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The next step in the electronics manufacturing supply chain

Reducing obsolete components at Global Electronics B.V.

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Preface

Dear reader,

In front of you lies the thesis 'The next step in the electronics manufacturing supply chain'. This thesis is part of my final assignment to finish the bachelor Industrial Engineering & Management at the University of Twente. The research I did, was performed at Global Electronics B.V. in Haaksbergen between April 2021 and July 2021. The main goal was to reduce the yearly obsolete components, but in this unique business there are many complications which made it quite tricky.

I want to thank everyone at Global Electronics for the opportunity they have offered me, and the time and efforts invested in me. I could ask any question and I have always felt taken seriously. For a while this topic has been concerning the company and therefore, I feel proud to have contributed in this way. I especially want to thank Meino for the involvement in all aspects that he offered. Also Wout, thank you for the fun times and important discussions we have had while both working on our graduation project.

Furthermore, I want to thank Engin Topan for the frequent and constructive feedback provided. Also, the meetings with Engin were of great value and I am happy that he was my lead supervisor.

Finally, I want to thank my family and friends for the continuous support and interest in my bachelor's project.

Enjoy reading this thesis!

Glossary

Table G.1. *List of abbreviations with corresponding meaning*

Abbreviation/term	Definition
Electronics manufacturing EOQ	The quantity which results in the least excess material cost.
EOQ	Economic order quantity, quantity which seeks the most cost-efficient balance between holding, order and order costs.
Factory package size	Package sizes in which components are supplied. For example, a reel. The same as a 'multi'.
GE	Global Electronics B.V.
Grit	Collective name for smaller PCB components. Containing resistors, capacitators and diodes.
IC	Integrated circuit. Electronic component
KPI	Key performance indicator
LEMQ	Least excess material-cost quantity
MOQ	Minimum order quantity. This is a restriction of a supplier
Multi	Standard package sizes of components. Could be a reel or a piece of tape with components on it. A multi can also be one.
OUL	Order-up-to level, inventory is replenished to this level when anticipating such a strategy in the inventory management.
PCB(A)	Printed circuit board (assembly)
TC	Total cost, usually a function of multiple cost aspects

Management summary

Global Electronics B.V. (GE) in Haaksbergen offers electronic manufacturing services such as the assembly of printed circuit boards (PCBs). Due to high supplier minimum order quantities (MOQs) and standard factory package sizes, GE orders too many components which are not used for the assembly of the number of PCBs from the customer order. These components are at risk of becoming obsolete because customers could order pretty unique components. Unique components cannot be used across different orders/customers and if more than the needed amount is ordered, they become obsolete.

Obsolete components at GE are components which are not used for nine months or more. After these nine months the entire value of the components are discarded assuming that they are fully depreciated. These items become waste for GE.

After having made a problem cluster and executing the steps determined by Heerkens and Van Winden (2017), the core problem is determined. Namely, GE does not provide proactive feedback to the customers about the material or quantity after having received an order request. This leads to excess components which are likely to become obsolete. Hence, the main research question is formulated as:

How to improve the order process at Global Electronics B.V. to reduce the yearly value of obsolete components?

This study started with the analysis of the current order process and the situation regarding inventory and obsolete components. The key steps in the order process were determined and also the order characteristics in the field of electronics were investigated. We found that GE uses a make-to-order policy in which no forecasts are made, and all steps are taken once a customer order triggers GE. Furthermore, it appeared that after an order, customers are very rarely contacted that there are still excess components left which must be paid for.

After the current situation analysis, the components were researched. It turned out that six out of twenty-three component types covered about 60% of the inventory value. The six categories are: transistors, diodes, resistors, integrated circuits, inductors, and capacitators. These six types are therefore considered high-impact components. For these six types, relevant characteristics were listed and evaluated: inventory value, complexity, order characteristics and possible spill. Because all these six categories have specific characteristics relevant for obsolescence, it was decided that all six are included in this study.

After the highest-impact components were identified and the current situation was clear, a literature study was performed on methods for reducing obsolete inventory in general. The main outcomes were methods which proposed correct mathematical forecast models, an economic order quantity (EOQ) ordering policy or offering alternative components to customers. The methods proposed in the literature were evaluated and for some were determined impossible to implement in the unique situation of GE.

We concluded that we need a different sort of EOQ formulation. In this business, the EOQ is defined by the quantity which minimizes the excess material cost (Keijzer, 2019). While the regular EOQ finds the optimal balance between order and holding costs (Chopra & Meindl, 2014). Offering alternative components is also possible in GE's situation but this depends on the customer because they have designed the PCB, GE did not.

In this way, we formulate the Least Excess Material cost Quantity model (LEMQ-model). This is a mathematical model which minimizes the excess material cost per order. The model calculates per quantity how much the excess material cost is. So, how much money is used to buy components which are not used for the customer his order? In the implementation of LEMQ, we focus on a local optimum by allowing the model to seek for a quantity within a certain ‘acceptable range’ around the originally requested quantity. Once the LEMQ is calculated, it can be discussed with the customer if he or she accepts it. For example, customer A requests 130 PCBs but the LEMQ is 124 PCBs then the sales employees can discuss this quantity change and hope that customer A accepts this. The LEMQ-model provides a proactive method to discuss with the customer up front about a (relatively small) quantity change, which reduces the excess material and therefore risk of unique obsolete components.

To track the performance of this LEMQ-model, KPIs are proposed which monitor if decreases in excess material per order are achieved. Because it is reasoned that less excess material per order results in less components with a chance of becoming obsolete, KPIs were proposed following the same logic with the end goal to reduce the KPI: yearly obsolescence cost.

A simplified implementation of the LEMQ-model was made in Excel in which simulation of real order requests were performed. The simplification means a limit on the number of components analysed, instead of all components of the order. The simulations resulted in an average decrease of excess material of €247,97 which corresponds to 18,83% per order. At last, through a customer survey it was validated that most customers are accepting small quantity changes of 5% or 10%.

Based on the results and conclusion of this study, the following main recommendations are formulated for GE:

- Calculate and discuss the LEMQ with customers before the order is officially placed.
- Offer alternative components to customers if large excess material cost is encountered. This can also be done via early collaboration. This means that GE could be involved in the design phase, to prevent critical components (with large MOQs or multis) being designed on the PCB.
- Implement KPIs to create awareness and to monitor the performance regarding obsolescence.

Table of Contents

1. Introduction

This bachelor thesis is executed at Global Electronics B.V.. The company is introduced in section 1.1. In section 1.2 the problem identification is stated and in section 1.3 the research approach is discussed.

1.1. Company introduction: Global Electronics B.V.

Global Electronics B.V. (GE) is located in Haaksbergen, the Netherlands. The company is founded in 1993 by Gerrit Versteeg and it is specialised in electronic manufacturing services (EMS). The company assembles so called printed circuit boards assemblies (PCBA), but it also creates semi-finished and finished products which contain electronics. For example, the ‘Homey’ is fully assembled at GE, this product is comparable to a ‘Google Home’. GE has surface-mount device (SMD) machines which execute the assembly of the electronics components on the green printed circuit board, but some parts need to be placed or repaired by hand because of complexity. In Figure 1.1 an example of a PCBA hand-assembly is shown. Global Electronics has a make-to-order strategy, so they only buy at their suppliers after receiving an order from customers. GE’s inventory mostly consists of components rather than PCBA’s, because PCBA’s are collected by the customer quite quickly after they are finished.

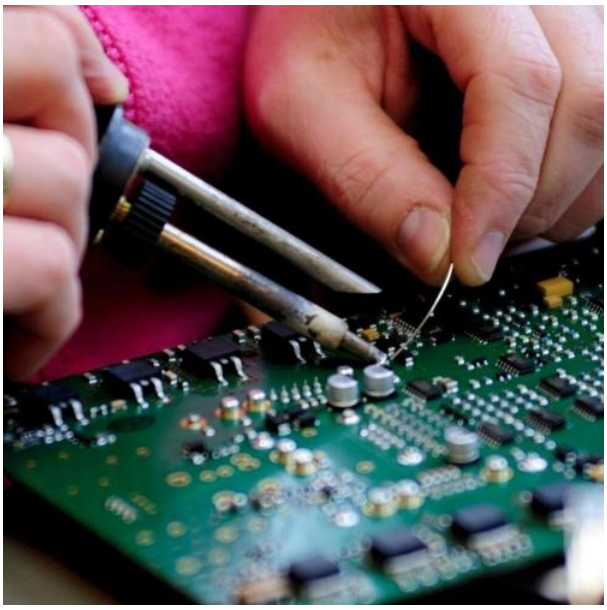

Figure 1.1. *Assembly of components on a PCBA at Global Electronics.*

According to Siemens (2018), companies in this sector (the EMS) often come across new inventions and the innovation is only increasing. GE also helps customers with these new inventions by manufacturing and testing prototypes.

It is important to note that GE is a small and medium-sized enterprise, in the exploding field of electronics and technology. Therefore, Global Electronics has many competitors of comparable company size, in the Netherlands as well as internationally. GE has an innovative team that seeks for growth within its sector. This ambition can also be found in the slogan of the company, which is ‘Samen groeien’.

1.2. The problem

This section describes the problem identification. Section 1.2.1 contains the action problem and the main research question. In section 1.2.2 the problem cluster is shown and explained and in section 1.2.3 the research approach is discussed.

1.2.1. Problem context

Market nature

Global Electronics is operating in the market of electronics. As said, they assemble printed circuit boards. On these blank green circuit boards, components are assembled such as resistors, capacitors and transistors. World-wide there are over 135 million different components which can be put on these boards and each year thousands of new components are invented and added to the catalogue. Customers send GE their bill of materials (BOM) after which GE orders the desired components at the suppliers. The processes in the supply chain of Global Electronics are performed according to *pull view*. Pull processes are initiated by a customer order (Chopra & Meindl, 2014). This can be reviewed as a purchase-to-order policy.

Since Global Electronics is in the electronics manufacturing sector, it is subject to trends such as the increase of new product introductions (Siemens, 2018). This means that there are customers who arrive at GE asking for a new PCBA. GE is a small- and medium enterprise which is not high on the priority list of suppliers and hence, GE experiences long and variable lead times of component supply. Together with the short time-to-market expectations from the customers, this leads to a complex situation.

Obsolescence of components

Apart from the complex situation described above, GE faces another problem, which is the obsolescence of components. Because of the wide variety of components and trends as mentioned by Siemens, a lot of unique ones are ordered. These unique components are highly unlikely to be used across different orders and therefore the excessive material which may be ordered, will become obsolete. Furthermore, inventory levels are likely to rise and high inventory levels are associated with high inventory costs which are the costs of warehousing, depreciation/obsolescence and lost opportunity (Tuovila, 2021). For GE, the obsolescence cost is the material cost of the components as well as the inventory cost of keeping those components in stock for a period of time. Although the inventory cost per component is relatively insignificant because of the size and amount of components on stock.

The definition of obsolescence in this research is the definition of Tuovila (2021). He states that obsolete inventory is the stock that is at the end of its life cycle. This inventory is not sold or used for a long period of time and is not expected to be sold in the future. So, these items must be written-off. GE writes off the components after they have not moved for nine months. 'Moved for nine months' means that they have not been used in any customer order for the last nine months. Components which are ordered in larger quantities than needed, are likely to become obsolete. These excessive components are not placed on PCBs of customers and therefore, they remain in GE's inventory before being printed on a PCB.

But the question is, why would GE order excessive material? This comes down to three different reasons:

1. The company orders electronical components at different suppliers with whom they have different agreements. They need to meet the minimum order quantity (MOQ) of their

suppliers. A minimum order quantity is an order requirement imposing that the amount of the production must be at least a certain quantity when that period has a positive production (Park & Klabjan, 2015). However, Global Electronics does not always inform their customers that these must be met and takes the possible excess material for their own account. This results in the fact that GE sometimes buys more components than necessary for their customer.
2. The machines of GE have a bit of waste for the grit components (smaller ones). This waste is variable per grit component but on average, a spill of 2% is anticipated at Global Electronics. It is important to note that this is not for all components but just for the grit ones (see chapter 3). This variable spill is a significant reason for excess grit components in the inventory of GE.
3. The machines are easier and faster to set-up if the ordered components come in standard package sizes, for example a reel with 1000 pieces. So, the production crew prefers full reels of components which are usually also larger than the needed number of components.

All in all, Global Electronics faces the challenge to reduce their own excess material costs. Excess material in this research is defined as the components which are unused after the assembly of an order is finished. This cost reduction should result in a more competitive supply chain. This would likely attract a higher number of customers, which is the ultimate ambition of the company.

Norm and reality
To clearly identify the action problem of the too high obsolete components, the norm and the reality need to be stated, because the difference between these two is defined as the action problem (Heerkens & van Winden, 2017) For this research the action problem is defined as follows:

The norm would be that Global Electronics has less than €10.000 yearly rise in value of obsolete components. In reality this is almost €18.000 each year.

Hence, the main research question of the thesis is formulated as follows:

How to improve the order process at Global Electronics B.V. to reduce the yearly value of obsolete components?

In Figure 1.2, the action problem is indicated in orange.

1.2.2. Problem cluster

The action problem defined in section 1.2.1 has different causes. These causes can be considered other problems and in Figure 1.2. the problem cluster is shown to give an impression on the relations between the problems.

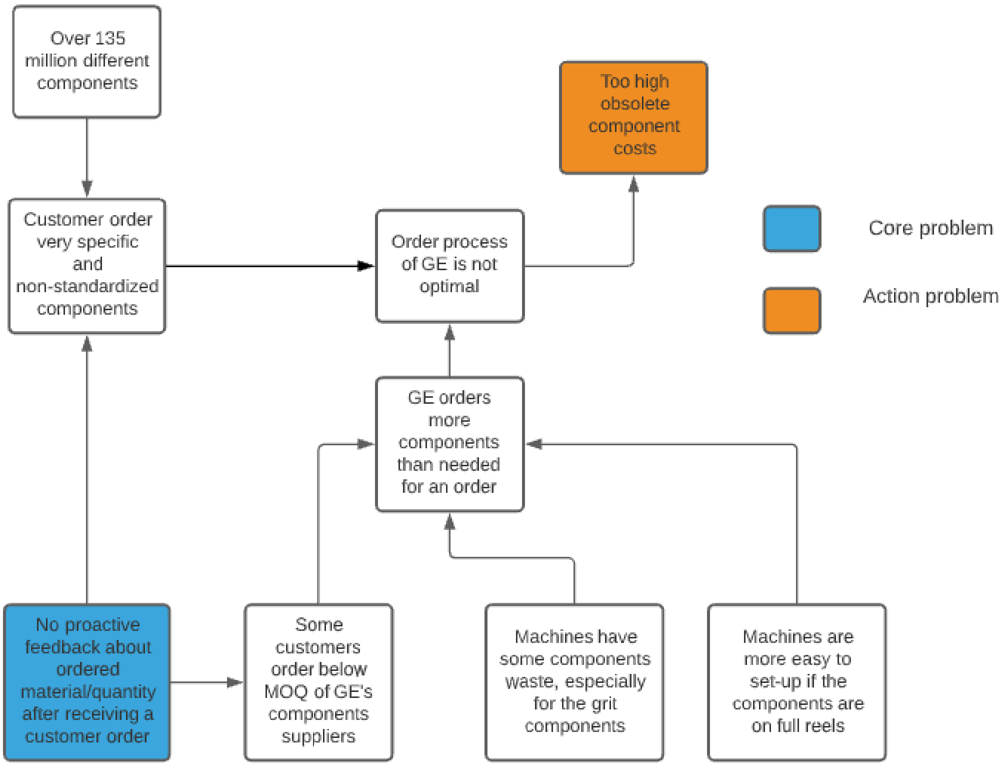

Figure 1.2. *Problem cluster of Global Electronics.*

In Figure 1.2 different boxes with problems are shown, all linked to each other with arrows. We start at our action problem which is orange in Figure 1.2. The obsolete components remain in the inventory at Global Electronics. After nine months the unmoved components are written-off, because no customer ordered these products. This does not generate revenue but only unnecessary holding and depreciation costs.

To reduce obsolete component costs, an effective order process is necessary. However, this is not the case right now at GE. This is caused on the one hand by the fact that there are over 135 million electronic components and customers can order very unique and uncommon ones. While the more common components should be suitable for a lot of orders as well. However, the customers just do not know that alternative components can be suitable for the product that they need. Each electronical component has its own specifications, but the purpose for which they can be used is not individual. In other words, several components can serve the same purpose and therefore standardization is a possibility.

On the other hand, the order process is not optimal because, GE orders more components than needed for an order. They order a bit more because of the waste which occurs when starting an assembly run. Furthermore, the production crew want components on full reels or other standard package sizes, because then the machines area easier and quicker to set-up. But GE also orders more than necessary because of the MOQs of the component suppliers. Some customers order a quantity below this MOQ and then GE must order at the suppliers' MOQ and take the excess material for granted. This eventually results in obsolete components with very unique components which are not of use in other orders. Global Electronics is a small and medium-sized enterprise (SME), they order at big corporate suppliers. Therefore, GE is not in the position to negotiate with the suppliers and thus, they are restricted to MOQs.

Both the standardization problem and the MOQ issues are results of the customers not receiving proactive feedback about the quantity or materials of their order. This is not a problem for the customers itself, but Global Electronics is eventually left with high obsolete components, so they want to change this situation. And this change can only be achieved if customers are willing to accept a change in their order. Because on the supply side no improvements can be made, due to GE's position.

1.2.3. Core problem

To determine the right core problem, the definition of a core problem is needed. According to Heerkens and van Winden (2017), a possible core problem does not have a cause in itself and it should be a problem which you can influence. If there are more problems which these two criteria hold for, then the most important problem is chosen as the core problem. The most important problem is considered to have the greatest impact effect at the lowest cost. This consideration can be 'an educated guess' since at this point it is unknown what the solution is going to be (Heerkens & van Winden, 2017).

So, since a core problem cannot have a cause in itself, only three options remain when looking at the problem cluster in Figure 1.2. Three of these problems cannot be influenced. These three are:

- The 135 million different components available in this business.
- The fact that the machine has a little bit of waste per assembly run.
- The preference for full package sizes because the machine is easier to set-up when those are anticipated.

This waste is just a characteristic of the machine, it needs a few components to 'warm-up' and the fact that the machine is easier to set-up is also considered non-influenceable. So, only one problem remains, this is also a problem which we can influence. So, we conclude that the core problem of this research is as follows:

No proactive feedback about ordered material/quantity after receiving a customer order.

In Figure 1.2, the core problem is indicated in blue. With feedback the following possibilities are meant:

- Excessive material and what to do with it.
- Discuss a different order size or order strategy with the customer to reach a more optimal quantity.
- Discuss the possibility of standardized components which result in less obsolete components.

1.3. Research approach

In this section, the research approach is discussed to solve the main research question, the action problem and the derived core problem. To answer the main research question, the problem is divided in smaller problems with a corresponding knowledge question and desired deliverable. Section 1.3.1 describes the global approach of this research, containing the focus and purpose. Finally in section 1.3.2 the sub-questions of this study will be discussed.

1.3.1. Global approach

The main purpose is to discuss with the customers up front that it might be beneficial to change their order. To achieve this, literature studies will help to identify obsolete reducing methods and a suitable method will be mathematically implemented at GE, such that the sales department can show customers what improvement can be made to benefit both, and eventually reduce the obsolete components for GE itself.

Eventually, this mathematical model with advice for an improved order process will be evaluated and discussed such that the benefits of this optimal policy are exploited.

To monitor the use and effects of the order process, some key performance indicators (KPIs) will be introduced. Some KPIs will be introduced to monitor the short-term actions regarding this topic, another KPI will be used to monitor the long-term effects of the mathematical model. This KPI can be measured yearly to check whether the situation is indeed improving.

In Figure 1.3 my global approach is shown in a flowchart and these steps are also seen in the sub questions in section 1.3.2.

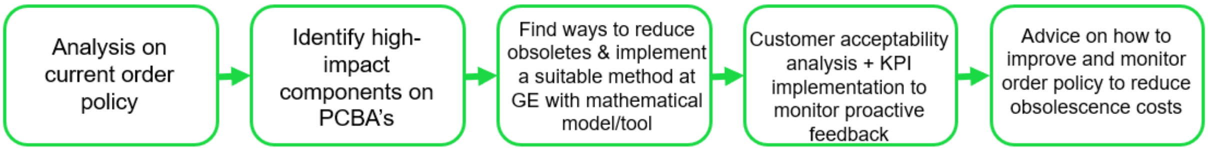

Figure 1.3. *Flowchart of global approach of my project.*

As described in section 1.1, Global Electronics also makes prototypes for new customers, however the focus will be on the already existing customers with recurring orders and the prospects, these are potential customers with big volume orders, opposite to prototyping customers. The reason for this focus is that proto customers are not leading to obsolete components for GE, since they have agreed to buy the potential excess material from GE. Global Electronics always tells proto customers up front that they must buy any excess material because experience taught that it is unlikely that these customers place a recurring order in which these components can be used again. Furthermore, proto customers order in very small quantities and therefore it is not feasible to order components on full reels, which is preferred by the assembly crew. That is also why we will work with full reels in this study.

Also, the company wants to let their recurring customers benefit from their improved supply chain because they generate the most revenues for GE. So, it would be fair to them as well. And in the end, the company aims at tempting prospects with big volume orders and one way to achieve this is by having loyal customers which can spread the word of mouth.

1.3.2. Sub questions

To answer the research questions, we need to know some more aspects of this problem. Several sub questions are made, which are knowledge questions. These sub questions set the scope for my research (Smith, 2020). For each sub question I have stated the reason and the goal of the sub question.

1. *What is the current order policy at Global Electronics B.V.?*

To find out what needs to be improved, the current situation and order policy at GE need to be analysed. The eventual goal is to make recommendations on the order process, but the current situation must be clear to achieve it and to be sure the recommendations that are made, are not in place already. This question will be answered through interviewing employees and analysing the order software systems that are used. This type of question requires a descriptive answer, since it is a 'what' question (Cooper & Schindler, 2014).

2. *What are the types of high-impact components on PCBA's?*

Interviews and meetings with the sales department staff will tell what the components on a printed circuit board assembly are. This is relevant because then we can decide on which components to focus because they have a high impact on the order, for example which components are famous for their high minimum order quantities or costly components which will increase obsolescence costs. This is also a descriptive question.

3. *What are methods to reduce obsolescence costs in the inventory?*

The goal is to reduce the obsolescence costs. So, I will perform a literature study on methods that reduce inventory obsolescence costs in general. Then an evaluation of these methods will tell which method is applicable to the unique situation of Global Electronics. Apart from describing the ways to reduce obsolescence, the reason why this works will also be studied. So, this is considered an explanatory question (Cooper & Schindler, 2014). After these methods have been identified, an evaluation will be done to find a (combination of) feasible method(s) to use at GE.

4. *What KPIs have to be implemented to monitor the new order process and obsolete component costs?*

To evaluate what the eventual effects of an improved order policy are on the obsolete components, KPIs need to be selected. These KPIs are of course depending on the type of improvement and they need to be easy to implement in the company's quality system, to set targets for the long-term. Because KPIs must be invented, tested and reconsidered, this is an exploratory question.

5. *How to implement a tool with a feasible method to change the order process at Global Electronics B.V. such that the obsolete components will reduce?*

The purpose of this sub question is to find out a way to implement a suitable method from sub question 3 in a transparent tool which GE can use when ordering. The goal of this tool is to show how to approach each individual order such that GE should have the least obsolescence costs as possible.

6. *How to incorporate GE' customers to ensure the improved order process will work?*

The change in order process has consequences for the customers of GE which we need to evaluate. We want to improve the new order policy but for the orders GE is dependent on the customers, so they need to be incorporated in the plan as well. We seek for a way to convince the customer that a different order will directly benefit him as well. This question is answered through an effect evaluation and customer acceptability analysis.

1.4. Intended deliverables

In this section I will elaborate on the intended deliverables of this research.

Firstly, a mathematical model is an intended deliverable. This model could be implemented in a tool in Excel which is used to show what adjustments in the customers' order can lead to less obsolescence costs for GE.

Secondly, I want to come up with some recommendations on how this improved order process is going to work and how to make sure it will reach its potential.

At last, I want to introduce KPIs which help the monitoring of the long-term effects of this improved order policy on the amount of obsoletes being depreciated each year. Think of short-term KPIs which measure the performance of the tool on the obsolete material. But also, long-term KPIs as simple as 'what is the yearly obsolete cost?'. Then these KPIs can be implemented in the company's quality management system and targets can be set for the future.

2. Current situation

In this chapter sub-question 1 is answered '*What is the current order process at Global Electronics B.V.?*'. We will dive into the current order process in section 2.1 and 2.2 and the situation regarding inventory will be dealt with in section 2.3.

2.1. Current order process

As mentioned before, Global Electronics assembles printed circuit boards (PCBs). The customers send a bill of materials (BOM) for their desired PCBA. In this BOM all desired components are listed with their position on the board and the amount of each component per board. This BOM is checked and analysed in the software called QuoteArchitect (QA). This software gathers all sorts of information, QA is extensively discussed in the next section. Eventually the software returns the cost of the entire BOM for all PCBs in an order, keeping certain restrictions in mind. Eventually a complete quotation is sent to the customer and once confirmation is received, GE orders the components at the suppliers as defined by QuoteArchitect. A simple representation of this order process can be seen in Figure 2.1. As soon as the components are ordered, the orders are put in another software called 'Exact'. Exact is the software which is also used in the company. It keeps track of all components in stock and tells the composition of each order.

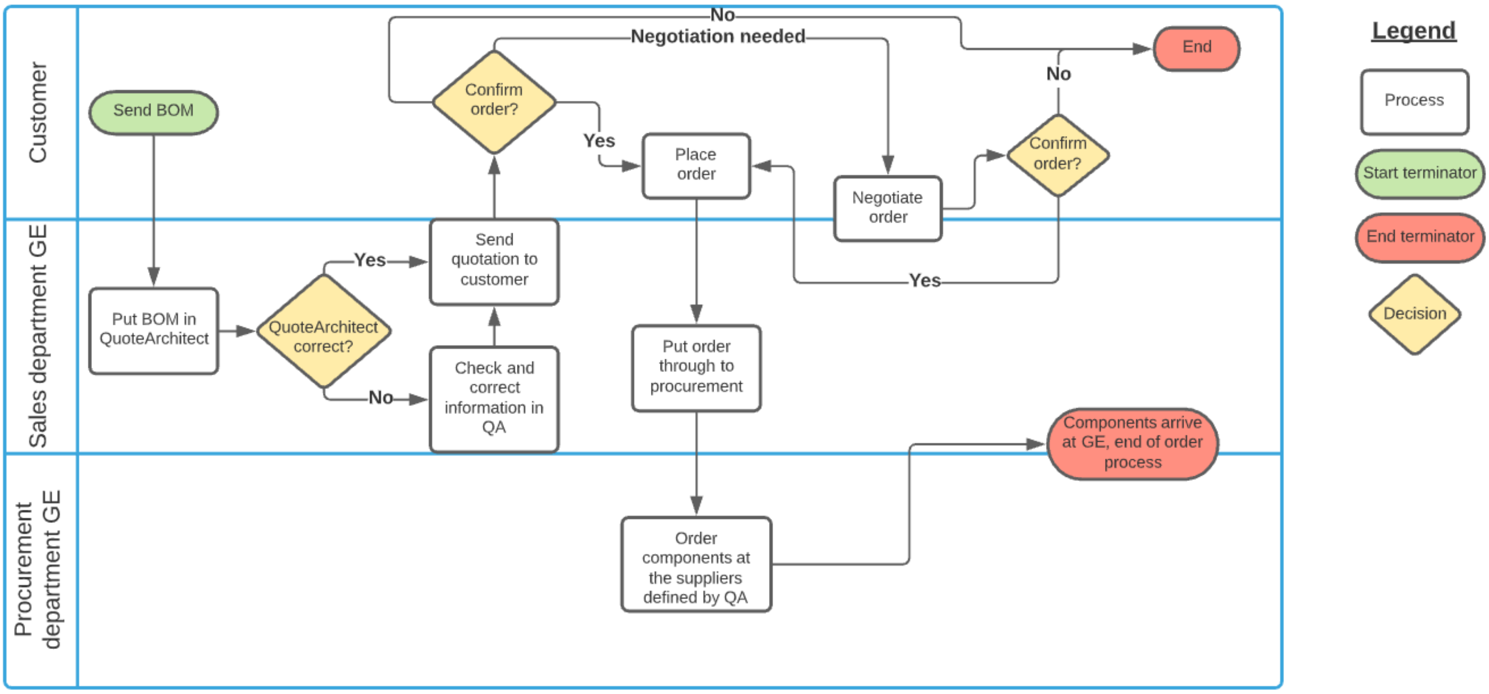

Figure 2.1. *Simple representation of order-placing process.*

2.2. Key order characteristics

The sub-question in this chapter can be answered most accurately when we look at a few key characteristics of the order process.

QuoteArchitect

As mentioned above, QuoteArchitect (QA) is the software which GE uses to analyse the BOM of customer orders. It analyses a lot of information. First of all, it offers the option to check if certain components are in stock at Global Electronics itself. Secondly, it checks across all suppliers if components are available (within an acceptable lead time), what the price of each component is and if there is an MOQ at that supplier for that specific component. Then the software determines which components to order at which supplier with corresponding costs and lead time. So, QA basically bundles all available information at each supplier in one overview. This helps the sales department, because they do not have to check for all components which supplier is the cheapest, has an acceptable lead time and anticipates which MOQ, because the software is doing that for them.

Figure 2.2. *Logo of QuoteArchitect.*

Even though QuoteArchitect saves a lot of time, it also has a few limitations. First, not all suppliers give this software access to their information. So, not all suppliers can be compared automatically. Furthermore, QA only compares the prices per component. It does not compare the MOQs per supplier. So, it can occur that supplier A is offering a lower price per piece but has a very high MOQ. While supplier B is a bit more expensive per component but has a low MOQ which results in less costs for the entire ordered quantity. The sales department ignores this problem unless a remarkably high cost of component type A is observed. Then they check manually what other MOQs are and if it is worth it to change supplier for this component type. This comparing of suppliers is done manually and takes time. Also, as mentioned above, the checking of current stock levels is an option in QA. Sometimes this option is not turned on by the crew because it makes QA slower and the analysis of the outputs becomes more complicated to interpret.

QA is continuously improving and adding new modules which relieves the sales employees.

Component types

Next to the distinction between the types of components, it is important to make another distinction which has already been recalled a few times in this paper: unique components and common components. Common components are components which are commonly used across different orders. For example, resistors are very common on all sorts of PCBs and therefore also common among a lot of different customer orders. Unique components are the opposite. They are very PCB and hence, customer specific. For example, a processor with unique capabilities which are only suitable for single customer orders. The procurement and warehouse crew of GE knows from experience which components are unique or common.

Furthermore, it is important to make the distinction between grit components and other components. Grit components are very small and usually cheap components which result in a bit of waste on the machines because of the size. This waste is on average 2%, other components do not have this waste.

In total Global Electronics distinguishes 23 types of components, from which six 'main' types. The components will be treated more elaborate in chapter 3.

Lot sizes

Global Electronics does not order components without a customer order as incentive (so make-to-order), apart from two customers which is elaborated on in the next section. Therefore, there is no consistent lot size in which components are ordered. For common components, the lot size is usually a multiple of the amount on a reel (see Figure 2.3) because these reels can be easily put in the machines. These reels are known as the factory packaging size (Keijzer, 2019). There are two types of supplier restrictions which partially determine the lot sizes. First the MOQ, this is a threshold which must be met at a supplier to order there, one of the next sections dives deeper in the MOQs. The second is the multi (Keijzer, 2019). Some suppliers only want to sell their components in full factory packages, and this is called a multi. So, components can only be purchased in steps of this package size, for example a reel or a piece of tape with the components on it, is considered a multi.

The lot size also depends highly on the inventory level, because only the missing components are ordered and of course the smaller components are purchased with plus 2% due to machine waste.

Figure 2.3. *Components on a reel in GE's warehouse.*

Safety inventory

Formally, safety inventory is defined as inventory held to satisfy demand when it is higher than forecasted (Chopra & Meindl, 2014). In the case of GE, unexpected demand is not an issue because of the *make-to-order* view. But the components on stock can still be considered safety stock because these components do not need to be ordered and therefore the risk of long lead times for these components is avoided. But on the other hand, it is important to note that these components are not procured with the intention to serve as back-up for demand uncertainties. They are ordered because of MOQs which had to be met or the fact that employees of the warehouse and machines prefer full reel packages over single components.

Minimum order quantities

Based on the distinction of component nature stated above, decisions regarding the MOQs/multis are made. For most common components, the MOQs (or multis) are not really an issue and they are ordered without too much hesitation. It just rises the stock level and in the next order, QuoteArchitect will identify that these components are in stock and therefore do not have to be ordered.

But with unique and expensive components, the procurement department is a bit more careful. They check and compare the component prices and MOQs. If there is a remarkable difference between the desired quantity and the MOQ of a component, then the MOQ and cost price are fed back to the sales staff to be discussed with the customer. The intention is to let the customer know that he must accept the excess quantity if he wants to order at Global Electronics. Most of the times, the customers agree with this and GE orders the components and stores them in their (GE's) own warehouse. If the customers do not place another order at GE, while they have a lot of non-moving components in GE's warehouse, they are contacted that they still need to buy these components. But it only happens very occasionally that GE makes the effort to find out which customer has to pay for which excess components.

The last important point about multis has to do with the average of 2% waste of smaller components on the pick-and-place machine. For example, if a customer wants to order 1000 PCBs, and he designed a resistor A (which is a grit component) with a multi of 1000 on the PCB. Each PCB contains one resistor A. Then this means that there need to be ordered 1020 components of resistor A due to the 2% waste. Now, 2000 resistors A are ordered because of the multi of 1000. This results in 980 residual resistors A which have a probability to become obsolete components. Fortunately, the grit components are usually not that expensive (see chapter 3) but there could always be a special case.

So, the MOQ/multi of distinctive and grit components are a big issue, resulting in rising stock levels and obsolescence costs. The cost impact of the MOQs and multis are analysed through three random real-life examples in the figure below. In Figure 2.4, we see that for some diode A, 90% of the total cost to order that diode is due to excess material. Also, for IC B and Resistor C the percentages of excess material cost are shown.

	Order size		**100**			
Component	Diode A		IC B		Resistor C	
# needed for all PCB's	300		100		2400	
MOQ	1		350		5000	
Multi	3000		25		5000	
cost per unit	€ 0,03		€ 17,59		€ 2,08	
Total cost	€ 81	100%	€ 6.156,50	100%	€ 10.400	100%
Needed material cost	€ 8,10	10%	€ 1.759	29%	€ 4.992	48%
Excess material cost	€ 72,90	90%	€ 4.397,50	71%	€ 5.408	52%

Figure 2.4. *Impact of MOQs/multis on the total costs of 3 random example components.*

In Figure 2.5 the order process is shown again, with the key decisions regarding the minimum order quantities shown explicitly. The red cross indicates that that step is taken very rarely since it is time consuming, as explained previously.

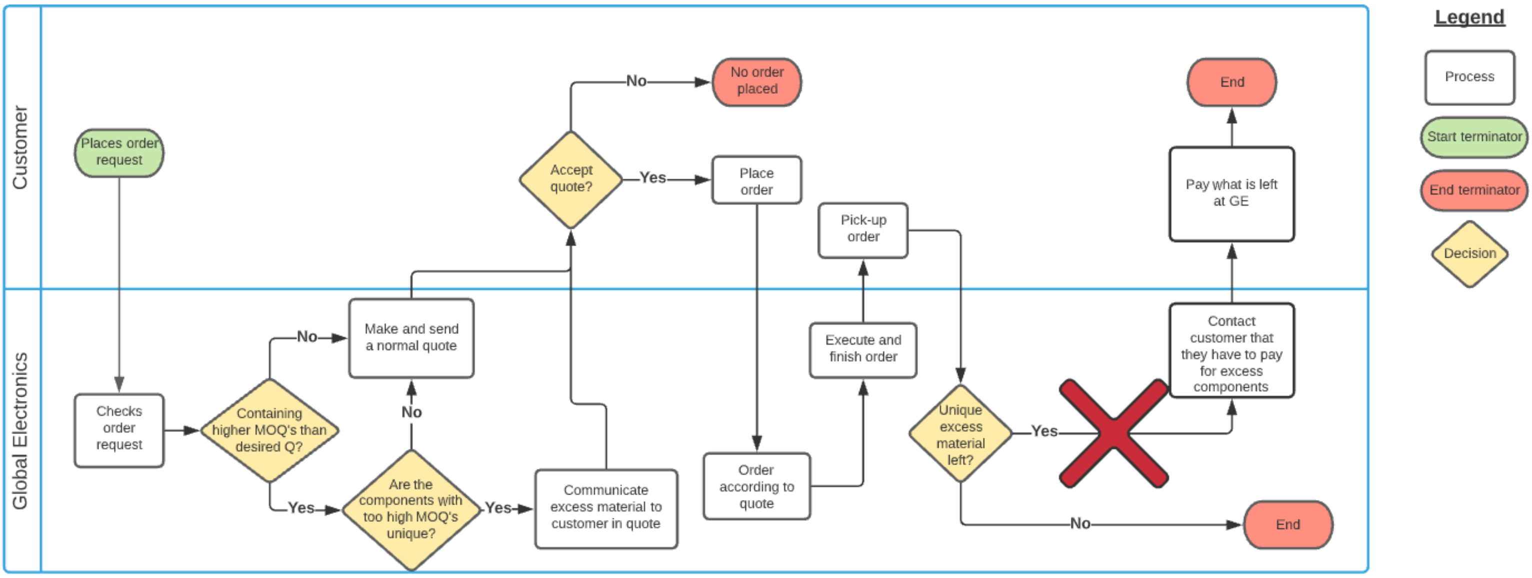

Figure 2.5. *Flowchart of order process with key decisions.*

Economic order quantity in electronic manufacturing

The EOQ in electronics manufacturing does not have anything to do with the classic definition. The classic EOQ seeks the optimum balance between holding and order costs (shortage costs can also be included). But the electronics manufacturing EOQ is about materials MOQs/multis and residual costs (Keijzer, 2019). The reason is that each order new and/or different components are ordered and these components are usually meant just for one customer.

The EOQ in this business is defined as the quantity at which the least residual material costs occur. Residual material costs are associated with components which are not used in a customer order but are purchased anyway to meet the MOQs of suppliers or to satisfy the full package sizes (multis). The EOQ in electronics manufacturing is from now on called the LEMQ (Least Excess Material-cost Quantity) to prevent any confusion with the classic definition of the EOQ (see chapter 5 for an extensive outline of the classic EOQ-model and the introduced LEMQ). At this point GE is not ordering (near) this LEMQ because no transparent tool is used which calculates this, and they also think that the most customers will return. For this reason, the excess is taken for granted.

2.3. Inventory characteristics

Warehouse

To understand the warehouse of Global Electronics, we need to examine the map that is shown in Figure 2.6.

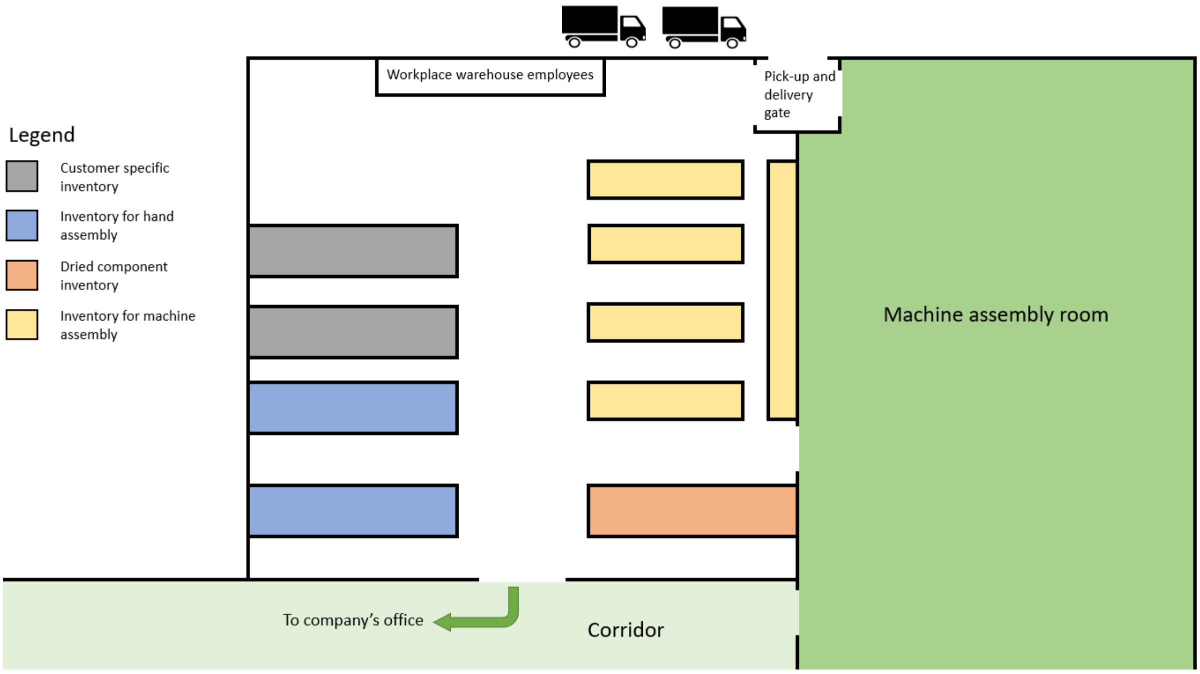

Figure 2.6. *Map of Global Electronics' warehouse.*

In this map we see three main rooms: the corridor, the machine assembly room and the warehouse (white). The warehouse contains 4 different types of racks on which the components are stored. The grey racks are racks containing components for specific customers. Two customers give GE a yearly forecast and GE can then order all the required components directly for these customers. This ensures that the customers are always certain that their needed components are present and hence, the risk of very long lead times (could be 52 weeks) is avoided.

The blue racks hold the components which need to be assembled by hand. The orange box in Figure 2.6 represents the dryers in which certain components are stored because of humidity reasons. And the yellow racks store the components which are used in the machine assembly. When components are delivered or finished orders are picked-up, they use the gate in between the warehouse and the machine operation room.

It is possible that a certain component is present in the grey racks, but a duplicate of that component is also in another rack. This is because of the 100% certain availability which the two customers of the grey racks demand. If GE orders a certain component with a quantity of 1000, for example, they could be divided among the grey and other racks if a customer of the grey rack needs 250 of those 1000. In other words, it is not the case that the components in the grey racks are all different than those in other racks.

Order picking

To eventually assemble the PCBs, the components need to be collected from the warehouse. The warehouse employees are usually too busy to perform this task entirely, so the surface-mount device (SMD) operators collect the needed parts for the machine assembly. The warehouse crew observes a small problem with this process. Since the operators pick the newest components in the front of the scaffoldings, they leave the components in the back. The ones in the back do not move anymore and therefore have a higher risk of reaching the point of not being moved for five years and become obsolete. This implies that a first in first out strategy is not being used when picking the orders and this is an important step.

Inventory monitoring

Naturally, the order process of GE has its effects on the inventory. The inventory is monitored using inventory management software 'Exact'. Exact shows a list of all component types, with their characteristics and the quantity in stock. To determine which components can be discarded, a filter in Exact can be applied. It tells which components have not been used in orders for the past five years and are also not scheduled to move in the near future. At the beginning of each calendar year, the warehouse employees go through the list from Exact and discard all parts that have not been used for five years by then. The components are put in a box and this is brought to a waste processor who pays GE an insignificantly small amount of money for the components.

Current obsolete inventory value

Part of the inventory check is the financial accounting which must be done yearly. For the financial administration, a 'nine months not used-rule' is being anticipated. At the end of the year GE checks which components have not moved for nine months or more within their inventory. Then, for their accounting record GE considers these unmoved components obsolete and therefore writes off the entire value that these had. Components are only depreciated once according to this rule. So, they will not be depreciated again if they remain unmoved for another nine months.

Table 2.1. *Yearly administrative mutation of obsolete inventory and the total administrative obsolete inventory value since 2015.*

Year	Change of administrative obsolete inventory in euros	Value of discarded components in euros	Total obsolete value in euros
2015	+ 23.759	n.a.	no data
2016	-/- 9.066	136.653	275.467
2017	+ 28.282	0	167.096
2018	+ 30.624	55.932	197.720
2019	+ 7.914	13.664	149.702
2020	+ 24.367	4.838	165.243
2015-2020	**+105.880**	**211.087**	**n.a.**

The changes in Table 2.1 are thus determined based on the nine-month rule. And these components are then depreciated for the financial administration. Last year a component value of almost €25.000 is not used in orders and has increased the total obsolescence value. For the past six years, the administrative obsolete inventory value has increased with €105.880. This implies an average increase of €17.647 of depreciated components per year. This average on an annual purchasing value of approximately €3.000.000 is 0,58%. So, almost 0,6% of the purchased value is thrown away at the end of the year.

However, these components are not thrown away but remain in the inventory for a total of five years. This five-year rule is used since 2016. Before 2016, basically everything remained in the warehouse. Even though the discarded components officially/administratively do not have any value anymore, they represent an original value. This can be seen in the third column of Table 2.1. The discarding process happens in the first days of the new year, so the value that is discarded corresponds to the previous year. For the year 2017, no components were discarded (in the first days of 2018) due to unknown reasons. And the value in 2016 obviously is high because it was the first year in which components were thrown away.

So, now we can calculate the total value of obsolescence, combining the real obsoletes from the five-year rule and the administrative obsoletes from the nine-month rule. But since the five-year rule is only used since 2016, we can only do it for the last five years. The last column in Table 2.1 represents the total obsolete value of all stock.

The last column is calculated as follows:
The total obsolete value = (previous total value) – (previous discarded value) + (change of administrative inventory value)

So, for example 149.702 = 197.720 – 55.932 + 7.914
And 167.096 = 275.467 – 136.653 + 28.282

2.4. Conclusion

In this chapter we looked at the current situation regarding inventory, but the main purpose was to answer research question 1: '*What is the current order process at Global Electronics B.V.?*

The order process can be summarized as order exactly what the customers want/need, while meeting the MOQs of suppliers. The default policy is reviewed as a make-to-order (MTO) policy, except for the two customers who send a yearly forecast to GE. For those two, a make-to-stock (MTS) policy is anticipated.

Most of the time the MOQs are taken for granted because the excess material is likely to be used in another order, but excess unique component(s) (costs) are rarely passed on to the customer. We have looked at the key decisions within the order process and that they are based on the distinction between unique and common components.

Regarding the current inventory situation, we can conclude that GE uses a 'five years not moved' rule to throw away components, but the costs of excess material are depreciated according to a 'nine months not moved' principle. We have looked at the inventory lay-out, the yearly obsolescence costs and we found out that the machine operators are collecting the parts in the warehouse which results in a small increase of obsolescence risk because they do not pick the orders FIFO (First-in-First-out).

3. High-impact components

In this chapter we will look at the components on a PCB and we will answer the second research question '*What are the type of high-impact components on PCBA's?*'. In semi-structured interviews and meetings with the employees of GE, we will find out what these high-impact components are and the reason for them being high-impact. We also look at quantitative historical data to examine amounts of components on PCBs. Once the components with the most impact are identified, a focus is decided.

This focus could be relevant because it is possible that one component more or less defines the tipping point at which an additional factory packaging (=a reel, for example) must be purchased (Keijzer, 2019). These MOQs or standard packages are different across components. And the aim of this research is to reduce obsolete components and these additional reels are only increasing the inventory and hence, probability of obsoletes.

In section 1.2.1. we have defined obsoletes as components which are not sold in a long time and are also unlikely to be sold in the future (Tuovila, 2021).

3.1. Component types

The different component types must be determined before looking into on the high-impact components. So, in this section the components are listed with their function and if applicable, key characteristics.

In total there are 23 different component categories which are distinguished at Global Electronics. In appendix A this list can be found. After internet research and discussions with the company, we found that there are six main types of components that cover about 80% of the total components on a PCB. These six are capacitators, integrated circuits, inductors, resistors, diodes and transistors. Furthermore, the obsolescence values of 2016-2019 were analysed and when looking in more detail to these six types, the data shown in Figure 3.1 was found. The year 2020 is not analysed since the obsolescence numbers of that year are not entirely according to the 9-month and five-year rule (see chapter 2.3.) due to the COVID-19 pandemic.

Component	Value
Capacitators	27.604,92
IC's	65.026,95
Inductors	18.712,50
Resistors	29.655,84
Diodes	32.956,38
Transistors	13.755,63
Subtotal	**187.712,23**
All components	275.467,00
6 comp. as % of total value	**68%**

a) 2016

Component	Value
Capacitators	6.991,30
IC's	39.348,15
Inductors	8.588,69
Resistors	15.104,38
Diodes	26.691,40
Transistors	9.122,64
Subtotal	**105.846,55**
All components	167.095,86
6 comp. as % of total value	**63%**

b) 2017

Component	Value
Capacitators	11.660,34
IC's	34.411,86
Inductors	7.187,22
Resistors	10.522,03
Diodes	17.615,78
Transistors	4.121,57
Subtotal	**85.518,80**
All components	149.702,18
6 comp. as % of total value	**57%**

c) 2018

Component	Value
Capacitators	10.084,21
IC's	39.393,38
Inductors	7.325,19
Resistors	18.481,42
Diodes	33.330,65
Transistors	5.684,60
Subtotal	**114.299,45**
All components	197.720,33
6 comp. as % of total value	**58%**

d) 2019

Figure 3.1. *Obsolete value of the six component types together with entire obsolescence value per year.*

Considering that only six out of twenty-three components already represent roughly 60% of the total obsolescence value, it can be suggested that these six categories indeed have a high impact on the obsolescence costs. These six types are also used the most. In the next sections we will dive deeper into these categories.

3.2. The six high-impact types

In the figure below, we see the six main categories. In the top left of each category the corresponding electronical symbol is shown and the rest of each box is filled with examples of possible designs for that component type.

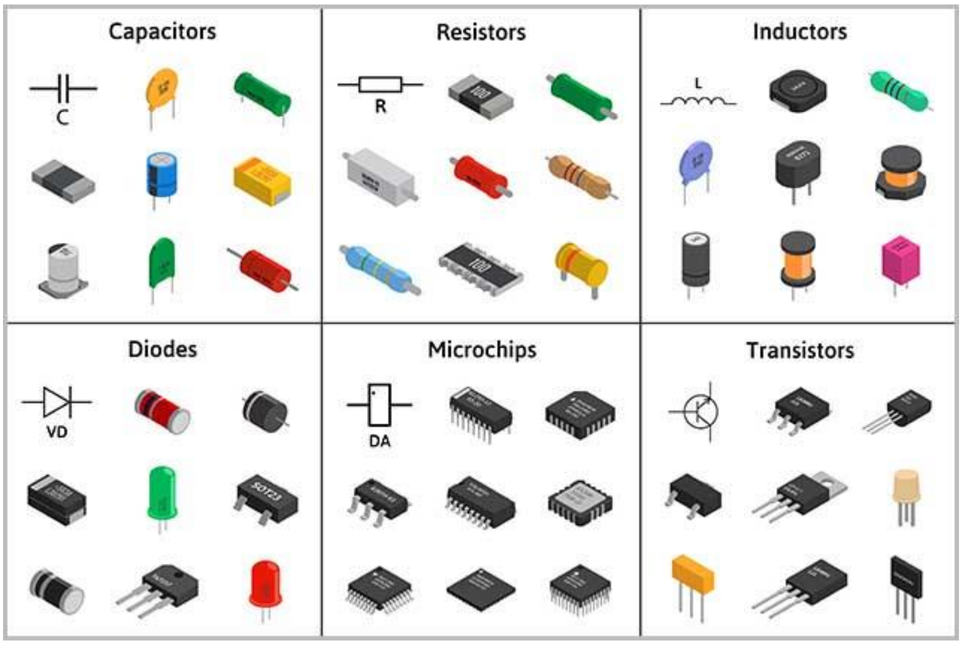

Figure 3.2. *The six main component types on a PCB. (Source: ourpcb.com)*

The categories in Figure 3.2 are also listed in Table 3.1, in which the functions of these six types can be found. The information is gathered from ourpcb.com.

Table 3.1. *List of six main PCB components with corresponding function.*

Component category	Function on PCB
Capacitors	Storing electrical charge
Resistors	Control the flow of current across PCB
Inductors	Store energy in magnetic form
Diodes	Allow current to flow in one direction
Microchips / Integrated circuits (ICs)	Integration of multiple components with very diverse functions. 'Brain of PCB'
Transistors	Switch or amplify electronic power

For each type, the relevant characteristics will be discussed in the next section. For example, properties regarding the order process or inventory management are considered relevant for this study.

3.3. Relevant characteristics

The component characteristics of importance to this study are sorted around three themes: Order characteristics, inventory value, ability of standardization. These properties were found during semi-structured interviews (see Appendix B) with employees from procurement and from the warehouse.

Order characteristics

When considering the order characteristics, we look at the suppliers, lead times and the MOQs. First, it is important to note that component types are not restricted to suppliers. It is possible to order all sorts at all suppliers from Global Electronics. The lead times, however, are different per supplier. These lead times are also independent from the component type, they just depend on the supplier and if the desired components are in the supplier's stock. Normally the lead time is a few weeks (2-8), but right now it is different. With the ongoing COVID-19 pandemic and the worldwide chip deficits, the lead times can rise to 52+ weeks. Again, no relation with the component sort can be recognized.

For the minimum order quantities, a relation between the component size and the MOQ can be found. Because the rule-of-thumb is that the smaller the component size, the larger the MOQ. The so-called grit components therefore generally have the highest MOQs. By grit we mean the smaller ones, so capacitators, resistors and diodes.

Inventory value

From the transcribed interview we can deduce that there are no significant differences in which component types are thrown away more often. In other words, each component type is equally likely to be thrown away after not having moved for five years.

Besides how often certain component types are discarded, also the value that the discarded components represent each year is of importance. According to the warehouse staff it is also hard to distinct which components are relatively valuable. Within each category there are great price differences because some integrated circuits are very complex, while other ICs are relatively simple. Between the categories there are also some large price differences, based on size and complexity of the component. Furthermore, the rarity or scarcity of the components plays a role in determining the price. In each category this results in big price differences between components. But overall, the ICs are the most expensive, since naturally they are the most complex.

Ability of standardization

The third characteristic we consider is the ability of standardization. In the semi-structured interview, it was mentioned that the grit can be replaced the easiest by alternative, but the same type of components. For example, a certain resistor can be replaced by another resistor. The only requirement that must be met is that the specifications should be identical and therefore that the function remains the same. Also, across different orders the grit components are the most likely to be used. So, specific capacitators are used in multiple orders.

Machine spill

At last, usually the grit components have 2% spill at the machine. The machine needs to 'warm-up' and especially for small components this results in a loss of 2%. So, if 100 components are needed, only 98 are used by the machine. This portion of 2% is variable but it is the standard/mean value that GE uses in their BOM analysis and order process.

3.4. Focus

To determine if there are components much more relevant to target than others within these six, an overview is created to show which component type has which key characteristic. If no general distinction can be made for a certain criterion, then all types are marked. No scores are assigned because there is too much variability to say for sure that one type is more expensive than another, so only the in general most fitting type is marked for each criterion.

Table 3.2. *Overview of component type and the criteria discussed in section 3.2 and 3.3.*

Type / ***Criteria***	**Capacitator**	**Resistor**	**Inductor**	**Diode**	**IC**	**Transistor**
Longest lead time	X	X	X	X	X	X
Highest MOQ	X	X		X		
Most expensive					X	
Most often discarded	X	X	X	X	X	X
Standardizable	X	X		X		

From the Table 3.2 we can deduce some conclusions. The IC is the most expensive component (also visible in Table 3.1) but does not have the highest MOQ and is also not easily standardized. The grit components have high MOQs but are usually quite cheap so may not have that much impact as well. However, the grits are the most commonly used components per PCB so in total they still represent some significant value.

All in all, it is impossible to indicate highest impact on the obsolescence costs. So, no more detailed focus is chosen and in this study we will look at all six.

3.5. Conclusion

In this chapter we have analysed the components present on a PCBA to seek for the sort of components with the highest impact on the obsolescence. We identified the six most common ones and decided that these would have a high impact on the obsoletes. In consultation with the company, it was decided that all six categories are included in this study.

4. Reduce obsoletes: a literature review

In this chapter we will explore sub-question 3: '*What are methods to reduce obsolescence costs in the inventory?'*. As mentioned in section 1.3.2 we will first perform a literature study on general methods to reduce obsolete inventory, and then evaluate if the general methods are applicable to the situation at Global Electronics.

4.1. Systematic literature review

Using this literature review we will answer sub-question 3: *What are methods to reduce obsolescence costs in the inventory*. The research strategy can be found in Appendix C.

4.1.1. Integration of theory

The literature that was found focuses on three topics which all contribute to reducing the obsolescence costs of inventory. These three topics are discussed in this section.

Forecasting/planning of demand and inventory

If a company exactly matches the number of sales with the number they produce/order, then no obsolete products or components occur. But the trick is this matching. Companies make forecasts of demand and a production planning will correspond to this predicted demand. According to Sanchez-Vega et al. (2018), obsolete components are due to an incorrect establishment of planning/forecast parameters. And Nnamdi (2018) also argues that the root cause of obsolescence are data errors in forecasting models. The solution would be to revise the forecasting models if high obsolescence occurs and to base these models on historical data. Also, these models should forecast sudden decreases in demand, because then this can be anticipated in the inventory planning (Nnamdi, 2018). Nnamdi outlines that for different demand patterns, different forecasting models exist. So, the right model should be applied to the specific demand pattern.

Another way to reduce excess inventory, and hence obsolescence, is to suggest alternative products or components to customers if a company is out of stock (Ghadge et al., 2020). This can be performed if there are small differences between the predicted demand and the eventual demand. Then that company can offer alternate products which ensures that still this demand is met, but they do not have to (back) order a large batch (due to supplier restrictions) of the initially desired product.

This method is supported by other writers from these five articles. Baker (2013) formulates this as 'emulation'. His idea is to not order specific components if you can create the same functionality with (a combination of) other components. Baker also mentions a downside to this emulation or alternate product suggesting, namely that the design process should be reconsidered when using this technique.

Order process

Each company has its own order policy. It is important to adapt this policy in such a way that you proactively try to reduce the obsolete products. In some cases, the probability of obsolescence is given beforehand, and this must be implemented in the (EOQ) order policy. Because then the outcomes of this policy are changed a bit and this can result in less excess inventory (Nnamdi, 2018). Furthermore, Nnamdi suggest to not fall for the discounts that suppliers offer on large quantities. Because this is unnecessary for some products or components and hence, these discounted large quantities will eventually result in obsolescence and therefore costs.

Another method to partially reduce the risk of obsolete components is to agree upon a planning horizon. During this time, order up to a certain level. But as the horizon approaches, decrease this order-up-to level Then at the end of the planning horizon this risk of obsolescence is reduced (Teunter

& Klein Haneveld, 2002). At last, helping a supplier with their planning by using an integrated order policy of periodic and continuous reviewing together with more in-depth contact with suppliers also contributes to identifying possible excess material in the earlier stages of the supply chain, which reduces the obsoletes a company itself (Sanchez-Vega et al., 2018).

Other internal activities

The last topic which helps the reduction of obsolescence is concerned with internal activities that are carried out within a firm. Nnamdi (2018) suggest the three following tasks:

1. Appoint an employee to be responsible for monitoring the excess inventory. This person knows how, when and why excess inventory has accumulated over the years and can help in forecasting obsolescence and anticipating this.
2. Assess if components are likely to be replaced by new inventions in the near future. Do not order these 'outdated' components anymore in large quantities.
3. Once excess inventory has been identified, offer a discount on these components. Consequently, customers will help you to prevent this stock from becoming obsolete.

4.1.2. Intermediate conclusion

In the previous section we have seen different strategies and reasons to reduce the obsolescence. To summarize, such a reduction can be achieved by first, have a very accurate demand forecast, and update this mathematical forecast regularly. Second, to have a suitable and flexible order policy which is in accordance with the demand forecast and recognizes the strength of suggesting alternative products. And as third, to perform some internal tasks which help monitoring and reducing the potential excess inventory.

4.1. Evaluation of methods

In this section we will evaluate the applicability of the methods identified in 4.1. In the next table all methods are listed together with an explanation of whether they are feasible at Global Electronics' situation or not.

Table 4.1. *Feasibility evaluation of identified methods to reduce obsolescence.*

Author	Method	Suitable to implement at GE?	Reason
Sanchez-Vega et al, 2018	Use correct forecasting methods based on historical data	Partially	At GE no forecasting tools are used because they anticipate a make-to-order strategy and it is impossible to make forecasts in this business with so many components. This can only be used for very common components or standardized ones.
Ghadge et al, 2020 / Baker, 2013	Suggesting alternative components / emulation	Yes	As mentioned earlier, there are components with equal specifications so alternatives should be possible.
Sanchez-Vega et al, 2018	Combine continuous and periodic order policy	Partially	Again, there is a make-to-order strategy so this order policy cannot be implemented for all components, only for standardized ones.
Teunter & Klein Haneveld, 2002	Agree on planning horizon and reduce OUL when time progresses	Partially	There is no order up-to-level at GE and this method also works only with a make-to-stock policy. So again, only for standardized

			components if those components are introduced.
Nnamdi, 2018	Include possibility of obsolescence in EOQ calculation	Yes	When calculating the electronics manufacturing EOQ, the possible residual material costs can be calculated. And this would also fit the make-to-order policy.
Nnamdi, 2018	Monitor inventions which can replace existing components	Yes	In theory this is possible to implement at GE. It may cost a lot of time, but it should be possible to assign this task to someone.
Nnamdi, 2018	Offer discounts on identified excess stock	Yes	It should be possible because lists of slow-moving components are available, also the excess stock is already being monitored by someone.

To summarize, we can implement (a combination of) the following methods found in literature to reduce obsolete components:

1. Accurately forecast common or standardized components.
2. Offer alternative components / emulation.
3. Calculate EOQ's with possibility of obsolescence included. In Global Electronics' situation this EOQ is called the Least Excess Material-cost Quantity (LEMQ, see chapter 2.2) since in the world of electronics manufacturing, the best order quantity is defined by the least amount of excess material costs (Keijzer, 2019).
4. Monitor new inventions in the electronics market.
5. Offer discounts on identified excess stock.

4.2. Selecting a feasible method

In the previous section we have evaluated the feasibility of the proposed methods in the literature. We identified five strategies that can potentially be implemented at Global Electronics. Now, we will determine which method(s) will be implemented during this research. The five methods were discussed with the company to set the scope for this study. For each of the five methods summarized at the end of section 4.2, the conclusion of the discussion with the company is shown below:

1. Forecasts are hard to make in this business, but for some standardized components it should be possible. In this research a forecast cannot be made because that would require a thorough historical data analysis which will not fall within the time available for this research, and these standardized components are not anticipated at GE yet.
2. For this research it is unfeasible to find a way to offer alternative components. Because for that, a lot of knowledge about the electronic components is required. Think of specifications of the components, but also shape sizes and material knowledge. But we may can give advice on which components in an order are suitable to replace because of the high residual costs they bring with them.
3. The LEMQ can be calculated for different orders. This can be done by creating a tool to calculate the LEMQ. A tool was also an intended deliverable of this study.
4. Currently new inventions are not monitored at GE. This active searching to new inventions is considered as a very time-consuming activity and therefore probably will not be executed on the long-term. So, it is decided that this will not be included in this research.
5. The offering of discounts on excess stock is currently not the case at GE for multiple reasons so it seems like a good way to reduce obsoletes. But the reason we do not include/research it in this study is because it is considered to be very hard to manage, and not worth it to put the time in since it is expected to result in a very small cost benefit.

4.3. Method implementation plan

So, now the scope for the rest of this study is defined, we will discuss the intended deliverables in more detail.

Residual cost calculating model or tool

The literature study identified that ordering at the EOQ should reduce obsolescence in general and in the scope for this study this EOQ is replaced by the LEMQ because of the business Global Electronics is in, the electronic manufacturing services. This LEMQ is discussed in section 2.2 but primarily in the next chapter. The main deliverable of this study is a LEMQ model which is implemented in an example tool to calculate for customer orders, what the optimal quantity is to reduce the excess material costs. This tool then shows a graph which plots the batch size to the rest material cost like Figure 4.1 from Keijzer (2019) does.

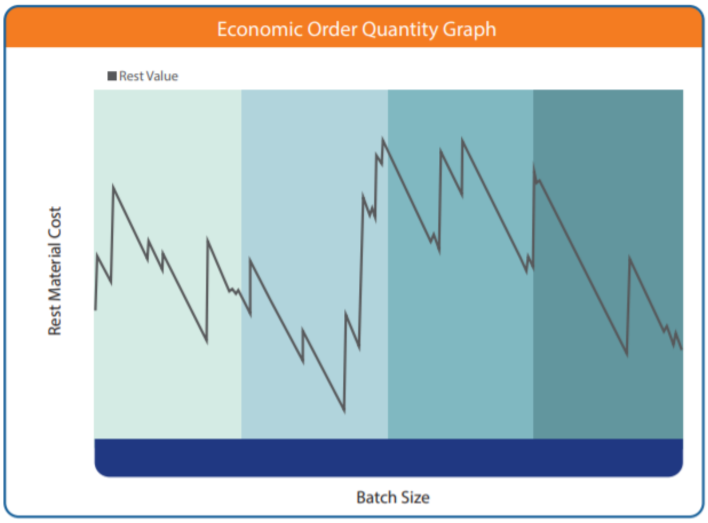

Figure 4.1. *Example of an EOQ graph (Keijzer, 2019).*

A tool which offers alternative components is out of the scope of this research. But the proposed tool can also identify which component(s) currently has/have the most residual costs and therefore is the most suitable to replace with an alternative which is already in stock or has fewer residual costs.

4.4. Conclusion

In this chapter we found several methods in literature to reduce the obsolete inventory. Some of those were more feasible to use at Global Electronics than others but after an evaluation we decided that five methods should be feasible to implement in GE's situation. In this study we will focus on an EOQ model which is created for GE in its unique situation, where the EOQ is replaced by the LEMQ. A LEMQ-model plus an example of how this model can be implemented in a tool are decided to be the focus of this study. This tool can also be used to identify which component should be replaced with an alternative.

5. Least Excess Material-cost Quantity model

In the previous chapter we learned about ways to reduce obsolete inventory in general and the feasibility of implementing those methods in Global Electronics' situation was assessed. It was determined that a tool would be created to simulate the economic order quantity in electronics manufacturing (Keijzer, 2019). In chapter 2.2 the EOQ in electronics manufacturing was defined as the LEMQ (the Least Excess Material-cost Quantity). The white paper of Keijzer in 2019 is mentioned a few times already because it indicates the difference between the classic EOQ model and the, in this paper called, LEMQ. In this chapter the LEMQ model will be dealt with. It lays the foundation for sub-question five: *How to implement a tool with a feasible method to change the order process at Global Electronics B.V. such that the obsolete components will reduce?* But the actual implementation is done in chapter 7. This model is an intended deliverable from chapter 1.4. This is the scientific contribution of this research: an adjusted EOQ model for the electronics manufacturing sector.

5.1. Difference between the EOQ and the LEMQ philosophy.

The classical EOQ model

A lot of studies using the EOQ model are performed worldwide, in this chapter the EOQ model with quantity discounts will be treated and then the shift to the LEMQ philosophy is explained. In this section the definitions of Chopra and Meindl (2014) and Keijzer (2019) are used.

In the EOQ inventory model, the question is in what size a single batch of products should be ordered. This batch size is determined by minimizing the total costs, because it is argued that the least total cost result in the most optimal economic situation. Chopra and Meindl assume the following inputs:

- D = annual demand of the product
- S = fixed cost incurred per order
- C = cost per unit of product
- H = Holding cost per year, usually written as H = hC where h is a fraction of product cost.

Hence, the three costs which need to be considered when looking for an optimal batch size are annual material cost, annual ordering cost and the annual holding cost. The basic assumptions in this model are:

1. Demand is steady at D units per time unit.
2. No shortages are allowed, all demand must be supplied.
3. Fixed replenishment lead time.

There are two types of quantity discounts. First there is the all-unit discount and second there is a marginal unit discount.

The all-unit discount is quite straightforward. If the order size is above a certain threshold, then all units cost a discounted price. There can be multiple thresholds. In Figure 5.1a, this is visualized. If threshold q_2 is met, then <u>all</u> components are priced at C_2.

Then the marginal unit quantity discounts are introduced. This implies that for units above a certain threshold q_i a price quantity is offered. So, the first q_1-q_0 units are priced at C_0 and the next q_2-q_1 units are priced at C_1 where $C_1 < C_2$, See Figure 5.1b.

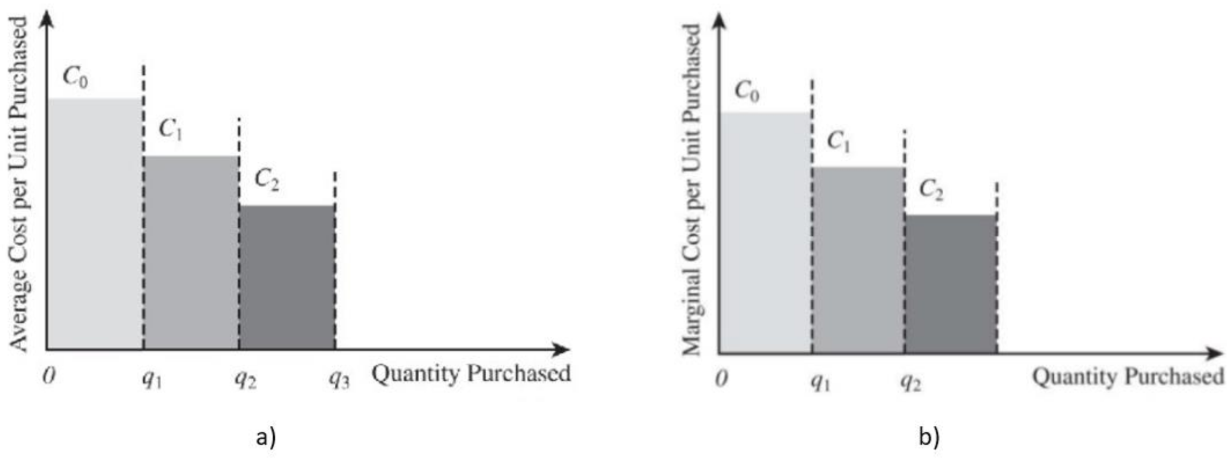

Figure 5.1. *Marginal unit cost with marginal unit quantity discount (Chopra & Meindl, 2014).*

The philosophy of an EOQ model is to seek for the optimal lot size which is determined by minimizing the overall cost function. This total cost (TC) function contains the order, holding and material cost while incorporating the quantity discounts if applicable. The optimal lot size is called the Economic Order Quantity (EOQ) and is usually found by taking the first derivative of the TC with respect to q (quantity) and then set that derivative equal to zero.

The EOQ in electronics manufacturing – The LEMQ model

In the field of EMS, the EOQ is not determined by finding the optimum between order, holding and material cost. The EOQ in electronics manufacturing is a very different type of EOQ because its impact can be much greater than the classic EOQ (Keijzer, 2019). Keijzer argues that the EOQ in electronics manufacturing seeks to find the optimal order quantity which minimizes the residual material costs. Therefore, in this research a different term is introduced: the Least Excess Material-cost Quantity (LEMQ). Because EMS companies order over millions of different components, from a lot of different suppliers with each specific MOQs or multis (package sizes), the goal is not to minimize holding or ordering cost but to minimize the residual material. This residual material can sometimes be very much and therefore, have a tremendous impact on the costs, especially when components are expensive. So, the aim of the LEMQ model is to formulate a total excess material cost function, rather than the overall TC function of the classic EOQ model. The quantity which minimizes this excess cost function is identified as the LEMQ and therefore most cost-efficient quantity. Like the EOQ is in a more regular situation. The goal of this research is to minimize the obsolescence, and the main reason for obsolescence is the large excess material being ordered (Keijzer, 2019). So, if this LEMQ can be achieved for each order, the obsolete component cost will overall decrease significantly.

The marginal quantity discount aspect of the EOQ model can be applied to the LEMQ model. When purchasing components, different package sizes can be bought with a different unit price. The smallest package size generally has the most expensive unit price and naturally, the largest package size has the cheapest unit price. It is <u>not</u> the case that all components are available for a discounted price if different package sizes combined reach a certain threshold and then. Rather, all components on a single package size cost the same price. Figure 5.2 visualizes how marginal unit quantities work at GE.

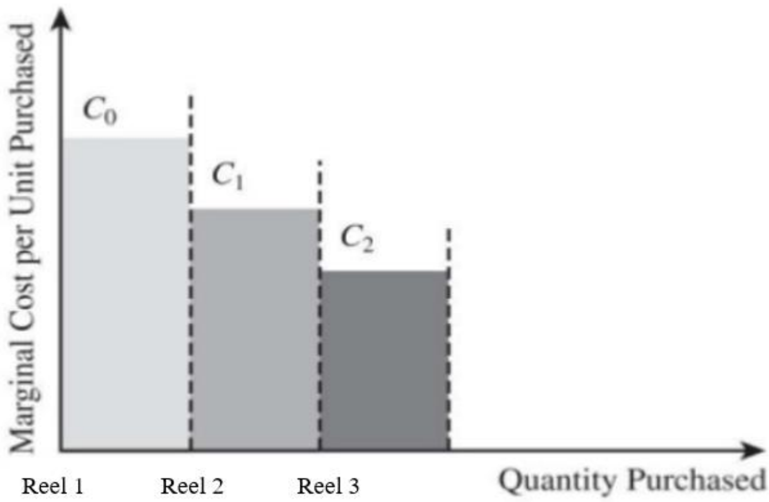

Figure 5.2. *Marginal unit discount for the thresholds: singular, taped and reel sizes.*

5.2. Mathematical LEMQ model

Now, the philosophy of the LEMQ-model is clear, the mathematical description is given. First the important assumptions are listed and explained:

1. There are different package sizes for each component. On average there are three different levels of package sizes and hence, three levels of multis for each component. These are the three different levels of full reels. Each level has a corresponding component unit cost.
2. All demand is to be satisfied through either purchasing components or using own inventory.
3. Each component has their own MOQ. The ordered quantity per component is larger than or equal to this MOQ.
4. Customers accept a range of a variable percentage below and above their original requested quantity.

Following the LEMQ philosophy, the excess (or residual) material cost must be minimized. Since customers allow the LEMQ to be in an acceptable range and not just any quantity can be offered to customers, the LEMQ is a local minimum.

This LEMQ of a single order is calculated by minimizing the objective function of the total excess material cost. The total excess material cost function is given by calculating for each component what the excess material cost are and then sum over all components in the order. See equation 1.

$$Total\ excess\ cost = \sum_{Components} (supplied\ quantity\ - required\ quantity) \times cost\ of\ comp.\ \ (\mathbf{1})$$

Equation **1** is still in words, to write it in a more mathematical notation, variables are introduced.

- i = Component type. On each PCB there are n component types. i = 1, 2, 3, … n
- Q_i = Supplied quantity of component type i.
- D = Eventual demand for in terms of PCBs.
  - D_0 = Original requested number of PCBs.
  - D_i = Demand for component i.
- m_i = Number of components of type i needed on a single PCB, include 2% waste for the grit.
- S_i = Stock level of component i.
- A = Acceptable range around D_0.
- x = percentage which determines range A.
- j = Degree of package reel. j = 1, 2, 3 (see assumption 1)
- $Multi_{ij}$ = Package size of component i at degree j.
- k_{ij} = Amount of $multi_{ij}$ ordered.
- C_{ij} = Unit price of component i at package degree j.

Variable j, $multi_{ij}$ and C_{ij} are explained in the table below. For a component i, there are three levels of multis with corresponding unit cost C_{ij}. The three possible multis are the possible package sizes. The smallest one is at j = 1. This is the smallest reel size for component i, usually a reel of 250 to 500 components. Then there is a medium package size at j = 2. This usually implies that the components are delivered on a larger reel with a quantity of 500 to 1000. And at j = 3 we have the largest full reel multi, which usually means a quantity on a reel of 1000 to 5000. These reel sizes are different for each component; therefore, the table below does not contain fixed values for the multis. Furthermore, the unit cost is component specific and depend on the reel sizes, so there are no fixed values in the C_{ij} column as well.

j	**$Multi_{ij}$**	**C_{ij}**
1	$Multi_{i1}$ (Reel 1, size 250-500)	C_{i1} (most expensive)
2	$Multi_{i2}$ (Reel 2, size 500-1000)	C_{i2}
3	$Multi_{i3}$ (Reel 3, size 1000-5000)	C_{i3} (usually cheapest)

Table 5.1. *Correlation between variables j, $multi_{ij}$ and C_{ij}.*

Now the variables are defined and explained, the 'supplied quantity' and the 'needed quantity' per component in equation 1 can be determined.

$$Supplied\ quantity\ of component\ i = Q_i\ (\mathbf{2})$$

$$Where\ Q_i = \sum_{j}^{3} Multi_{ij} \times k_{ij}\ \geq\ Required\ quantity\ (\mathbf{3})$$

$$Required\ quantity\ of\ component\ i\ = D_i - S_i\ = D\ \times m_i - S_i\ \ \ (\mathbf{4})$$

Equation **3** shows that the supplied quantity of component i is the sum of a certain of amount (k_{ij}) of different multis for component i. This is not just a random summation of different multis, but it is larger or equal to the required quantity. Furthermore, Q_i needs to be larger than the MOQ of component i, otherwise the component cannot be ordered. This restriction is introduced in the full model further on in this section.

The required quantity of component i is given by the demand for that component minus what is in stock. And the demand of component i is calculated as the demand for a PCB, times the amount that component i is placed on that PCB, see equation **4**.

From the defined variables and equations **2 to 4**, the function from equation **1** can be mathematically formulated:

$$\begin{aligned} &Total\ Excess\ cost \\ &= \sum_{i=1}^{n} \left(Q_i - (D_i - S_i)\right) \times C_i \\ &= \sum_{i=1}^{n} ((\sum_{j=1}^{3} Multi_{ij} \times k_{ij}) - (D \times m_i - S_i)) \times C_i \quad (\mathbf{5}) \end{aligned}$$

$$Where\ C_i = \frac{\sum_{j=1}^{3} Multi_{ij} \times k_{ij} \times C_{ij}}{\sum_{j=1}^{3} Multi_{ij} \times k_{ij}} \quad (\mathbf{6})$$

C_i in equation **6** is the weighted average of all C_{ij}. So, in equation **5** we can see that the summation over all components i is taken from which the difference between the supplied and the needed quantity are multiplied by the weighted average cost of that component. The weighted average is used because of the different unit prices per multi degree. The components which are residual can have different unit costs due to the multis, so therefore the weighted average C_i is used.

The goal is to minimize the total excess cost of the entire order by seeking for an optimal D, the eventual PCB order size. This optimal D must be in the acceptable range, so it is a local optimum. This range A is defined in equation **7**. Recall that D_0 is the original requested quantity and with a margin of x around D_0 the optimal D is sought.

$$D \in A = [(1-x)D_0;\ (1+x)D_0] \quad (\mathbf{7})$$

Hence, the objective function is formulated as follows:

$$\min_{D \in A} \sum_{i=1}^{n} ((\sum_{j=1}^{3} Multi_{ij} \times k_{ij}) - (D \times m_i - S_i) \times C_i \quad (\mathbf{8})$$

Equation **7** has to meet some restrictions, based on the assumptions stated, to complete the model.

Firstly, all variables are nonnegative. Equation six is also already a restriction, since D cannot be changed to a number outside acceptable range A. Variable x determines the size of the acceptable range and is expressed as a percentage in the form of a decimal, the values of x are assumed to be between 0 and 1. Secondly, in equation **3** a restriction is also already found: because the supplied quantity is always equal or larger than the needed quantity since all desired PCBs of customers are produced by Global Electronics. Also, the supplied quantity for i, needs to be larger than component's i possible MOQ. So, the entire LEMQ model is formulated below, with a copy of **8**. Some parentheses are coloured for increased understanding.

Full LEMQ-model

$$\min_{D\in A} \sum_{i=1}^{n} \left(\left(\sum_{j=1}^{3} Multi_{ij} \times k_{ij} \right) - (D \times m_i - S_i) \right) \times C_i \quad \mathbf{(8)}$$

$$Where\ C_i = \frac{\sum_{j=1}^{3} Multi_{ij} \times k_{ij} \times C_{ij}}{\sum_{j=1}^{3} Multi_{ij} \times k_{ij}} \quad \mathbf{(6)}$$

And

$\mathrm{D} = $ Eventual PCB order size
$\mathrm{D_0} = $ Original requested PCB order size
$\mathrm{m_i} = $ Amount of component type i on one PCB
$\mathrm{A} = $ Acceptable range tos earch in for optimal D, $\quad \mathrm{A} = [(1-\mathrm{x})\mathrm{D_0}; (1+\mathrm{x})\mathrm{D_0}]$
$\mathrm{x} = $ Percentage above and below in range A
$\mathrm{i} = $ Component type, with n component types in total $\mathrm{i} = 1, 2, 3, \ldots \mathrm{n}$
$\mathrm{j} = $ Degree of multi, $\mathrm{j} = 1, 2, 3$
$\mathrm{Multi_{ij}} = $ Package size of component i at degree j
$\mathrm{k_{ij}} = $ Amount of $\mathrm{multi_{ij}}$ ordered
$\mathrm{S_i} = $ Stock level at GE of component i
$\mathrm{C_{ij}} = $ Unit price of component i at multi degree j

For the restrictions it is easier to rewrite the summation of the multis and hence, the j summation by another variable, Q_i. This is shown in **9**. Q_i is not just an amount larger than or equal to the needed quantity (see equation **3**.), when optimizing the objective function, it is reasoned that this Q_i is the smallest quantity which is still ≥ the needed quantity. That is why in equation **9** below, the 'min' operator is introduced.

$$\mathrm{Qi} = \text{ordered quantity for component i} = \min \sum_{j=1}^{3} \mathrm{multi_{ij}} \times \mathrm{k_{ij}} \quad \mathbf{(9)}$$

Objective function is subject to the following restrictions:

$$\mathrm{D}, \mathrm{D_0}, \mathrm{m_i}, \mathrm{multi_{ij}}, \mathrm{k_{ij}}, \mathrm{S_i}, \mathrm{C_{ij}} \geq 0 \ \ \forall i\ and\ \forall j$$
$$0 \leq x \leq 1$$
$$n \geq 1$$
$$Q_i \geq MOQ_i$$
$$Q_i \geq D \times m_i - S_i \quad see\ equation\ \mathbf{3}$$

Since the LEMQ-model works with full reels, it should not be applied to proto customers or customers with an order quantity lower than 100 PCBs. Because for those customers it is not recommended to order on full reels because of the small number of components needed.

6. Key performance indicators

In the previous chapters we have concluded on the model to implement and the mathematical tool which contains this methodology. In this chapter we will deal with sub-question four '*What key performance indicators (KPIs) have to be implemented to monitor the new order process and obsolete component costs?*'. We will look at what the proposed tool will need to be able to calculate by determining which KPIs have to be included in the tool. Furthermore, the goal of reducing obsolete component costs needs to be monitored and therefore, we will discuss which KPI(s) will contribute to tracking if obsolete component cost indeed is decreasing.

6.1. What are KPIs?

In this section I will elaborate on what key performance indicators are and why we intend on using them.

KPIs represent the approach to the monitoring and management of the enterprise performance, they are critical indicators of progress toward an intended result (Repa, 2019). Furthermore, KPIs provide a focus for strategic and operational improvement, create an analytical basis for decision making and help focus attention on what matters most (Strategy management group, n.d.). So, since KPIs support strategic decision making, monitor performance and indicate the progress towards a desired result, they are implemented in this research. The solution proposed will hopefully be used on a long-term basis and thus KPIs are important to measure the long-term effects of this study's outcome.

KPIs are usually classified according to their use for the management of an enterprise, but KPIS can also be classified in lagging or leading. A lagging indicator typically measures an output, a result. It measures something that has already happened. A leading indicator measures an input. It is a predictor of the desired result (Repa, 2019)

Now we know what KPIs are, we will decide upon the KPIs used in the tool with the implemented LEMQ model from the previous chapter.

6.2. KPI selection

What has been discussed so far about a proposed LEMQ tool, is summarized in the list below:

- It needs to show for different quantities what the excess material cost is. The quantity with the least is the LEMQ (see chapter 2.2).
- Quantities will have to be within a range, this range can be customer specific, so the range should be variable.
- The tool should identify the component with the highest excess material.

KPIs calculated in the tool

In this research it is reasoned that a reduction of the excess material per order, will decrease the overall obsolete stock. Therefore, for each order the tool should calculate the excess material costs. The excess material costs are calculated in the KPI <u>total residual cost</u> per quantity in the defined range. The total residual costs are the cost of the ordered excess material, so for all components in an order. The reason this KPI is chosen is that it is necessary for creating the LEMQ graph. This LEMQ graph can be used to find the minimum of the <u>total residual cost</u> per quantity. Residual cost is abbreviated to 'res cost'.

Furthermore, it is decided to include the <u>Δ res cost in €</u> per quantity in the range compared to the desired (original) quantity. So, if a customer originally wants to order 100 PCBs with a residual material cost of 250€, and a quantity of 97 PCBs only has 100€ residual cost, then the <u>Δ res cost in €</u> = 100 −

$250 = -150$. The reason for this KPI is that it is desired to get insight in how much money is potentially being saved when changing quantity. Logically, this KPI is zero if we do not change the ordered quantity.

At last, the <u>Δ res cost as %</u> per quantity in the range is introduced as KPI which the tool should calculate. This KPI calculates for each quantity in the range, how much percent the rest costs have in- or decreased compared to the original rest cost of the customer. If we stick to the same example as above with 100 and 97 PCBs, then we see that <u>Δ res cost as %</u> = $\frac{100-250}{250} * 100\% = -60\%$. This KPI is included because then we can quickly see what percentage of excess material cost we have saved. For each order the absolute <u>Δ res cost in €</u> is highly dependent on the order size. But working with percentages gives a more general view from which overall conclusions can be drawn more accurately.

The tool calculates for each quantity in the range what the values of the above determined KPIs are. It is still debatable whether these costs and other values are the real values once the order is processed eventually, because prices or MOQs/multis could change in the time between the request and the real order placing. Therefore, these KPIs can be considered predictors and hence, leading KPIs (Repa, 2019). However, in this research these possible changes are assumed to be zero, because no other accurate assumption can be made due to the randomness in this business, and therefore these KPIs can also be considered lagging.

Order-tracking KPIs

To track the performance of the implemented LEMQ model, from each order some KPIs need to be saved. These KPIs should be stored after the order is placed and processed. After having a discussion with the quality management employee at the company, it was decided that from *each* processed order we want to store the following KPIs:

- <u>Original quantity</u>, this is the quantity which the customer desired when he placed the order request.
- <u>Ordered quantity</u>, this is the quantity ordered after having discussed any improvements regarding the quantity. It could be the same as the original quantity.

These two KPIs are included because it shows whether the sales crew is indeed able to change the quantity of the customer. If the two parameters are identical for some orders, then apparently with those customers, the sales employees are not able to discuss cost-saving quantities, or the original quantity was already very close to the LEMQ.

- <u>Δ Res cost in €</u>, this KPI is included because it shows how much rest cost material has been saved and thus exactly how much money is saved on that order. This value is also calculated in the example tool.
- <u>Δ Res cost as %</u>, this KPI is stored per order such that in the long run the average savings of excess material cost per order as a percentage can be calculated (see the 'long-term KPIs' section below). Because percentages are more general than absolute values from the previous KPI. This value (<u>Δ Res cost as %</u> per order) can also be directly copied from the tool output.

Since these KPIs are saved and stored once an order is processed, these KPIs are measuring the result of that order, and therefore are lagging indicators (Repa, 2019).

Long-term KPIs

The previous list of key performance indicators aims to track each single order. On the long-term we also want to track the benefits of changing quantities. Therefore, *per quartile* the following two KPIs are calculated:

- Total res cost saved, this is the sum of the Δ res cost in € per order. It tells what the savings in euros are, regarding the excess material.
- Average Δ res cost as %, this is the average of the Δ res cost as % per order. It tells how much (in %) rest material cost is saved per order in that quartile. After a year, and hence four quartiles, it is possible to set a target for this KPI to motivate the sales crew to actively reduce the obsolete component costs. For example, -4%.

The last long-term KPI which is used to measure the performance of this research and tool, is the yearly depreciation of obsolete components according to the 'nine-month not used' rule (see chapter 2.3). Table 6.1 shows what the value of this KPI was in the last four years.

All long-term KPIs are considered lagging KPIs because they measure an output (Repa, 2019).

Table 6.1. *Value of yearly depreciated obsolete components according to the nine-month rule.*

Year	Value of depreciated obsolete components according to 9-month rule
2017	+ 28.282
2018	+ 30.624
2019	+ 7.914
2020	+ 24.367

Eventually the order tracking KPIs and the KPIs per quartile can be inserted in an Excel sheet overview. See Figure 6.1. In this example the KPIs are shown for three different orders from three different customers. So, if GE would have these three customers in quartile 1 of 2021 and they agreed on ordering the LEMQ, then they have saved a total of €541,72 on excess material costs with an average of 11,85% reduction of excess material cost *per* order.

Quartile	1			**Year**	2021			
Startdate	1-1-2021			**Enddate**	1-4-2021			
Ordernumber	**Client**	**Total order value**	**Original Q**	**Original rest cost in €**	**Ordered Q**	**Ordered rest cost in €**	**Δ residual cost in €**	**Δ residual cost as %**
EXAMPLE 1	Customer A	8538,08	130	1884,24	136	1720,14	-164,1	-8,71%
EXAMPLE 2	Customer B	13602	200	1583,1	183	1219,64	-363,46	-22,96%
EXAMPLE 3	Customer C	4045	80	365,11	90	350,95	-14,16	-3,88%
							Total Δ residual cost in €	**Avg. Δ residual cost as %**
							-541,72	-11,85%

Figure 6.1. *Example of an order tracking Excel sheet for Global Electronics.*

6.3. Conclusion

In this chapter the KPIs for the tool and for the performance tracking of the LEMQ model are introduced. We know what should be calculated and why it is relevant for the company. We have made a division between the key performance indicators anticipated for each specific order, and the KPIs used for the long-term. In the next chapter we will look at the implementation of the LEMQ-model together with these KPIs.

7. Implementation of the LEMQ-model

In the previous two chapters we have seen what model should be implemented in a tool, and we have defined what the tool should be able to calculate. In this chapter the tool is explained and shown. This tool description will answer sub-question five: *How to implement a tool with a feasible method to change the order process at Global Electronics B.V. such that the obsolete components will reduce?*

7.1. Objectives of the tool

Before we start with the tool explanation, the goals of the tool are briefly summarized below. These objectives are a result of the KPIs determined in the previous chapter and the mathematical LEMQ-model.
The tool should:

1. Calculate the excess material cost per batch size, and seek the minimum, so the Least Excess Material-cost Quantity (LEMQ).
2. calculate the Δ rest cost in € between the ordered quantity and the original desired quantity.
3. calculate the Δ rest cost as % between the ordered quantity and the original desired quantity.
4. contain a variable quantity range.
5. identify the component with the highest excess material cost.
   Because this component would be the most suitable to replace with an alternative because of the high excess cost. However, the alternative offering is out of scope of this study.

Keeping this list of objectives in mind, we can start with implementing the LEMQ-model in the example tool. How does it work? And what does it look like?

7.2. Tool description

In this section we will take an in-depth look at the created tool. In section 7.2.1. the inputs and assumptions are discussed and in section 7.2.2. the outputs are treated.

In Figure 7.1. an overview of the empty tool is shown to get an idea of the layout. The red rectangle will be covered in section 7.2.1. The yellow rectangles will be covered in section 7.2.2.

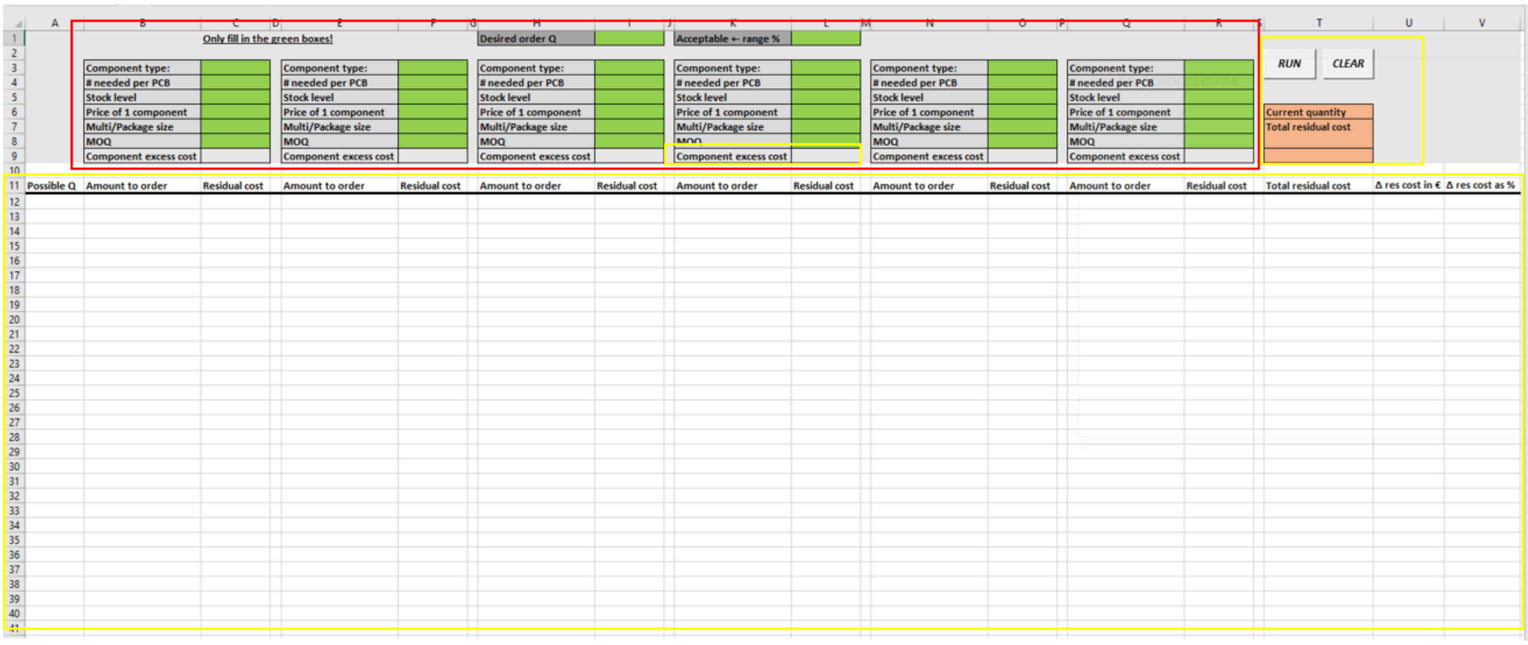

Figure 7.1. *The empty tool's layout with a red rectangle representing the inputs.*

7.2.1. Tool inputs

As mentioned before, we will treat the red rectangle from Figure 7.1 in this section, these are the input sections of the tool. This area covered by the red rectangle in Figure 7.1 can be seen in Figure 7.2a, together with another red rectangle which leads to Figure 7.2b. The tool inputs are determined by the variables in the LEMQ-model.

a)

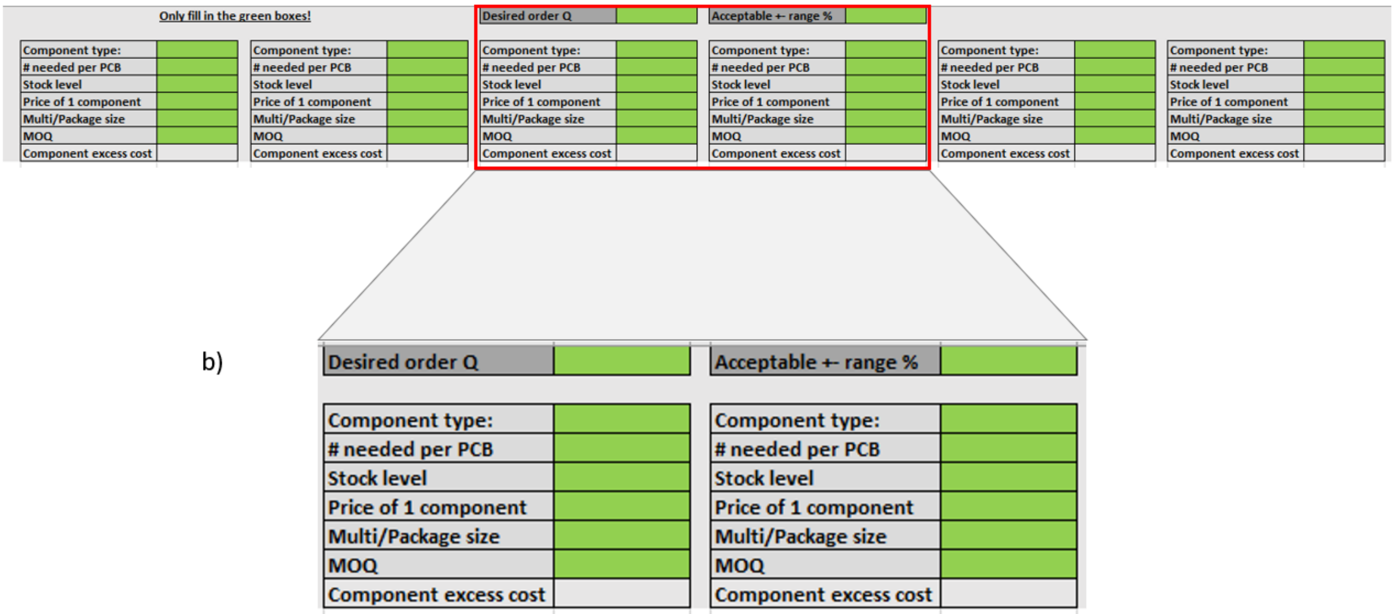

Figure 7.2. *Input section of the tool (a), with a zoom-in on a specific input section (b).*

When taking a closer look, there are six identical tables in Figure 7.2a. Two of those six are zoomed in on in Figure 7.2b together with two sections called 'Desired order Q' and 'Acceptable +- range %'. The 'Desired order Q' is the original quantity which the customer asked for in their order request. This is variable D_0 from the LEMQ-model. The acceptable range defines the variable range which is customer dependent. For example, if a customer originally orders 150 PCBs, and after a discussion he/she is allows GE to look for a (local) LEMQ within a range of 10%, then the tool will calculate in the range between 135 and 165 PCBs. This 150 and 10% need to be respectively, given as input in the top two green boxes.

Then we arrive at the two (out of six) identical table sections in Figure 7.2b. Each one of these six tables can be used to put in the characteristics of high-impact components. So, for a maximum of six high-impact components of a single customer order, this tool can calculate the LEMQ of that order. To check which components are considered high-impact components a flow chart has been made, also based on the findings in chapter 3. This flow chart can be found in Appendix D. The reason why we can give six components as input is because in consultation with the company, it is assumed that with six spots, 80% of the orders can be analysed accurately. There are orders with more than six high-impact components, but those occur very rarely and for this research it is impossible to create a tool which can analyse all components on a BOM. Also, it is a very time-consuming task to put in all characteristics of each and every component on this BOM.

So, assume that we have a customer which orders 150 PCBs, which allows for a 10% range, and we have identified only two (because the other components can be bought singular, for example) high-impact components on his BOM: IC A and Diode B. Both of these components are new to Global and therefore no stock of these is present in the warehouse. IC A must fit two pieces on a PCB, costs

€2,83/unit, can be bought in a multi of 20 and has an MOQ of 150.
Diode B has 11 pieces on a PCB, costs €1,23/unit, can be bought in multis of 200 and has an MOQ of 1000. Then we fill in Figure 7.2b as in Figure 7.3:

Desired order Q	150	Acceptable +- range %	10

Component type:	IC A	Component type:	Diode B
# needed per PCB	2	# needed per PCB	11
Stock level	0	Stock level	0
Price of 1 component	2,83	Price of 1 component	1,23
Multi/Package size	20	Multi/Package size	200
MOQ	150	MOQ	1000
Component excess cost		Component excess cost	

Figure 7.3. *Filled in Figure 7.2b according to the sketched example.*

From this example in Figure 7.3, the variables from the mathematical LEMQ-model (chapter 5) are as in the table below.

Table 7.1. *Variables of the LEMQ-model applied to the presented example.*

Variable	IC A	Diode B
M_i (components on 1 PCB)	2	11
J (degrees of multis)	1	1
$Multi_{ij}$	20	200
S_i (stock level)	0	0
MOQ_i	150	1000
C_{ij} (unit cost at multi degree j)	2,83	1,23
D_0 (Original requested quantity)	150	
X (Percentage determining A)	0,10	
A (Acceptable range)	[0,9×150;1,1×150] = [135; 165]	

In Figure 7.3 it can be seen that the bottom grey box still is empty. This box represents the component specific excess cost in the state that 150 PCBs are ordered. So, if there would be no change in quantity, then the value that would appear in that grey box is the excess material cost which will occur at that specific component. This box is filled with a value once the tool has run. In this example we only look at two high-impact components, but it is of course possible to let the tool run with a maximum of six.

7.2.2. Tool outputs

As mentioned before, in this chapter we will cover all yellow rectangles of Figure 7.1. Let us start with the smallest one. This one is shown in Figure 7.4 below. And now the boxes are not empty anymore because the tool has run with the sketched example from the previous section. So, these are outputs.

Desired order Q	150	Acceptable +- range %	10

Component type:	IC A	Component type:	Diode B
# needed per PCB	2	# needed per PCB	11
Stock level	0	Stock level	0
Price of 1 component	2,83	Price of 1 component	1,23
Multi/Package size	20	Multi/Package size	200
MOQ	150	MOQ	1000
Component excess cost	0	Component excess cost	184,5

Figure 7.4. *Output of example with the yellow rectangles representing the current excess cost per component.*

The yellow rectangles show what the value is of the excess material of the desired order quantity, so the original quantity requested by the customer. It can be seen that IC A does not have any excess material cost if the order quantity is 150 PCBs. That is because there are $2 \times 150 = 300$ IC A's necessary for this quantity. The MOQ of 150 is met because 300 ≥ 150. Furthermore, $300 \div 20\ (multi) = 15$ and since this is an integer number, there is no excess material.
For Diode B there are $11 \times 150 = 1650$ parts needed. The MOQ of 1000 is therefore met, but $1650 \div 200\ (multi) = 8{,}25$ and since this is not an integer number, there is excess material. 1800 Is the first multiple of 200 larger than 1650. So, the rest cost of this component at the quantity of 150 PCBs is equal to: $(1800 - 1650) * €1{,}23 = €184{,}5$.

Now, we move on to the top right yellow rectangle of Figure 7.1. This part is zoomed-in on in Figure 7.5.

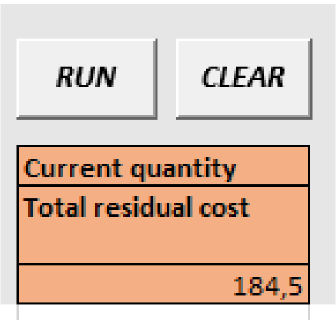

Figure 7.5. *Buttons for activating the tool and the orange boxes containing the current quantity output.*

In the figure above, see two buttons. One 'RUN' button and one 'CLEAR' button. The first button activates the tool, so it calls the programmed macro to calculate all outputs. This button has to be ticked once all inputs are given (see section 7.2.2). The 'CLEAR' button clears all calculated output boxes and prepares the tool for another run when entering different inputs.

The orange boxes show the output of the current quantity. So, the total residual material costs for 150 PCBs with IC A and Diode B as inputs, are $€184{,}5 + €0 = €184{,}5$.

Once we have clicked the button 'RUN' and then entire tool looks like Figure 7.6 below.

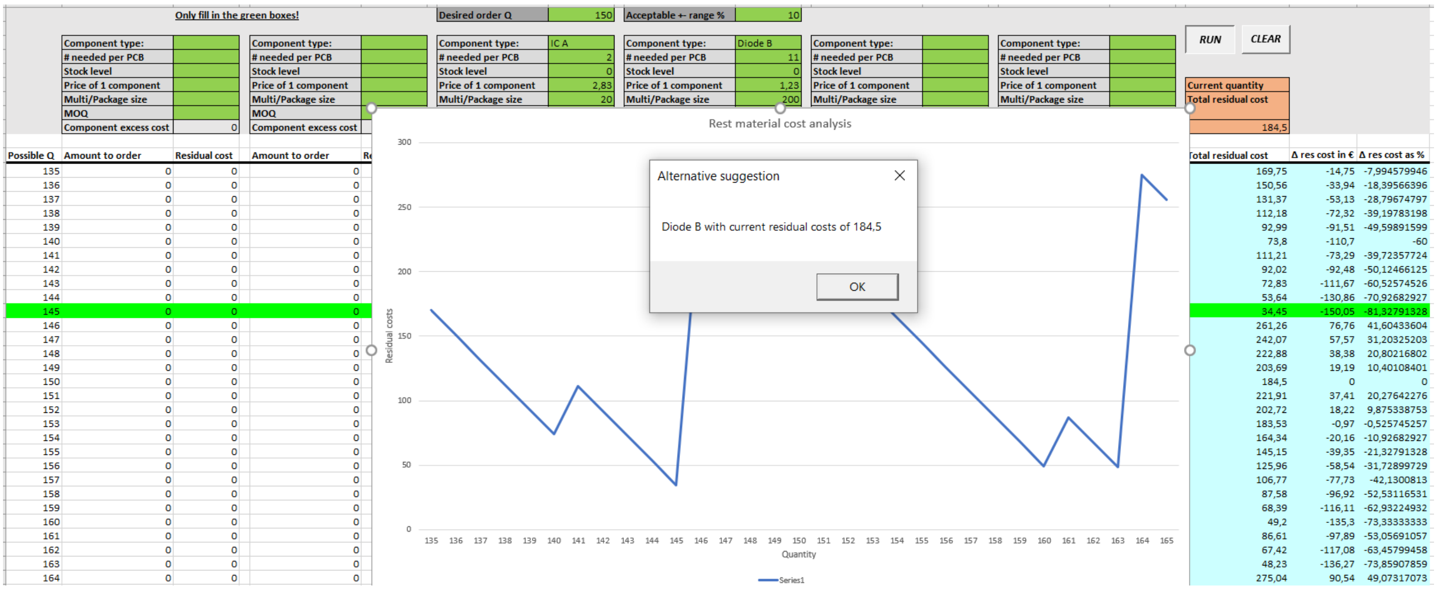

Figure 7.6. Overview of the tool after it has just run.

The green input tables can be seen, the individual excess component costs are visible and the orange box we have just discussed is visible. Now, let us move on to the biggest yellow rectangle from Figure 7.1.

The first striking thing from the outputs in Figure 7.6 is the message box. It is called 'alternative suggestion' and identifies the single component with the highest current excess material costs. If a customer is not willing to change the order quantity, there might be a chance that that customer accepts a component swap to still reduce the excess material cost. So, the tool identifies which component has the highest cost and is therefore the most suitable to replace with an alternative.

The graph called 'Rest material cost analysis' is the LEMQ-graph and shown below in Figure 7.7. It plots the total residual costs against the quantity in the acceptable range.

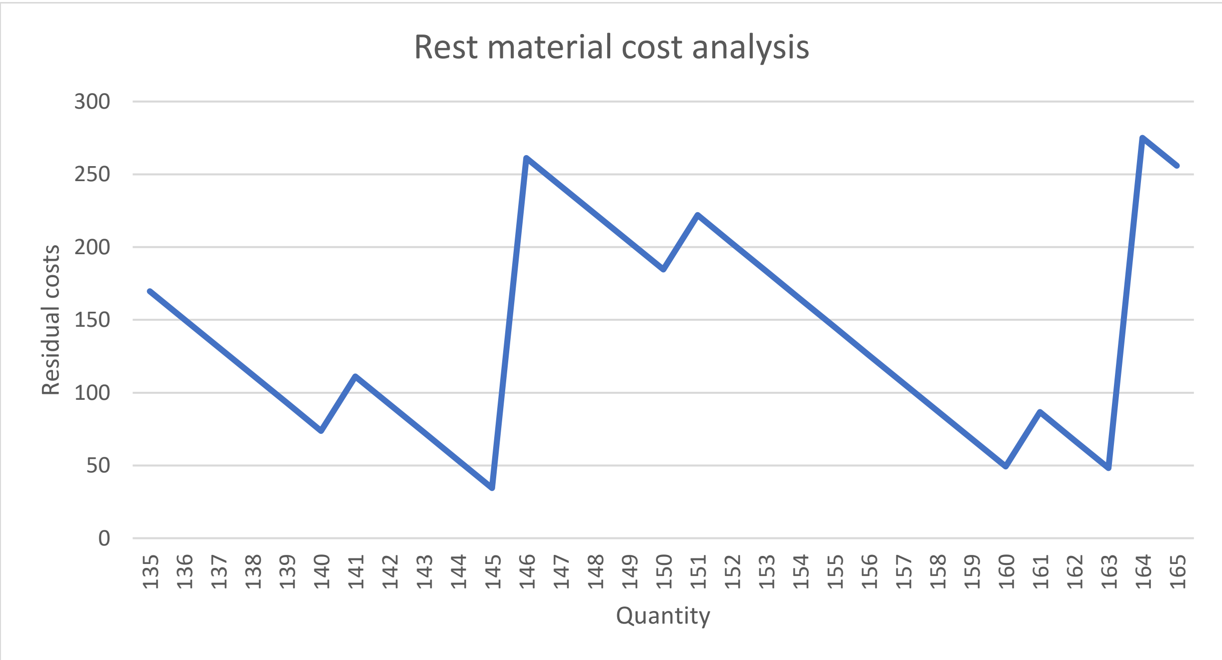

Figure 7.7. LEMQ-graph of IC A and Diode B plotting the total residual costs vs the quantity.

From this graph we can see that 145 PCBs is the LEMQ, since it has the lowest residual costs. This graph is based on the data shown in the sheet below. Where for all quantities in the acceptable range, the residual costs per component are calculated and then summed in the last blue column 'total residual cost'. Four out of the six component show only zero values, because in our example we used only two components as input. The green row represents the LEMQ since the total residual costs are the lowest, at €34,45. We can also see per component what quantity results in which residual costs, and thus how the total residual cost column is constituted.

Possible Q	Amount to order	Residual cost	Amount to order	Residual cost	Amount to order	Residual cost	Amount to order	Residual cost	Amount to order	Residual cost	Amount to order	Residual cost	Total residual cost
135	0	0	0	0	280	28,3	1600	141,45	0	0	0	0	169,75
136	0	0	0	0	280	22,64	1600	127,92	0	0	0	0	150,56
137	0	0	0	0	280	16,98	1600	114,39	0	0	0	0	131,37
138	0	0	0	0	280	11,32	1600	100,86	0	0	0	0	112,18
139	0	0	0	0	280	5,66	1600	87,33	0	0	0	0	92,99
140	0	0	0	0	280	0	1600	73,8	0	0	0	0	73,8
141	0	0	0	0	300	50,94	1600	60,27	0	0	0	0	111,21
142	0	0	0	0	300	45,28	1600	46,74	0	0	0	0	92,02
143	0	0	0	0	300	39,62	1600	33,21	0	0	0	0	72,83
144	0	0	0	0	300	33,96	1600	19,68	0	0	0	0	53,64
145	0	0	0	0	300	28,3	1600	6,15	0	0	0	0	34,45
146	0	0	0	0	300	22,64	1800	238,62	0	0	0	0	261,26
147	0	0	0	0	300	16,98	1800	225,09	0	0	0	0	242,07
148	0	0	0	0	300	11,32	1800	211,56	0	0	0	0	222,88
149	0	0	0	0	300	5,66	1800	198,03	0	0	0	0	203,69
150	0	0	0	0	300	0	1800	184,5	0	0	0	0	184,5
151	0	0	0	0	320	50,94	1800	170,97	0	0	0	0	221,91
152	0	0	0	0	320	45,28	1800	157,44	0	0	0	0	202,72
153	0	0	0	0	320	39,62	1800	143,91	0	0	0	0	183,53
154	0	0	0	0	320	33,96	1800	130,38	0	0	0	0	164,34
155	0	0	0	0	320	28,3	1800	116,85	0	0	0	0	145,15
156	0	0	0	0	320	22,64	1800	103,32	0	0	0	0	125,96
157	0	0	0	0	320	16,98	1800	89,79	0	0	0	0	106,77
158	0	0	0	0	320	11,32	1800	76,26	0	0	0	0	87,58
159	0	0	0	0	320	5,66	1800	62,73	0	0	0	0	68,39
160	0	0	0	0	320	0	1800	49,2	0	0	0	0	49,2
161	0	0	0	0	340	50,94	1800	35,67	0	0	0	0	86,61
162	0	0	0	0	340	45,28	1800	22,14	0	0	0	0	67,42
163	0	0	0	0	340	39,62	1800	8,61	0	0	0	0	48,23
164	0	0	0	0	340	33,96	2000	241,08	0	0	0	0	275,04
165	0	0	0	0	340	28,3	2000	227,55	0	0	0	0	255,85

Figure 7.8. *Data from IC A and Diode B with the total residual costs per quantity in the blue column and the LEMQ shown in the green row.*

The only columns from Figure 7.6 which we have not discussed yet, are the two most right blue columns. These columns are shown in Figure 7.9 together with the quantity column (most-left column in Figure 7.8) and the total residual cost column of the tool.

Current quantity
Total residual cost
184,5

Possible Q	Total residual cost	Δ res cost in €	Δ res cost as %
135	169,75	-14,75	-7,994579946
136	150,56	-33,94	-18,39566396
137	131,37	-53,13	-28,79674797
138	112,18	-72,32	-39,19783198
139	92,99	-91,51	-49,59891599
140	73,8	-110,7	-60
141	111,21	-73,29	-39,72357724
142	92,02	-92,48	-50,12466125
143	72,83	-111,67	-60,52574526
144	53,64	-130,86	-70,92682927
145	34,45	-150,05	-81,32791328
146	261,26	76,76	41,60433604
147	242,07	57,57	31,20325203
148	222,88	38,38	20,80216802
149	203,69	19,19	10,40108401
150	184,5	0	0
151	221,91	37,41	20,27642276
152	202,72	18,22	9,875338753
153	183,53	-0,97	-0,525745257
154	164,34	-20,16	-10,92682927
155	145,15	-39,35	-21,32791328
156	125,96	-58,54	-31,72899729
157	106,77	-77,73	-42,1300813
158	87,58	-96,92	-52,53116531
159	68,39	-116,11	-62,93224932
160	49,2	-135,3	-73,33333333
161	86,61	-97,89	-53,05691057
162	67,42	-117,08	-63,45799458
163	48,23	-136,27	-73,85907859
164	275,04	90,54	49,07317073
165	255,85	71,35	38,67208672

Figure 7.9. *Quantity with the blue columns of the tool containing the KPIs.*

The blue columns in Figure 7.9 represent the KPIs defined in chapter 6.2. When we look at the column 'Δ res cost in €' we find the absolute difference between the total residual cost of the quantity of that row and the current/original order quantity. For example, at q = 145, we have $\Delta \text{ res cost in €} = €34{,}45 - €184{,}5 = -€150{,}05$. This corresponds to a decrease of 81,33% of the rest cost compared to q = 150 (see the most right blue column) because: $\frac{-150{,}05}{184{,}5} \times 100\% = -81{,}328\%$.

7.3. Order simulations

Now it is time to check what the value could be of using this tool optimally. This will be done by putting real orders in the tool and check what money could have been saved if the quantity is changed to the LEMQ.

To execute this, six recent order requests of in total four different customers were analysed. These were all the order requests in one single week. For each order, a maximum of six components were determined following the flowchart in Appendix D. So, in that process the multis, MOQs and prices were determined and then based on the decision points in the flowchart six components at most were chosen as inputs for that order. Please consult Appendix E to see the exact inputs used. An acceptable range of 10% was used in these simulations.

The results of the simulation of these six order requests are shown in Figure 7.10 below. The KPIs from chapter 6 are calculated as results for these simulations.

Client	Total order value	Original Q	LEMQ	Δ residual cost in €	Δ residual cost as %	No Q change? suggest alternative for
x = 10%						
Customer A	25475	500	500	0	0	ID73633-DCQTI
Customer B.1	38710	1000	980	-675,98	-60,73	ID71Q21BAABMH
Customer B.2	24800	400	375	-545,54	-37,40	ID3172-EIUZRS
Customer C	2244	60	66	-29,57	-0,90	ESP32-WROOM-32D
Customer C	15000	510	500	-324,71	-18,99	SOT-89-MB3_L
Customer D	4300	100	110	-174,78	-12,93	ID5215----LIF
			Total Δ res cost in €	-1750,58		
			Avg Δ res cost in €	-291,76		
			Avg Δ res cost as %	-21,83		

Figure 7.10. *Results of the simulation of the requested orders in a week.*

For confidentiality reasons the customer names are made anonymous. In the second column the total order value is roughly estimated, this is to put the deltas in perspective. In the last column the highest-impact component can be found. This is the component with the most excess material cost when not changing the quantity.

Customer A was, according to the tool, already ordering at the LEMQ because the original Q and the ordered Q are the same. Furthermore, it can be seen that customer B placed two requests with 400 and 1000 PCBs respectively but those were requests for different PCBs. For both requests the LEMQ is below the original quantity and leads to a significant residual cost reduction of €675,98 and €545,54 respectively. Customer C also placed two different quantity requests but this time of the same PCB. The first request of Customer C should increase the quantity from 60 to 66 to get a very small reduction of residual cost. This is a decrease €29,57 which is only a reduction of 0,9% of the total residual cost. Note that this is an order request below 100 PCBs and therefore it is not feasible to order on full reels. That is why this reduction in percentages is relatively low.

The second order request of Customer C leads to a bigger decrease of total residual cost, namely a decrease of almost 19%, if the order quantity is changed from 510 to 500. For customer D it would be beneficial to order 110 PCBs rather than 100, because then a reduction of €174,78 which is 12,93% of the residual cost would be achieved.

Overall, in total for these six orders a decrease of €1750,58 in excess material and hence, potential obsolete components, is achieved when changing the order quantity to the LEMQ. This implies an average of -€291,83 per order request in that week, corresponding to an average decrease of 21,83% is achieved for these six order requests. It is important to note that these are order requests and not placed orders. It could be that some of those requests will not be executed as an order eventually. So, this €1750,58 decrease in excess material is not achieved that week if some requests have not become final orders. The in- or decrease of the quantity because of the LEMQ, could imply an increase in excess cost for components which were not used as inputs for the simulations. But those cases have relatively low impact, otherwise they would have been used as inputs.

With these simulations we have proven that the use of the LEMQ-model indeed results in lower excess material cost per order, such an excess in the business of GE is likely to result in obsolete components.

Stock level impact

In all simulations for each component the stock level was set to zero. The reason for this is that GE has a make-to-order policy and hence, a zero-stock level can be assumed. However, for some orders still some excess components remain in the inventory, even if the LEMQ is anticipated. Recall: the LEMQ-model minimizes the excess component costs; zero excess cost are not guaranteed. So, some components will probably be (partially) in stock in GE's inventory. Naturally, the Least Excess Material-cost Quantity (LEMQ) depends on the stock level of certain components, see the model in chapter 5. So, the aspect of components in stock needs to be evaluated.

That is why the impact of the stock levels on the LEMQ is investigated. One order of customer B is used and experiments with the stock levels are performed. This is done in three ways:

1. The stock level of the component with the highest <u>current</u> residual cost is changed. This change is from 0% to 95% of the needed components to fulfil the order. So, if 800 components of resistor A are needed and 45% is on stock, then 360 resistors A are on stock. For steps of 5% the LEMQ is calculated and plotted as the grey line in Figure 7.11.
2. Change the stock level of all components except the one with the highest current residual costs. So, this exception is not in stock. The other stock levels are changed from 0% to 95% of the needed components with steps of 5%. This one is plotted as the blue line in Figure 7.11.
3. Change the stock level of all components in the tool simultaneously. Again, varying the stock level of the components from 0 to 95% of the amount of needed to fulfil the order, with steps of 5%. This is plotted as the orange line in Figure 7.11 below.

Figure 7.11. *Dependence of LEMQ on the stock level of components at GE.*

From the figure above, a repetitive pattern can be seen with small variations between the grey and orange line. A change in stock of +5% for all components or a single component, could lead to big changes of the LEMQ. But the LEMQ does not change that significantly if the component with the highest current residual costs is not on stock (the blue line). This implies that the LEMQ is heavily depending on the stock level as well as on the highest-impact component. Therefore, it is important to use correct stock levels in the model, otherwise inaccurate LEMQs could be recommended.

7.4. Tool Evaluation

Now we understand the example tool with the implemented LEMQ-model, let us check if the objectives from section 7.1 are met. First of all, we have seen that there is a variable quantity range, since we can enter a percentage to check the quantities around the desired order quantity. Furthermore, we have seen that it shows a LEMQ-graph of the order (Figure 7.7) and in Figure 7.9 the desired KPIs are calculated. At last, a message box pops up which identifies the component which is most suitable to replace for an alternative if the customer does not accept a change in the quantity.

7.4.1. Limitations

Even though the objectives from 7.1 are met, this has its limitations as mentioned before. First of all, the tool can only analyse six components at maximum. This is assumed to be sufficient for 80% of the orders. This is considered a limitation even though the tool analyses the highest-impact components identified in chapter 3. Secondly, the tool has not exactly implemented the LEMQ-model presented in chapter 5. In this tool there is only one degree of multis possible, so $j = 1$. This ensures an easier process of using this tool but results in a less accurate result. At last, this tool is limited in the sense that it could be a time-consuming task to gather the needed characteristics manually.

7.4.2. Tool usage

Still the question remains about how to implement this tool in the daily quotation routine of GE?

In the white paper of Keijzer (2019), it is argued that 'good' quotation software should be able to perform the calculations of excess material cost for different quantities. QuoteArchitect is such software and this one is already used at GE. The calculation of the LEMQ-graph is only an extra module of this software which GE does not have yet. But it could be purchased and implemented in the software which they already are familiar with. This LEMQ-graph of QA is also more accurate because it does not have the limitation of the Excel tool.

In the simulations above, we have seen that on average a 21,83% of excess material could be saved. Although this approximates the reality, it still shows that the excess components are indeed decreasing which eventually should lead to lower obsolescence costs per year. So, now GE knows that a significant percentage of excess material, and hence, a significant amount of money could be saved, the implementation of the mathematical LEMQ-model is rather easy because such a tool is available in the new module of QuoteArchitect.

7.5. Conclusion

In this chapter we have build a tool which achieves all objectives, from KPI calculations to the generated LEMQ-graph. This tool was then used to understand how the LEMQ-model works in practice and to run approximated simulations of real orders. We have simulated for six order requests in a week, how much money could have been saved on residual material. This resulted in an average decrease of €291,76 or 21,83% of excess material for each of the six order requests. So, we have proven that (the implemented) LEMQ-model indeed reduces excess material for Global Electronics. Important is to include the correct stock level of components, since the LEMQ depends on that heavily.

Furthermore, we have validated that this method is indeed feasible to implement at GE because of the capabilities which QuoteArchitect has. A new module of QuoteArchitect is capable of calculating the LEMQ-graph, which can be discussed with the customer before actually placing the order. QA does not have the limitations of the example tool presented in this chapter, because no manual gathering of data is required, all multis are considered and the entire BOM of customers will be analysed, rather than six high-impact components. Though, the assumption that customers are willing to accept the ordered quantity to be in a certain range or accept alternative components, needs to be validated. This will be done in the next chapter.

8. Customer validation

In this chapter we will deal with the last sub-question '*How to incorporate GE' customers to ensure the improved order process will work?*'. So far, we have assumed that customers will accept a small change in their ordered quantity, in this chapter we will validate that assumption by sending out a survey. Furthermore, we will elaborate on the benefits this improved order process has, in order to convince the customer to order differently.

8.1. The survey

A survey using Qualtrics was created, and it contained questions about the acceptable range regarding the order quantity. The aim of this survey was to find out if there indeed is some room for changes in the ordered quantity. Because the strategy to discuss a more optimal quantity only saves obsolete components if the customers are willing to accept such quantity change. The last question in the survey was about offering alternative components, whether the customer is open for alternatives if this saves excess material cost or offers other benefits.

This survey was sent to five customers who all match the three criteria in the table below.

Table 8.1. *Criteria (and reason) to select the customers who will receive the survey.*

Criteria	Reason
Not a proto customer	Proto customers order very few (<5) PCBs, so quantity shift is not feasible.
Not either of two customers with own racks in GE's warehouse	These customers have agreed to pay for any excess material if that even occurs with their reliable and regular orders. So, for those two it is not useful to change order quantity because no obsolescence for GE occurs there.
Customer should order somewhat regularly, so recurring customer	This scope was set in section 1.3.1, GE wants to offer their recurring customers this benefit in the first place, rather than customers who order infrequently.

One of the customers who has received the survey was also used for the simulation of orders in section 6.4. This customer indicated in the survey that he was open for a change in the quantity with an acceptable range which could be determined for each order specifically. He indicated that there was no boundary for him in terms of a percentage. Still, it seems reasonable to not let this percentage be very high, because high percentages would affect the quantity enormously. Especially considering that this customer is on average ordering between 100 and 500 PCBs per order. This customer is open to alternative components, depending on the component.

Another customer responded to the survey and indicated that a change of at most 5% was acceptable. This customer ordered on average less than 100 PCBs so, in practice this implies that the quantity is almost fixed but can deviate with less than five PCBs. An important comment that this customer made was that a possible deviation of at most 5%, depended on the cost savings for him. Alternative components are impossible for this specific company since the designs are mostly made by their own customers using a special database.

A third customer wrote that their requested quantities were fixed. The reason was that this customer has a make-to-order policy which means that their quantities are also depending on their own customers. But it is important to note that this customer is a small one, with a maximum of 100 PCBs per order, just like the second customer above. This third customer was open to alternative components if that would be discussed carefully.

The last and fourth respondent of the survey was also open for a quantity change. This customer orders between 100 and 500 PCBs per order and stated to accept a range of 5%. However, no use of alternative components was allowed in his orders.

The main outcome of the survey is that most customers indeed indicated that they are willing to change quantities and that two customers also mentioned that they would probably accept alternative components, although this still depends on the component itself. For clarity, Table 8.2 gives an overview of the survey results.

Table 8.2. *Overview of the survey results.*

Topic	***Participant:***	**1**	**2**	**3**	**4**	**5**
Open to changing order quantity		Yes	Yes	No	Yes	-
Acceptable range		unlimited	5%	-	5%	-
Open to alternative components		Yes	No	Yes	No	-

8.2. Implementing survey results

From the survey results it can be deduced that an acceptability range of 5% seems reasonable, however it is possible that some customers accept a larger range or no range at all. In the simulations of chapter seven a range of 10% was anticipated. To estimate the impact of this range the simulations are executed again with the exact same inputs (See Appendix E), but now the acceptability range is changed to 5%. The overall results of this 10% and 5% range, together with the average of the two are shown in the figure below.

Total Δ res cost in €	**-1750,58**
Avg Δ res cost in €	**-291,76**
Avg Δ res cost as %	**-21,83**

a) 10%

Total Δ res cost in €	**-1225,01**
Avg Δ res cost in €	**-204,17**
Avg Δ res cost as %	**-15,84**

b) 5%

Total Δ res cost in €	**-1487,79**
Avg Δ res cost in €	**-247,97**
Avg Δ res cost as %	**-18,83**

c) Average

Figure 8.1. *Overall results of an acceptability range of 10% (a), 5% (b) and the average of both (c).*

From Figure 8.1 it can be deduced that a larger acceptable range results in a bigger reduction of excess material cost. This is because the LEMQ is searched for in a larger range and hence, the possibility of an even better LEMQ is larger. From the survey we have learned that some customers desire a 5% range, but one customer did state that this range was variable and could be higher. This is for example 10%, see Figure 8.1a. So, sometimes a customer wants a 5% and sometimes a 10% range. This results in Figure 8.1c which is the average of both. This implies an average residual material cost reduction of 18,83%.

8.3. Benefit evaluation

The improved order process which leads to a decrease of excess components, has potential benefits in different aspects. In this section we elaborate on those and evaluate if those benefits are of value or importance Global Electronics' customers as well.

Cost-savings

The reduction of excess inventory has the economic advantage of having less costs. This contains multiple aspects.

1. First and foremost, a reduction in excess material ensures that GE has less excess material cost. GE now pays for less useless components which are fully written-off after nine-months (see chapter 2).
2. Inventory holding cost. The stock which is not needed but still stored, results in higher holding cost. Not only the space, but also the resources to hold it must be paid for (Walts, 2020).
3. Reduced labour cost. A decrease in excess material will reduce the time that it takes to discard the excess material and therefore labour cost (Walts, 2020).

These three aspects will save costs for GE, but indirectly this benefit can be passed on to the customers. We have seen in the previous chapter that on average, the excess material cost is reduced with €247,97 per order (for the order requests in the specific simulated week). After consultation with the company, it was decided that this €245 is significant enough to pass the benefit on to the customer as well. Since GE benefits in three aspects, it is decided that the *entire* reduction of excess material cost of a specific, is passed on to the customer. Note, this is not a discount of €245 for the customers if they want to change quantities. It is a discount of whatever value is saved when ordering close to or at the LEMQ. This €245 is just the value to show that on average per order a significant amount of money of excess material could be saved. If a quantity change results in €400 decrease of excess material, then the customer will receive a discount of €400 on their final order.

This decision is made based on the reasoning that GE already saves money on two other aspects, namely reduced inventory holding costs and labour costs. Furthermore, GE aims to satisfy their customers and the discount may result in returning customers. This leads to larger and/or more orders which contributes to the ultimate goal of company growth (see chapter 1).

Environmental sustainability

The reduction of excess material can also be reviewed from an environmental sustainability perspective. Less material will be discarded since the excess material will be minimized. It is possible that as a whole, more material will be ordered if the PCB quantity increased after the LEMQ-model is applied. But the material that is ordered is less likely to become waste. So, a bigger percentage of the total material ordered is used and adds value to customers and end-users rather than being thrown away. The electronics manufacturing sector is an energy-intensive industry with a significant emission of greenhouse gases (Chang et al., 2021). So, in this already polluting sector, it is important to minimize the pollution or waste as much as possible. Customers might value this environmental advantage of reducing the excess material and hence, obsolete components too.

8.4. Conclusion

In this chapter the assumptions made in the LEMQ-model so far were validated by conducting a survey. The survey had four respondents and three from those mentioned a certain acceptable range. Only one customer indicated that the requested quantities were fixed. So, it is validated that some customers are willing to accept a change in quantity if that results in certain advantages. The range of 10% was reduced to 5% due to the survey results and this resulted in a small change in the effectiveness of the LEMQ model, because a smaller range had a somewhat smaller residual cost reduction.

Some respondents would also accept standardized components but that should be discussed extensively because not each component could be replaced according to them. Furthermore, the advantages were evaluated, and it was found that GE would benefit in three economic ways. This justifies offering the customers all saved money on excess material as a discount, because GE benefits already from an advantage in labour cost and inventory holding cost. This discount is on average €247,97 per order (see Figure 8.1c) and is considered as quite a significant discount.

9. Conclusion and recommendations

In this chapter we will conclude on this entire research. First, in section 9.1 the general conclusions will be drawn. Then in 9.2 the recommendations are listed and in section 9.3 interesting topics for further research are discussed.

9.1. Conclusion

This thesis is focussed on the core problem observed at Global Electronics. This core problem was that there was no proactive feedback to customers about the ordered quantity or material, which eventually led to the action problem of too high obsolete components. This obsolescence occurred because of the challenging position that GE is in; with strict suppliers, very unique components and a make-to-order strategy. The main research question was hence:

How to improve the order process at Global Electronics B.V. to reduce the yearly excessive material value?

First of all, the current situation was analysed in which we identified the recent yearly obsolescence costs and where we looked at the inventory and order characteristics. Then we dove into the component details where next to the unique and common components, six main categories were identified which have a high impact on the obsolescence costs. From the literature study in chapter 4 we learned about general methods to reduce obsolescence. Unfortunately, those methods were very hard to apply to the unique situation of Global Electronics. However, the inspiration of an EOQ order process had potential but needed some changes.

In the field of electronics manufacturing, the economic order quantity is defined as the quantity with the least excess material cost, since the impact of excess components is huge in this business (Keijzer, 2019). Therefore, we introduced a LEMQ-model which is a mathematical model which seeks the Least Excess Material-cost Quantity (LEMQ). Then we decided which KPIs would be relevant to track the obsolescence and performance of the correct implementation of this LEMQ-model.

A simplified example tool implemented this LEMQ-model and then simulations were executed. These simulations were performed to show that this LEMQ-model indeed decreased excess material and hence, the risk of (unique) components becoming obsolete is reduced as well. In the six simulations an average decrease of excess material of 21,83% was achieved when changing the ordered quantity to the LEMQ. However, these simulations were executed with an acceptable range of 10%. The assumption that the requested quantities of customers are not fixed was validated in chapter 8 where three out of four respondents of a survey indicated that a quantity change was okay. However, 10% was too large for some customers, so the same simulations were executed with a 5% range. Since one survey respondent indicated that the requested quantities are fixed, it cannot be assumed that *all* customers will accept a change in quantity. But if a customer accepts a change in general, on average €247,97 on excess material can be saved. This corresponds to an excess material cost reduction of 18,83%, which is the average of the simulations with 5% and 10% (Figure 8.1c).

Furthermore, the benefits for the customer have been evaluated and especially the economic advantage is considered convincing, since accepting a quantity change could imply a significant discount for them.

Overall, we have proposed a mathematical model which minimizes the excess material cost per order. This LEMQ-model can easily be implemented at Global Electronics B.V. because an extension of the already used software QuoteArchitect could calculate the LEMQ-graph. In this study we have also identified how much money could be saved if GE would discuss the outcomes of this software with the customers, because we validated that some customers do accept quantity changes. So, the obsolete components at Global Electronics can significantly be reduced when transparently discussing the outputs of the LEMQ-graph with customers during the order process. Also, alternative components can be offered in order to reduce obsolescence. The KPIs presented in this study are to be implemented in the quality management system and then the long-term KPIs will show if the small extra efforts up front, will indeed lead to this obsolete component reduction.

9.2. Recommendations

1. **GE should buy the extension of QA to discuss the LEMQ with customers.**

Due to the stock levels at GE, supplier MOQs or multis and the 2% waste at grit components, the requested quantity of the customers is not always (near) the Least Excess Material-cost Quantity of that order. Therefore, when using the graph from QuoteArchitect, the sales crew should transparently explain that the LEMQ is not being met, and that a change of quantity (within an acceptable range of 5% or 10%, see survey results) will result in economic advantages for both (discount for the customer and less labour and inventory costs for GE). This can potentially reduce the excessive material per order with an average of 18,83%.

Furthermore, the impact of stock levels is significant on the LEMQ of an order. So, the current and correct stock levels should be used in QA before generating the graph otherwise the inaccurate LEMQ will not result in a decrease of excess material. For customers from whom it is certain that they will place recurring orders in a year, this LEMQ does not need to be discussed, because the excess components placed in stock will be used anyway. Also, the LEMQ-graph should only be consulted for customers with a significant number of PCBs (100+) because then full-reel ordering is feasible.

2. **Offer alternative components for problematic components in an order request.**

During this study it was identified that problems occur due to the millions of different components requested by customers. It is recommended to seek a way to work with standardized components which are on stock or much cheaper. On the one hand, offering (standard) components from stock results in decreasing the inventory value at GE. On the other hand, this prevents the inventory to increase with unique or very expensive components. So, this measure will have two-sided benefits for the inventory. Literature also recommended the use of alternatives to reduce obsolescence cost.

If customers are not willing to accept a change in the quantity, then it is recommended to discuss with the customer about replacing the most problematic component with the most residual cost by an alternative (from stock). Because the survey taught us that some customers are open to alternatives if that is communicated well. This alternative component suggestion is also possible if GE manages to be more involved in the PCB design process of the customers. Because then the cost of changing the design is lower then after the order request has been placed (Kobeda, Isaacs, & Pymento, 2016).

3. Implement KPIs to track the performance regarding obsolescence.

Global Electronics should implement KPIs to ensure that the effects of the improved order process are monitored. The KPIs are shown in Table 9.1.

Table 9.1. *KPIs to be implemented at GE.*

KPI	Time dimension
Original Q	Per order
Ordered Q	Per order
Δ Res cost in €	Per order
Δ Res cost as %	Per order
Total Δ Res cost in €	Per quartile
Average Δ Res cost as %	Per quartile

For each order, the KPIs show if an agreement is made on a different quantity and how much money on residual components has been saved. The last two KPIs are used to track the long-term performance. These KPIs should be calculated per quartile and this will lead to concrete results about the effects of the improved order process and whether set goals are achieved. In the end it is important to monitor if the yearly obsolescence cost is decreasing by using these KPIs.

4. Make stricter agreements with customers about excess material and contact the customers.

The fourth recommendation involves the issue we identified in chapter 2. In the quotes the customers agree to buy off any excess material if that is left, but we found out that in reality this is not happening, because the customers are not contacted afterwards. So, GE should call the customers after, for example, one month to ask what he wants with his excess material. Will he place a repeat order or is he going to buy the excess components? This call is an extra contact moment with the customer to maintain a good relationship and to reduce obsolete inventory for GE.

9.3. Further research

Apart from the conclusion and recommendations above, some interesting topics for further research at Global Electronics B.V. are listed. It could be useful to perform a study regarding the following topics:

- Standardize components and which order policy to anticipate for standardized parts.
- Cost and benefits of collaborative design of the PCB.
- Extension of the LEMQ-model with machine set-up cost if no full reels are used.
- Effects of smaller lot sizes on the production line.

References

Baker, A. (2013). Configurable Obsolescence Mitigation Methodologies. *Procedia CIRP*, 352-356.

Chopra, S., & Meindl, P. (2014). *Supply chain management.* London: Pearson .

Cooper, D. R., & Schindler, P. S. (2014). *Business research methods.* New York: McGraw-Hill Education.

Ghadge, A., Bag, S., Goswami, M., & Tiwari, M. K. (2020). Mitigating demand risk of durable goods in online retailing. *International journal of retail and distribution management*, 165-186.

Heerkens, H., & van Winden, A. (2017). *Solving managerial problems systematically.* Groningen, The Netherlands: Noordhoff Uitgevers.

Keijzer, J. (2019). *The economic order quantity in electronics contract manufacturing.* Adeon software house.

Kobeda, E., Isaacs, P., & Pymento, L. (2016). Critical success factors for electronic manufacturing services. *2016 Pan Pacific Microelectronics Symposium.* Big Island: IEEE.

Nnamdi, O. (2018). Strategies for managing excess and dead inventories: A case study of spare parts inventories in the elevator equipment industry. *Operations and supply chain management*, 128-139.

Repa, V. (2019). Deriving Key Performance Indicators from Business Process Model. *18th International Conference on Perspectives in Business Informatics Research* (pp. 148-162). Katowice: University of Economics Prague.

Sanchez-Vega, M. D., Caballero-Morales, S. O., Sanchez-Partida, D., & Martinez-Flores, j. L. (2018). Risk-based Strategic Inventory Supply Model for New Products. In *Best practices in manufacturing processes* (pp. 75-95). Springer, Cham.

Siemens. (2018). Smart Manufacturing For electronics. Siemens.

Strategy management group, T. (n.d.). Retrieved from kpi.org/KPI-Basics.

Teunter, R. H., & Klein Haneveld, W. (2002). Inventory control of service parts in the final phase. *European journal of operational research*, 497-511.

Tuovila, A. (2021). *Inventory carrying cost definition.*

Walts, A. (2020). *How inventory reduction actually helps you make more money.* https://www.skuvault.com/blog/how-inventory-reduction-actually-helps-you-make-more-money/: SKUVault.

Zheng, L., Terpenny, J., & Sandborn, p. (2015). Design refresh planning models for managing obsolescence. *IIE Transactions*, 1407-1423.

Appendices

A. List of components at GE

- PCB (bare board)
- Mounting material
- Capacitator
- Wire
- Fuse
- Software component
- Tools
- ICs
- Connector
- Relays
- Inductor
- Machine
- Optocoupler
- Case
- Resistor
- Switch
- Transformator
- Battery
- Diode
- Universal part, for variety of applications.
- Crystal / Transistor
- Others (usually mechanical parts)
- Label

B. Semi-structured interviews

Order characteristics (Procurement employee, 28-04-2021)

- *Which components usually have the longest lead time?*
  Logically, this is very supplier specific. It depends on the stock level they have and other circumstances. For example, at this point the lead times are really unreliable and variable. With the COVID-19 pandemic and the chip deficit currently. Usually the lead times are a few (2-8) weeks but right now this can be 52+ weeks. And there is not really a correlation between component type and lead time length.

- *Which component types usually have the highest MOQs?*
  This also is highly dependent on the component rather than just the component type. But the rule of thumb is that the smaller the component, the higher the MOQ. So, this is for the grit components, which are the resistors, capacitators and diodes.

- *For which components do you usually find the MOQ an issue?*
  The most expensive ones, especially when it also is a very unique component. Usually these are the integrated circuits (ICs).

Inventory value (Warehouse crew, 21-04-21)

- *Each year you throw away the components which have not moved for 5 years, what type of components are those mainly? Is there any relation between those?*
  No, there is no relation to be found between which component types are thrown away more than others. Each year it is different of course but overall, there is no relation between the component type and how often they are thrown away.

- *What are the most expensive components?*
  Overall, the most expensive components are ICs (integrated circuits) because of complexity. But in each category, there are more expensive and more cheap variants. The value of a component depends on the complexity and how rare or scarce that component is, and therefore not very type dependent. But on average the ICs are the most complex ones.

- *Are there components which are fragile? In transport process or in the machine? Which?*
  No, for the inventory there is no such thing as fragility. The components are on reels in plastic. But at the warehouse the components arrive in cardboard boxes, within these boxes multiple component types are present. If a box has been damaged then some components can be damaged as well, this can be random as well. And if somebody drops components on the floor there is a possibility that these are broken, but this is also not occurring more often with a specific type.
  In the machines of the assembly process, the smaller components are more likely to break or to be misplaced. A lot of component types can be very small (2 x 1 mm for example) but usually the resistors, diodes and some ICs are among the smaller one's.

Ability of standardization (Procurement employee, 28-04-2021)

- *What components are easy to replace with alternatives?*
  These are the smaller components such as resistors, capacitators and diodes. As mentioned before, a collective name for these smaller components is grit. Alternatives for these need to have the same specifications, but that is usually not too hard to find.
- *What components are common across different orders? Frequency that this occurs?*
  Also, the grit. Because they are usually less PCBA specific. Hard to make a frequency estimation. These are anyway also the components with highest quantity on a single PCB.

C. Systematic literature review sub-question 3.

Knowledge question

The sub-question that I will answer with this SLR is sub-question 3: What are methods to reduce obsolescence costs in the inventory?

Inclusion and exclusion criteria

To get the most relevant literature for me, I made some inclusion and exclusion criteria to filter the number of results. These criteria, together with my motivation, can be found in Table C.1.

Table C.1. *In- and exclusion criteria for literature review*

Inclusion criteria	Motivation
Dutch or English language	I must be able to understand the paper/article completely.

(Industrial) Engineering or business/management topic	It must be in my field of research. For example, it should not be in the field of medicine or social sciences.
Exclusion criteria	
Paid sources	For my research, I do not have any money. If a source cannot be accessed for free (via the University of Twente), then I cannot read it and therefore these are not relevant for my result list.
Term obsole* not present in title/abstract.	The focus is on the obsoletes, so this should be found somewhere in the title/abstract. Otherwise, I exclude that result.

Database

In this systematic literature review, I have used the following database:

- Scopus

Scopus is one of 'the most important databases' according to Peter Noort and Marit van Eck. I have found this on the University of Twente website in the library when I searched for my discipline, Industrial Engineering and Management. Scopus has a very large amount of scientific literature available.

Search strategy

The key concepts in my sub-question are defined as following:
~~**What are**~~ methods ~~**to**~~ reduce obsolescence costs ~~**in the**~~ inventory?

Table C.2 below shows my search matrix for this knowledge question. In this search matrix I also added a key concept 'make-to-order supply chain' because that is the case for Global Electronics and hence, literature should be applicable to this situation.

For most concepts I did not mention any broader terms since I expect to get enough papers on this topic. So, a broader search would not be necessary. I also added more specific characteristics of GE in the search matrix, because eventually a more specific search is performed.

Table C.2. *Search matrix*

Key concept	Synonyms	Broader terms
Method*	Approach, way, manner, strategy	-
Reduce	Decrease, cut down, lower, curtail, minimize	Avoid, prevent, management
Obsole*	Out-of-date, outdated, outmoded, antiquated	Excess
Costs	Value, expenditure, charge	-
Inventory	Stock, on-hand	-
make-to-order supply chain	Pull supply chain	

With the synonyms together with the in- and exclusion criteria in mind, the search itself is started. In Table C.3 below, I have logged my literature search in a systematic way.

Table C.3. *Search log.*

Database	Search string	Date of Search	Number of entries	Relevant entries based on abstract/keywords
Scopus	method* AND reduce AND (obsoletes OR obsolescence) AND costs	28th of April 2021	13	2
Scopus	Avoid OR prevent) AND (obsole* OR outdated) AND (inventory) AND management	28th of April 2021	48	1
Scopus	reduce OR minimize AND obsole* AND inventory	28th of April 2021	123	2
So far, we have looked at ways to reduce obsolete components/products in general. Now, we will also add a bit more characteristics of Global Electronics in the search string, such that we hopefully find more comparable cases.				
Scopus	obsole* AND manage* AND "Make-to-order"	28th of April 2021	64	1
Total found			184	6
Duplicates			6	1
Total entries			178	5

Using the snowballing technique under one of my found entries in Scopus, I have found the article *The Fourth Dimension in Building: Strategies for Minimizing Obsolescence*. (1993) by Iselin and Lemer. I put this title in the FindUT tool, but this article was not found in the UT library.

In total I had 6 relevant entries based on the abstract. I started to read them all and found in the early sections of the papers that 3 sources were not as relevant as I thought. Mainly because it was not necessarily about the type of obsoletes that fit to my situation, but more about perishability of food for example. So, I was left with 4 relevant sources which will be used for the integration of theory.

So, the following articles are the sources which will be read for this literature study:

1. Baker, A. (2013). Configurable Obsolescence Mitigation Methodologies. *Procedia CIRP,* 352-356.

2. Ghadge, A., Bag, S., Goswami, M., & Tiwari, M. K. (2020). Mitigating demand risk of durable goods in online retailing. *International journal of retail and distribution management*, 165-186.

3. Nnamdi, O. (2018). Strategies for managing excess and dead inventories: A case study of spare parts inventories in the elevator equipment industry. *Operations and supply chain management*, 128-139.

4. Sanchez-Vega, M. D., Caballero-Morales, S. O., Sanchez-Partida, D., & Martinez-Flores, j. L. (2018). Risk-based Strategic Inventory Supply Model for New Products. In *Best practices in manufacturing processes* (pp. 75-95). Springer, Cham.

5. Teunter, R. H., & Klein Haneveld, W. (2002). Inventory control of service parts in the final phase. *European journal of operational research*, 497-511.

After reading these four articles, the following conceptual matrix was constructed. This can be seen in Table C.4. In this table the authors can be found, and they are sorted around the main topics/concepts. In the last column the key findings of a certain article regarding this main topic can be read.

Table C.4. *Conceptual matrix, sorted per topic.*

Author	Main topic/concept	Key finding
(Sanchez-Vega, Caballero-Morales, Sanchez-Partida, & Martinez-Flores, 2018)	Forecasting/planning of demand and inventory	Excess inventory, and hence risk of obsolescence, are due to an incorrect establishment of planning parameters or variation in the predicted demand. Correct models and thorough data analysis should solve this partially.
(Nnamdi, 2018)	Forecasting/planning of demand and inventory	The root cause of excess inventory are data errors in the forecasts. Avoid these.
(Ghadge, Bag, Goswami, & Tiwari, 2020)	Forecasting/planning of demand and inventory	Problem of difficulty with forecasting can be tackled partially by suggesting alternate products to customers. If a company is out of stock of something and small variation of predicted demand occurs, that company can suggest alternate products such that the demand is still met, but no big new orders at suppliers must be placed. (Big because of supplier restrictions)
(Baker, 2013)	Forecasting/planning of demand and inventory	Make use of emulation, which is replacing original parts by another one or combination of parts to achieve same function.
(Nnamdi, 2018)	Forecasting/planning of demand and inventory	Mathematical models should forecast sudden demand decreased based on historical data. For several demand patterns, different models exist.
(Sanchez-Vega, Caballero-Morales, Sanchez-Partida, & Martinez-Flores, 2018)	Order process	Use a combination of periodic and continuous inventory order policy. This reduces risk of excess and hence, obsolete products/components. Periodic policy helps the suppliers in their planning, and the continuous review helps to compensate excess inventory in between the periodic orders. This integrated policy ensures more contact with suppliers and therefore possible excess material can be identified earlier in the supply chain.
(Teunter & Klein Haneveld, 2002)	Order process	For orders you have agreed on a planning horizon. Start with a certain order-up-to level and as time progresses and this horizon comes closer, decrease this order-up-to level. This ensures a smaller risk of obsolescence at the end of the planning horizon.
(Nnamdi, 2018)	Order process	If probability of obsolescence is given beforehand, include this probability in EOQ order policy. This EOQ will change and result in less obsolescence.
(Nnamdi, 2018)	Order process	Do not order the big quantities at suppliers for the sake of the discount that comes with this quantity. For some components these big quantities are unnecessary and will only result in obsolete components, and hence costs.
(Nnamdi, 2018)	Other internal activities	Make someone in the company responsible for monitoring the excess inventory. This person knows how, when and why excess inventory has accumulated over the years and can help in forecasting obsolescence and anticipating this.
(Nnamdi, 2018)	Other internal activities	Track if components are likely to be replaced by new inventions. Then do not order these 'outdated' components anymore. On excess inventory, sales discounts should be offered. Then customers are more likely to buy these.

D. Determining tool input components

High-impact component identification rules:

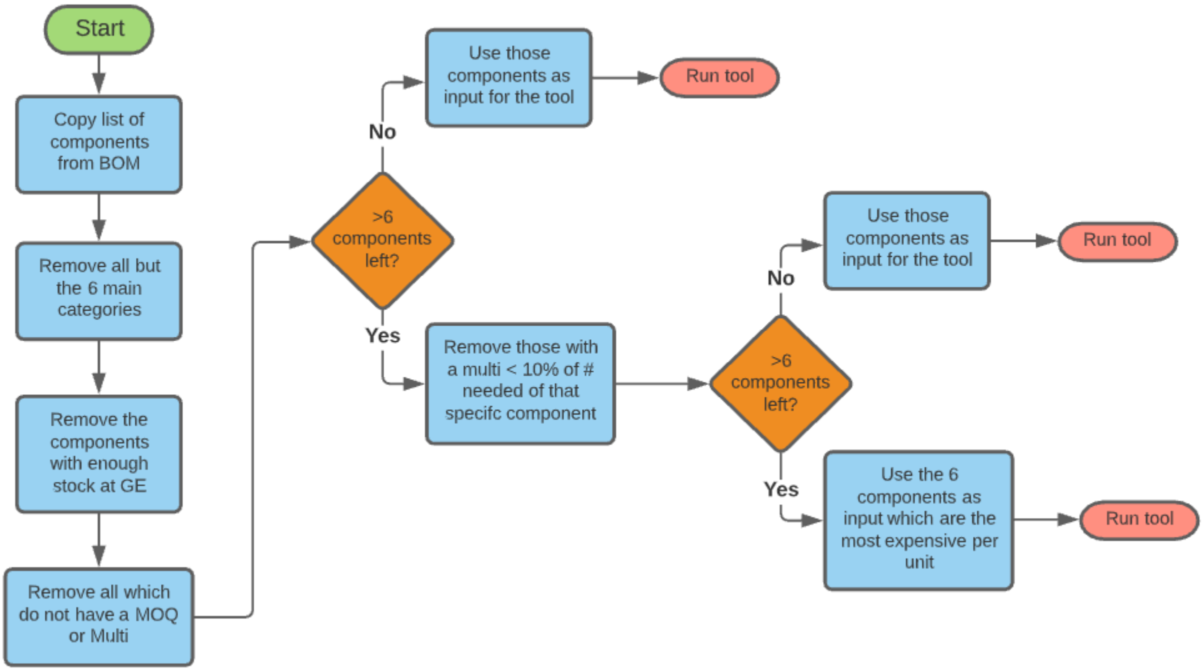

Figure D.1. *Flow chart of the identification of the high-impact components to be used in the tool.*

In the figure above, the process of identifying which components to put in the tool is shown in a flow chart. First, the list of components is copied and filtered on the six categories identified in Chapter 3. These six were: capacitators, diodes, transistors, resistors, ICs and inductors. Then all components which are already in stock and those without a MOQ or multi are removed. Now, the first check is done. If there are six or less components left on the list, then those components should be put in the tool. If there are more than six components left, then we remove all those with a multi which is smaller than 10% of the amount of needed of that specific component. The reason for this is that with such a small multi, there usually are not that many residual components, and hence, the excess material costs of that component are also not that large. If there are still more than six components left than the six components with the highest unit cost are used as inputs for the tool, because they are the ones with the highest impact on the residual costs. In general, it is assumed that for the first orange decision point there are six or less components left but it could occur that there are a lot of high-impact components in an order. So, that is why there are two more filters applied to get to a maximum of six.

E. Inputs of simulations

Ordernumber	[illegible]	Desired Q	500	range %	10	
	1	2	3	4	5	6
Component type	YDCAM-M	YDWT41U	JDAXK6S6	ID743861	ID73633-[	ID25512A
# needed per PCB	1	1	1	2	1	1
Stock level	0	0	0	0	0	0
Price of 1 component	9,85	28,308	1,38	0,271	0,9605	0,407
Multi/Package size	250	500	500	500	1000	100
MOQ	1	500	1	1	1	1

Ordernumber	[illegible]	Desired Q	510	range %	10	
	1	2	3	4	5	6
Component type	PCB-be9z	Capacitor	PCB-p5rj6	SOT-89-M	PCBComp	PCB-5750
# needed per PCB	1	1	1	1	1	1
Stock level	0	0	0	0	0	0
Price of 1 component	0,69	0,035	0,7	0,246	3,2	0,058
Multi/Package size	500	4000	370	3000	650	500
MOQ	500	1	1	1	1	1

Ordernumber	[illegible]	Desired Q	1000	range %	10	
	1	2	3	4	5	6
Component type	ID3172-EI	ID71Q21B	ID54531-[	ID2562--E	ID4728--E	VDV25PN
# needed per PCB	8	1,02	1	1	1	1
Stock level	0	0	0	0	0	0
Price of 1 component	0,8	11,1	1,58	0,669	1,28	0,45
Multi/Package size	1000	100	25	25	100	1500
MOQ	1	1	1	1	1	1

Ordernumber	[illegible]	Desired Q	100	range %	10	
	1	2	3	4	5	6
Component type	JK236412	CD47635-	VDES3BE3	ID5215---LIF		
# needed per PCB	2	2	14	7		
Stock level	0	0	0	0		
Price of 1 component	2,077	0,117	0,16	1,55		
Multi/Package size	105	1000	3500	1		
MOQ	420	1	3500	1000		

Ordernumber	[illegible]	Desired Q	60	range %	10	
	1	2	3	4	5	6
Component type	PCB-be9z	Capacitor	PCB-p5rj6	SOT-89-M	PCBComp	PCB-5750
# needed per PCB	1	1	1	1	1	1
Stock level	0	0	0	0	0	0
Price of 1 component	0,69	0,035	0,7	0,246	3,2	0,058
Multi/Package size	500	4000	370	3000	650	500
MOQ	500	1	1	1	1	1

Ordernumber	[illegible]	Desired Q	400	range %	10	
	1	2	3	4	5	6
Component type	CD10550-	ID3172-EI	LD742792	RD3241-5	LD120RSR	ID803SN3
# needed per PCB	19,4	8	6,12	1,02	8	2,04
Stock level	0	0	0	0	0	0
Price of 1 component	0,038	0,8	0,154	0,25	0,18	0,198
Multi/Package size	4000	1000	1000	1000	2000	3000
MOQ	1	1	1	1000	1	3000

Figure E.1. *Inputs of the six simulations of the implemented LEMQ-model.*