolated between zero inspections and the number of inspections measured at the reference site. In this validity check the testing of the relationship is important therefore a zero frequency is compared with a 20 inspection frequency.

Inspection frequency	Low	High	Measured	Expected
Nr of inspections	0	20	Up	Up
Equipment costs	100%	0%	Equal	Equal
Maintenance costs	100%	50%	Up	Up
Technical availability	99,68%	0,25%	Up	Up

Table 4.3: validity check for different sections in the system

Again as can be found in table 4.3 the validity check for different levels of redundancy in the system corresponds with the expected outcome as described above.

The stock levels of spare parts

The final validity check concerns the decision variable spare part levels. In this validity check it is expected that the higher the stock levels the higher the spare part investment and holding costs and the higher system availability. The extreme values of zero spare parts on stock are compared with 100 spare parts on stock chosen in order to check the relationship.

Spare parts inventory	Low	High	Measured	Expected
Nr of SP on stock per	0	20	Up	Up
Equipment costs	100%	0%	Equal	Equal
Spare parts investmer	100%	500000%	Up	Up
technical availability	99,18%	43%	Up	Up

Table 4.4: validity check for different sections in the system

Again as can be found in table 4.4 the validity check for different stock levels of spare parts corresponds with the expected outcome as described above.

The general conclusion of this validity check by extreme values is that all the relationships in the model are well incorporated in the MS Excel tool.

4.1.4 Sensitivity analysis

To get an insight in the robustness of the model, the sensitivity of some of the determined and assumed relationships are tested. This sensitivity analysis does not compare the optimal values of different modeling relationships, but it does compare the outcomes of different modeled relationships.
The model's sensitivity is tested to;

- The determined MTBF based on field data.
- The assumed linear relationship between inspection frequency and the MTBF.
- The function for the expected number of delayed baggage items (down time costs), by two ways;
    - Changing the constant factor *g* of formula
    - Changing the type of relationship

For all tables hold, that the values for LCC and technical system availability are expressed in a percentage change with respect to the basic (100%) situation.

MTBF based on field data
Currently VI is working with failure data based on extrapolated figures obtained in a test environment. This study works with values that are obtained from an operating system at a reference site. Unfortunately, the available data was not stored over a long enough time span to fit a failure distribution. Still these obtained figures were considered to be very valuable, because they were the first field based MTBF. In order to test how sensitive the model is to these figures, a comparison is made between the outcomes of a system with these field-based MTBF and a MTBF which is 1,5 or 0,5 times as large. The results are shown in table 4.5 and figure 4.1 provides the trend lines for the values in between 0,5 and 1,5.

	Obtained field MTBF	1,5 times field MTBF	0,5 times field MTBF
Technical availability	100%	**0,26%**	**-0,77%**
LCC	100%	**-0,27%**	**1,99%**

Table 4.5: Sensitivity of the determined MTBF.

Table 4.5 shows that the model is somewhat sensitive to deviations in the determined field MTBF, therefore it is important to replicate MTBF measurements in the future in order to establish more reliable distributions for section MTBF. Furthermore one should take into account that these sensitivities will also depend on the system size and system design in terms of redundancy. The sensitivity effects could be larger for a larger system with little redundancy.

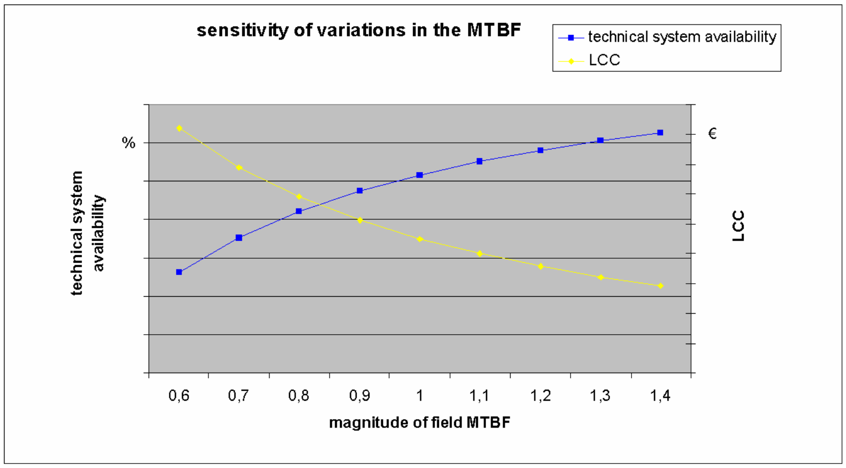

Figure 4.1: Sensitivity of the determined MTBF (values are scaled)

Linear relationship between frequency of inspections and the MTBF

This study has assumed a linear relationship between the inspection frequency and the MTBF. As described in subsection 3.1.3 a concave relationship will probably more appropriate in this case. In order to test the sensitivity of this assumption a concave relationship will be assumed. The MTBF that is determined at the reference site after 4 inspections is similar to 1 inspection in a concave relationship. The results are presented in table 4.6.

	Linear maintenance effect	First inspection determines all MTBF extending effects
technical availability	100%	**0%**
LCC	100%	**-0,29%**

Table 4.6: Sensitivity of the assumed relationship between inspection frequency and MTBF.

The results show that the model is robust to changes in the relationship between the inspection frequency and the MTBF.

The function for the expected number of delayed baggage items

Previous studies executed in the field of LCC at VI have either excluded down time costs or incorporated down time costs as a linear function of the expected flow of baggage items. This study has established a relation between down time cost, AT and utilization based on field data (see subsection 3.2.4 and appendix C). The sensitivity of the established relationship is compared to a situation where the constant *g* (of formula 22) changes with a factor of 1,1 (resulting in model with a less good fit $R^2 = 0{,}43$).

	established trendline	10% increase of constant *g*	10% decrease of constant *g*
technical availability	100%	0%	0%
LCC	100%	6%	5%

Table 4.7: Sensitivity of the deviations in constant factor *g*

The results of table 4.7 show that the model is quite sensitive to deviations in the function for the expected delayed baggage items. Therefore it is highly recommended to replicate the data-analysis for the function of the expected delayed baggage items.

A second analysis is conducted in order to test the sensitivity to the type of function. As described in appendix C, three different types of relationships have been tested. Table 4.8 presents the sensitivity of these different types of relationships.

	established trendline	Linear relationship	Logarithmic relationship
technical availability	100%	0%	0%
LCC	100%	0,6%	0,74%

Table 4.8: Sensitivity of different types of relationships

The results presented in table 4.8 show that the model is quite robust to different type of relationships. Still when operational utilization gets outside the observed field utilizations the differences between the different relationships can get larger, and the system becomes more sensitive. However, the designed capacity (influences the designed utilization rate) is hardly ever outside the obtained field utilizations. Therefore the system is robust to different types of relationships between the expected number of delayed bags and the designed utilization rate.

4.2 Case study: comparing alternative values for decision variables

The applied version of the model is described in the previous section, now it becomes interesting to obtain some managerial insights into what this model can evaluate. Therefore part of a real project is used as test case. In this project the four types of decision variables (level of redundancy, sections, inspection frequency and spare part stock levels) have been modified to see the impact on LCC and AT.

Two general remarks about the results have to be made:

- The first remark concerns the generalizability of the results found in this section. As described before, this study does not aim at finding optimal values for the decision variables, but it evaluates different alternatives. Therefore the results and options provided here do not hold for every material handling system, because each system is specific in size, complexity and design.
- The second remark is about the determined function for the expected delayed bags, which forms the most important element for the down time costs during the life cycle. Formula *20* (section 3.2.4), which describes the expected delayed bags, is based on data obtained at a specific reference site. Therefore it cannot directly be assumed that this formula holds for every airport site, factors as complexity and system dependency can play a role in the number of bags that are delayed. In order to evaluate this system on LCC and availability it is assumed that the reference site and this project have similar system complexity and system dependency.

4.2.1 Redundancy

In the first sensitivity analysis the redundancy level of the system is gradually increased. The first design is the most basic design with no redundancy, the second design provides redundancy after between check in islands. The third is similar as the second only it also has a redundant line after the screening area. Finally the fourth design is similar to the third, but it also contains an extra departure carrousel, which also increases total system throughput capacity. A basic lay-out of these four different designs and their characteristics can be found in appendix F. The results of this sensitivity analysis are presented in table 4.9 below:

	Design 1	Design 2	Design 3	Design 4
Equipment investment	100%	2,7%	6,0%	20,8%
LCC	100%	2,0%	2,1%	-4,7%
Technical system availability	100%	0,1%	0,2%	0,4%
Designed capacity (hour)	100%	0,0%	0,0%	50,0%
Expected peak flow (hour)	100%	0,0%	0,0%	0,0%
Expected delayed bags (LC)	100%	-0,1%	-0,5%	-30,6%

Table 4.9: The effect of redundancy on LCC and AT

The column behind each design presents the percentage increase or decrease with regard to the first design. The extra investments of design 2 and design 3 result in a LCC increase around 2%. Furthermore the expected delayed bags are expected to decrease by 0,1%, which does not result in a substantial reduction of down time costs. Remarkably in this analysis is the effect of the investment in design 4, although the initial investment increases with 21% the LCC decrease with of 4,7%. This decrease in LCC is mainly caused by the increase in the designed capacity and the increase in AT, which result in less expected delayed bags.

4.2.2 Sections

In the second sensitivity analysis the effect of different type of sections is evaluated. Some customers require shorter conveyors in stead of longer conveyors. To get an insight in the effect of different section length (with different cost, MTBF, MDT, spare part and maintenance properties) on LCC and AT a comparison is made. Based on design 3 mentioned in subsection 4.2.1 it is analyzed which conveyors could be replaced by either shorter or longer conveyors. In the first alternative the system is build up from as much long conveyors as possible, in second alternative is build up from as much middle length conveyors as possible and the third alternative is build up from as much short conveyors as possible. The results of this analysis are shown in table 4.10.

	Option 1	Option 2	Option 3
Equipment investment	100%	2,1%	7,8%
LCC	100%	0,4%	3,4%
Technical system availability	100%	0,0%	-0,2%
Designed capacity (per hour)	100%	0,0%	0,0%
Costs per bag expected flow	100%	0,0%	0,0%
Expected delayed bags	100%	0,1%	0,5%

Table 4.10: The effect of different conveyor length on LCC and AT

In general this pattern shows that for conveyors hold; that if they are replaced by multiple shorter conveyors the LCC increase due to higher investment costs and more maintenance and spare part costs. Furthermore a slight decreasing trend in AT can be found due to more equipment that can fail. The effect of a decreasing trend in AT will also reflect in an increase in the expected number of delayed bags.

4.2.3 Frequency of inspections

The third sensitivity analysis presents the effect of the frequency of inspections on LCC and AT. The frequencies have been chosen between zero and the maintenance frequency of measured at the reference site. As described in subsection 3.1.2 the relationship between inspection frequency and MTBF is assumed to be linear, therefore only two frequencies of inspections have been analyzed. The first alternative has zero inspections per section and the second alternative has 4 inspections per section. The outcome is presented in table 4.11 below:

	Inspection 0	Inspection 4
Direct maintenance costs	100%	7,6%
Technical system availability	100%	0,2%
LCC	100%	0,3%
Designed capacity (per hour)	100%	0,0%
Expected peak flow (per hour)	100%	0,0%
Expected delayed bags	100%	-0,5%

Table 4.11: The effect of inspection frequency on LCC and AT

This sensitivity analysis shows that increasing the number of inspections leads to a higher system availability. But the related savings on expected number of delayed bags are currently not substantially high (0,5%). Still there is a good reason why inspections need to done. This reason is based on the fact that in this study indirect maintenance costs are not taken into account. These indirect costs consist of labor costs for overhead and labor costs of maintenance engineers that are not performing preventive maintenance activities, but are present in case a technical or operational failure occurs. This means that indirect maintenance labor costs are paid even when engineers are not performing preventive or corrective maintenance activities.

4.2.4 Spare part stock level

In the fourth analysis the spare part stock levels are deviated from the levels that are proposed by the current policy. The stock levels are deviated by adding and removing section spare parts from the shelf. The outcome is presented in table 4.12:

	SP opt current	SP opt current -1	SP opt current +1
SP investment + holding costs	100%	-24,1%	23,2%
LCC	100%	5,1%	0,4%
Technical system availability	100%	-2,7%	0,0%
Designed capacity (per hour)	100%	0,0%	0,0%
Expected peak flow (per hour)	100%	0,0%	0,0%
Expected delayed bags	100%	6,8%	-0,1%

Table 4.12: The effect of different spare part level on LCC and AT

This analysis shows that lowering the entire spare part inventory with 1 unit, has quite some impact on the AT and the related delayed bags. Interesting to see is that the LCC substantially increase when removing 1 unit for each critical spare part. This is mainly caused by a decrease in AT, which increases the expected number of delayed bags and extra costs for emergency transshipments. While investing in the spare part inventory by adding 1 extra unit to the inventory has hardly any positive impact on the AT. This analysis did not had as objective to find the optimal stock level, therefore improvements can be found in terms of minimizing spare part investments, but these optimizations will not affect LCC to a large extent.

4.2.5 Equipment maintainability

This last sensitivity analysis is a hypothetical analysis. It provides insight in the effect of possible reductions of MTTR (mean time to repair) on LCC and AT. Since it is currently not known how to decrease MTTR, this analysis gives insight in the effect of MTTR reduction. The first alternative presents the MTTR as it is currently estimated, the second alternative is a reduction in MTTR of 10% and the third alternative presents a reduction in MTTR of 50%. The outcome is presented in table 4.13:

	MTTR 1	MTTR 2	MTTR 3
Reduction in MTTR	100%	10,0%	50,0%
LCC	100%	-0,05%	-0,2%
Technical system availability	100%	0,0%	0,1%
Designed capacity (per hour)	100%	0,0%	0,0%
Expected peak flow (per hour)	100%	0,0%	0,0%
Expected delayed bags	100%	-0,1%	-0,3%

Table 4.13: The effect of reduction in MTTR on LCC and AT

From this analysis it can be concluded that the effect of reducing the current MTTR contains little benefits (0,05% and 0,2% on the LCC respectively). Of course when it is possible to reduce MTTR with little effort and investment this will positively affect AT and LCC.

4.3 Implementation

An important aspect of implementing a new model, is fitting it into the current business processes and way of working. Subsection 4.3.1 suggests the best location of where the model should be managed within the organization. Moreover subsection 4.3.2 describes how the tool fits within the current business processes and the last subsection looks ahead to cope with coming developments related to the model and the tool.

4.3.1 Location within VI

As described before the goal of this research was to create a model that supports in steering LCC at the beginning of the pipeline. Furthermore this model should be worked out into a straight-forward tool. Since the model deals with aspects from sales, and service departments, it should be seen as beneficial for the company as a whole, because it prevents sub optimizations. Still input of all departments involved is required, therefore it is important to create support from these departments. Furthermore they should also be involved in further developing the model. Since it might be difficult not to get into the pitfall of sub optimizations it is suggested to manage the model by a department that has the overview of the entire process. For VI this will best fit within the systems department.

4.3.2 The tool in the current processes

In order to benefit optimally from the model, the fit within the current business processes must be well thought over. Figure 4.2 below presents how the developed tool (based on the model) fits in the current pricing and simulation processes.
A first draft version of a CAD drawing provides the input for the model. Based on the given design lay-out an availability structure must be created in order to denote the parallel and sequential relationships in the system. When this availability structure is developed the calculation requires input in terms of MTBF and MDT and costs. All costs information on the equipment used in the system follows from the pricing tool (CAP).
As described in this report the MTBF and MDT can be influenced by investments in the decision variables. The resulting MTBF and MDT form the input for the availability calculation. The related costs of the decisions are processed in the LCC calculation. The effect of different decisions can easily be checked by changing the parameters related to the system information that affects LCC and AT.
The cost buckets that are not covered in this model follow from the current LCC methodologies. Combining the LCC outcomes of the model and the current methodologies, provide the total LCC for material handling systems.

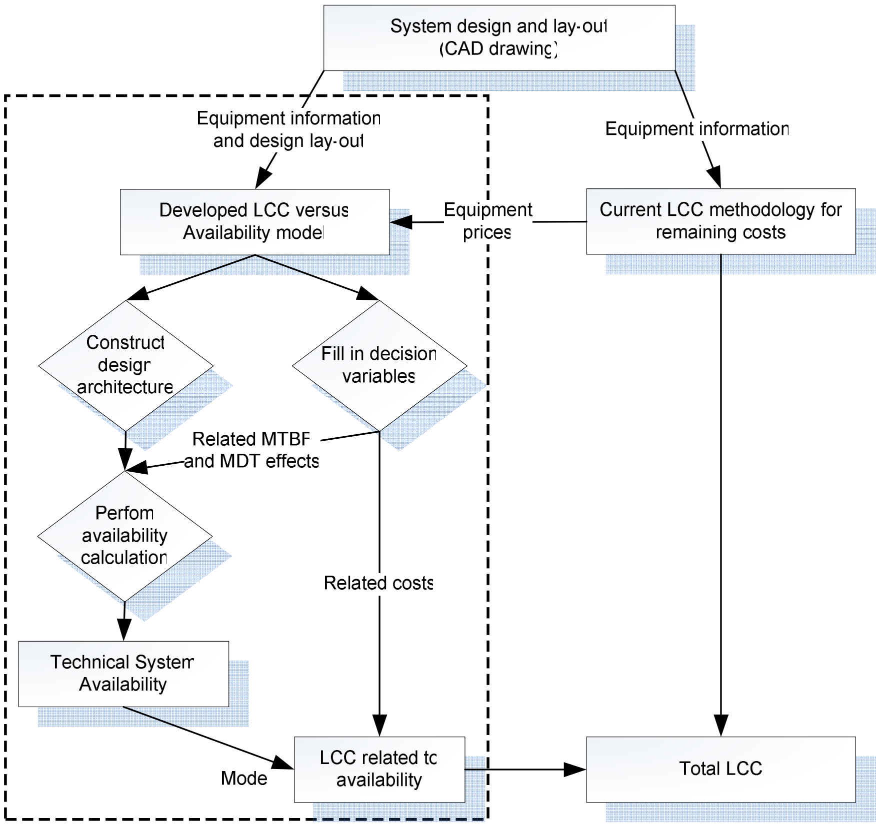

Figure 4.2: Fit of LCC versus availability model into the current business processes of VI

4.3.3 Developments

The LCC versus availability tool currently requires substantial manual work for large projects. For relatively small projects the model provides quick insights in the effects of design and maintenance decisions on the total LCC and availability.

Currently the simulation department is executing projects to generate automatically a CAD lay-out in simulation software (see appendix H). This automated process can also be applied to availability studies of designed systems. If this simulation method is combined with the LCC versus availability methodology described in this report an easy and fast method to judge different alternatives based on LCC and availability can be created. Appendix I presents schematically how the two methodologies can be combined.

5 Conclusions

This chapter describes the main findings of this study, moreover it describes also limitations and it provides recommendations for further research.

5.1 Main findings:

General

Below an overview of the general findings of this study is provided:

- Customers are evermore requiring insight in LCC and AT in the early phase of a project.
- Although VI has a lot of knowledge regarding LCC, currently no central calculation model is available, which provides insight in the relationship between LCC and AT.
- Mathematical relationships between the concept of LCC and AT have been established and modeled into a tool, which uses a given system design as input and provides LCC and AT as output.
- The model is generalizable and can be applied to other segments (distribution and express parcel) as well. Of course these applications would require other input variables, but these can be obtained in a similar way as was done for BHS.

Data analysis

This study has used field measurements on section level obtained at a large reference site, while previous calculations have always used data based on experience. This resulted in the following obtained innovative relationships:

- Measurements for spare part consumption at the reference site have provided insight in yearly consumption of spare parts per section. This provides a reliable estimation and prevents a detailed calculation in the early stage of the project.
- The model has incorporated the effect of inspections on the MTBF of sections. This effect has been established based on data from the reference site.
- A formula for the expected number of delayed bags (important indicator for down time costs) has been established from data at the reference site. This formula relates throughput, designed system capacity, technical and operational system availability to the expected number of delayed bags.

Applicability

Findings regarding the applicability of the research are given below:

- Special attention has been paid to create an intuitive and understanding tool, which uses standards that are well known within VI.
- This model will be easy to integrate in the current business processes. Because it uses the basics of the sandglass model (appendix B) with section level as lowest workable level. A fit with the current business processes has been visualized in section 4.3.
- In stead of LCC calculations on spare part level (element and material level) an aggregate spare part is created on section level, which prevents too detailed analysis in an early project phase.

Managerial insights

The sensitivity analysis conducted in section 4.2 provided the following insights:

- Different design alternatives can be evaluated based on total LCC and system performance in terms of AT. Investments in increasing designed capacity can earn it self back by savings on downtime costs.
- The replacement of long conveyors by multiple shorter conveyors increases the LCC and AT. Due to the increasing amount of critical components in the system.
- The effect of inspections on the MTBF of sections is positive on AT, but it does require extra direct maintenance costs, which in the end leads to an increase in LCC.
- Extra spare part investments with respect to the current policy did not provide substantial higher AT. Whereas reducing the spare part levels can have a negative impact on availability, and increases the LCC. This means that due to the downtime cost function optimal spare part levels for each system can be found.
- Investments in reducing the MTTR will probably not pay-off substantially in an increase of AT and a reduction of LCC. Because MTTR values are already extremely small compared to MTBF values, and therefore this will not result in a significant higher system availability.

5.2 Limitations and Recommendations:

With regards to further studies on this subject, the limitations and recommendations are presented below:

- Since the data at the reference site is tracked over a relatively short time span the distributions for failure rates on section level and spare part level were not to be detected. Therefore the MTBF figures used in this study are based on the best estimates possible as described in appendix D.
- The analyzed data is based on one reference site and not replicated to test reliability. It is recommended to replicate this data at different reference sites to increase reliability of the input parameters of the model.
- Since the effect of higher and lower level control is not known yet the effect is considered as a constant, while in reality this might have a variable impact on AT. A study should be set up to measure the effects of different levels of higher and lower control in order to incorporate these relations into the model.
- In this study the effect of inspections on the MTBF is considered to follow a linear relationship. In reality it can be assumed that the relationship will behave more like a concave relationship. Further research on these relationships between different maintenance frequencies and the MTBF is highly recommended.
- For the expected number of delayed bags (an important indicator for down time costs) counts that system complexity and country specific aspects (costs of labor) are not taken into account, while these factors will most probably affect the down time costs as well. Therefore it is also highly recommended replicating the same analysis at other reference sites under different circumstances.
- For the current developed tool substantial manual input is required, but provides flexibility advantages at this stage. In a later stage (when the calculation model will be further developed) the tool can be rebuild in another environment than MS Excel, which will lead to time saving improvements.

General recommendations
Further a list of general recommendations is presented below:

- General agreements on standardizing system availability will be made in the future. Therefore it is important to take these new developments into account when updating the model.
- In the future system lay-outs will automatically be uploaded into simulation models and availability calculation models. Therefore it is important to consider section 4.3, which describes the business process in case these features are fully developed.
- Service teams at multiple reference sites (under different conditions) should continue to store data in their maintenance databases. In order to provide more reliable failure data of sections and spare parts in order to fit a failure distribution, this will improve failure-behavior prediction.
- The methodology described in appendix D to obtain this failure information from the maintenance database should be stored and executed periodically to improve insights in failure data.
- Another field of improvement is to get an insight in the effect of a time based preventive maintenance policy. Of course when applying such a policy, it is of great importance to have reliable failure data.
- It is recommended to update the model periodically with new information on:
    - MTBF and MTTR figures of sections and spare parts from the field
    - Effect of inspection frequency
    - Different maintenance policy
    - Related to the expected missed bags due to system unavailability

Symbols and abbreviations

AO_s = Operational availability of system *s*, assumed to be constant (in percentage)
AT_{ar} = Technical availability of area of type *ar* (in percentage)
AT_{az} = Technical availability of aggregate zone *az* (in percentage)
$AT_{az,ar}$ = Technical availability of aggregate zone *az* present in system *ar* (in percentage)
AT_j = Technical system availability for section *j*
AT_s = Technical availability of system *s* (in percentage)
AT_z = Technical availability of zone of type *z* (in percentage)
$AT_{z,ar}$ = Technical availability of zone *az* present in system *ar* (in percentage)
ar = Corresponds to area *ar* (for *ar* ϵ 1…AR)
az = Corresponds to aggregate zone *az* (for *az* ϵ 1…AZ)
B_s = Number of baggage items arriving too late (in number of items/capacity/hour)
cd = Direct maintenance hour rate (in euros)
$ci_{cp,j}$ = The initial spare part cost per critical spare part *cp* of section *j* (in euros)
cm = Expected costs per missed bag (in euros)
CM_s = Total corrective maintenance costs for system of type *s* (in euros)
cp = Corresponds to SKU *cp* (for *cp* ϵ 1…CP)
ct_s = Emergency transshipment costs for system *s*
cu_j = The expected spare part usage costs per failure on section *j* (in euros)
d = Constant 1 determined by data-analysis at the reference site (see appendix C)
DMC_s = Direct maintenance costs of system *s* (in euros)
DTC_s = Down time costs of system *s* (in euros)
g = Constant 2 determined by data-analysis at the reference site (see appendix C)
h_j = Yearly number of inspections at section *j* in a new system
i_s = Annual inflation rate of system *s* (in percentage)
INS_s = Total inspection maintenance costs for system *s* (in euros)
IRR_s = Internal rate of return of system *s* (in percentage)
j = Corresponds to section *j* (for *j* ϵ 1…J)
l_j = Yearly number of inspections at section *j* done at reference site
LC_s = Life cycle of system *s* (in years)
LCC_{AT_s} = Life cycle costs related to technical system availability *AT* of system *s* (in euros)
$LCCD_{AT_s}$ = LCC related to technical system availability of system *s* after discounting (in euros)
$m_{cp,j}$ = Failure rate of SKU's *cp* of section *j* (per hour) (appendix D.7)
M_j = Failure rate of section *j* (per hour)
$MADT_j$ = Mean administrative delay time for section *j* (in hours)

MDT_j = Mean system downtime after a failure of section *j* (in hours)

$MDT_{j,z}$ = Mean down time of section *j* (in hours)

$MLDT_j(S_{cp,j})$ = Mean logistic delay time for section *j* depending on SKU level $(S_{cp,j})$ (in hours)

$MTBF_j$ = Mean time between failures of section *j* (in hours)

$MTBF_j(h_j)$ = Mean time between failures of section *j* after inspection frequency h_j (in hours)

$MTBF_{j,z}(h_j)$ = Mean time between failures of section *j* in zone *z*, affected by inspection frequency h_j (in hours)

$MTBF_{j,l_j}$ = Mean time between failures of section *j* with inspection frequency *l* measured at the reference site (in hours)

$MTTR_j$ = Mean time to repair section *j* (in hours)

n_{az} = Number of zones in parallel in aggregate zone *az*

$p(h_j)$ = The probability (corresponding to the frequency of inspections on section j) of preventive maintenance after an inspection

$P_{cp,j}(SO)$ = Probability that SKU *cp* for section *j* is out of stock

PM_s = Total preventive maintenance costs for system of type *s* (in euros)

q_{az} = Agreed minimal throughput capacity per aggregate zone *az* (in number of bags)

r_s = The yearly percentage paid for SKU's for system *s* (in percentage)

s = Corresponds to system *s*

$S_{cp,j}$ = The total number of stocked SKU's *cp* according to current spare part policy

$S_{cp,j,VI}$ = The number of spare parts of section *j* of spare part type *cp* calculated by current approximation method (in integer spare parts)

$S^-_{cp,j}$ = The minimal fixed stock level of spare parts type *cp* (in integer spare parts)

$S^+_{cp,j}$ = The maximal fixed stock level of spare parts type *cp* (in integer spare parts)

SI_s = The initial spare part investment for system *s* (in euros)

SH_s = The life cycle holding costs for stocking spare parts for system *s* (in euros)

SO = abbreviation for Stock Out

SPC_s = Spare part costs of system *s* (in euros)

ST_s = The life cycle spare part emergency transshipment costs for system *s* (in euros)

STC_j = Sales to customer price of section *j* (in euros)

STC_s = Sales to customer price of system *s* (in euros)

SU_s = The life cycle spare part usage costs for system *s* (in euros)

TBI_j = Time between inspections on section *j* (in hours)

TC_j = Corrective maintenance time required for section *j* (in hours)

$TE_{cp,j}$ = Expected emergency transshipment time of SKU *cp* for section *j* (in hours)

$th_{\max,z}$ = Maximum capacity for zone *z* (in bags per hour)

$th_{\max,s}$ = Designed maximal hourly capacity of system *s* (in bags per hour)

th_s = Expected throughput per hour in system *s* (in number of bags)

TI_j = Inspection time required for section *j* (in hours)

$TP_{cp,j}$ = The expected regular replenishment time for SKU *cp* (in hours)

TP_j = preventive maintenance time required for section *j* (in hours)

TT_j = Expected travel time from the warehouse to the location of the failure for spare part section of type *j* (in hours)

w_s = Agreed warranty period of system *s* (in years)

x_{az} = Minimum number of operating zones required in aggregate zone *az*

y_j = The number of sections of type *j* in the system (in integer number of sections)

yh_s = Yearly operating hours of system *s* (in hours)

z = Corresponds to zone *z* (for $z \in 1 \ldots Z$)

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Appendix A: Cost break down structure BHS

Franssen's cost break down structure for a typical BHS

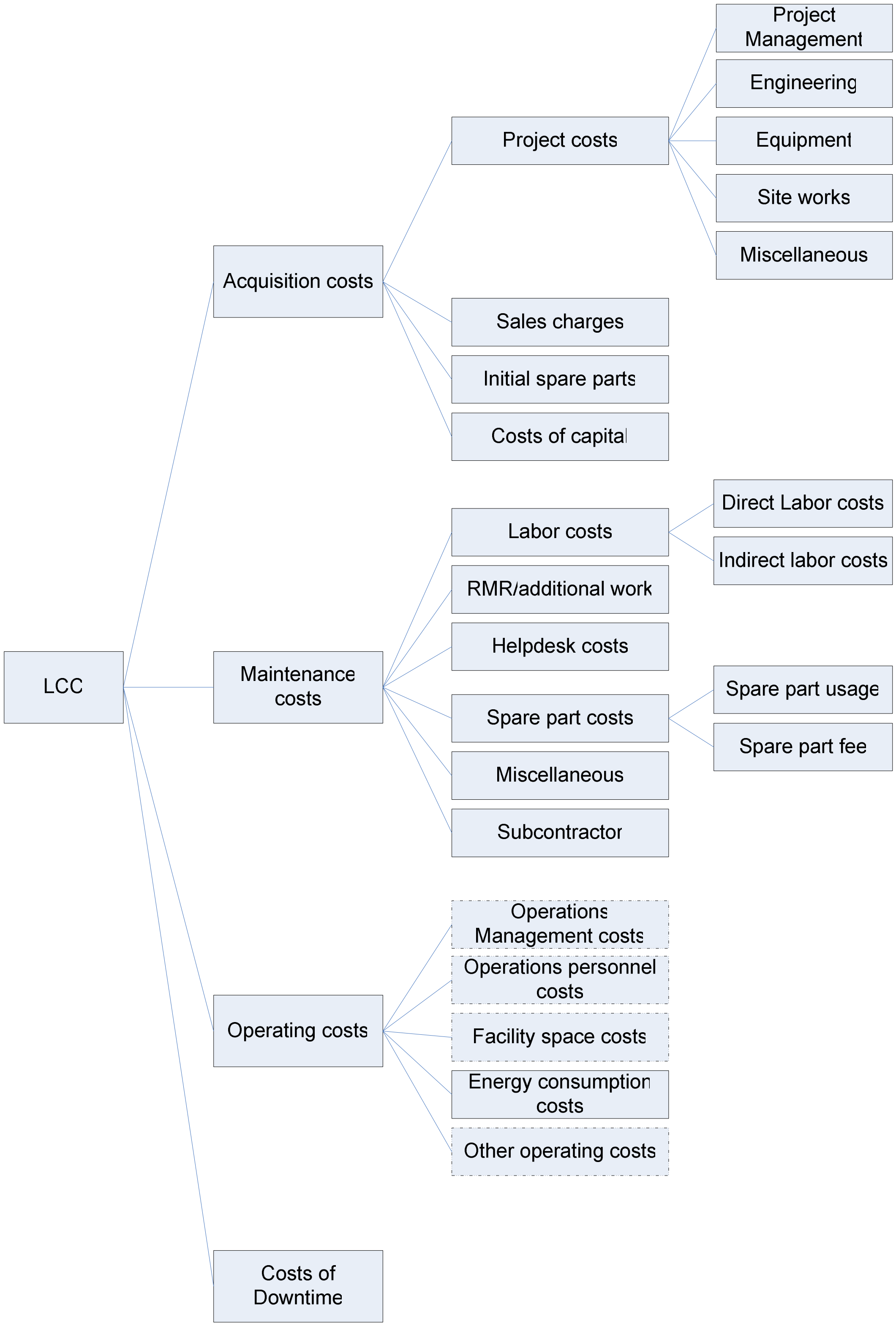


Figure A.1: Cost break-down structure by Franssen (2006)

Appendix B: VI's sandglass model

Shortly VI introduced a sandglass model for its systems, which breaks down a system into its basic materials and elements. This model has become the backbone of VI's systems. For this research it is decided to use section level as building blocks for LCC and technical system availability. The system (eg BHS) consists of process areas, which are a combination of areas where a transition takes place (eg from unscreened bags to screened bags, check in area and screening area). An area is a sequential or parallel combination of zones, which consist of sections that are used as building blocks.

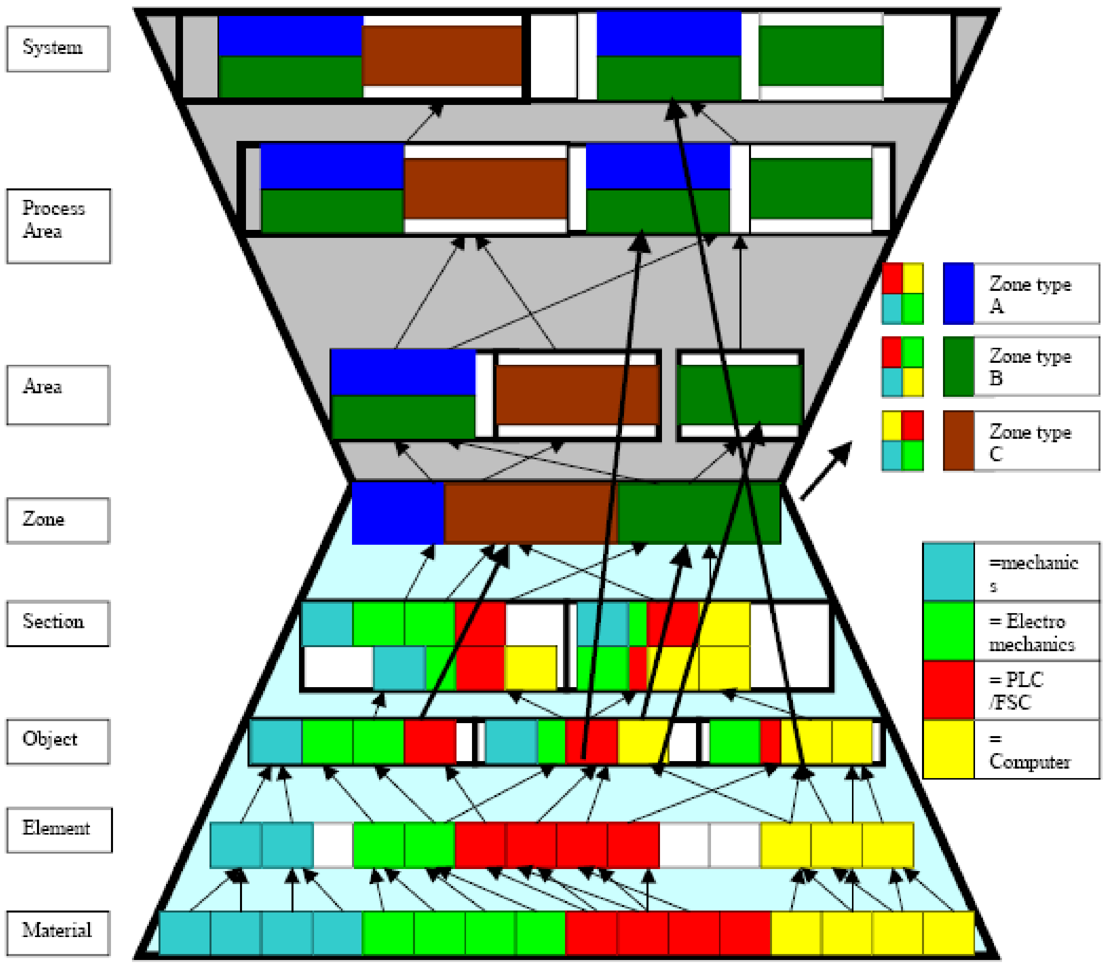


Figure B.1: Sandglass model for material handling systems of VI

Appendix C: Down time costs

NB: figures used in this appendix are all fictive

The expected number of delayed bags in the BHS is an important indicator for down time costs. In order to establish a relationship between the expected number of delayed bags and the design of the system, the following aspects have been identified; the system designed capacity, the throughput, and the technical and operational system availability. Furthermore system complexity and customer dependency on the system are also aspects that have influence on the expected delayed bags. These latter two aspects can only be assessed qualitatively since there are currently no indicators that can quantify these aspects. The first four aspects are combined in formula *c.1* and result in the operational utilization rate of the system.

$$Ut_s = \frac{th_s}{th_{\max,s} \cdot (A_{t,s} \cdot A_{o,s})} \qquad (c.1)$$

Ut_s = Operational utilization rate of system s

th_s = expected throughput per hour in system s

$th_{\max,s}$ = designed maximal hourly capacity of system s

TA_s = Technical availability of system s

OA_s = Operational availability of system s

Table c.1 shows that the independent variable (operation utilization) is highly correlated with the independent variable (delayed bags/capacity)

	operational ulilization	Delayed bags/capacity
operational ulilization	1	
Delayed bags/capacity	0,857873851	1

Table C.1: correlation between operational utilization and bags/capacity

A typical daily pattern at the reference site can be found in figure C.1, this figure shows approximately 7 peak hours (blue area depicts baggage flow and the bars depict the number of delayed bags) that cause around 70 percent of the number of bags that are delayed.

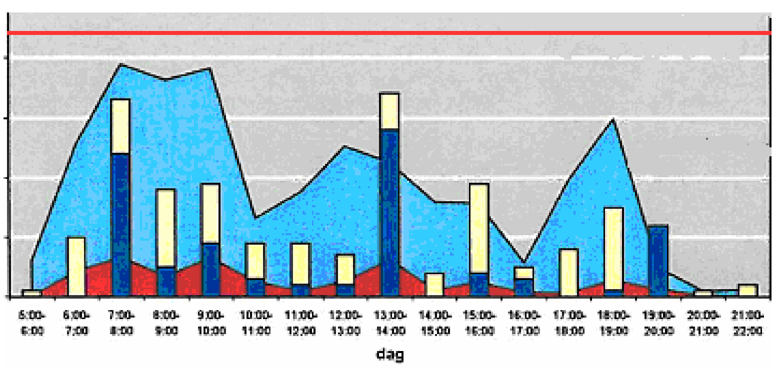


Figure C.1: Typical day pattern of reference site

The reference site has these figures available for a period of 240 days (between 1-3-2008 until 1-12-2008).

For the site holds that system complexity is considered to be high, due to its size and level of technology in the system. Concerning the system dependency, it can be concluded that the customer highly depends on the performance of the system, because in case of a technical or operational system failure there is no other option for bags to continue than to wait for the repair. A general model for systems with similar complexity and customer dependency requires control for the designed capacity. Therefore the expected delayed baggage items obtained at the site should be divided by the expected system capacity.

Below in figure C.1 till C.3 the general trend line of the expected delayed baggage items is plotted. First a linear regression analysis has been conducted and secondly two nonlinear regression analysis (exponential and logarithmic).
The following assumptions for regression analysis (Hair et al, 2006) were checked and were found true:

- The variability of values around the curve follow a Gaussian distribution.
- The variability is the same everywhere, regardless of the value of the operational utilization rate. This assumption is termed homoscedasticity .
- The model assumes that you know the operational utilization rate exactly. It is sufficient to assume that any imprecision in measuring the operational availability is very small compared to the variability in bags/capacity.
- The errors are independent. The deviation of each value from the curve is random, and not be correlated with the deviation of the previous or next point.

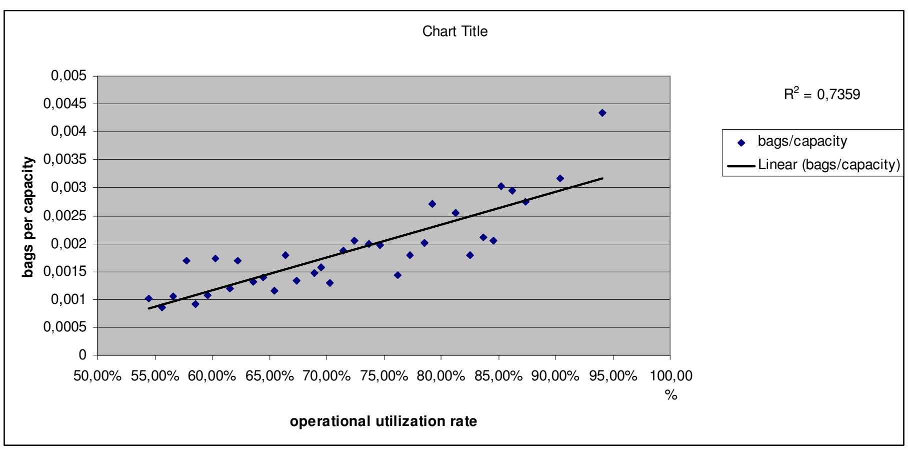


Figure C.1: linear relationship between operational utilization rate and bags/capacity

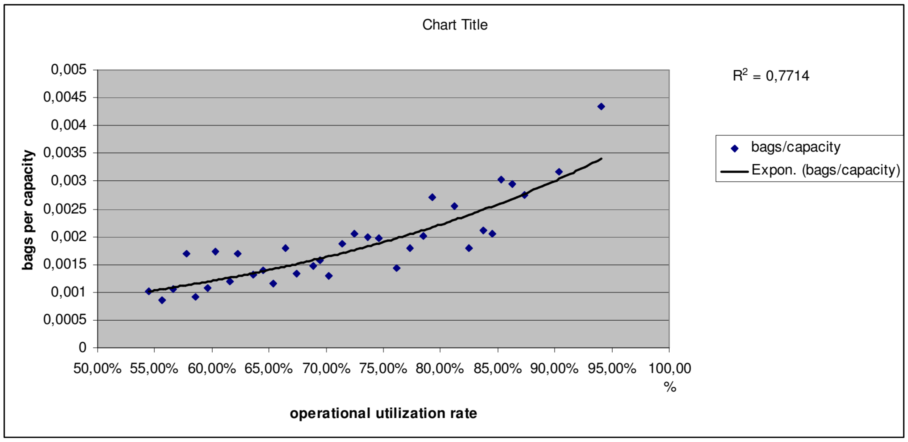


Figure C.2: exponential relationship between operational utilization rate and bags/capacity

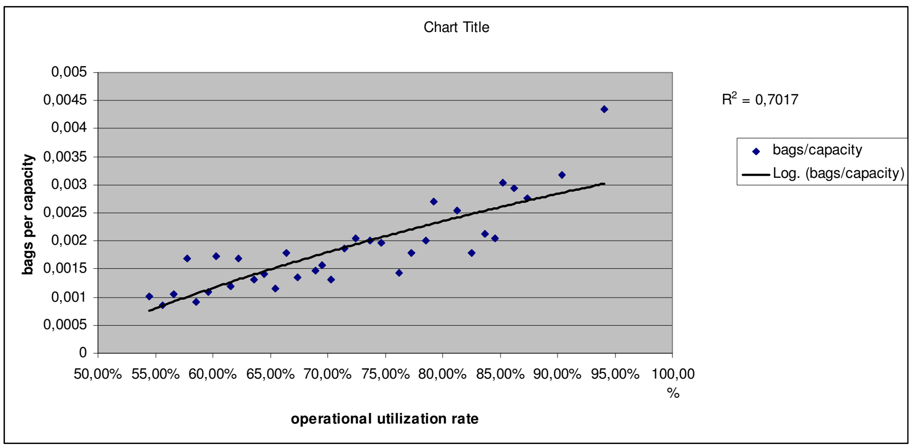


Figure C.3: logarithmic relationship between operational utilization rate and bags/capacity

Of these relationships the exponential model fits the best to the observed data. It has an R-squared of 77% and with a high F-value resulting in a significant model fit ($p<<0,001$).

Appendix D: Methodology of data analysis

In the first phase of the master thesis project a data-analysis is conducted in order to improve the experience figures currently used in LCC and technical system availability calculations. This appendix consists of seven different sub parts;

1. Data-source
2. Sections analyzed
3. Determining field MTBF figures of sections
4. Effect of maintenance inspection frequency
5. Expected direct maintenance hours
6. Average spare part usage costs
7. Repair versus replacement

D1. Data-source

The source of the data is the maintenance database (MAXIMO) of the reference site. This database stores all technical maintenance on section level of system. This means that whenever an inspection, preventive maintenance action or corrective maintenance action is done, it is stored in this database. Although the database is running for quite some time at the reference site, it appeared that the database was not used properly in the past. Therefore the data until a specific moment should be left out of the analysis. The database can be analyzed and accessed by an especially designed tool called Discoverer. This tool provides insight in the database structure of MAXIMO.

When the database is approached by discoverer the following fields have been exported:

- Work order
- Location
- Work type
- Organization
- Actual start date and time
- Actual labor hours
- Article
- Article prices

By combining this database with a data-base that describes the hierarchy of the entire system at the reference site, it becomes possible to analyze the data by section.

D2. Sections analyzed

As described in the demarcation of this study, the focus is on conventional BHS. A selection of these sections is made for further data-analysis this selection is given in table D.1.

Carrousel
Belt curve (0-45)
Belt curve (60-90)

Belt curve (130-180)
Bidirectional conveyor
Belt Floorveyor (<3m)
Belt Floorveyor (3m-10m)
Belt Floorveyor (>10m)
Belt Junction
Vertimerge
Sorter tilt-tray
Vertisorter
Vertibelt
Weighing belt

Table D.1: List of selected sections for data-analysis

D3. Determining field MTBF figures of sections

An important aspect when measuring field data is that it is subject to external influences after analyzing some of the data and discussions with service experts the following influences are mapped and taken into account:

- The current preventive maintenance policy, because the operating MTBF of sections measured is affected by the applied policy.
- The current spare part management policy, because this affects the downtime (MDT) of the system.

The available technical failure data could not provide enough information in order to fit a failure distribution to the failure rates of the analyzed sections. Therefore only an estimation could be made about the MTBF of different sections based on the number of total operating hours and the total failures in that period on a specific section. Still this information is valuable, because figures from practice have never been obtained before.

D4. Effect of maintenance inspection frequency

The effect of the maintenance inspection frequency is based on the same failure data as described above. Since the maintenance frequency at the reference site did not vary in the analyzed period it was not possible to measure the difference in effect between different frequencies. Therefore an approach to filter out the effect of inspections and preventive maintenance actions is done to determine the MTBF of the sections without doing any inspections. This was possible by assuming that preventive actions that followed from inspections (stored as work type: WINSP) were actually technical failures. The degree of reality in this assumption depends very much on the quality of service engineers. For the reference site it can be stated that due to a lot of experience with technical failures the quality of service engineers can be considered as high, and therefore the assumption is justified.
Furthermore based on the detailed maintenance schedule of equipment developed by the reference site the maintenance frequency per section was given. This analysis provided two points on the relationship between maintenance frequency and the extending effect on MTBF of sections.

D5. Expected direct maintenance hours

With the failure data it became possible to obtain an expected time for preventive maintenance and corrective maintenance per section. By analyzing the time of corrective maintenance actions it appeared that related down time of the system was much smaller than corrective maintenance time. This was caused by the fact that restoring the system could be done faster than the total direct labor hours related to the specific technical failure. Hence it could not be stated that the corrective maintenance time found in the system is a representative of the mean time to repair (MTTR) the system in order to continue operation. Therefore it was decided to use MTTR figures from the test center.
The values obtained for corrective maintenance activities can still be considered as direct labor hours, because these are the expected hours due to technical failures. Moreover, the analysis has shown that the preventive maintenance actions in general take shorter than corrective maintenance actions. This is mainly caused by the fact that preventive maintenance actions can be better prepared than corrective actions.
For the expected time per inspection it must be noticed that these are not stored per section but are attributed to the entire system. Therefore in this study the figures used are obtained from the judgment of service experts, who developed the inspection maintenance sheet at the reference site.

D6. Average spare part usage costs

Ever since VI has done LCC analysis the estimates for spare part usage were based on experience figures. To improve these figures the maintenance database approached with as goal to obtain expected spare part consumption (in terms of costs) per section in the system. Therefore the database was combined with a database containing all spare parts at the reference site. This has provided insight in the average costs per section failure. Although there were doubts about the degree of correctly filled in spare part items per section failure, experts at the reference site confirmed that the database was also used to replenish the stock levels based on the items used. This confirmed the reliability of the registration of spare parts.

D7. Repair versus replacement

When technical failures occur in the system there are two options; the system can be repaired without spare part replacement or with spare part replacement. When working with the spare part levels it is important to know the probability of requiring a spare part when a technical failure occurs. Therefore for each section the maintenance database is analyzed in order to determine a deterministic probability of requiring a spare part when a technical failure occurs.

Appendix E: Equipment surcharges

Example of current pricing CAP methodology:

$$STC_j = ce_j \cdot (1 + rp_j) + TC_{m,j} \cdot cc_j + TL_j \cdot cl_j + TN_j \cdot cn_j + TA_j \cdot ca_j + TO_j \cdot co_j$$

$ce_{\mathrm{j}} =$ equipment costs for section type j

$rp_j =$ surcharge rate for equipment profit for section type j

$TC_j =$ expected mechanical engineering hours for section type j

$cc_j =$ mechanical engineering hour rate for section type j

$TL_j =$ expected direct electrical engineering hours for section type j

$cl_j =$ electrical engineering hour rate for section type j

$TN_j =$ expected direct installation engineering hours

$cn_j =$ installation hour rate for section type j

$TA_j =$ expected direct system engineering hours for section type j

$ca_j =$ system engineering hour rate for section type j

$TO_j =$ expected direct production engineering hours for section type j

$co_j =$ production hour rate for section type j

These STC values form the input for the LCC versus technical availability model developed in this study.

Appendix F: Project designs of scenario analysis

NB: figures used in this appendix are all fictive

For the sensitivity analysis an actual VI project is used and modified in four different designs to test the sensitivity of redundancy on LCC and technical system availability. First of all the input parameters for the project are described in table F.1.

Costs per baggage not loaded	€ 200,00	euro
Costs direct maintenance hour	€ 20,00	euro
Costs indirect maintenance hours	€ 30,00	euro
Operating LC (years)	15	years
Operating weeks/year	52	weeks
Operating days/year	360	days
Operating hours/day	20	hours
Operating hours/year	7200	hours
Equipment running hours/day	12	hours
Equipment running hours per year	4320	hours
hours per LC	64800	hours
energy saving factor	xx%	percent
kWh price	€ 0,070	kWh
SP average commission rate	xx%	percentage
SP warranty period	2	year
Down time (delayed bags)		
expected throughput in peak hours	2430	per hour
expected throughput remaining hours	1000	per hour
designed capacity per hour	2880	per hour
number of peaks hours	6	per day
remaining hours	8	per day
expected operational availability	100%	average

Table F.1: Project specific input parameters (figures are fictive)

In appendix F.1 until F.4 a simple lay-out structure is given for the four types of design. In the remaining sensitivity analyses design 3 is used.

F.1: Design 1 (no redundancy)

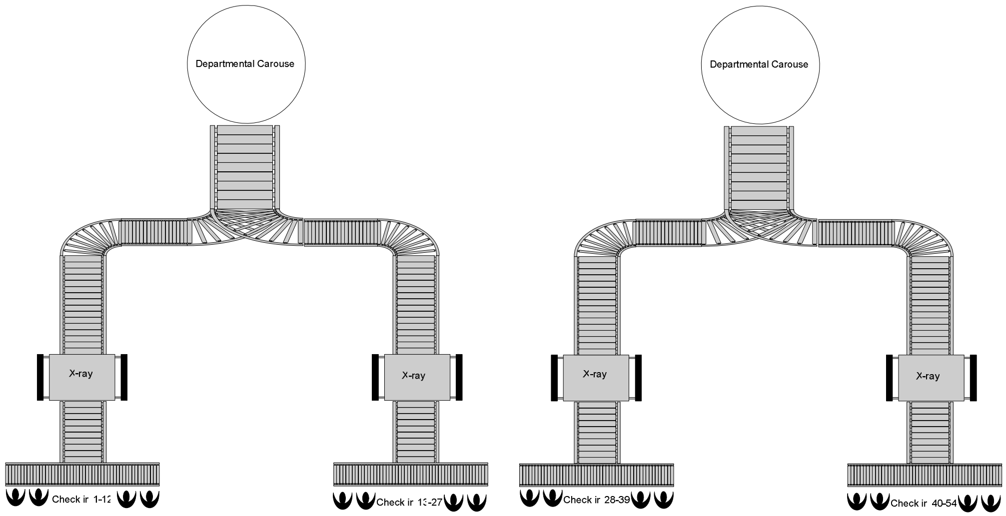


Figure F1.1: Design 1

design 1

section	nr in system	capacity (per hour)	tot value stocked	est holding	INSP frequency
BC2 (60-90)	8	1440	9770	25647	4
BF1 (klein)	78	1440	3967	10413	4
BF2 (middel)	8	1440	4452	11687	4
BF3 (lang)	10	1440	5387	14141	4
Dcar	2	1440	4459	11704	4
HBS1/2	4	1420	external		4
HBS3	2	800	external		4
WB	54	60	0	0	4

Table F1.1: features design 1 (figures are fictive)

F.2 : Design 2 (redundancy between two check in areas)

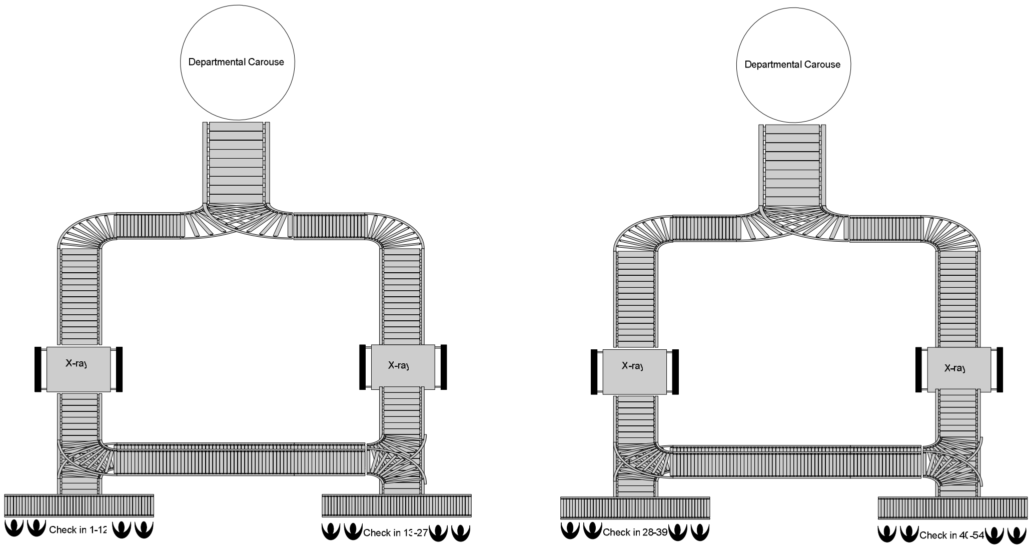


Figure F2.1: Design 2

design 2

section	total number of sections in system	capacity (per hour)	tot value stocked	est holding	INSP frequency
BC2 (60-90)	8	1440	9770	25647	4
BDC	8	1440	3453	9063	4
BF1 (klein)	78	1440	3967	10413	4
BF2 (middel)	8	1440	4452	11687	4
BF3 (lang)	6	1440	5387	14141	4
Dcar	2	1440	4459	11704	4
HBS1/2	4	1420	external		4
HBS3	1	800	external		4
WB	54	60	0	0	4

Table F2.1: features design 2 (figures are fictive)

F.3: Design 3 (similar as design 2 + redundancy between the two departure carrousels)

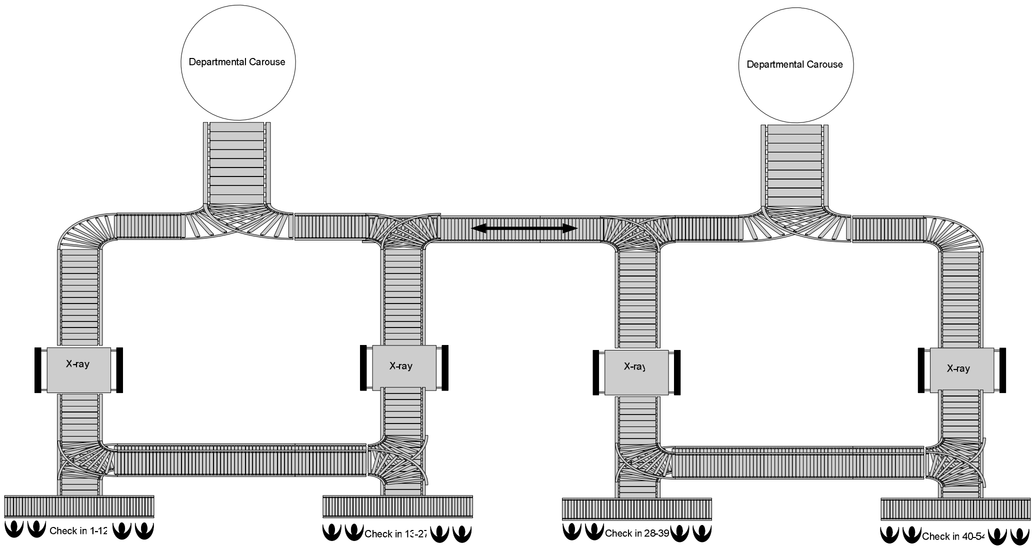


Figure F3.1: Design 3

design 3

section	total number of sections in system	capacity (per hour)	tot value stocked	est holding	INSP frequency
BC2 (60-90)	10	1440	9770	25647	4
BDC	10	1440	3453	9063	4
BF1 (klein)	78	1440	3967	10413	4
BF2 (middel)	8	1440	4452	11687	4
BF3 (lang)	6	1440	5387	14141	4
Dcar	2	1440	4459	11704	4
HBS1/2	4	1420	external		4
HBS3	1	800	external		4
WB	54	60	0	0	4

Table F3.1: features design 3 (figures are fictive)

F.4: Design 4 (same as design 3 + a third carrousel)

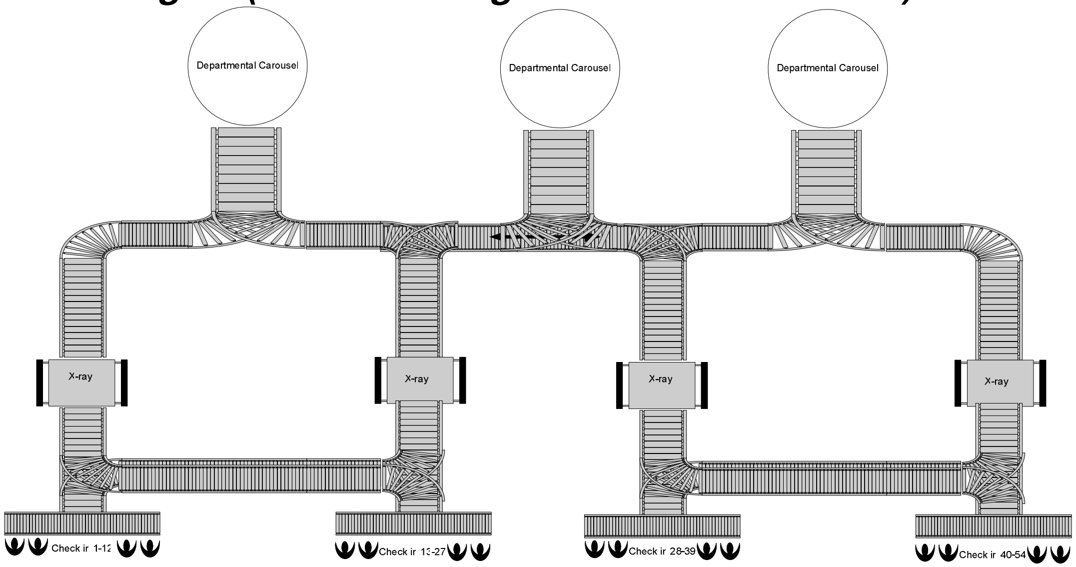


Figure F4.1: Design 4

design 4

section	total number of sections in system	capacity (per hour)	tot value stocked	est holding	INSP frequency
BC2 (60-90)	15	1440	9770	25647	4
BDC	11	1440	3453	9063	4
BF1 (klein)	78	1440	3967	10413	4
BF2 (middel)	12	1440	4452	11687	4
BF3 (lang)	9	1440	5387	14141	4
Dcar	3	1440	4459	11704	4
HBS1/2	4	1420	external		4
HBS3	1	800	external		4
WB	54	60	0	0	4

Table F4.1: features design 4 (figures are fictive)

Appendix G: Initial spare part investment and holding costs

Since spare part availability can determine a big part of the mean logistic delay time it is important to take the expected time into account when calculation the downtime of a system. All calculations throughout the entire model are based on section level. Since physical spare parts are stocked on a lower level than section level it is necessary to assume an aggregate spare part at section level. The prices and critical components are based on spare part lists of VI and information provided by R&D. Failure rates of critical components are determined by R&D by testing the components. Since there are many doubts about the accuracy of these figures, it is decided to conduct a field data-analysis at a reference site. Unfortunately, the data at this reference site did not store the data on a lower level than section level. Therefore it is decided to use the failure rates on section level and use the figures (of the critical components) determined by R&D to indicate the ratio between the different critical components when a failure to a section occurs. This methodology is considered to be the most accurate one, because of the doubts about current "theoretical data". For the lead time counts that the average replenishment time is used, the average is considered to be sufficient in this case due to the assumption of PALMS theorem described in subsection 3.1.3.
Table G.1 presents an example (fictive data) of how the expected delay time and total stock value are calculated for an aggregate spare part on section level. For 100 belt floorveyors in the system the current policy of VI calculates a proposed spare part level using a percentage (based on experience) and a minimum and maximum value. Furthermore based on the failure rate of the section and, ratio of the critical components and the leadtime, it is determined what the probability of backorder is. This results in expected delay times and total stocking costs per section.

Nr of Belt Floorveyors	100										
Emergency Transshipment time	24	hours									
	Type	Stock %	min	max	Proposed stock	Failure rate of section	Ratio critical component	Leadtime	P(BO)	Delay	price
equipment 1	motor	xx%	1	10	5	0,25	0,5	168	0,0009696	0,0465	500
equipment 2	belt	xx%	1		5	0,25	0,15	168	0,0000014	0,0001	250
equipment 3	support	xx%	1	10	5	0,25	0,15	168	0,0000014	0,0001	250
equipment 4	misc	xx%	1	10	5	0,25	0,2	168	0,0000069	0,0003	2500
									Tot delay/price	0,047	3500

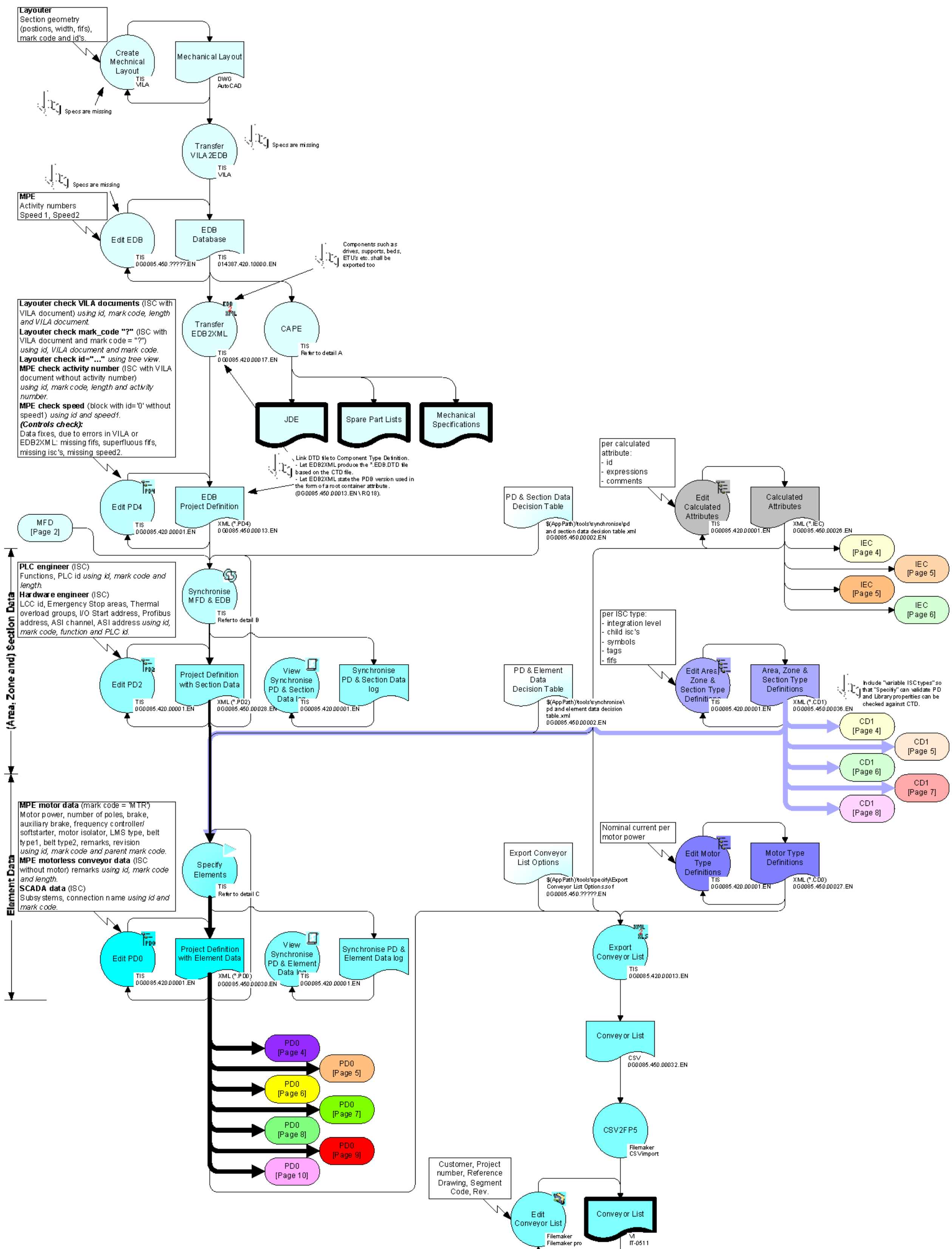
Figure G.1: Example of aggregate spare part on section level (fictive data)

Appendix H: Business process schedule

Figure H.1 presents the business process of VI schematically. This flow-chart is focused on automating the current processes, and using company wide the same project information.
The process starts with a mechanical lay-out of the system, this lay-out is developed in an early stage in the sales process and considered as the first solution. Based on this mechanical lay-out various departments involved in the sales process will work with the same data. Each department will extract a file from the mechanical lay-out and will add specific information in order to process their tasks. Updates in the sales process, which result in system changes should be changed as well in the mechanical lay-out. The departments, depending on this data, should extract a new file based on the updated mechanical lay-out. In this way all departments involved in the sales process are working consistently with the same data.

For example lay-out changes will influence the price of the project. Therefore the department of pricing can extract all equipment information from the mechanical lay-out and combine this with the prices and engineering surcharges stored in their database.

For systems simulation department count that they use an extracted file based on mechanical lay-out to do system performance tests to simulate whether desired capacity can be met and which routing decisions to incorporate. Furthermore in the future they also want to perform system availability studies based on the mechanical lay-out, by combining it with MTBF and MDT failure data. These MTBF and MDT can follow from the calculation model developed in this study.



Page: 3

Filename: 0g0085.420.00011.en.012 process diagram.vsd

Appendix I: Future fit with processes

As described in section 4.3, currently VI Systems simulation is working on automating the process of technical system availability calculation. Therefore it is important to look ahead to the future to picture where the developed tool in this model fits in. Figure I.1 presents the location of the tool in the future improved business processes.
The flow-chart starts with a CAD drawing from the pre-sales phase this is translated into a file that describes the system structure. This file should be filled with MTBF and MDT figures. These figures follow from the decisions in the LCC versus technical system availability model as described in chapter 3. Now, the file with system design and lay-out information can be (automatically) uploaded to the simulation software. Simulation will be done by importing a customer load file and the system properties, in order to estimate the technical system availability, throughput and the related maintenance, down time (bags too late) and energy consumption costs. Furthermore the decisions in LCC versus technical system availability model affect the spare-part, maintenance and equipment costs of the system.

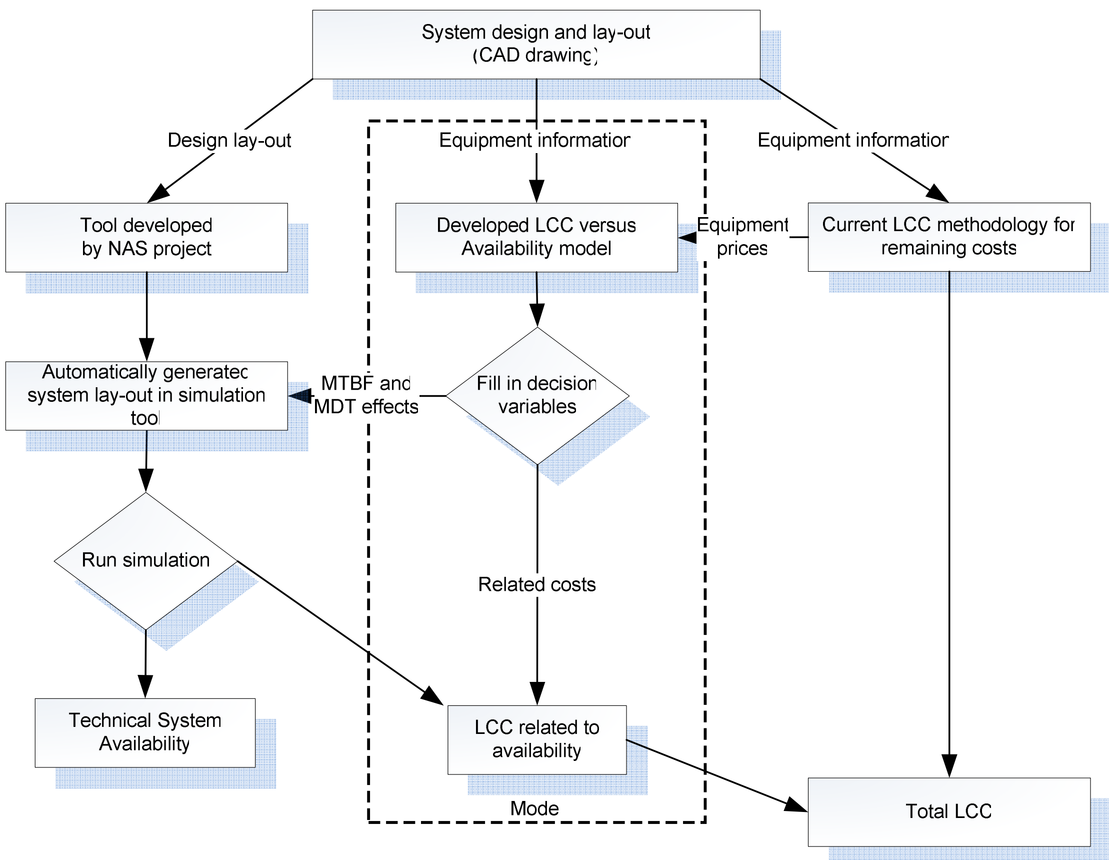


Figure I.1: the developed model/tool in the future processes

Appendix J: Screenshots tool

This appendix describes the developed LCC and technical availability tool, which is used for scenario testing for;

- different design alternatives
- different section selection
- different inspection frequencies
- different spare part stock levels

There are five screenshots in this appendix, namely;

- the lay-out and equipment selection page
- information stored in a library page
- customer and project specific information page
- spare part stock level calculation page
- results (availability and LCC) page

NB: figures used in screenshot are fictive

Figure J.1 present part of a lay-out of a system design. The lay-out is organized in areas (indicated by yellow lines), zones (indicated by the green lines) and sections (indicated by the pink lines). The framework, in terms of what sections are in which area and sequential and parallel relations, should be constructed first. Secondly, within a zone the sections and their number can be selected from a drop down list under the label "sections". These section will be picked from a library page (explained in figure J.2), which contains static information. There are two other white fields that need to be filled in, the first field with the label "number" represents the number of areas, zones or sections. The second white field with the label "restriction>" is the field where one needs to fill in the minimal required throughput that in any case should flow through. With this information the availability is calculated.

area	area name	zones	zone name	sections	capacity	relation	parallel to	number	total nr	unavailability	aggr unavail	availability	restriction >	tot capacity
XX	XX	XX	XX	XX										
a1	check in area	XX	XX	XX				1	1		0,00021952	99,97805%		1440
		ci1	check in zone	XX	60	parallel	a1	27	27	0,00012	0,0000000		1215	1620
			ci1	BF1 (klein)	1440	sequential		1	27	5,78222E-05	0,9999422			1440
			ci1	WB	60	sequential		1	27	6,27984E-05	0,9999372			60
		trz1	transport zone	XX	1440	sequential		1	1	0,00022	0,0002195		1215	1440
			trz1	BDC	1440	sequential		4	4	5,48852E-05	0,9997805			1440
		trz2	transport zone	XX	1440	parallel	trz2	1	1	0,00012	0,0000000		1215	5760
			trz2	BF1 (klein)	1440	sequential		2	2	5,78222E-05	0,9998844			1440
		trz3	transport zone	XX	1440	parallel	trz2	1	1	0,00012	0,0000000		1215	5760
			trz1	BF1 (klein)	1440	sequential		2	2	5,78222E-05	0,9998844			1440
a2	HBS area	XX	XX	XX				1	1		0,0000001	99,99999%		2840
		hbs1	HBS zone	XX	1420	parallel	hbs1	1	1	0,00031	0,0000001		1215	2840
			hbs1	BF1 (klein)	1440	sequential		4	4	5,78222E-05	0,9997687			1440
			hbs1	HBS1/2	1420	sequential		1	1	7,99936E-05	0,9999200			1420
		hbs2	HBS zone	XX	1420	parallel	hbs1	1	1	0,00031	0,0000001		1215	2840
			hbs2	BF1 (klein)	1440	sequential		4	4	5,78222E-05	0,9997687			1440
			hbs2	HBS1/2	1420	sequential		1	1	7,99936E-05	0,9999200			1420
a3	check in area	XX	XX	XX				1	1		0,00021952	99,97805%		1440
		ci2	check in zone	XX	60	parallel	a5	27	27	0,00012	0,0000000		1215	1620
			ci2	BF1 (klein)	1440	sequential		1	27	5,78222E-05	0,9999422			1440
			ci2	WB	60	sequential		1	27	6,27984E-05	0,9999372			60
		trz4	transport zone	XX	1440	sequential		1	1	0,00022	0,0002195		1215	1440
			trz4	BDC	1440	sequential		4	4	5,48852E-05	0,9997805			1440
		trz5	transport zone	XX	1440	parallel	trz2	1	1	0,00012	0,0000000		1215	5760
			trz5	BF1 (klein)	1440	sequential		2	2	5,78222E-05	0,9998844			1440
		trz6	transport zone	XX	1440	parallel	trz2	1	1	0,00012	0,0000000		1215	5760
			trz6	BF1 (klein)	1440	sequential		2	2	5,78222E-05	0,9998844			1440

Figure J.1: lay-out of a system design order in area, zone and section level.

Figure J.2 presents the library sheet which is composed of figures that are obtained from the field data analysis. The availabilities mentioned in this sheet are influenced by the decision variables presented in figure J.3. The grey line in this figure presents the equipment costs, these costs follow from the current pricing methodology (stored in CAP8). Furthermore the data in this library page should be updated frequently.

section	Acar	BC1 (0-45)	BC2 (60-90)	BC3 (130-180	BDC	BF1 (klein)	BF2 (middel)
availability input parameters							
MTBF (Schiphol STO + WINSP)	10000	12500	15000	17500	20000	22500	25000
length/equipment	1	1	1	1	1	3	7
MTBF (Schiphol STO)	20000	22500	25000	27500	30000	25000	27500
MTBF after PM	10000	11250	12500	13750	15000	12500	13750
MTTR (constant)	1	1	1	1	1	1	1
MLDT (influenced by SP)	0,167	0,167	0,194	0,167	0,172	0,173	0,169
MADT (constant)	0,2	0,2	0,2	0,2	0,2	0,2	0,2
MDT	1,367	1,367	1,394	1,367	1,372	1,373	1,369
availability	0,999863	0,999879	0,999888	0,999901	0,999909	0,999890	0,999900
unavailability	0,000137	0,000121	0,000112	0,000099	0,000091	0,000110	0,000100
capacity (per hour)	1440	1440	1440	1440	1440	1440	1440
total number of sections in system	0	0	10	0	10	78	8
cost input parameters							
Preventive maintenance							
P(having PM related to the frequency of inspections)	0,5	0,5	0,5	0,5	0,5	0,5	0,5
Expected section failures during LC	0	0	0	0	0	0	0
INSP time per activity	0,2	0,2	0,2	0,2	0,2	0,2	0,2
PM time per activity	1	1	1	1	1	1	1
CM time (STO Schiphol) per activity	2,5	2,5	2,5	2,5	2,5	2,5	2,5
Spare parts							
SP usage replacement purchase costs (per failure)	€ 100	€ 100	€ 100	€ 100	€ 100	€ 100	€ 100
SP usage replacement selling costs (per failure)	€ 105	€ 105	€ 105	€ 105	€ 105	€ 105	€ 105
SP hold costs (per year)	10%	10%	10%	10%	10%	10%	10%
MLD time when out of stock (in hours)	0,0000	0,0000	0,0273	0,0000	0,0055	0,0067	0,0023
MLD time when on stock (in hours)	0,1667	0,1667	0,1667	0,1667	0,1667	0,1667	0,1667
Equipment costs + energy consumption							
equipment costs	€ 10.000	€ 10.000	€ 10.000	€ 10.000	€ 10.000	€ 10.000	€ 10.000
kWh usage	1	1	1	1	1	1	1

Figure J.2: Library with availability and cost input parameters

Figure J.3 presents in the first box two decision variables, namely the frequency of inspections and the stock level of spare parts. The first decision variable can be in filled in for each section and the effects will be seen in the availability and maintenance hours of that section. The second decision variable will be explained in figure J.4. Furthermore specific customer settings, and information regarding the expected baggage flow (for down time cost calculations) can be added. Finally financial figures can be filled in order to take into account discounting and inflation rates.

section	Acar	BC1 (0-45)	BC2 (60-90)	BC3 (130-180)	BDC	BF1 (klein)	BF2 (middel)
frequency of inspections per year	2	2	2	2	2	2	2
Change SP stock level	SP AC	SP BC1 (0-45)	BC2 (60-90)	SP BC3 (130-180)	SP BDC	SP BF1 (klein)	SP BF2 (middel)

customer specific settings		
Costs per baggage not loaded	€ 200,00	euro
Costs direct maintenance hour	€ 20,00	euro
Operating LC (years)	15	years
Operating weeks/year	52	weeks
Operating days/year	360	days
Operating hours/day	20	hours
Operating hours/year	7200	hours
Equipment running hours/day	12	hours
Equipment running hours per year	4320	hours
hours per LC	64800	hours
kWh price	€ 0,09	kWh
SP average commission rate	5%	percentage
SP warranty period	2	year

Down time (delayed bags)		
expected throughput in peak hours	2430	per hour
expected throughput remaining hours	1000	per hour
designed capacity per hour	2880	per hour
number of peaks hours	7	per day
remaining hours	13	per day
expected operational availability	100%	average

Financial figures		
inflation (percent)	0,0%	percentage
discounting rate	0,0%	percentage
IRR	0,0%	percentage

Figure J.3: Project and customer specific information

Figure J.4 presents the spare part stock level selection per section. In the yellow field the model calculates the proposed stock level according to the methodology of VI. This level can be adjusted manually and the impact on the LCC and technical system availability can be determined.

												BF1 (klein)
BF1 (klein)	0,215											
name	perc	price	av price fai	min	max	proposed stock	rate	prob of fail	LT	P(SO)	Delay	price
					drag down	0						
motor	2%	494,07	494,07	1	10	2	2,97E-05	0,324675	168	0,00703985	0,337913	988,14
belt	1%	64,25	64,25	1		2	2,97E-05	0,155844	168	0,00173169	0,083121	128,5
assy (misc)	5%	40,34	6,723333	1	10	4	2,97E-05	0,38961	168	0,00001894	0,000909	60,51
take ups	2%	1394,83	154,9811	1	10	2	2,97E-05	0,12987	168	0,00121476	0,058309	2789,66
									0,879909		em trsh	
											tot price	3966,81
						Back to overview					tot MLDT	0,480251419

Figure J.4: spare part stock level of critical components per section

Figure J.5 shows the outcome of the calculations split up in technical system availability for the entire system and for the LCC.

Technical system availability		**99,732%**
check in area a1		99,968%
HBS area a2		100,000%
check in area a3		99,968%
HBS area a4		100,000%
transport and make-up area a5		99,796%
LCC	**€**	**1.861.000**
costs determined in this model		
INSP cost labour	€	40.000
PM costs labour	€	16.000
CM costs labour	€	50.000
JAM costs labour	€	-
SPP initial investment	€	30.000
SPP consumption investment	€	80.000
SPP holding cost investment	€	45.000
equipment + fees costs	€	1.000.000
downtime costs (system)	€	600.000

Figure J.5: Technical system availability and LCC