School of Innovation, Design and Engineering

Finding Optimum Batch Sizes for a High Mix, Low Volume Surface Mount Technology Line

Master thesis work
30 credits, Advanced level

Product and process development
Production and Logistics

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Report code: KPP231
Commissioned by: Westermo Teleindustri AB
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Abstract

Production of Printed Circuit Boards (PCBs) requires high-tech pick and place machines that can produce significant number of boards in short time. However, increase in the variety of boards causes interruptions in the production process. Frequent setups can lead to small lots and low inventories. In contrast, bigger batch sizes save production time by having fewer setups but they increase inventory value. Finding optimum batch sizes is a problem faced by many manufacturers in a High mix, Low volume production environment.

In this thesis, the problem of finding optimum batch sizes is investigated using optimization techniques in Operations Research. Furthermore, inspired by Single Minute Exchange of Die theory, some improvements are suggested for the setup process. The conclusions from the empirical part show that reducing setup times can help producing smaller batch sizes. It also increases production capacity and system's flexibility. Operations Research methods also showed to be very effective tools that can lead to significant savings in terms of money and capital.

Keywords: High mix-Low volume Production, Single Minute Exchange of Die (SMED), Surface Mount Technology (SMT), Optimal Lot Sizing

Acknowledgment

I would like to express my very great appreciation to Antti Salonen, my supervisor at MDH, for his help and advice throughout this project. Special thanks to Sabah Audo, my professor in Operations Research for his help during this thesis. I am particularly grateful to Christer Andersson and Kari Parkkila, my supervisors in Westermo Teleindustri AB. Without their valuable and constructive suggestions and their warm support, this report could not have been realized.

At the end, I would also like to thank Heidi Panni-Pauninen for her friendship and kindness, and the staff of Westermo for their patience and assistance in collection of my data.

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Abbreviations

DES	Discrete Event Simulation
DIN	Deutsches Institut für Normung
EOQ	Economic Order Quantity
ERP	Enterprise Resource Planning
GA	Genetic Algorithm
HMC	Hybrid Microcircuit
IDT	Akademin för Innovation, Design och Teknik
IED	Inside Exchange of Die
IFS	Industrial and Financial Systems
LP	Linear Programming
MAPE	Mean Absolute Percentage Error
MDH	Mälardalens Högskola
MRP	Materials Requirement Planning
NLP	Nonlinear Programming
OED	Outside Exchange of Die
OEE	Overall Equipment Effectiveness
OR	Operations Research
PCB	Printed Circuit Board
R&D	Research and Development
RS	Recommended Standard
SAP	Systems Applications Products
SMED	Single-Minute Exchange of Die
SMT	Surface Mount Technology

1. Introduction

In this chapter, an introduction to the thesis problem is given. The problem is explained in short and research questions are described.

1.1 Background

Anyone involved in the practice of production planning and management of certain number of products is faced with two important questions that should be answered: when to produce and how much to produce? The advent of Enterprise Resource Planning (ERP) software like SAP (Systems Applications Products) or IFS (Industrial and Financial Systems) has made the answer to the first question very easy. However, the second question, how much to produce, still remains unanswered. The second question, famous as lot sizing problem, has an important role in plant's financial function. Inventories have long been seen as necessary evils. They are necessary since without them the customer service level of the plant falls down. They are evil because they tie up large amounts of capital to themselves and tend to decrease the plant's turnover rate. Finding an answer to this problem is quite complicated since there are many different variables involved in the process. Nonetheless, each manufacturing plant is unique, each production process is especial in its own way and they all involve different types of constraints and variables. Therefore, finding an answer that can be applied to all different situations is cumbersome.

However, there are numerous articles discussing this problem in different manufacturing contexts. For example, Wang, et al. (2005) propose a modified Wagner-Whitin method that uses a forward focused algorithm to make lot-sizing decisions under chaotic demand. Gutiérrez, et al. (2002) address the dynamic lot-size problem using dynamic programming. Gupta and Magnusson (2005) consider the capacitated lot-sizing and scheduling problem for a single machine with sequence dependent setup costs and non-zero setup times having setups able to be carried over from one period to another. Kim and Hosni (1998) formulate a multi-level capacitated optimization model that works properly under Manufacturing Resource Planning (MRP II). Vargas (2009) finds an optimal solution for the stochastic version of the Wagner-Whitin dynamic lot-size model. Chiu, et al. (2007) study the optimal lot-sizing problem for a production system with rework, random scrap rate and a service level constraint. Lee, et al. (2005) analyze a dynamic lot-sizing problem in which order size of multiple products and a single container type are simultaneously considered. Adacher and Cassandras (2013) extend a stochastic discrete optimization approach to tackle the lot-sizing problem and Schemeleva, et al. (2012) consider a stochastic multi-product lot-sizing and sequencing problem with random lead times, machine break downs and part rejections.

Although there are numerous articles addressing the issue of lot sizing in different production environments, there is a lack of research on using mathematical optimization tools with respect to addressing the problem in the context of electronic manufacturing systems. A typical example of such a system is a high mix, low volume production system which produces a high variety of products with low volumes trying to meet a highly variant and lumpy customer demand. Many assumptions that are the bases of the previous models do not apply in this context. Therefore, there is a need to investigate this problem separately.

1.2 Problem formulation

Today there is a lack of knowledge and competence in companies regarding the use of mathematical optimization for finding optimum batch sizes. The smaller batch sizes will reduce the inventory and help the company toward production according to customer orders which is one of the aims of Lean manufacturing. However, increased number of long setups may decrease the available production time and expose the production line with the danger of unmet customer demand. Bigger batch sizes will reduce the number of setups and increase the available production time but they will also increase the inventory value. More products will be in stock for a longer period of time and they are exposed to deterioration. There will also be a need for a larger storage for keeping the items in stock. In addition, bigger batches are an obstacle for producing a high mix of products. Due to longer production time of bigger previous batches; each job should wait for a longer time until it can enter the line. The focus of this thesis project is to answer this question: *What are the optimum batch sizes for a High mix, Low volume production line?* In order to answer this question, two methods are used. Economic Order Quantities (EOQ) is the first method that is tested. Followed by that, the use of Operations Research (OR) techniques are investigated on lot sizing problem.

1.3 Aim and research questions

The aim of this project is to explore the potential of utilizing mathematical optimization tools on a real case and to find a proper method to calculate the optimum batch sizes and to present the results. There will also be an analysis of the capacity to investigate the effect that changes in capacity can have on the system in terms of batch sizes, inventory value and ability to meet customer demand. The capacity analysis part is performed due to the management request. The research questions can be described as shown below:

- What are the optimum batch sizes?
- What is the relationship between setup times and batch sizes?
- What is the relationship between setup times and inventory value?
- What is the relationship between capacity with batch sizes and inventory value?
- Is it possible to reduce the work time requirements and reduce the batch sizes at the same time?

1.4 Project limitations

The main limitation for this project was time. More time could lead to more precise evaluations of the current state and could give way to examine different methods to solve the problem. Limited project time leads to early conclusions and less detailed work, with a variety of methods untested.

During building the optimization model and preparing the input data, it was decided that some of the boards should be excluded and not take part in the model. A series of these boards were prototypes. Prototypes are occasionally produced and present boards that will be a part of production flora in the future. However, they are not a part of companies products now and they are not produced regularly. Therefore, it is not reasonable to involve them in the optimization process since they can negatively influence the optimization result for other boards.

There were two other groups of boards that went under the same decision. A set of boards used to be produced regularly in the past but now their production has been discontinued. The information related to these boards was combined with other boards and therefore it had to be filtered out. Another group of boards are produced based on customer orders. The batch sizes for these boards depend on the order size from customers. Therefore, it is not reasonable to include them in the model.

The cycle times that are used in the model have been obtained from the companies data base. The accuracy of these cycle times are not clear. However, it was not possible to measure the cycle times personally due to the large number of different boards produced and due to the shortage of time. Therefore, it was decided to trust these data and use them as an input for the model.

In order to obtain the optimum batch sizes, the annual data for the year 2013 for each board was used. Previous years were excluded and current year (2014) was not used either, since the data for the remaining months of this year is not available yet. However, for the capacity analysis part, the data for year 2014 was used (January to April). This was due to the management request.

The part in the impirical section which gives suggestions regarding reducing setup times is short despite the fact that the work on this section was thourough and numerous suggestions were given. Reducing setup times influences batch sizes and is closely related to capacity analysis, but since it is not the focus of this report, it was mentioned shortly. However, a thourough description of the methods are given in the theoretical framework.

2. Research method

It is a matter of importance during any research process to let the research problem decide the choice of approach and it is equally important to take its consequences into consideration. Accordingly, research problem will determine the perspective and the perspective will decide the choice of method (Johansson, 1995).

2.1 Quantitative vs. Qualitative method

Qualitative and quantitative research methods have long been two main research methodologies among academia. Qualitative research is a method to explore and understand the meaning individuals or groups give to a social or human problem. The research includes the process of emerging questions and procedures, collection of data typically in the participant's settings, inductive analysis of data moving from particulars to general themes and making interpretation of the data by the researcher (Creswell, 2009).

Quantitative research at the other hand, is a tool for testing objective theories through examining the relationship among variables. These variables, in turn, can be measured and turned into numbered data that can be analyzed using statistical procedures. The final report of this research method should have a structure consisting introduction, literature and theory, methods, results and discussion. Those involve in this type of research are interested in deductive analysis and testing of theories, evaluating alternative explanations and being able to generalize and replicate the findings (Creswell, 2009).

There are a set of differences between these two traditions. The most important difference between them is the way in which each tradition treats data (Brannen, 1992). In quantitative approach, the researcher tries to test a theory by specifying and narrowing down a hypotheses and by collecting data to support or refute the hypotheses (Creswell, 2009). In theory, if not in practice, the researcher defines and isolates variables and variable categories. The variables then, are linked together to frame hypotheses often before the data is collected, and are then tested upon the data (Brannen, 1992). The qualitative researcher at the other hand, begins with defining very general concepts which will change in their definitions as the research progresses. For the former, the variables are the tools and means of the analysis while for the latter, they are the product or outcome of the research (Brannen, 1992). As an example, in qualitative method, the researcher tries to establish the meaning of a phenomenon from the views of participants. This requires to identify a culture-sharing group and to study how it develops shared patterns of behavior over time (Creswell, 2009). The qualitative researcher is said to look through a wide lens, looking for patterns of inter-relationship between a set of concepts that are usually unspecified while the quantitative researcher looks through a narrow lens at a set of specified variables (Brannen, 1992).

The second important difference between the two methods is the way they collect data. In the qualitative tradition, the researcher must use himself as the instrument, attending to his own cultural assumptions as well as to the data. In order to gain insights to the participants' social worlds the researcher is expected to be flexible and reflexive and yet manufacture some distance (Brannen, 1992). Qualitative approach includes three main kinds of data collection methods: in depth, open-ended interviews; direct observation; and written documents (Johansson, 1995).

In quantitative tradition, the instrument is a finely tuned tool which allows for much less flexibility, imaginative input and reflexivity, for example a questionnaire. By contrast, when the research issue is less clear and questions to participants may result in complex answers, qualitative methods like in-depth interviewing may be called for (Brannen, 1992). Compared to qualitative method, the main quantitative research techniques include the use of questionnaires, structured interviews, measurement, standardized tests, statistics and experiments (Johansson, 1995).

Qualitative approach studies selected issues in depth and detail. This is due to the ability to approach the fieldwork with openness and without being constrained by predetermined categories of analysis. On the other hand, quantitative methods require the usage of standardized methods so that the wide variety of perspectives and experiences of people can be fitted into a small number of predetermined response categories. The most advanced method in quantitative research is experiment where fieldwork is replaced by laboratory (Johansson, 1995).

In quantitative approach, the researcher often tries to minimize the effects of intervening factors on the research phenomenon. In qualitative approach, the researcher tries to find out and describe what the intervening factors are and how they influence the research phenomenon under study (Johansson, 1995).

In quantitative research, the researcher works with statistics and uses the average, the frequency, the causality and the prediction as a base for the report. In qualitative research, the researcher believes that if something has happened once, it can happen again even if you cannot calculate where and when (Johansson, 1995).

2.2 Case study

As a research strategy, case study has been used in many different situations to contribute to our understanding and knowledge about individual, group, organizational, social, political, and related phenomena. Case study is even used in economics, where the structure of a given industry or the economy of a given region or city is investigated by case study techniques. In all of these cases, the need for a case study arises out of the desire to understand complex phenomena. In brief, the case study allows the researcher to retain the holistic and meaningful characteristics of real-life events (Yin, 2003).

Case study is defined as:

> "An empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident. The case study inquiry copes with the technically distinctive situation in which there will be many more variables of interest than data points, and as one result relies on multiple sources of evidence, with data needing to converge in a triangulating fashion, and as another result benefits from the prior development of theoretical propositions to guide data collection and analysis" (Yin, 2003, p.13).

In other words, you use case study method because you deliberately want to cover contextual conditions believing that they are highly important to your phenomenon of study. Second, because phenomenon of study and its context are not always distinguishable in real-life situations, a whole new set of technical characteristics like data collection and data analysis strategies is required (Yin, 2003).

A case study research can include both single-case and multiple-case studies. Although some fields have tried to distinguish sharply between these two approaches, they are in reality two variants of case study designs. A case study can also include or even be limited to quantitative evidence and as a related but important note, the case study strategy should not be confused with qualitative research (Yin, 2003).

In order to investigate the problem of *"lot sizing"* or *"finding optimum batch sizes"* in a high mix, low volume production environment a case company has been selected. The company is a manufacturer of different types of electronic products. To focus more on the problem, one of the main workstations of the company that produces different types of electronic boards using surface mount technology is chosen.

2.3 Case company

The case company chosen for this thesis report is Westermo Teleindustri AB, an electronics manufacturing company. Westermo was established in 1975. Its first data communication product was an RS-232 line driver, allowing data transmission over large distances using twisted pair cables. With its head office in southwest of Stockholm, it grew over the past three decades to establish subsidiaries in Sweden, UK, Germany, France, Singapore, North America, Taiwan with sales partners over 35 countries. In 1990s, Westermo created the world's first industrial DIN rail mount telephone modem. Today it designs and manufactures robust data communication devices for harsh environments. With its strong commitment to develop its own industrial data communications solutions, last year it invested 13% of its turnover in R&D. Westermo's ambition is to deliver a customer service level of 98% with return ratios below 0.25%. As a result, Westermo conducts business with a large number of system integrators around the world while having special partner programs with some of them (Westermo.com, 2014).

Amongst different products of the company are the printed circuit boards (PCBs). Today, up to 188 different boards are produced in the company. High variety of boards and low volumes classify the production as High mix, Low volume. The need for frequent long changeovers forces the production line to produce the boards in batches.These boards are used as a component in company's other final products or they are delivered directly to the customers as finished products. The boards are produced in one of the company's production lines using Surface Mount Technology (SMT). The SMT assembly involves three basic processes: screen printing of the solder paste on the bare boards, automatic placement of components on the boards using two placement machines in series (one for small components and the other for large components), and solder reflow oven. There are inspections after the solder printing, placement machines and reflow oven. The boards are produced in batches. Batch sizes are specified in an ERP system called IFS. Whenever customer demand cannot be met by finished boards in inventory, a production order of a specified quantity is sent to the workstation through IFS.

2.4 Research method, data collection and analysis

The nature of the batch sizing problem requires the description of the demand pattern, finding averages, dealing with large amount of numeric data and carrying on optimization procedures. Due to the nature of the research problem, it is necessary to continue with a quantitative approach.

At the beginning of the project, a thorough literature review was carried on on similar topics and articles in peer reviewed journals and in previous thesis works on relevant subjects. Articles from the university data base and the textbooks from the university library were the main sources of data. Afterwards, in order to make a better understanding of the problem at hand in detail levels, an investigation of the production process was performed through daily visits of the SMT line, making close observations, asking questions from operators and the production manager and searching relevant data through company's data base.

The data required to solve the research problem was collected from company's ERP system. This data includes information related to demand patterns for each board, prices, production quantities, cycle times, capacity and etc. The data from ERP system was in raw form and had to be processed before turning into meaningful information, therefore a great deal of time was spent on processing and manipulation of raw data using Excel. To continue, an optimization model was created which enabled this data to be used. The model was used not only for calculating the optimum batch sizes, but also to perform capacity analysis and investigating the effect of setup time reduction on both batch sizes and capacity.

3. Theoretic framework

In this chapter, the theoretic framework of this report is explained. Relevant theories are described and later used in the empirical part.

3.1 Description of an SMT line

Printed Circuit Boards (Figure 1) are the central part of an electronic product and are manufactured through automated assembly lines with one or several stations where necessary components are placed on the boards (Salonen, 2008). Surface-mount technology refers to assembling of the electronic components on boards by soldering them onto their surface where components are placed on one side or both sides of the board (Coombs, 2008). SMT technology can be traced back to 1960s when it was first used for assembling hybrid microcircuits (HMC). The surface-mount technology provides manufacturers with the ability to use smaller components and create greater densities on the boards (Coombs, 2008).

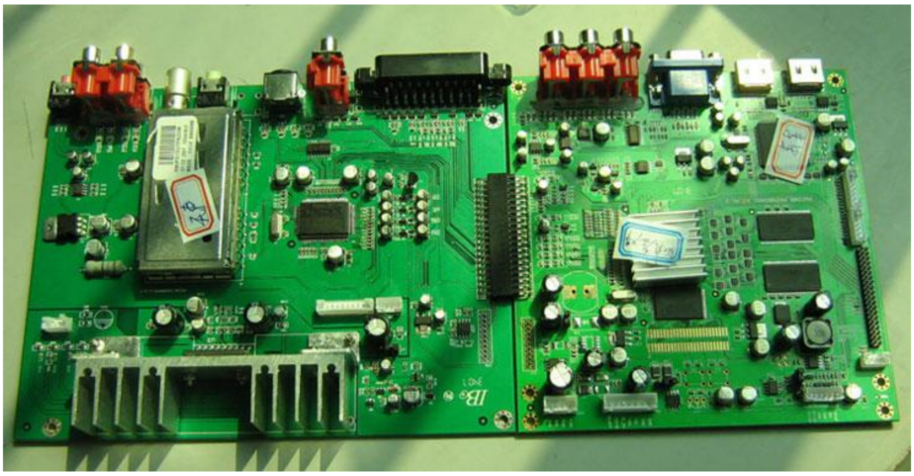

Figure 1: A printed circuit board (O-digital.com, 2014)

According to Coombs (2008), the main advantage obtained from surface-mount technology is lower manufacturing cost resulting from automated assembly processes. There are three basic assembly processes in an SMT line including (1) printing of solder paste on the boards, (2) placing the components on the boards, and (3) reflow the solder in a furnace (Coombs, 2008). Solder paste which is a combination of solder powder, thixotropic agents and flux is applied on the boards with great precision (thickness and area). One common method for applying solder paste is *screen or stencil printing*. In this method, the solder paste is applied on the boards through openings in the screen or stencil called *apertures*. The apertures are located on exact locations on the boards where solder paste is required (Coombs, 2008). Figure 2 is an example of a solder paste printing machine:

Figure 2: A solder paste printing machine

Pick and place machines can handle small or large electrical components and put them precisely where solder paste deposits are placed. The tacky nature of the flux in the solder paste keeps the components in place (Coombs, 2008). According to Salonen (2008), placing machines are classified as either gantry or turret style based on the design of the pick and place system. Gantry style machines have a number of nozzles on a movable placement head which can move between the feeder bank and component placement location on the board and can pick any component and place it on the board. Feeder banks and the boards are usually fixed and do not move during the placement process. In contrast, a rotary turret style machine has a fixed head and a movable feeder carrier that provides the next required component for the placement head and a movable table that holds the board in the exact placement position (Salonen, 2008). Figures 3 to 6 show two pick and place machines, a horizontal turret placing head and a feeder bank.

Figure 3: A pick and place machine for small components

Figure 4: A pick and place machine for large components

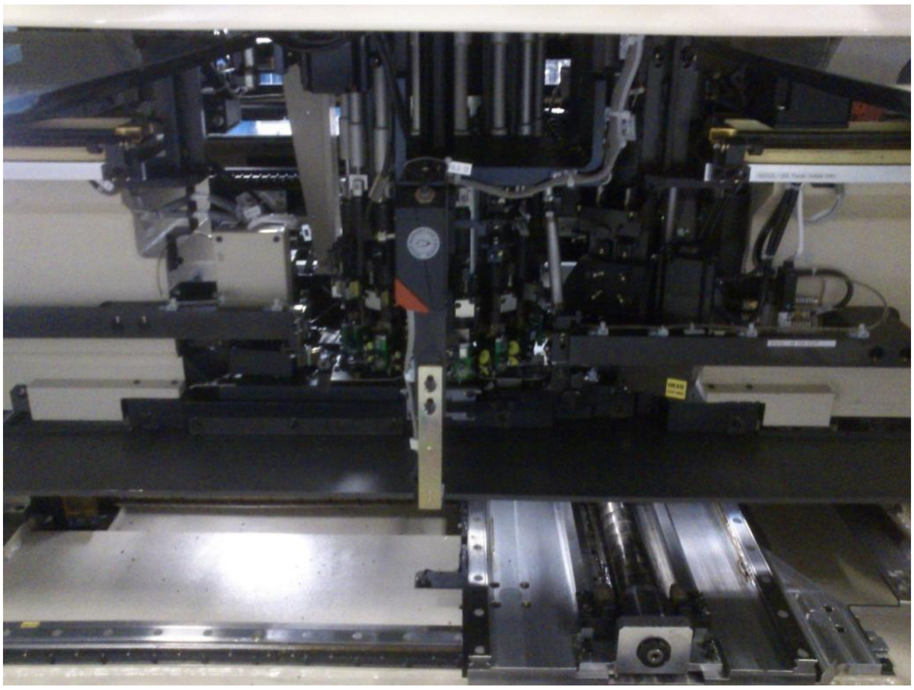

Figure 5: A horizontal turret head rotating around z axis

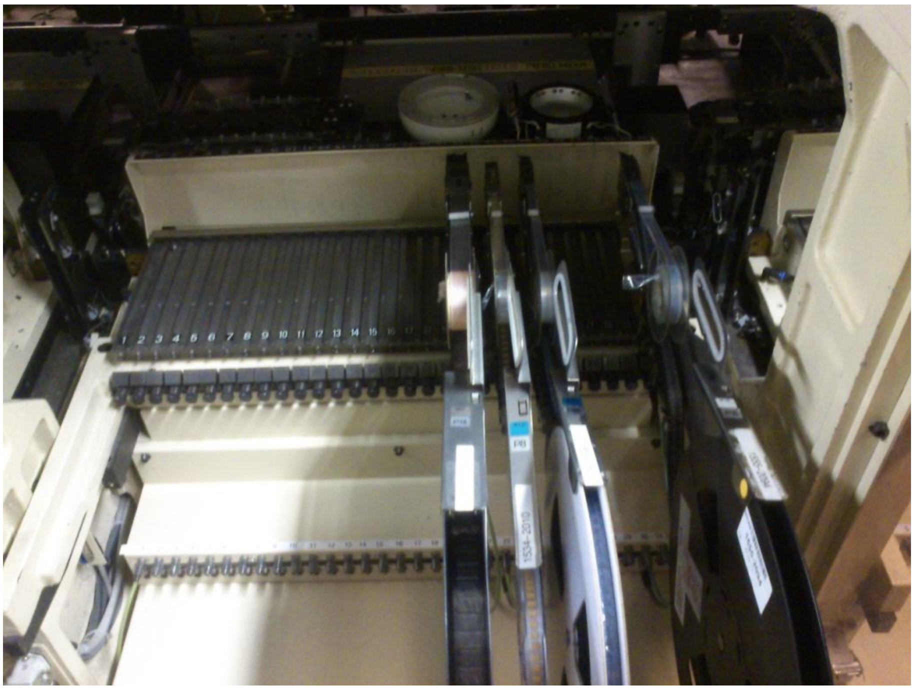

Figure 6: A movable feeder carrier

The next main process in an SMT line is passing the boards through a reflow furnace or oven to melt the solder and form the joints. The furnace can be a batch type in which boards are loaded and unloaded - one batch at a time - or an inline configuration where circuit boards continuously enter one end unsoldered and exit the other end soldered. Therefore an inline furnace can be a part of an overall assembly line that connects all the assembly processes through automatic conveyor belts without operator intervention (Coombs, 2008). Figure 7 illustrates an inline reflow oven.

Figure 7: An inline reflow oven

3.2 Economic Order Quantity

Manufacturing companies face conflicting pressures to keep inventory level low enough to reduce inventory holding costs but at the same time high enough to avoid excess ordering or setup costs. A good starting point to balance out these two conflicting costs and to determine the best inventory level or production lot size is to find the **economic order quantity** (EOQ), which is a lot size that minimizes the sum of total annual inventory holding costs and setup costs (Krajewski, Ritzman and Malhotra, 2007). According to Krajewski, Ritzman and Malhotra (2007) there are a set of assumptions that should be considered before calculating the EOQ:

1. The demand rate is constant and is known for certain.
2. No constraint is set for lot sizes (such as material handling limitations).
3. Inventory holding cost and setup cost are the only two relevant costs.
4. Decision for each item can be made independently from other items.
5. The lead time is constant and the ordered amount arrives at once rather gradually.

The EOQ is optimal when all the assumptions above are satisfied. However, there are few examples in reality where the situation is that simple. Nonetheless, the EOQ is still a reasonable approximation of the optimum lot size even when several of the assumptions above are not met (Krajewski, Ritzman and Malhotra, 2007).

In order to calculate the EOQ, first we need to calculate the average quantity hold as inventory over the year. When all the five assumptions of EOQ are held, the cycle inventory for an item behaves as shown in Figure 8:

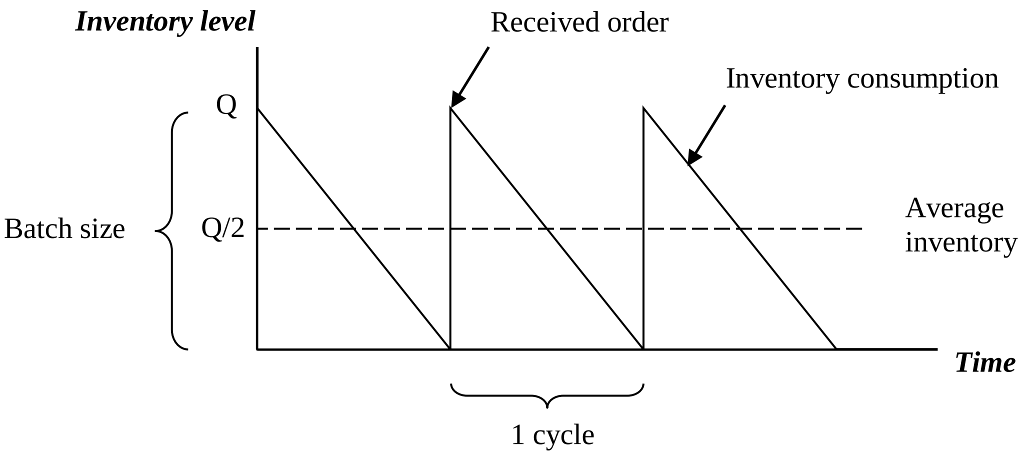

Figure 8: The cycle inventory (Krajewski, Ritzman and Malhotra, 2007)

The cycle begins by a batch size of Q held in inventory. As the time goes on, inventory is consumed at constant rate. Because the demand is constant and certain, the new lot can be ordered in time and be received precisely when inventory level falls into zero. Since inventory level varies uniformly between zero and Q, the average inventory level equals to half the lot size, Q/2 (Krajewski, Ritzman and Malhotra, 2007).

According to Krajewski, Ritzman and Malhotra (2007), the annual holding cost for this amount of inventory, as shown in Figure 9 is equal to:

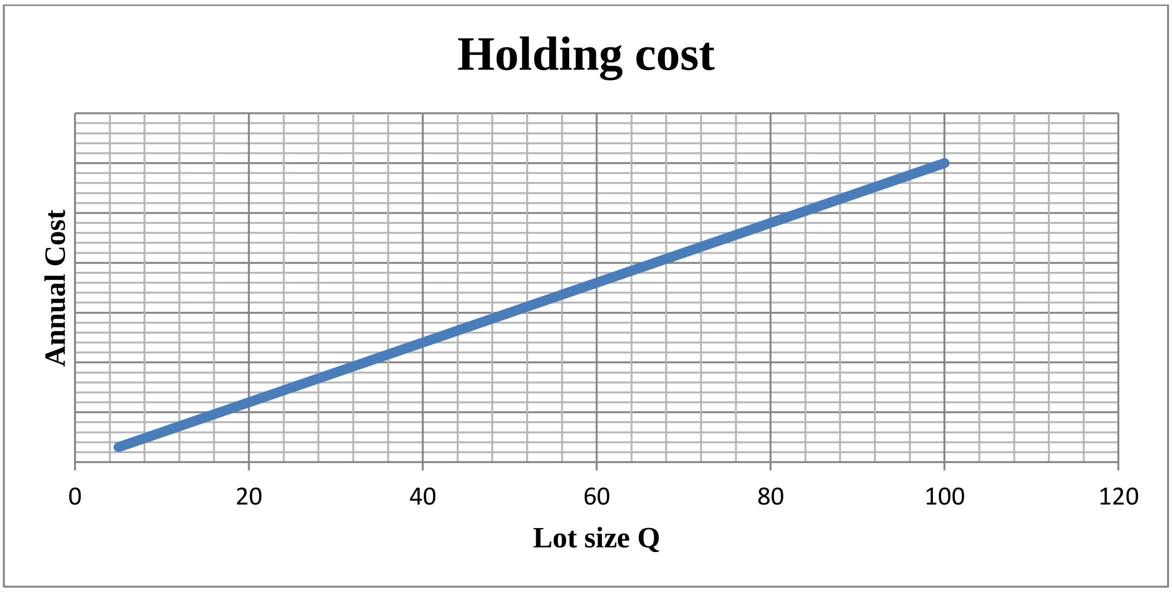

Figure 9: Annual holding cost (Krajewski, Ritzman and Malhotra, 2007)

$$Annual\ Holding\ Cost = (Average\ cycle\ inventory) \times (Unit\ holding\ cost) = \frac{Q}{2} \times H$$

And

$$Annual\ Setup\ Cost = (Number\ of\ setups\ per\ year) \times (Setup\ cost) = \frac{D}{Q} \times S$$

Where

C = total annual inventory cost

Q = lot size

H = cost of holding one unit in inventory for a year

D = annual demand in units

S = cost of setup for one lot

The number of setups per year is equal to annual demand divided by Q. As it is shown in Figure 10, the annual setup cost decreases nonlinearly as Q increases.

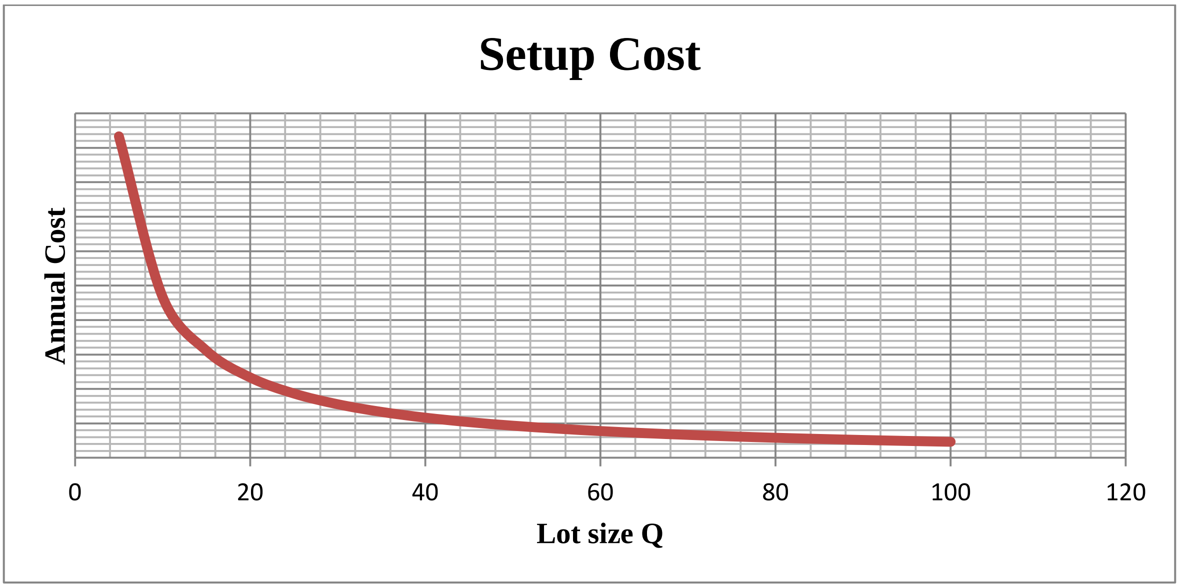

Figure 10: Annual setup cost (Krajewski, Ritzman and Malhotra, 2007)

The total annual inventory cost which is depicted in Figure 11 is the sum of the two components of cost and is equal to:

$$Total\ cost = (Annual\ holding\ cost) + (Annual\ setup\ cost)$$

Or

$$Total\ Cost, C = \frac{Q}{2}(H) + \frac{D}{Q}(S)$$

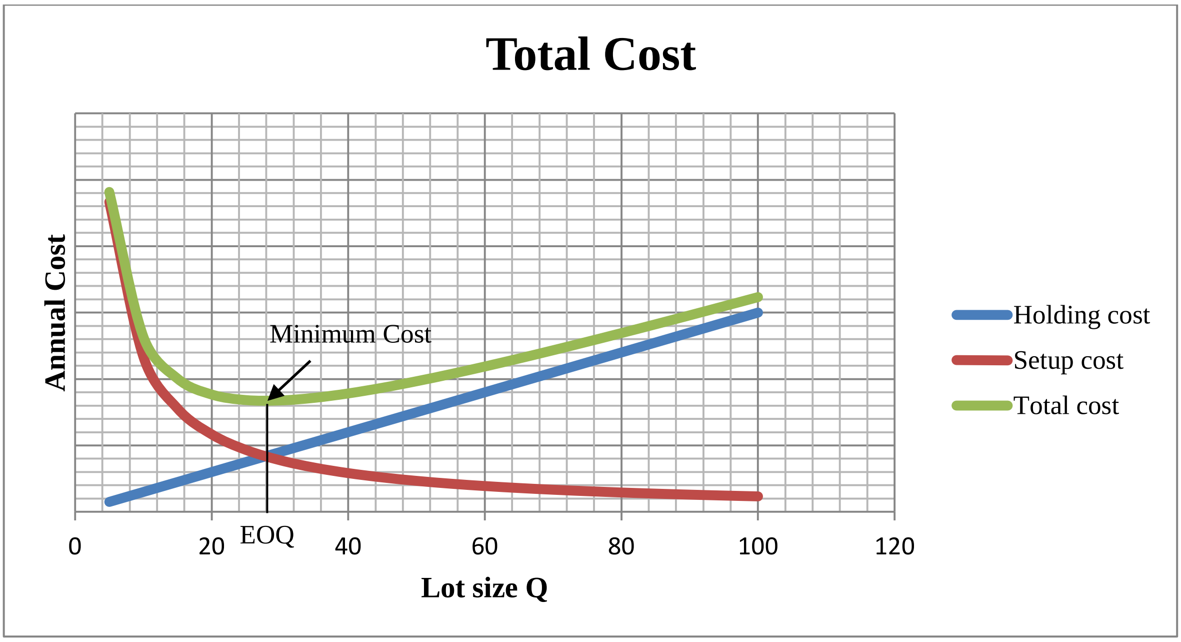

Figure 11: Annual total cost (Krajewski, Ritzman and Malhotra, 2007)

The graph shows that the best lot size, or EOQ, is the one that belongs to the lowest point in the total cost curve which happens at the intersection of holding cost and setup cost curves (Krajewski, Ritzman and Malhotra, 2007).

The value of Q that minimizes the total annual cost is calculated by setting the first derivative of total cost formula with respect to Q, equal to zero (Hillier and Lieberman, 2001). Therefore:

$$First\ derivative = 0$$

$$\frac{dC}{dQ} = \frac{H}{2} - \frac{DS}{Q^2} = 0$$

$$Q^2 = \frac{2DS}{H}$$

$$Economic\ Order\ Quantity = Q = \sqrt{\frac{2DS}{H}}$$

3.3 Discussion about setup cost

Among different parameters in the EOQ formula, setup cost requires more attention since it is more difficult to calculate. Krajewski, Ritzman and Malhotra (2007) describe setup cost as the cost involved in changing over a machine to produce a different item. It can include costs relevant to labor and time, cleaning, inspection, scrap and rework or tools and equipment. Setup cost is independent of order size which makes it tempting for companies to produce large batches and hold them in inventory rather than making small batches.

However, Silver, Pyke and Peterson (1998) argue that several of these factors can become quite complicated when it comes to calculating the setup cost. For example, imagine a mechanic who performs setups. If this person is paid only when he sets up a machine, his wages are definitely a part of the setup cost. However, what happens if this person is on salary? Meaning that whether the machines are set up or not, the wages are still paid. According to Silver, Pyke and Peterson (1998), consideration of these wages as a part of setup cost depends on the use of the mechanic's time when he is not performing setups and on whether a short-term or long-term perspective is taken. If he is involved in other activities, including setting up other machines when he is not performing setups for this part, then there is an opportunity cost for his time. Therefore, his wages should be included in the setup cost. However, there is another side to this story. If we decide not to perform setups for this part frequently, we do not save actual money in the short-term since the wages are still paid. The cost of mechanic's time is fixed and one can argue that it should not be a part of setup cost. The key to solve this, according to Silver, Pyke and Peterson (1998), is whether a short-term perspective is taken or a long-term. In a long-term perspective the wages should be included since in the long-term, this person could be laid off. Therefore the decision to not perform setups can affect the firm financially. To generalize that, all kinds of costs are variable in the long-term because people can be laid off, plants can be closed down, etc. A short-term view argues that the wages should not be included. The answer remains whether a short-term perspective is appropriate or a long-term.

Karmarkar (1987) makes a different argument. He considers a manufacturing plant consisting of a part manufacturing and an assembly stage. Such plant would typically use some sort of

MRP system to determine parts' demands (which is usually lumpy), bill-of-materials, production times, lead times, waiting times and batch sizes. There is a sizable literature on this area that studies lot-sizing under these dynamic conditions and develops models that consider capacity constraints, multiple items or multiple stages. All these models try to make a tradeoff between productivity losses from making too many small batches and opportunity costs of tying up too much capital in inventory as large batches. These costs are represented by fixed setup costs and variable inventory holding costs respectively. This representation of cost, although common, fails to capture the nature of the batching problem. In reality, there is often no real setup cost with respect to cash flows being affected. Setup costs are rather a surrogate for violation of capacity constraints. Therefore, the idea of a fixed setup cost, independent of the solution, is quite misleading since it is rather a consequence of the solution. There are real setup costs in terms of material consumption but they should be distinguished from opportunity costs caused by lost production capacity (Karmarkar, 1987).

Finally, one can spend months to nail the exact value of the setup cost precisely, but it is more useful to change the condition of the processes that determine the value of the setup cost, in order to actually reduce it (Silver, Pyke and Peterson, 1998). Single Minute Exchange of Die (SMED) is a renowned theory in lean manufacturing that deals with this issue.

3.4 Single Minute Exchange of Die

Many manufacturing companies consider High mix, Low volume production as their single greatest challenge. However, at any rate, problem facing companies is not High mix, Low volume production but production involving frequent setups and small lot sizes. SMED system, also known as Single-minute setup, refers to theory and techniques for performing setup operations under ten minutes, i.e., a number of minutes that can be expressed in a single digit. Although not every setup operation can be performed in single-digit minutes, this is the goal of the system and can be met in surprisingly high percentage of cases. Even when it cannot, drastic reductions in setup times are usually possible. SMED was later adopted by all Toyota plants and became one of the core elements of Toyota Production System (Shingo, 1985).

According to Shingo (1985), setup operations have traditionally demanded a great amount of time and have caused a great deal of inefficiencies in manufacturing companies. Increasing lot sizes was a solution found to this problem. If lot sizes are increased, the ratio of setup time over the number of operations is greatly reduced (Table 1):

Table 1: Relationship between setup time and lot size (Shingo, 1985)

Setup Time	Lot Size	Principal Operation Time Per Item	Operation Time	Ratio (%)	Ratio (%)
4 hrs.	100	1 min.	$1\,min. + \frac{4 \times 60}{100} = 3.4\,min.$	100	
4 hrs.	1000	1 min.	$1\,min. + \frac{4 \times 60}{1000} = 1.24\,min.$	36	100
4 hrs.	10000	1 min.	$1\,min. + \frac{4 \times 60}{10000} = 1.024\,min.$	30	83

As Table 1 shows, increasing the lot size from 100 to 1000 will result in 64% reduction in man-hours. Increasing the lot size by another factor of ten will result in only 17% further reduction. This means increasing the lot size for a small lot tends to create a greater reduction in man-hours than for a large lot. Therefore as size increases, the rate of reduction decreases. Similarly, as it is shown in Table 2, the gains in man-hours reduction are greater for longer setup times (Shingo, 1985):

Table 2: Relationship between setup time and lot size for a longer setup time (Shingo, 1985)

Setup Time	Lot Size	Principal Operation Time Per Item	Operation Time	Ratio (%)	Ratio (%)
8 hrs.	100	1 min.	$1\ min. + \frac{8 \times 60}{100} = 5.8\ min.$	100	
8 hrs.	1000	1 min.	$1\ min. + \frac{8 \times 60}{1000} = 1.48\ min.$	26	100
8 hrs.	10000	1 min.	$1\ min. + \frac{8 \times 60}{10000} = 1.048\ min.$	18	71

However, there are a series of disadvantages accompanied by large lot sizes (Shingo, 1985):

- Capital turnover rates decrease.
- Inventory itself does not produce any added value and the physical space it occupies is entirely wasted.
- Storing large lots as inventories requires installation of racks and pallets and so forth, which increases the cost.
- Transportation and handling the inventory require excess man-hours.
- Large lots create long lead times and long lead times mean new orders are delayed and deadlines are missed.
- If any changes happen in the models, previous stocks must be disposed.
- Inventory quality deteriorates over time.

Economic Order Quantities (EOQs) were a solution found to balance out the advantages and disadvantages of large lot sizes. There is no doubt that the concept of Economic Order Quantity is entirely true, but it conceals a massive blind spot: the assumption that setup times cannot be reduced (Shingo, 1985).

If a four-hour setup time for a press machine was reduced to three minutes – adoption of SMED methods has made this possible at Toyota – then without increasing the lot size, the ratio of setup time over main operation time would decrease dramatically. As shown in Table 3, increasing the lot size of an operation with the setup time of three minutes will decrease the man-hours only by three percent (Shingo, 1985):

Table 3: Relationship between setup time and lot size for a short setup time (Shingo, 1985)

Setup Time	Lot Size	Principal Operation Time Per Item	Operation Time	Ratio (%)
3 min.	100	1 min.	$1\ min. + \frac{3}{100} = 1.03\ min.$	100
3 min.	1000	1 min.	$1\ min. + \frac{3}{1000} = 1.003\ min.$	97

3.4.1 Fundamentals of SMED

According to Shingo (1985), setup operations are classified into two categories: *Internal Setup* (IED, or inside exchange of die) which can be performed only when the machine is shut down and *External Setup* (OED, or outside exchange of die) which can be performed while machine is running. For example, a new die can be attached to a press only when the machine is stopped but the bolts to attach the die can be sorted and assembled while the press is working. As it is shown in Figure 12, setup improvement activities are classified into four conceptual stages (Shingo, 1985):

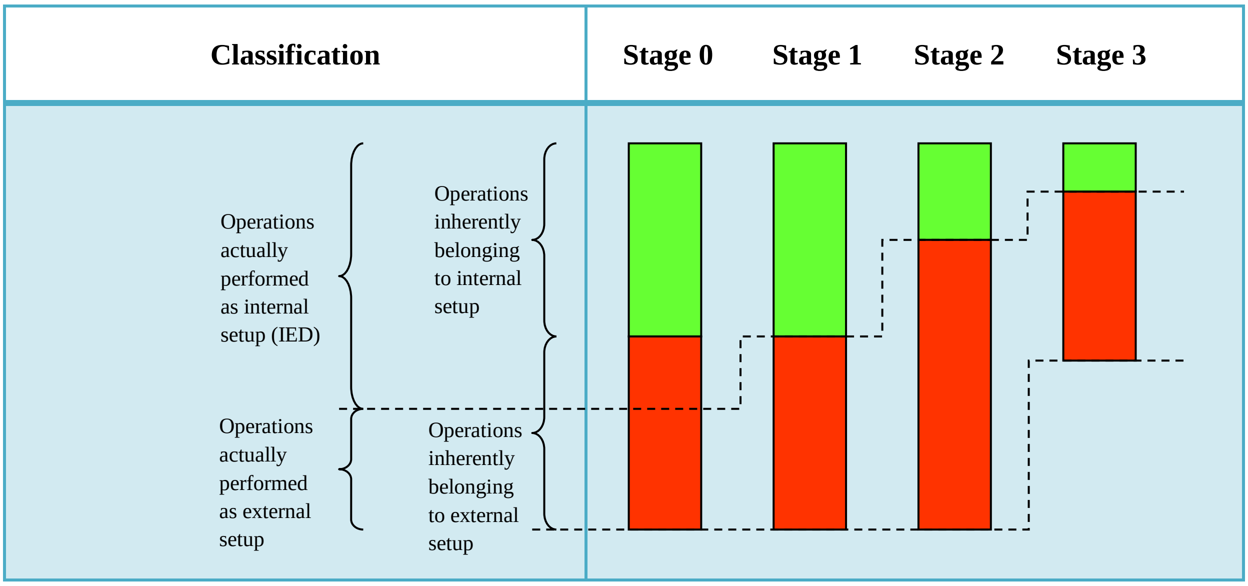

Figure 12: Conceptual stages for setup improvement (Shingo, 1985)

Preliminary Stage: Internal and external setups are not distinguished

In traditional setup operations, internal and external setups are confused; what could be done as an external setup is performed as internal and therefore setup operations are long and machines stay idle for a longer period. In order to distinguish between the two, one must study the actual shop floor conditions in great detail.

Stage 1: Separating internal and external setup

The most important step in implementing SMED is distinguishing between these two. Mastering this distinction is the passport towards SMED goal.

Stage 2: Converting internal setup to external

Distinguishing between internal and external setup activities alone can result in significant setup time reduction in some cases. However, this is still insufficient to achieve SMED objective. The second stage involves two important notions:

- Re-examining the operations to see if any step is wrongly assumed to be internal
- Finding ways to convert these steps to external setup activity

An example could be preheating some elements that have previously been heated only when setup starts or converting centering to an external operation by doing it before the production begins.

Stage 3: Streamlining all aspects of setup operation

Although the single-minute goal can be achieved by converting to external setup in many occasions, this is not true in majority of cases. Therefore one must make a strong effort in streamlining all elements of internal and external setup. Therefore, stage 3 requires detailed analysis of each element of setup operations. Parallel operations involving more than one operator can be very helpful in speeding up this kind of work. For example, an internal operation that takes 12 minutes by one operator can be performed in less than 6 minutes in many cases by involving two operators, thanks to the economies of movements.

3.4.2 Discussion over SMED

Despite the many arguments for setup time reductions in the existing literature, the issue of justifying investments on setup reductions and optimally allocating finite resources has to a large extent been glossed over (Nye, Jewkes and Dilts, 2001). For example, one of the main objectives of SMED system is to reduce setup times to less than 10 minutes (Shingo, 1985), without offering any reason for this particular target, nor mentioning what target is appropriate in many cases where setup times cannot be reduced to less than 10 minutes (Nye, Jewkes and Dilts, 2001). The philosophy that companies should strive for zero setup times is laudable, but it may not be a realistic objective. For example, a manufacturer of N different products can achieve zero setup time by allocating N parallel production systems. Clearly, N does not need to be very large before the cost of investments to reach zero setups far exceeds any potential economic advantages (Nye, Jewkes and Dilts, 2001).

However, it is clear that flexibility is strongly linked with small lot sizes. The smaller the lot sizes are, the easier it is for a manufacturing company to react to changes in the market demand (Sherali, Goubergen and Landeghem, 2008). Goubergen and Landeghem (2002) describe three reasons why short setups are appropriate for any company:

- Companies need to be flexible. Flexibility requires small lot sizes and small lot sizes need short setups.
- Setups need to be reduced to maximize the capacity and reduce the bottlenecks.
- Short setups increase machine performance and OEE and therefore decrease production cost.

Ferradás and Salonitis (2013) argue that although SMED is known for about twenty five years and has been implemented successfully in many companies, a number of plants have failed to implement it. One reason is that some companies put too much attention on transferring internal activities to external activities, missing the importance of streamlining both activities by design improvements (Ferradás and Salonitis, 2013). Gest, et al. (1995) say that the main reason some companies fail in SMED implementation is that they lack structure and focus. It is not uncommon for a SMED project to lose momentum and wither away after a while. In many cases, the SMED improvements have been through shop floor kaizen-based initiatives and early gains have reverted back to previous levels once the management focus has changed (Gest et al., 1995). Ferradás and Salonitis (2013), as shown in Figure 13, argue that if focus of a SMED project is only on methodology, the result can be poor. By combining design modifications and methodology improvements the results can be acceptable with moderate investments. The design of a completely new system is out of scope of a SMED project; however, the outcome can be excellent.

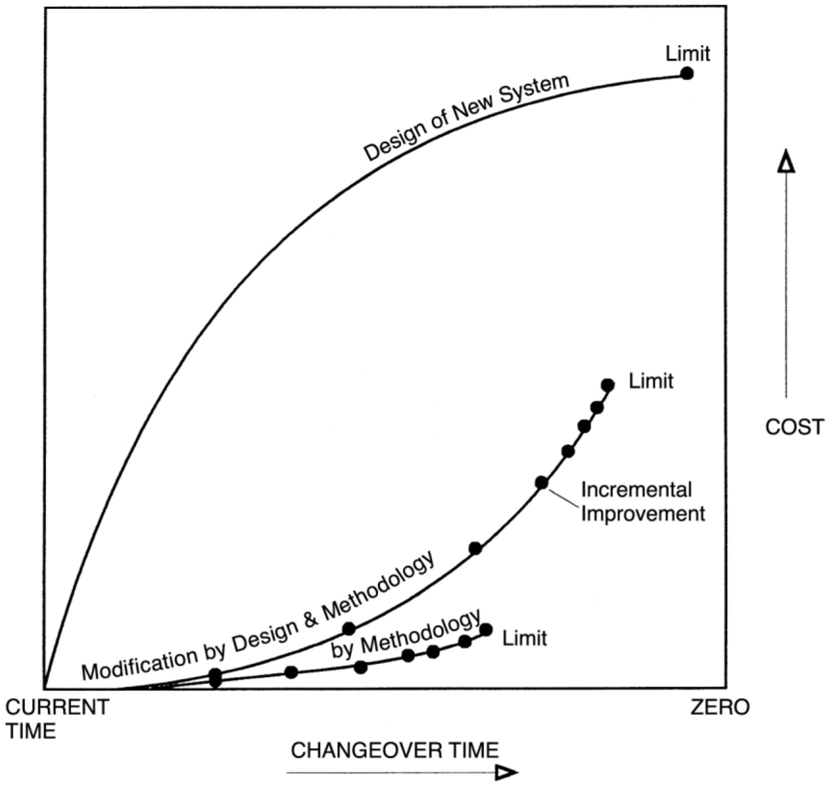

Figure 13: Limits and costs of changeover improvement strategies (Ferradás and Salonitis, 2013)

Another shortcoming of SMED method is that it discusses setup operations performed on one machine and by one operator while in practice, implementation should be performed in a manufacturing line formed by multiple machines (Sherali, Goubergen and Landeghem, 2008). When a changeover is performed in a manufacturing cell, SMED methodology is not specific about how the setup time should be measured (Ferradás and Salonitis, 2013). Sherali, Goubergen and Landeghem (2008) argue that when an entire line needs to be set up, it is the downtime of the entire line that should be considered. Therefore, the overall setup time should be measured at the last machine in the line since we are adding value only when products are coming out of the end of the line.

3.5 Linear optimization, nonlinear optimization

Another technique that can be used to find optimum batch sizes is Operations Research (OR). OR is a field that uses mathematical programming to find optimum values of an optimization problem. Linear programming (LP) is the most basic mathematical programming. LP refers to an optimization problem where both objective function and constraints are linear (Pinedo, 2005). According to Pinedo (2005), an LP can be expressed as follows:

$$Minimize\ Z = c_1x_1 + c_2x_2 + \cdots + c_nx_n$$

Subject to

$$a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \leq b_1$$

$$a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \leq b_2$$

$$\vdots$$

$$a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \leq b_m$$

$$x_i \geq 0 \qquad for\ i = 1, 2, 3, \dots, n$$

The vector $c_1, c_2, \dots, c_n$is referred to as cost vector. The objective of the LP is to minimize the cost by determining the optimum value of variables $x_1, x_2, \dots, x_n$. The Column vector $a_{11}, \dots, a_{mn}$ is called activity vector. The value of the variable x_i refers to the level at which the activity i is performed. The vector $b_1, b_2, \dots, b_m$ is called the resource vector and determines the resource limitations (Pinedo, 2005).

The main assumption of LP is that all of its functions - objective function or constraint functions - are linear. Although for many cases and examples this assumption applies, there are numerous cases where linearity assumption does not hold. For example, economists agree that some degree of nonlinearity is a rule not an exception in their economic planning problems (Hillier and Lieberman, 2001). A nonlinear programming (NLP) is a generalization of linear programming which allows the objective function or the constraints to be nonlinear (Pinedo, 2005).

3.6 Exact methods, Heuristics

In order to solve an OR problem one needs to implement a proper optimization algorithm. In general there are two classes of optimization algorithms: *exact methods* and *heuristic methods*. Exact methods try to find a global optimal solution to the problem no matter how long it takes. Heuristics try to find a near optimal answer in a short time. Exact methods use mathematical methods to guarantee that their solutions are optimal. They can be efficient for problems with small or medium size but they require large amount of time for problems with larger size. Heuristics, however, are algorithms based on rules of thumb or common sense, or refinements of exact methods (Rader, 2010).

Exact methods may have to examine every feasible solution before confirming optimality. Therefore, for many problems concerning the real world, exact methods can be very time consuming. Besides, those who are interested in solving the real world problems often do not have the time for guaranteed optimality when a reasonable solution will suffice. In these cases, heuristic methods are often used (Rader, 2010). For instance, from 2003 to 2004 a group of researchers tried to find the optimal tour through 24978 cities, towns and villages in Sweden. This is an example of famous traveling salesperson problem that has been studied for years by operations researchers. The optimal tour was obtained using heuristic methods within a few hours of CPU time and it was later confirmed to be optimal after 84.4 CPU years – exact algorithm was run in parallel in a series of workstations – (Rader, 2010).

3.6.1 Genetic Algorithm

Genetic Algorithm (GA) is one of the most famous and widely used heuristic algorithms. GA is a heuristic method that solves large constrained and unconstrained optimization problems by using a process that mimics natural selection in biological evolution. The algorithm works by repeatedly modifying a population of candidate solutions. At each iteration, the algorithm selects individuals from the current population and uses them as parents to create the next generation. Over successive generations, the population evolves towards a better optimal solution (Mathworks.se, 2014). Genetic algorithm is highly suited for optimization problems where standard algorithms cannot be applied easily. This includes problems where objective function or constraints are discontinuous, non-differentiable, stochastic or highly nonlinear (Mathworks.se, 2014).

Genetic algorithm is different from other classical heuristics in two main ways (Mathworks.se, 2014):

1) The classical algorithms create a single point at each iteration and the sequence of single points moves towards an optimal solution while GA produces a population of points at each iteration and the best point in the population approaches the optimal solution.
2) Classical algorithms create each successive point using deterministic computation while GA computes successive generations using random number generators.

The following procedure describes how genetic algorithm works (Mathworks.se, 2014):

1) The algorithm begins by creating an initial population using random numbers.
2) The algorithm starts to generate a sequence of populations. In order to create the next generation, the algorithm uses the individuals in the current population by performing the following steps:

    a) Rates each member of the current population by evaluating its fitness value
    b) Scales the scored values to turn them into more usable set of values
    c) Selects individuals, called parents, based on their fitness value
    d) Some of the individuals with the best fitness value are chosen as elites. These elites pass to the next generation.
    e) From the parents, children are produced. Children are produced either by *crossover* or by *mutation*.
    f) Children replace the current population and form the next generation

3) The algorithm stops, when one of the stopping criteria is met.

The process of mutation and crossover are depicted in Figure 14:

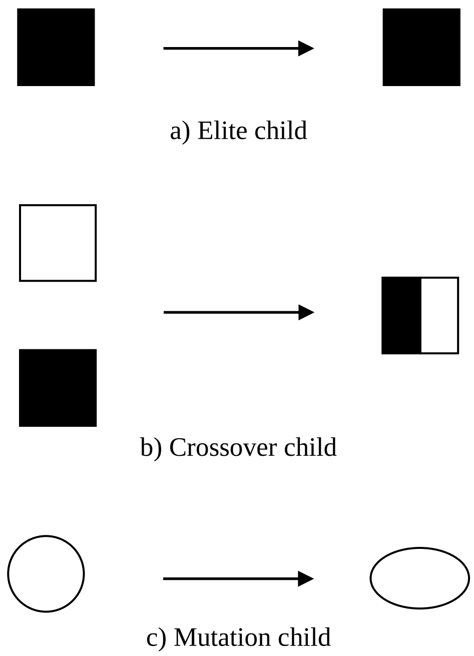

Figure 14: a) Elite child. b) Crossover child. c) Mutation child (Mathworks.se, 2014)

4. Results (Empirics)

In this chapter, empirical results are presented. The EOQs are calculated for the boards followed by a discussion over setup cost. Then, an optimization model is presented for solving the problem and results are illustrated with tables and figures.

4.1 Calculating EOQs

Through IFS system, one can find the current batch sizes used for different boards. In order to find the optimum batches for each board, the first idea was to calculate the EOQs for every board and compare them with the current batch sizes to get a general idea of the current situation. According to EOQ formula $\sqrt{\frac{2DS}{H}}$, there are three parameters that need to be identified for each board to calculate the economic order quantity: D, representing the annual demand for each board; S, representing the setup cost for each board and H, representing the annual inventory holding cost for each board. The annual demands for boards are obtainable through IFS. Every demand or production order is recorded in the system by the date of order and is transferable to an excel file. Through the excel file, the total demand for each board can be calculated. The time span for the orders was chosen as first day of January to last day of December 2013. This way, there is no need to rely on this year forecasts and recent historical data can be used. After calculating annual demands, inventory holding costs should be defined. Based on information from the financial department, the annual inventory cost is 10 percent of the inventory value of the boards. The price of each board is accessible through IFS. By multiplying this price with 0.1 – the inventory holding rate – the annual holding cost can be obtained. The last parameter to define is the setup cost. According to the company's financial department, setup costs are consisted of three parts. The employee's salary, the overhead cost for the whole factory and the overhead cost for the SMT workstation with values 1190 SEK, 716 SEK and 414 SEK per hour respectively and the total cost of 2320 SEK. The logic behind it is that this is the cost that company has to bear. When setups are performed, no value added activity is performed to cover these costs and therefore they are considered as setup cost. The average setup time is about 22 minutes or 0.36 hr based on IFS data. Although this number is not accurate and setup durations differ for each board, but it is a good approximation of the average time spent for changing over the machines from one board to another. The setup cost therefore will be this time presented in hour, multiplied by the hourly setup cost. The results of these calculations are presented in Table 4.

The boards are represented by X_i in the table below. Minimum lot sizes are the current batch sizes used for production. They refer to the amount that should be produced if the demand cannot be met by the existing boards in inventory. For example, for a minimum lot size of 30, if the inventory level for that particular board is 15 units and the demand is 20, a production order of 30 will be issued to meet the demand. The new inventory level will be 15 + 30 – 20 = 25. However if the demand is even more, for example 55, a lot size of 30 cannot satisfy the demand. In order to meet this large demand, a production order of 55 – 15 = 40 will be issued.

Some of the boards – which usually have low demand and high price – are produced only based on customer order quantity, meaning that if the customer wants a batch of 25, a batch of 25 will be produced and delivered. Some other boards are prototypes and are not produced regularly. These boards, all together, have a minimum lot size of zero, indicating that there are produced only when there is a demand for them.

Standard lot sizes are used to calculate the setup cost per each board. For example, if the standard lot size for a particular board is 30, the cost of setup for this type of board is divided over 30 to calculate the setup cost per board.

Table 4: The Economic Order Quantities calculated for boards

Boards	Min Lot Size	Standard Lot Size	Annual Demand	Price SEK	EOQ
X1	10	10	150	158,52	126
X2	20	30	24	112,88	60
X3	3	60	21	161,45	47
X4	10	10	62	245,93	65
X5	20	20	92	168,03	96
X6	20	20	328	82,49	258
X7	30	30	133	105,02	145
X8	30	40	690	62,64	429
X9	0	20	6	84,96	34
X10	3	3	24	338,81	34
X11	40	40	590	63,45	394
X12	0	20	364	83,44	270
X13	20	20	36	154,16	62
X14	30	30	372	182,45	185
X15	20	20	44	147,75	71
X16	20	20	49	299,15	52
X17	0	30	19	138,76	48
X18	40	40	792	119,02	333
X19	60	60	192	70,11	214
X20	60	60	808	69,05	442
X21	30	30	284	118,63	200
X22	12	12	464	408,35	138
X23	12	12	212	350,13	101
X24	18	18	8	425,35	18
X25	60	60	264	295,43	122
X26	60	60	268	147,69	174
X27	20	20	24	579,93	26
X28	20	20	814	227,25	245
X29	20	20	412	232,47	172
X30	60	60	1226	79,07	509
X31	24	24	196	135,8	155
X32	0	50	1076	213,88	290
X33	40	40	996	214,02	279
X34	40	40	472	217,73	190
X35	100	100	2560	190,29	474
X36	50	50	2424	168,67	490
X37	30	40	970	184,89	296
X38	100	100	2443	142,56	535
X39	16	20	140	191,06	111
X40	20	20	370	465,1	115
X41	100	100	4378	375,24	441
X42	250	250	6590	261,8	648
X43	20	20	280	305,97	124
X44	20	20	281	424,09	105
X45	60	60	1499	370,84	260
X46	80	80	1480	85,44	538

X47	60	60	1586	197,85	366
X48	50	60	1406	230,18	319
X49	20	40	432	247,47	171
X50	42	60	1794	97,1	556
X51	12	12	42	195,23	60
X52	40	80	1449	91,47	514
X53	80	80	1632	96,66	531
X54	20	20	363	317,25	138
X55	80	80	2981	92,77	733
X56	70	70	2185	393,22	305
X57	90	90	2176	39,31	962
X58	100	100	2030	357,56	308
X59	90	90	2014	30,78	1045
X60	300	300	4327	44,41	1276
X61	20	20	180	481,59	79
X62	60	60	180	73,03	203
X63	0	24	174	110,19	162
X64	20	20	152	439,06	76
X65	10	10	24	300,08	37
X66	0	10	17	1572,85	13
X67	8	8	77	569,25	48
X68	10	20	294	668,33	86
X69	180	180	5821	581,26	409
X70	60	60	1830	167,52	427
X71	40	40	462	167,89	214
X72	70	70	1348	125,22	424
X73	20	20	688	144,07	282
X74	60	60	230	847,85	67
X75	60	60	230	464,95	91
X76	100	100	3603	962,17	250
X77	10	50	15	373,26	26
X78	100	100	3660	379,99	401
X79	200	200	5251	335,64	511
X80	40	40	996	1905,95	93
X81	5	8	4	374,05	13
X82	200	200	3520	51,98	1064
X83	120	120	3789	202,94	558
X84	0	30	200	227,75	121
X85	0	60	200	43	279
X86	120	120	3794	39,46	1267
X87	0	20	72	498,67	49
X88	0	20	113	704,04	52
X89	0	20	95	1083	38
X90	0	20	28	1628,67	17
X91	0	20	8	609,96	15
X92	0	12	88	570,33	51
X93	0	20	37	610,19	32
X94	0	20	113	410,81	68
X95	0	20	52	525,68	41
X96	0	10	106	1969,74	30
X97	0	20	54	2022,11	21
X98	0	20	58	704,04	37
X99	0	20	72	1010,5	34
X100	0	20	40	514,65	36
X101	0	20	38	410,81	39

X102	0	20	35	1927,21	17
X103	0	20	16	296,6	30
X104	80	80	2484	434,81	309
X105	40	40	951	381,37	204
X106	0	20	4	1239,87	7
X107	0	30	221	227,75	127
X108	0	60	311	43	348
X109	40	40	260	156,06	167
X110	20	40	210	305,33	107
X111	30	30	252	269,25	125
X112	0	20	28	292,4	40
X113	50	50	322	204,03	162
X114	40	40	640	347,37	175
X115	0	80	180	318,62	97
X116	40	40	338	491,88	107
X117	40	40	1220	458,89	211
X118	0	20	232	636,37	78
X119	0	20	112	480,16	62
X120	40	40	1286	472,91	213
X121	0	20	233	505,74	88
X122	0	20	127	494,4	66
X123	20	20	342	207,92	166
X124	40	100	774	190,92	260
X125	40	40	338	672,44	92
X126	0	30	16	588,15	21
X127	0	20	948	1462,96	104
X128	0	20	1516	634,65	200
X129	0	20	539	2206,97	64
X130	0	20	334	2025,49	52
X131	0	20	493	1371,23	77
X132	0	20	247	1472,85	53
X133	0	20	118	1937,11	32
X134	0	20	764	1558,08	91
X135	0	20	787	571,11	152
X136	200	200	9685	329,99	700
X137	0	20	188	345,42	95
X138	160	160	4944	971,25	292
X139	40	40	277	1451,76	56
X140	40	40	175	974,01	55
X141	40	40	320	1023,75	72
X142	40	40	18	1283,37	15
X143	40	40	1693	1084,07	162
X144	60	100	774	1143,52	106
X145	60	120	774	173,75	273
X146	60	60	2433	1168,08	187
X147	60	60	2433	310,5	362
X148	0	20	109	1455,41	35
X149	0	20	99	634,65	51
X150	0	20	83	2206,97	25
X151	0	20	38	1462,16	21
X152	40	40	1011	1059,75	126
X153	0	40	267	777,51	76
X154	0	20	72	1283,74	31
X155	60	60	669	537,3	144
X156	0	40	24	637,17	25

X157	0	20	69	565,14	45
X158	80	80	2519	472,03	299
X159	40	40	378	271,92	152
X160	0	20	23	650,64	24
X161	0	20	76	534,67	49
X162	20	20	641	891,38	110
X163	20	40	138	811	53
X164	0	20	76	891,38	38
X165	0	20	4	832,26	9
X166	20	20	641	781,26	117
X167	0	20	73	781,26	40
X168	60	60	1648	57,27	693
X169	40	40	372	509,43	110
X170	60	60	1316	477,9	214
X171	20	20	128	864,07	50
X172	20	20	267	711,74	79
X173	20	20	354	1196,4	70
X174	40	40	950	1139,62	118
X175	60	60	623	217,67	219
X176	40	60	676	55,32	452
X177	0	20	68	143,45	89
X178	0	20	75	272,07	68
X179	20	20	382	1087,27	77
X180	0	20	56	1308,66	27
X181	0	20	42	69,5	100
X182	0	20	16	69,5	62
X183	0	80	37	547,55	34
X184	0	40	45	483,92	39
X185	0	20	27	2022,11	15
X186	0	20	44	143,45	72
X187	0	80	59	466,78	46
X188	0	40	12	618,69	18

As it is clear from the table above, the EOQs are extremely big. Some of the boards with low demands have EOQs even larger than their total annual demands, meaning that it is better to produce the whole demand in one batch! One board with annual demand of 24 (X_2) had an EOQ of 60! Another board with a demand of 21 (X_3) had an EOQ of 47! For one board (X_{60}), which has a total demand of 4327, price of 44.41 SEK and minimum batch size of 300 units, the EOQ was 1276 units! In contrast, board X_{74} with the demand of 230, price of 847.85 and minimum lot size of 60, has an EOQ, very close to its minimum lot size, of only 67. As another example, X_{75} with demand of 230 and minimum batch size of 60, has an EOQ equal to 91 which is not so much higher than its minimum lot size. However, these two are exceptions. The reasons behind these large quantities are large *defined setup costs* and low *defined inventory holding costs*.

4.2 Discussion over setup cost

If we assume that the value of the setup cost is true, then we should turn our attention somewhere else to find the reason behind these large batches. It should be remembered that inventory holding cost was defined very low – 0.1 or 10% – while it is common to consider it between 0.2 and 0.4. There are many costs that are obviously not included in the current value. For example, the cost of inventory deterioration or corrosion of the boards, the cost of space for holding large inventories or the opportunity cost of the capital tied up to inventory.

However, even by considering an inventory holding cost of 0.4 – the EOQs would be half – the batch sizes are still too large (Table 5):

Table 5: The Economic Order Quantities calculated for boards

Boards	Min Lot Size	Standard Lot Size	Demand	Price (SEK)	EOQ with inventory holding cost of 40%
X1	10	10	150	158,52	63
X2	20	30	24	112,88	30
X3	3	60	21	161,45	23
X4	10	10	62	245,93	32
X5	20	20	92	168,03	48
X6	20	20	328	82,49	129
X7	30	30	133	105,02	73
X8	30	40	690	62,64	214
X9	0	20	6	84,96	17
X10	3	3	24	338,81	17
X11	40	40	590	63,45	197
X12	0	20	364	83,44	135
X13	20	20	36	154,16	31
X14	30	30	372	182,45	92
X15	20	20	44	147,75	35
X16	20	20	49	299,15	26
X17	0	30	19	138,76	24
X18	40	40	792	119,02	167
X19	60	60	192	70,11	107
X20	60	60	808	69,05	221
X21	30	30	284	118,63	100
X22	12	12	464	408,35	69
X23	12	12	212	350,13	50
X24	18	18	8	425,35	9
X25	60	60	264	295,43	61
X26	60	60	268	147,69	87
X27	20	20	24	579,93	13
X28	20	20	814	227,25	122
X29	20	20	412	232,47	86
X30	60	60	1226	79,07	254
X31	24	24	196	135,8	78
X32	0	50	1076	213,88	145
X33	40	40	996	214,02	139
X34	40	40	472	217,73	95
X35	100	100	2560	190,29	237
X36	50	50	2424	168,67	245
X37	30	40	970	184,89	148
X38	100	100	2443	142,56	268
X39	16	20	140	191,06	55
X40	20	20	370	465,1	58
X41	100	100	4378	375,24	221
X42	250	250	6590	261,8	324
X43	20	20	280	305,97	62
X44	20	20	281	424,09	53
X45	60	60	1499	370,84	130
X46	80	80	1480	85,44	269

X47	60	60	1586	197,85	183
X48	50	60	1406	230,18	160
X49	20	40	432	247,47	85
X50	42	60	1794	97,1	278
X51	12	12	42	195,23	30
X52	40	80	1449	91,47	257
X53	80	80	1632	96,66	266
X54	20	20	363	317,25	69
X55	80	80	2981	92,77	366
X56	70	70	2185	393,22	152
X57	90	90	2176	39,31	481
X58	100	100	2030	357,56	154
X59	90	90	2014	30,78	523
X60	300	300	4327	44,41	638
X61	20	20	180	481,59	40
X62	60	60	180	73,03	101
X63	0	24	174	110,19	81
X64	20	20	152	439,06	38
X65	10	10	24	300,08	18
X66	0	10	17	1572,85	7
X67	8	8	77	569,25	24
X68	10	20	294	668,33	43
X69	180	180	5821	581,26	205
X70	60	60	1830	167,52	214
X71	40	40	462	167,89	107
X72	70	70	1348	125,22	212
X73	20	20	688	144,07	141
X74	60	60	230	847,85	34
X75	60	60	230	464,95	45
X76	100	100	3603	962,17	125
X77	10	50	15	373,26	13
X78	100	100	3660	379,99	201
X79	200	200	5251	335,64	256
X80	40	40	996	1905,95	47
X81	5	8	4	374,05	7
X82	200	200	3520	51,98	532
X83	120	120	3789	202,94	279
X84	0	30	200	227,75	61
X85	0	60	200	43	139
X86	120	120	3794	39,46	634
X87	0	20	72	498,67	25
X88	0	20	113	704,04	26
X89	0	20	95	1083	19
X90	0	20	28	1628,67	8
X91	0	20	8	609,96	7
X92	0	12	88	570,33	25
X93	0	20	37	610,19	16
X94	0	20	113	410,81	34
X95	0	20	52	525,68	20
X96	0	10	106	1969,74	15
X97	0	20	54	2022,11	11
X98	0	20	58	704,04	19
X99	0	20	72	1010,5	17
X100	0	20	40	514,65	18
X101	0	20	38	410,81	20

X102	0	20	35	1927,21	9
X103	0	20	16	296,6	15
X104	80	80	2484	434,81	154
X105	40	40	951	381,37	102
X106	0	20	4	1239,87	4
X107	0	30	221	227,75	64
X108	0	60	311	43	174
X109	40	40	260	156,06	83
X110	20	40	210	305,33	54
X111	30	30	252	269,25	63
X112	0	20	28	292,4	20
X113	50	50	322	204,03	81
X114	40	40	640	347,37	88
X115	0	80	180	318,62	49
X116	40	40	338	491,88	54
X117	40	40	1220	458,89	105
X118	0	20	232	636,37	39
X119	0	20	112	480,16	31
X120	40	40	1286	472,91	107
X121	0	20	233	505,74	44
X122	0	20	127	494,4	33
X123	20	20	342	207,92	83
X124	40	100	774	190,92	130
X125	40	40	338	672,44	46
X126	0	30	16	588,15	11
X127	0	20	948	1462,96	52
X128	0	20	1516	634,65	100
X129	0	20	539	2206,97	32
X130	0	20	334	2025,49	26
X131	0	20	493	1371,23	39
X132	0	20	247	1472,85	26
X133	0	20	118	1937,11	16
X134	0	20	764	1558,08	45
X135	0	20	787	571,11	76
X136	200	200	9685	329,99	350
X137	0	20	188	345,42	48
X138	160	160	4944	971,25	146
X139	40	40	277	1451,76	28
X140	40	40	175	974,01	27
X141	40	40	320	1023,75	36
X142	40	40	18	1283,37	8
X143	40	40	1693	1084,07	81
X144	60	100	774	1143,52	53
X145	60	120	774	173,75	136
X146	60	60	2433	1168,08	93
X147	60	60	2433	310,5	181
X148	0	20	109	1455,41	18
X149	0	20	99	634,65	26
X150	0	20	83	2206,97	13
X151	0	20	38	1462,16	10
X152	40	40	1011	1059,75	63
X153	0	40	267	777,51	38
X154	0	20	72	1283,74	15
X155	60	60	669	537,3	72
X156	0	40	24	637,17	13

X157	0	20	69	565,14	23
X158	80	80	2519	472,03	149
X159	40	40	378	271,92	76
X160	0	20	23	650,64	12
X161	0	20	76	534,67	24
X162	20	20	641	891,38	55
X163	20	40	138	811	27
X164	0	20	76	891,38	19
X165	0	20	4	832,26	4
X166	20	20	641	781,26	59
X167	0	20	73	781,26	20
X168	60	60	1648	57,27	347
X169	40	40	372	509,43	55
X170	60	60	1316	477,9	107
X171	20	20	128	864,07	25
X172	20	20	267	711,74	40
X173	20	20	354	1196,4	35
X174	40	40	950	1139,62	59
X175	60	60	623	217,67	109
X176	40	60	676	55,32	226
X177	0	20	68	143,45	44
X178	0	20	75	272,07	34
X179	20	20	382	1087,27	38
X180	0	20	56	1308,66	13
X181	0	20	42	69,5	50
X182	0	20	16	69,5	31
X183	0	80	37	547,55	17
X184	0	40	45	483,92	20
X185	0	20	27	2022,11	7
X186	0	20	44	143,45	36
X187	0	80	59	466,78	23
X188	0	40	12	618,69	9

The logic behind economic quantities is to balance out the two costs of inventory holding and setups (Figure 15). The new economic quantities, as shown in the table above, are almost twice as big as the current batch sizes in most cases. As mentioned before, there is no doubt that the concept of economic lot sizes is entirely true. However, the value we choose as input data for the formula is our choice. The more accurate the data is, the more reasonable our answers will be. If we assume that our defined setup cost is correct, then we should accept the results for these new batch sizes. We should believe that by doubling the batch sizes we will get the optimum quantities and we will save money. In theory, if the setup cost is that high, then this conclusion is true. But before making any conclusion it is worth to take another look at the setup cost.

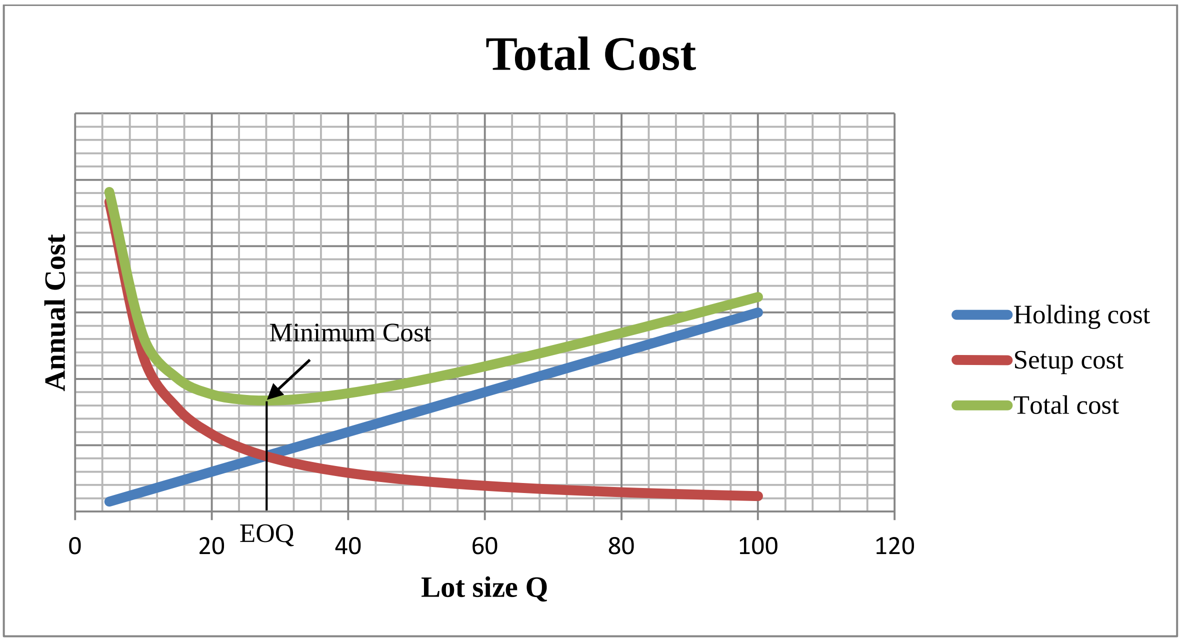

Figure 15: Annual total cost (Krajewski, Ritzman and Malhotra, 2007)

Let's consider a scenario where the SMT line works in three shifts during the week – current situation – and manages to produce all the demand for each week. There will be a number of setups performed every week and based on *our defined setup cost*, they will cause a total setup cost equal to number of setups during the week multiplied by the setup cost (Total setup cost = number of setups * setup cost). Based on this definition, any increase or decrease in number of setups must affect the total setup cost. Let's assume that the SMT line can produce all boards before the end of the week and there will still be some time left. For example, suppose the total available production time is 100 hours per week and the boards can be produced in 95 hours. If number of setups is slightly increased, the production of boards may take 96 hours. Having the total setup cost as the number of setups multiplied by setup cost (2320 SEK/hr × 0.36 hr), there should be an increase in the total setup cost for that week, but in reality there will be no changes in the cash flow. We will still pay the same amount of money for employee's salary and overhead costs. If the number of setups is reduced by having bigger batch sizes and boards are managed to be produced in 92 hours, there should be some money saved based on our assumptions but there will still be no changes in the cash flow. In reality, there will be no money saved. There can be as much increase in the number of setups as it causes the production of boards to take 100 hours, a number equal to the total production time. Even now there are no real changes in the cash flow.

However, there is a limit for the number of setups to which if they are increased more, the production of boards will take more than the available total time per week, for example 101 hours. The fact that this week's demand cannot be met this week and should be covered by next week's capacity, creates a real change in the cash flow since 1 hour production opportunity belonging to next week is lost. This time could be used to meet the next week's demand but now is lost and creates an unmet demand and therefore incurs a cost. This cost of production loss creates a real change in the cash flow and is directly caused by setups. Notice that before, many changes were made in the number of setups but cash flow did not change because there was no production loss. The moment this week's time limit is surpassed and next week's capacity is used to cover this week's demand, a negative change in the cash flow is created due to production loss. Therefore it is not unreasonable to define the setup cost as the cost of lost production, not the cost of employee's salary or overhead costs. This definition of setup cost complies with the setup cost definition by Karmarkar (1987) as it was mentioned before in the theory part.

However, this definition of setup cost creates a problem in calculation of economic order quantities. If setup cost is the cost of lost production rather than salaries and overheads, then it is a variable quantity, not a fixed value. The number of setups can be increased without facing any cost as long as no production loss is created. The moment the capacity constraint is violated, a cost related to lost production is incurred. This cost increases linearly as production loss increases. The new defined setup cost can be assumed to have a pattern as illustrated in Figure 16:

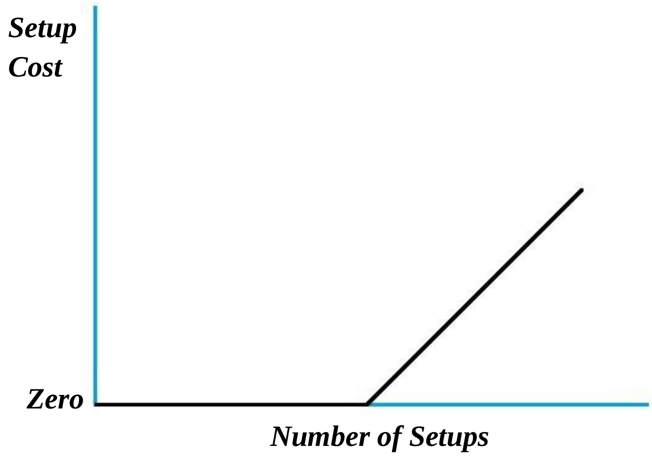

Figure 16: Setup cost based on number of setups

The economic order quantity formula requires us to assume a fixed value for setup cost. By contrast, the new definition of setup cost as the cost of lost production assumes setup cost to be a variable. As it was mentioned before in the theoretic framework, setup cost is a consequence of the solution (Karmarkar, 1987) rather than a fixed parameter of the problem. Having setup cost as a variable makes it impossible to use EOQ formula for calculating optimal batch sizes and therefore the EOQ formula should be put aside. A new way should be found for calculating optimum batch sizes.

4.3 Writing an optimization model

The annual inventory holding cost for an item is the result of multiplying its yearly average inventory level by its annual holding cost per unit. As it was mentioned before, based on the information from the financial department, the inventory holding cost per unit for an article (PCB board) is defined as 10 percent of its value. Therefore, if the price of a board is represented by C, its annual holding cost per unit can be expressed as $0.1 \times C$. If 0.1 is denoted by (a), the expression can be written as $a \times C$. By denoting the average inventory level for the same board as I_{ave}, the annual inventory holding cost for that board can be calculated by $a \times C \times I_{ave}$. This expression for one board can be extended to other boards too. By calculating the holding cost for each board and adding them together, the total inventory holding cost for all boards is obtained. If C_i represents the price of board (i) and $I_{ave,i}$ represents the average inventory level for board (i), by having a *10 percent* as a constant the total inventory holding cost for all the boards can be expressed as:

$$Total\ inventory\ holding\ cost = a \times C_1 \times I_{ave,1} + a \times C_2 \times I_{ave,2} + \ ... + a \times C_n \times I_{ave,n}$$

Where (n) is the total number of boards: $i = 1, 2, 3, \dots, n$.

This expression can be turned to the objective function of a minimization problem:

$$Minimize\ Z = a \times C_1 \times I_{ave,1} + a \times C_2 \times I_{ave,2} + \ ... + a \times C_n \times I_{ave,n}$$

$$for\ i = 1, 2, 3, \dots, n.$$

In order to find the optimum batch sizes for the boards, one can pursue the goal of minimizing the total inventory value of all boards. Since average inventory level for an item is in direct relation with its batch size, the I_{ave} for board i can be overwritten as a function of its batch size. As minimization tries to find the minimum value of Z, the optimal values for the batch sizes can be obtained. The only thing that remains is to find the relationship between each board's average inventory level (I_{ave}) and its batch size. After that, by adding appropriate constraints, this objective function can be turned into a complete optimization model in Operations Research.

In order to find the relationship between I_{ave} for board i and its batch size, one should start from probing the annual demand pattern for each board. The annual demands for a few of the boards are illustrated in Figures 17 to 20 below:

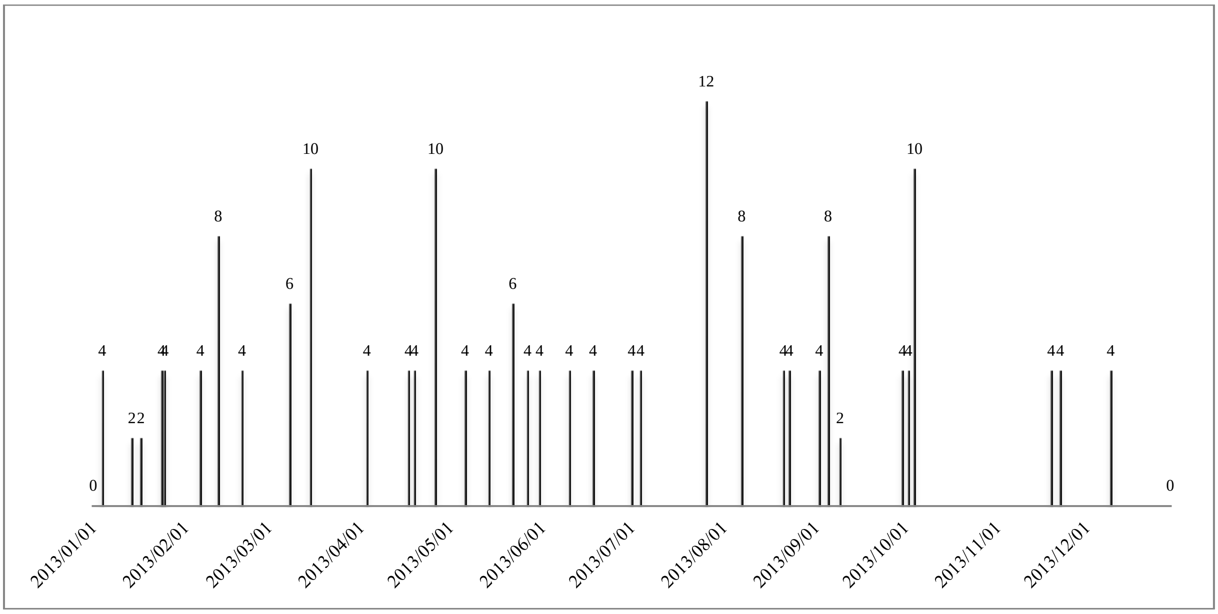

Figure 17: Annual demand for a board

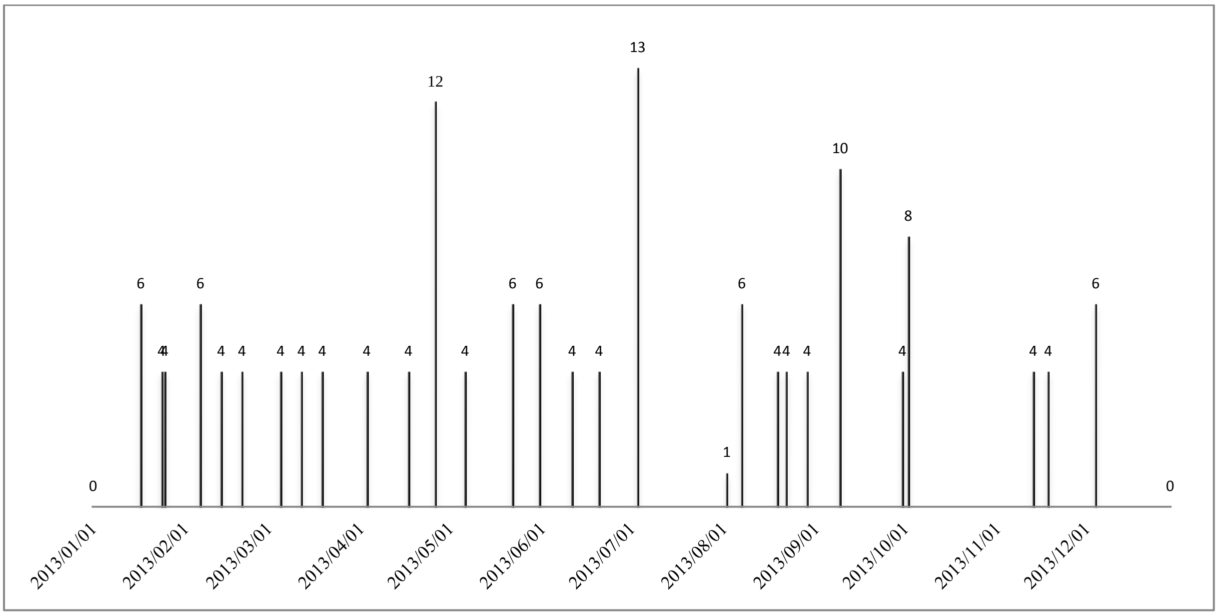

Figure 18: Annual demand for a board

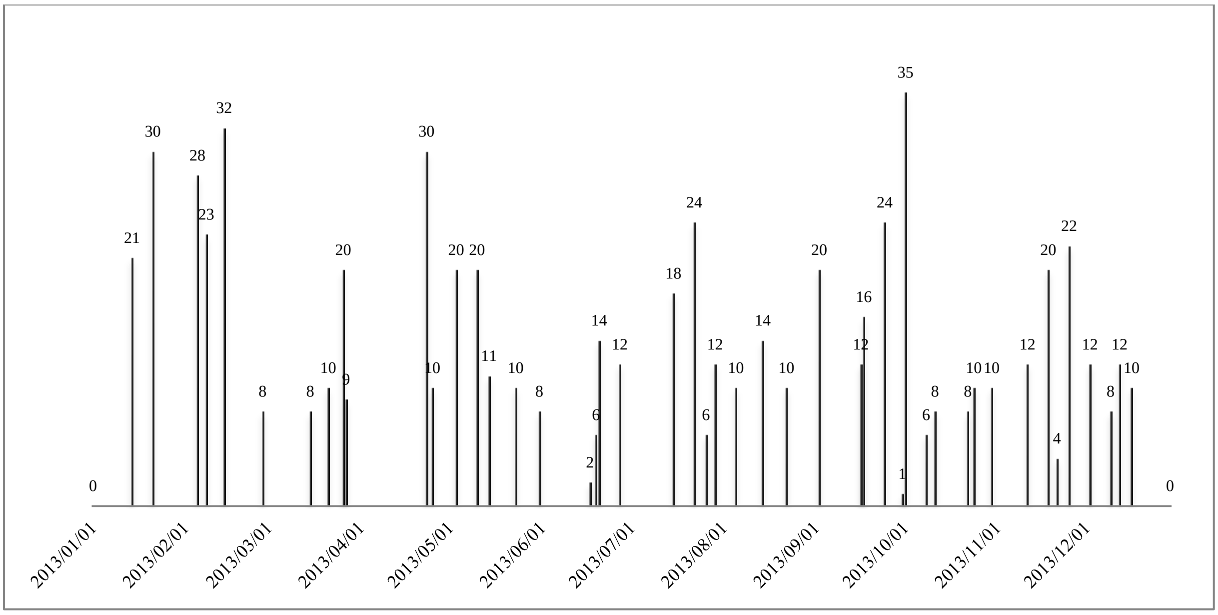

Figure 19: Annual demand for a board

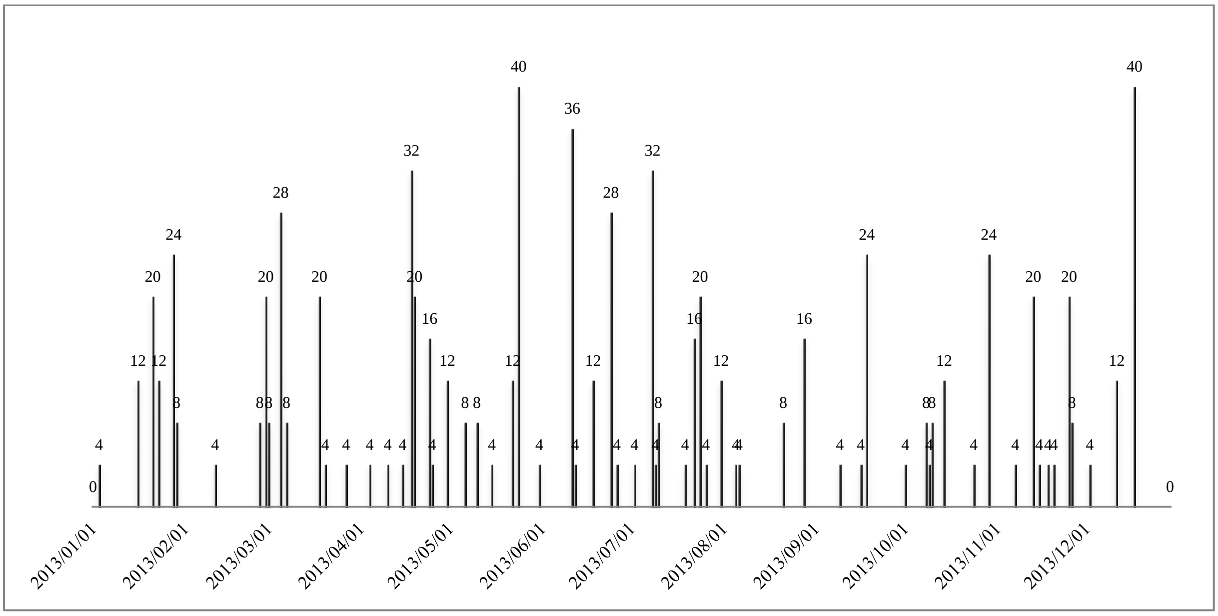

Figure 20: Annual demand for a board

As it is clear from the charts, the demand has a lumpy nature. This pattern applies for all other boards too. If demand was continuous and steady, it would be easy to calculate the average inventory. As it was mentioned before in the theoretic framework, the average inventory for such demand was half of the batch size, $\frac{x}{2}$ (x is the batch size). However, here there is a different situation. Demand arrives in a series of random discrete points in time with various quantities and in the remaining of the period between the intervals, demand is zero. This discontinuous and unsteady demand has a different nature from one discussed in the theory part and requires a separate investigation.

In order to formulate the average inventory caused by this lumpy demand there needs to be some assumptions and simplifications. It is known from the charts that orders arrive in different sizes (d_i) and in different time intervals (t_i). Let us assume that all the orders arrive in the same size equal to $\bar{d}$ which is the average of all d_i and in the same time interval of $\bar{t}$ which is the average of all the t_i. By making these simplifications, the demand will have the following pattern as shown in Figure 21:

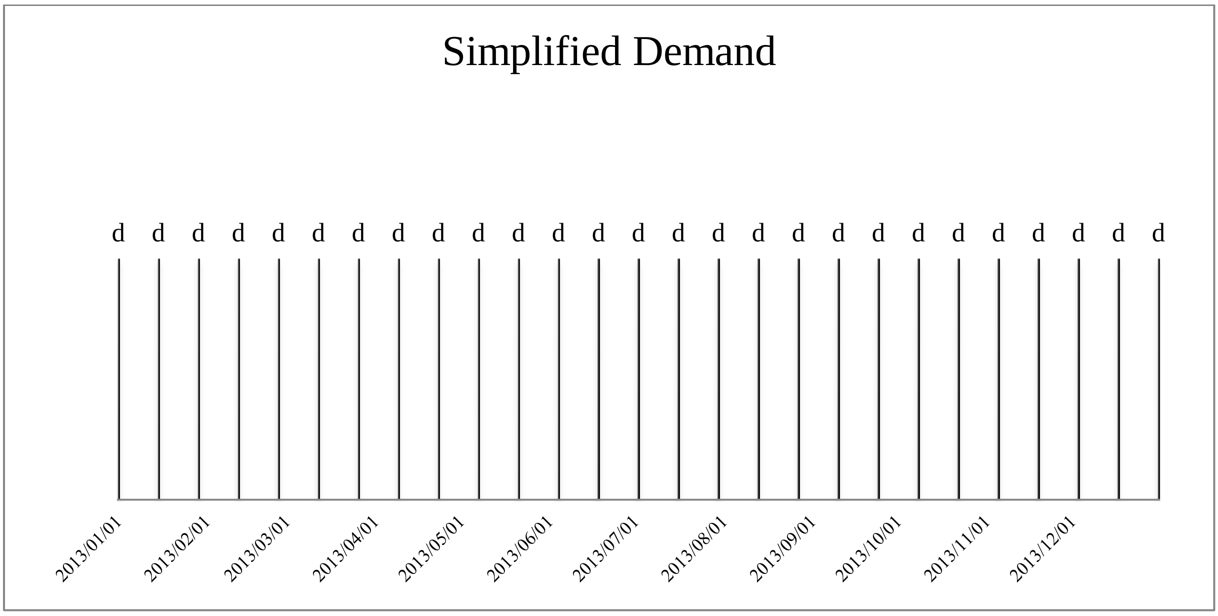

Figure 21: Simplified demand

Every order that arrives has the same size "$\bar{d}$" as its previous or successive order and they all arrive with the same time interval "$\bar{t}$". If the batch size x is big enough to cover a few successive orders, then the inventory level will change based on the pattern illustrated in Figure 22 below:

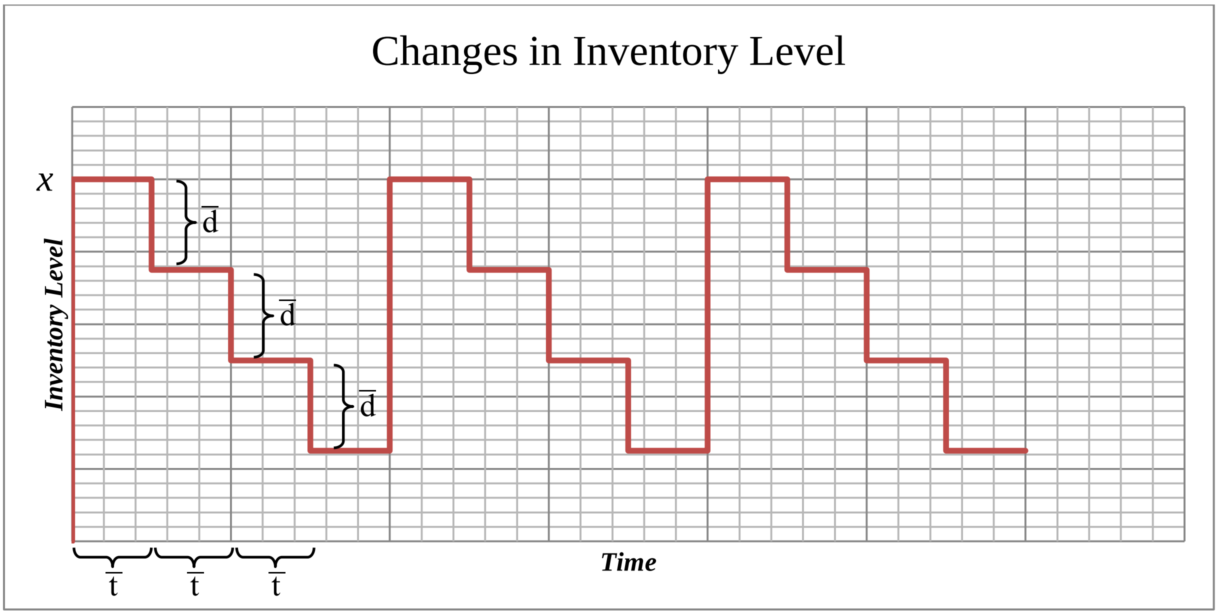

Figure 22: Changes in inventory level

Assuming that the number of intervals "$\bar{t}$" for each cycle is equal to n, the average inventory for one cycle is equal to the area below the graph for that cycle divided by sum of all intervals, $n \times \bar{t}$. Since there is going to be the same cycle repeated over and over throughout the whole time scale, the average inventory level for the whole year is equal to the average inventory level for one cycle. Let us assume that the batch size is big enough to cover all the demand during n period and is exactly equal to the demand in that period: $x = n \times \bar{d}$. Therefore:

$$I_{ave} = \frac{\bar{t}\times(x+(x-\bar{d})+ (x-2\bar{d})+ \ldots+(x-(n-1)\bar{d}))}{n\times\bar{t}} = \frac{nx-\bar{d}\times\frac{n(n-1)}{2}}{n} = x - \frac{\bar{d}n(n-1)}{2n} = x - \frac{\bar{d}(n-1)}{2}$$

Since $x = n \times \bar{d}$, we have:

$$I_{ave} = x - \frac{x-\bar{d}}{2} = \frac{x}{2} + \frac{\bar{d}}{2}$$

In order to test the accuracy of this conclusion, some boards are randomly chosen and their average inventory level is calculated based on historical data. The results are shown in Tables 6 to 9 below:

Table 6: Average inventory for a board

Date	Demand	Inventory level (batch size = 60)	Days in inventory	Inventory × Days
2013-01-01	0	60	3	180
2013-01-04	8	52	6	312
2013-01-10	4	48	1	48
2013-01-11	24	24	4	96
2013-01-15	32	52	2	104
2013-01-17	8	44	6	264
2013-01-23	12	32	5	160
2013-01-28	20	12	7	84
2013-02-04	4	8	2	16
2013-02-06	4	4	8	32
2013-02-14	28	36	1	36
2013-02-15	4	32	7	224
2013-02-22	4	28	6	168
2013-02-28	28	0	1	0
Average demand	13,8	Total	59	1724
Historical average inventory				29,2
Theoretical average inventory				36,9

Table 7: Average inventory for a board

Date	Demand	Inventory level (batch size = 180)	Days in inventory	Inventory × Days
2013-01-01	0	180	1	180
2013-01-02	20	160	5	800
2013-01-07	36	124	7	868
2013-01-14	10	114	1	114
2013-01-15	26	88	1	88

2013-01-16	20	68	2	136
2013-01-18	19	49	3	147
2013-01-21	21	28	7	196
2013-01-28	16	12	3	36
2013-01-31	8	4	4	16
2013-02-04	8	176	8	1408
2013-02-12	12	164	2	328
2013-02-14	28	136	12	1632
2013-02-26	30	106	2	212
2013-02-28	8	98	6	588
Average demand	18,7	Total	64	6749
Historical average inventory				105,5
Theoretical average inventory				99,4

Table 8: Average inventory for a board

Date	Demand	Inventory level (batch size = 40)	Days in inventory	Inventory × Days
2013-01-01	0	40	1	40
2013-01-02	16	24	5	120
2013-01-07	2	22	4	88
2013-01-11	2	20	5	100
2013-01-16	2	18	1	18
2013-01-17	4	14	6	84
2013-01-23	2	12	1	12
2013-01-24	4	8	5	40
2013-01-29	2	6	7	42
2013-02-05	8	38	1	38
2013-02-06	6	32	1	32
2013-02-07	2	30	6	180
2013-02-13	4	26	2	52
2013-02-15	2	24	3	72
2013-02-18	4	20	7	140
2013-02-25	4	16	2	32
2013-02-27	2	14	1	14
2013-02-28	8	6	1	6
Average demand	4,4	Total	59	1110
Historical average inventory				18,8
Theoretical average inventory				22,2

Table 9: Average inventory for a board

Date	Demand	Inventory level (batch size = 60)	Days in inventory	Inventory × Days
41275	0	60	10	600
41285	10	50	11	550
41296	30	20	1	20
41297	18	2	6	12
41303	28	34	1	34
41304	23	11	1	11
41305	7	4	4	16
41309	4	0	1	0
41310	3	57	6	342
41316	5	52	7	364
41323	3	49	1	49
41324	29	20	1	20
41325	10	10	1	10
41326	20	50	8	400
41334	2	48	3	144
41337	10	38	4	152
41341	4	34	4	136
41345	17	17	3	51
41348	2	15	3	45
41351	6	9	1	9
41352	20	49	1	49
41353	35	14	1	14
41354	8	6	13	78
41367	13	53	1	53
41368	19	34	7	238
41375	21	13	1	13
41376	12	1	4	4
41380	16	45	2	90
41382	10	35	4	140
41386	2	33	2	66
41388	24	9	2	18
41390	12	57	4	228
Average demand	13,6	Total	119	3956
Historical average inventory				33,2
Theoretical average inventory				36,8

The *Mean Absolute Percentage Error* (MAPE) for the approximation of *"I_{ave}"* can be worked out as shown below:

$$MAPE = \frac{100\%}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| = \frac{100\%}{5}\left(\left|\frac{29.2-36.9}{29.2}\right| + \left|\frac{105.5-99.4}{105.5}\right| + \left|\frac{18.8-22.2}{18.8}\right| + \left|\frac{33.2-36.8}{33.2}\right|\right) = 15.27\%$$

Where A_t is the actual value and F_t is the forecasted value.

Although this is not a very close approximation, it is good enough for continuing the calculations. Now that the value of I_{ave} has been expressed based on the batch size x and the average demand "$\bar{d}$", it can be replaced in the objective function of our minimization problem:

$$Minimize\ Z = a \times C_1 \times \left(\frac{x_1}{2} + \frac{\bar{d}}{2}\right) + a \times C_2 \times \left(\frac{x_2}{2} + \frac{\bar{d}}{2}\right) + \ ... + a \times C_n \times \left(\frac{x_n}{2} + \frac{\bar{d}}{2}\right)$$

Since *"a"* is a constant and it is present in all the sentences, it can be taken away from the objective function without affecting the optimization result:

$$Minimize\ Z = C_1 \times \left(\frac{x_1}{2} + \frac{\bar{d}}{2}\right) + C_2 \times \left(\frac{x_2}{2} + \frac{\bar{d}}{2}\right) + \ ... + C_n \times \left(\frac{x_n}{2} + \frac{\bar{d}}{2}\right)$$

$\frac{\bar{d}}{2}$ and C_i are also both constants and when they are multiplied with each other, they form another constant $\frac{\bar{d}}{2} \times C_i$. Since their value is fixed and they do not affect the optimization result, they can be taken away from the objective function too:

$$Minimize\ Z = C_1 \times \frac{x_1}{2} + C_2 \times \frac{x_2}{2} + \ ... + C_n \times \frac{x_n}{2}$$

Nonetheless, "$\frac{x}{2}$" is a better approximation for average inventory level. By calculating the new MAPE for "$\frac{x}{2}$", the result will be:

$$MAPE = \frac{100\%}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| = \frac{100\%}{5}\left(\left|\frac{29.2-30}{29.2}\right| + \left|\frac{105.5-90}{105.5}\right| + \left|\frac{18.8-20}{18.8}\right| + \left|\frac{33.2-30}{33.2}\right|\right) = 8.36\%$$

In addition, denominator 2 is also a common constant in all the expressions above and can be omitted. The final objective function will look like this:

$$Minimize\ Z = C_1 \times x_1 + C_2 \times x_2 + \ ... + C_n \times x_n$$

Now that the objective function is prepared, the constraints should be added to complete the model. The objective of the model is to minimize the total inventory value. As a consequence, many of the batch sizes will be minimized while some others will increase. Based on the definition that was presented for the setup cost, the batch sizes can be minimized with numerous setups performed, as long as they do not cause any production loss and therefore a setup cost. Within the available capacity, setups have a cost of zero. They create a cost when the capacity limit is violated and this week's orders have to be met next week. If the capacity is defined as the total time available for producing boards and performing setups, the constraint can be defined as shown below:

$$Total\ Production\ time + Total\ Setup\ Time\ \leq Capacity$$

If D_i, is the total demand for board i and x_i is the batch size, then the number of setups for board i is the ceiling function of their division. For example, demand of 100 and batch size of 30 requires a total number of $\left\lceil \frac{100}{30} \right\rceil = \lceil 3.33 \rceil = 4$ setups in total. By multiplying this number by the average setup time of 22 minutes – based on information from IFS – the total setup time for one type of board is calculated. For calculating the total production time, the total demand for each board has to be multiplied by its cycle time "$t_{pi(min)}$" (t_p denotes the cycle time, *"i"* denotes the board i and *"min"* says that the times are in minutes). For example, if the demand for a board is 100 units and cycle time $t_{pi(min)}$ is two minutes, the total production time for that board is $100 \times 2 = 200$ min. The sum of these two times, for all boards should be less than or equal to available capacity in minutes "A_{min}". Mathematical expression of capacity constraint is shown below:

$$\sum_{i=1}^{n} \left(22_{min} \times \left\lceil \frac{D_i}{x_i} \right\rceil + D_i \times t_{Pi(min)} \right) \leq A_{min}$$

In order to complete the optimization model, the boundaries for the variables must be defined. All of the parameters in the objective function and constraint are constants except the batch sizes"x_i". These batch sizes cannot be greater than total demand for each board $x_i \leq D_i$. At the other hand, based on previous assumptions that where set over calculating the average inventory, each batch should be big enough to meet the average demand. This can be expressed as $x_i \geq \bar{d}_i$. Therefore, the boundaries for batches can be written as follows:

$$\bar{d}_i \leq x_i \leq D_i \qquad for\ i = 1, 2, 3, \dots, n$$

The complete model with all its components is shown below:

$$Minimize\ Z = \sum_{i=1}^{n} C_i \times x_i$$

Subject to:

$$\sum_{i=1}^{n} \left(22_{min} \times \left\lceil \frac{D_i}{x_i} \right\rceil + D_i \times t_{Pi(min)} \right) \leq A_{min}$$

And

$$\bar{d}_i \leq x_i \leq D_i \qquad for\ i = 1, 2, 3, \dots, n$$

As it is clear from the model, the objective function has a linear nature but there is some nonlinearity in the constraint. The term $\left\lceil \frac{D_i}{x_i} \right\rceil$ is a nonlinear term (because of x_i in the denominator) and classifies the model as a nonlinear optimization problem. The next step is to solve the problem.

4.4 Solving the optimization model

Before taking the effort to solve the problem, there are a number of issues that should be considered. Specifying a batch size to boards is mostly suitable for those boards that have a regular demand. Observing the demand pattern for all the boards, reveals that some of them do not have such demand. Some others, despite of having a regular demand are only produced based on customer orders. Therefore, the production quantity for theses boards is not based on predetermined batch sizes, but based on customer's order quantity. These boards usually – but not always – have lower demand and higher price than other boards. Since inclusion of these boards can mislead the optimization model to a wrong solution – due to optimizing the wrong board – they should be excluded from the problem. Prototypes are another example of this kind of irregular demand that should be excluded. Prototypes are boards that are produced occasionally based on company's need and there is no real customer demand for them. However, they will be on production in the future. Some examples of these boards are shown in Figures 23 and 24. Finally, a series of boards that used to be produced in high volumes in the past are now discontinued. Considering them as a decision variable in the problem is unreasonable. At the end, after excluding all these boards, a total number of 111 boards remain as decision variables for the problem.

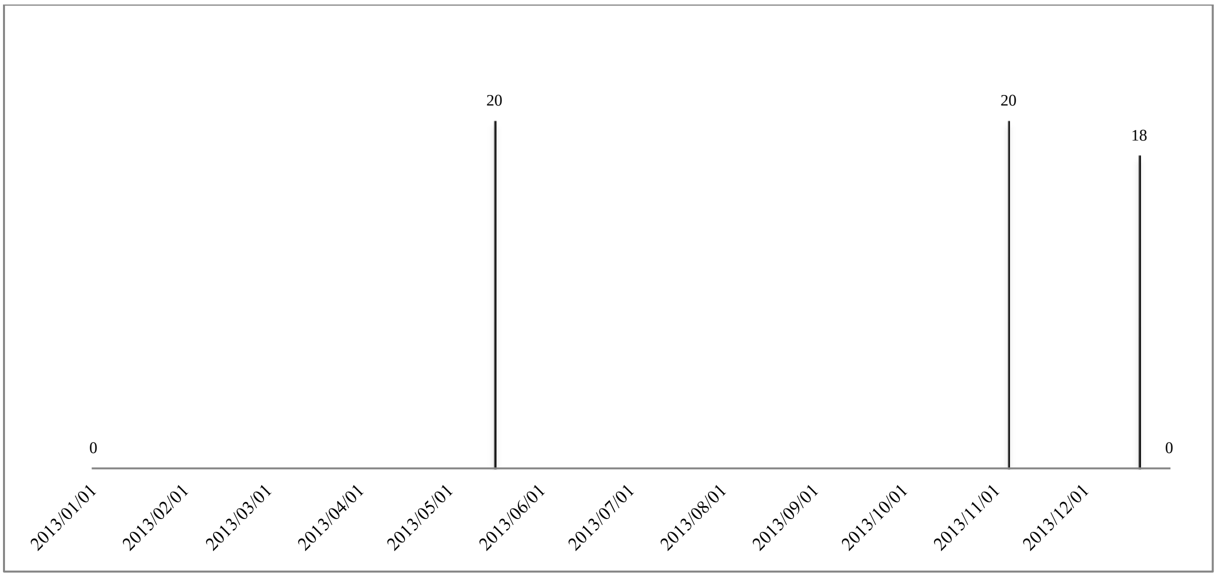

Figure 23: Customer demand for a board produced by customer order

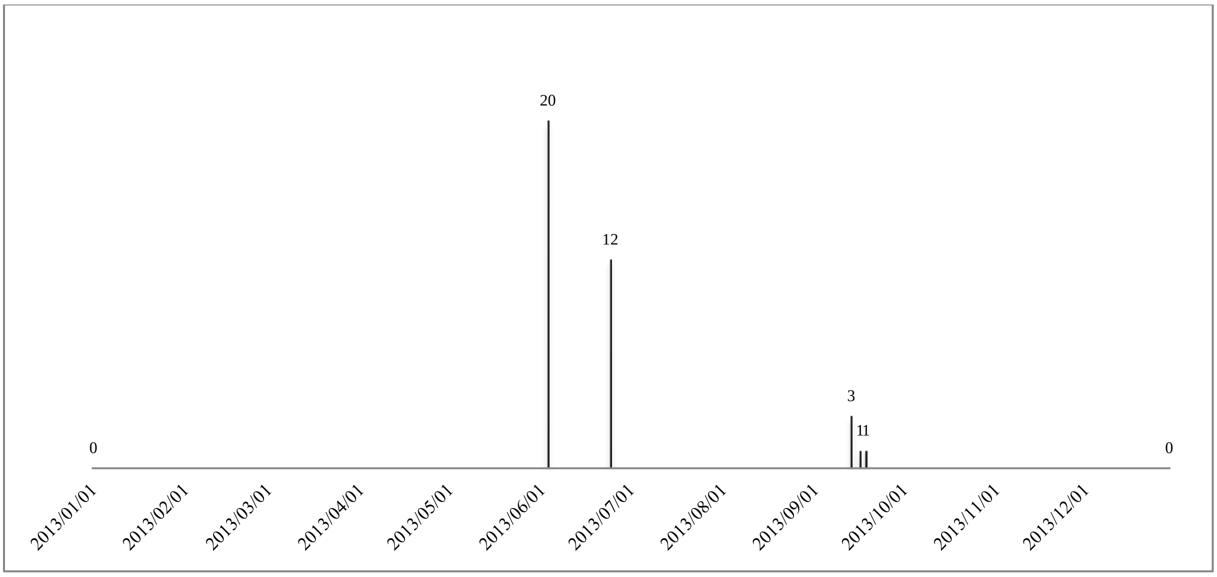

Figure 24: Demand for a prototype board

Another matter to discuss is more of technical nature. Circuit boards are not produced individually one by one, but in panels. A panel is a structure that can hold one, two, three or even more boards together in one body (Figure 25). During the production, it is the panel that goes through the production line not individual boards. As a result, if the panel for one type of PCB includes two boards, the batch size for that board cannot be an odd number. Some panels comprise of 4, 6, 10, 30 or 60 boards which should be reflected on batch sizes. In addition, some of the boards have shown some sort of level demand, a pattern in which the demand is quite constant with little deviation. When the demand is regular with fixed quantities, it is less costly and more convenient for inventory management if the batch sizes are a multiple of demand sizes. For these kind of boards, it was preferred to specify a predetermined fixed value as a batch size and remove them from being a decision variable. One more modification in the problem was changing the actual value of demand for some of the boards. Looking at the demand pattern of the boards shows that some of the data are outliers. They are special orders from some customers in special point of time with very high volumes. They do not happen on a regular basis and they should be taken away. The new modified demand is used as an input data for the problem.

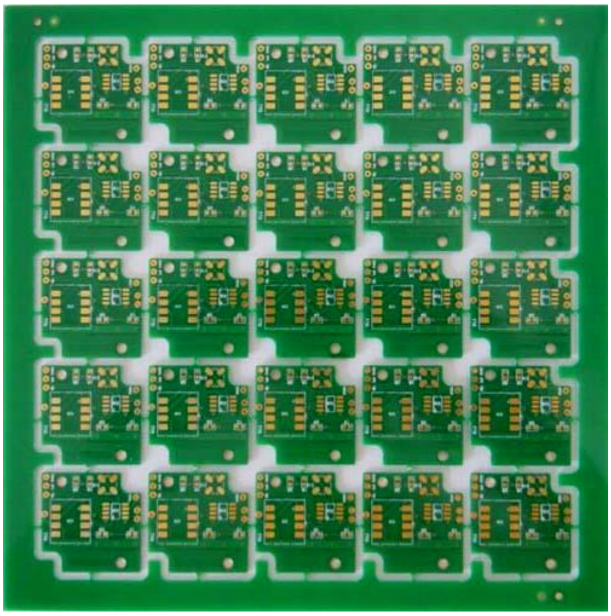

Figure 25: A panel with 25 PCBs (Pcbfabrication.com, 2014)

The first idea coming to mind for solving the problem is using an exact method. As it was mentioned previously in the theoretic framework, exact methods search the solution area to find the global optimum answer (best answer). There is a couple of software that is designed for optimization problems. One of the main optimization software is LINGO, a tool designed by LINDO Systems Inc. which can handle linear, nonlinear (convex & nonconvex/Global), quadratic, quadratically Constrained, Second Order Cone, Stochastic, and Integer optimization models (Lindo.com, 2014). In order to solve the problem by LINGO, the optimization problem was rewritten based on LINGO's programming language as it is shown below:

```
!Describing the sets, we only have one set with four attributes;
sets:
boards: price, demand, average, lotsize;
end sets

!Describing data,importing data from an excel file with @OLE;
data:
boards, price, demand = @OLE();
end data

!the objective function;
Min= @sum(boards(i): price(i)*lotsize(i));

!constraints;
@sum(boards(i):22*(@floor(demand(i)/lotsize(i))))<= 43956;
@for(boards(i): lotsize(i)<= demand(i));
@for(boards(i): lotsize(i)>= average(i));
end
```

Unfortunately, the available software was a trial version and it could not handle problems with large number of variables. The software failed to solve the large nonlinear problem and explained the reason for the failure in a pop-up dialogue box as shown in Figures 26, 27 and 28:

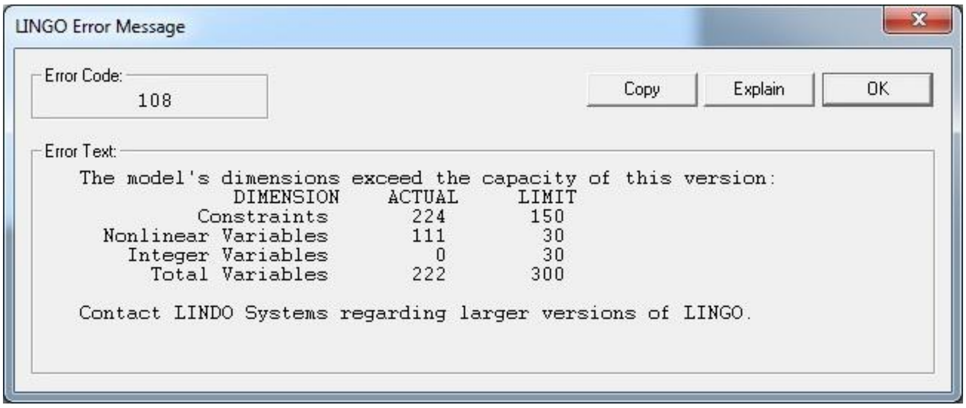

Figure 26: Lingo's error message

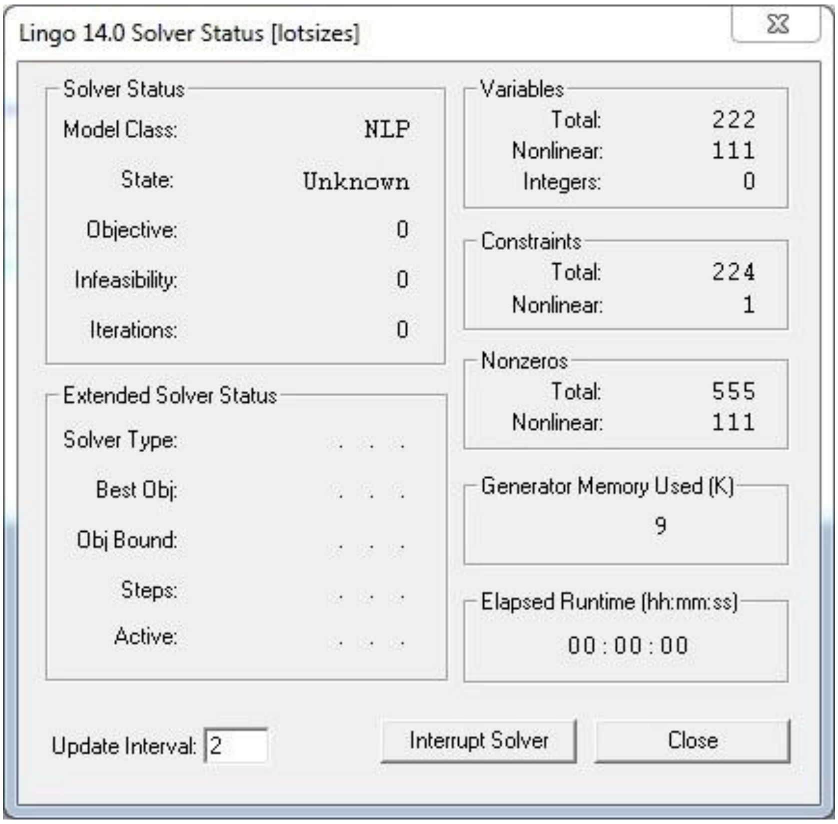

Figure 27: Lingo's solver status

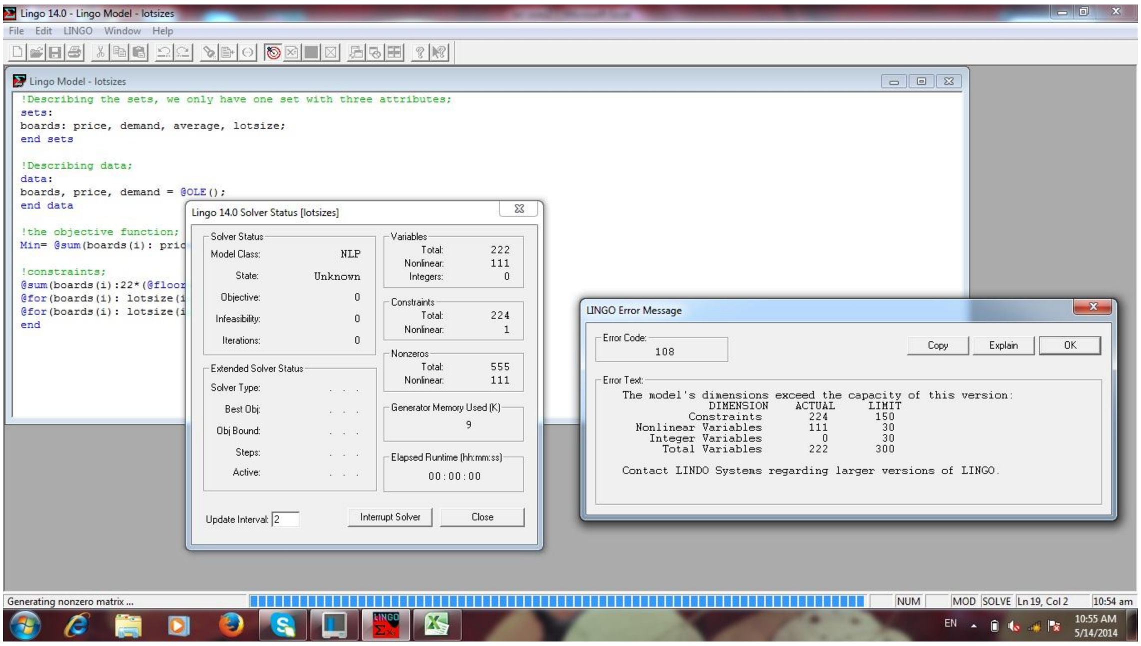

Figure 28: Lingo's interface

However, another way to solve an optimization problem using exact methods is MATLAB. MATLAB is a programming language for numerical computation and visualization and it can be used for analyzing data, developing algorithms and creating models and applications (Mathworks.se, 2014). MATLAB provides different toolboxes for various engineering fields. Here, the optimization toolbox is used (Figure 29):

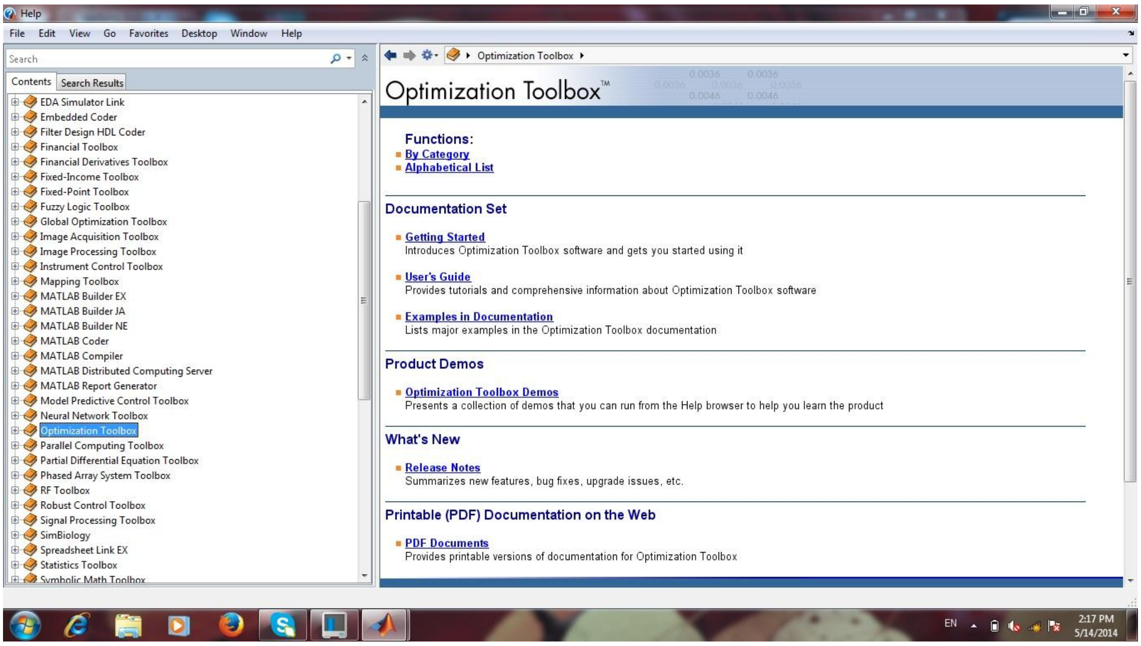

Figure 29: MATLAB's optimization toolbox

The next step is to choose a solver. MATLAB provides us with different options for different optimization problems. In order to choose a proper solver, MATLAB's Optimization Decision Table is used (Figure 30):

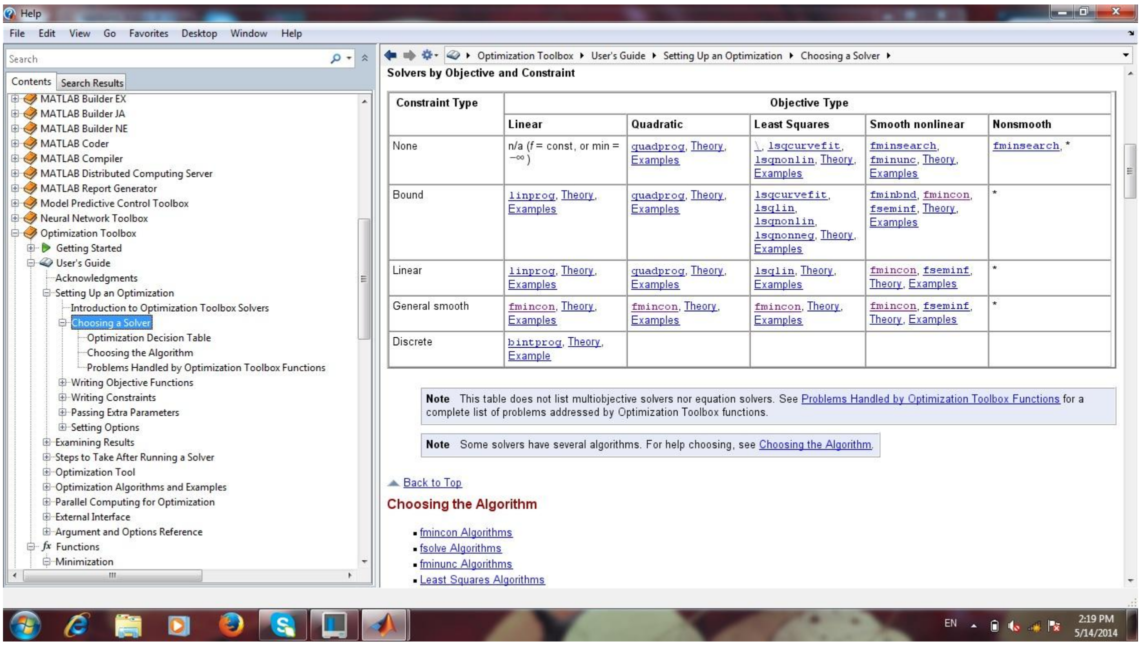

Figure 30: MATLAB's optimization decision table

The table is consisted of five columns and five rows. The columns represent different types of objective functions and the rows are for choosing the constraint type. The intersections of the columns and rows indicate the proper solver to use. The objective function used for this optimization problem is linear. Therefore, the first column should be selected. Among the rows, the first row is for problems with no constraint or bounds, the second row is for problems with bounds but no constraints and the third row is for problems with linear constraint functions. As it was mentioned before, the constraint function for this problem is nonlinear and therefore none of the above three options are suitable here. The fourth row is for solving the problems with smooth linear and nonlinear constraints and the fifth row is for problems with linear integer constraints. Therefore, the fourth row is the proper choice for the problem in hand. The intersection of the fourth row and first column is *fmincon* ("f" for function, "min" for minimization and "con" for constrained), a solver that is used for *constrained nonlinear optimization*.

However, the solver fails to find an answer to this problem and responds with an error message. The reason for this failure is the constraint type of the problem. As it is clear from the table, *fmincon* is used for *smooth* linear or nonlinear constraints (general smooth). A smooth function is a function that has derivatives of all orders. Optimization solvers like those in optimization toolbox are derivative based. They are accurate and fast but they are designed to solve minimization problems that have *smooth* functions (functions that are continuously differentiable to some order) since they use derivatives to find direction of minimization (Mathworks.se, 2014). The constraint function of this problem is not smooth because of the term " $\left\lceil \frac{D_i}{x_i} \right\rceil$ ". Having the variable "*x*" in the denominator and inside the ceiling function makes the constraint function discontinuous and non-smooth in several points. The derivative of the function ceiling (x) is zero when *x* is not integer and is undefined when *x* is an integer number. As a result derivative based solvers in optimization toolbox are unable to solve such a problem. A simple version of the constraint function with only two variables is illustrated in Figure 31, to show the discontinuity of the function.

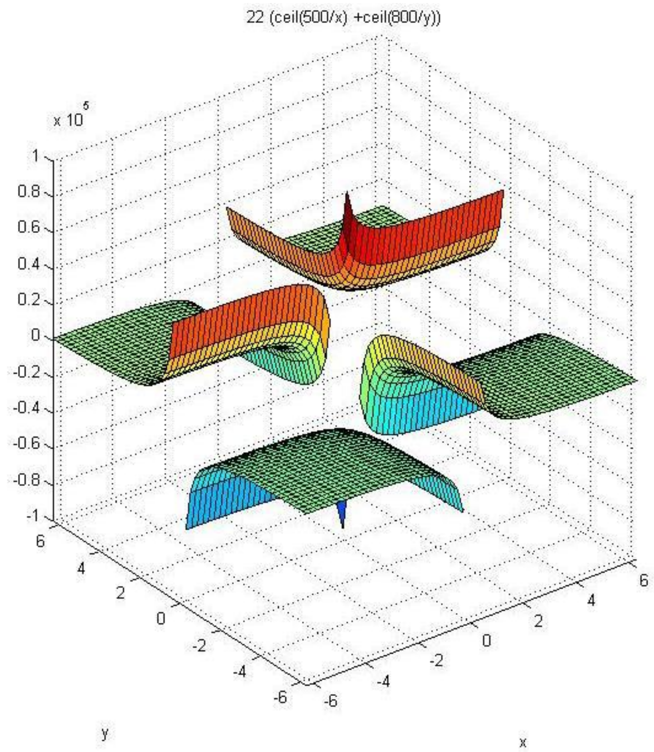

Figure 31: Constraint function with only two variables

With this attempt failing, the idea of solving the problem with exact methods should be put aside. The alternative is to use heuristic methods for finding a near optimum solution. As it was mentioned before, heuristic algorithms do not guarantee a global optimum solution but they provide an answer good enough in an acceptable amount of time. Fortunately, MATLAB has the ability to perform optimization using different heuristic solvers. The Global

Optimization Toolbox in MATLAB is a tool that provides us with this opportunity (Figure 32):

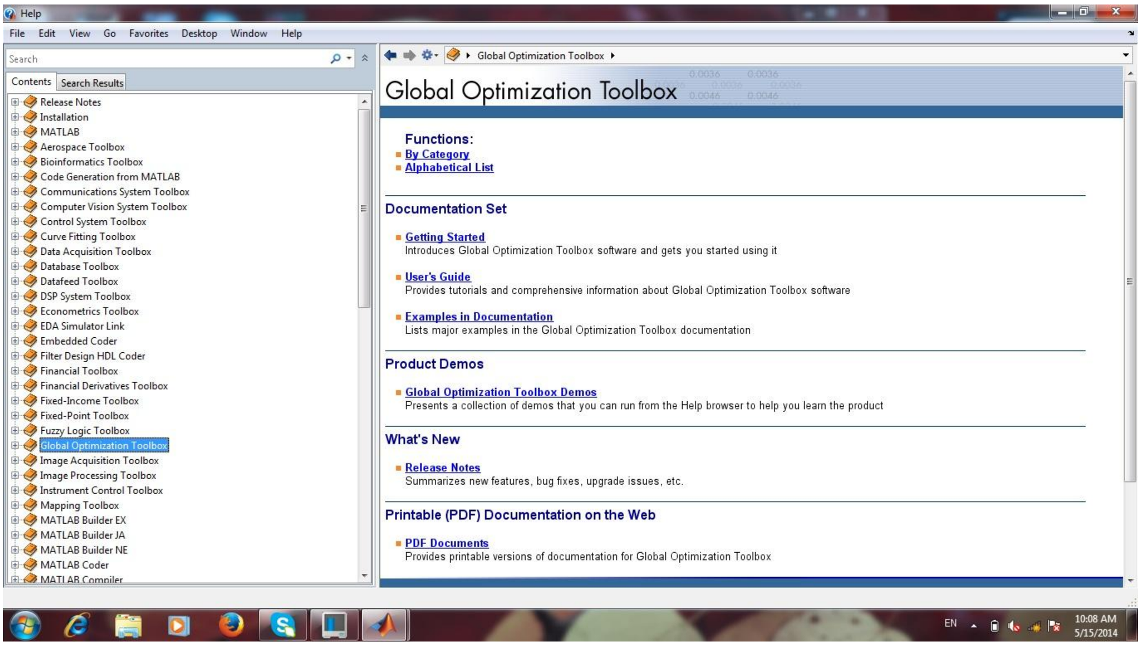

Figure 32: Global Optimization Toolbox in MATLAB

The next step is similar as before. In order to choose a proper solver, MATLAB has created a table with different heuristic algorithms and different problem types. MATLAB's Table for Choosing a Solver is shown in Figure 33:

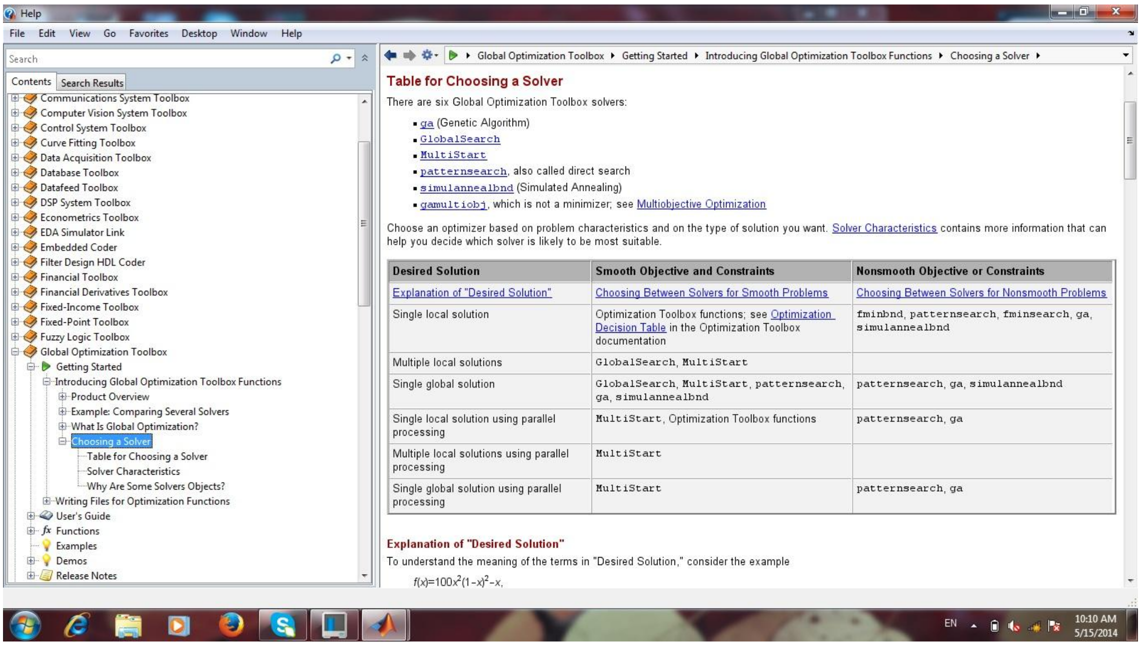

Figure 33: Table for Choosing a Solver

As it is shown above, the table has two columns and six rows. The first column belongs to problems where both objective function and constraints are smooth, despite the linearity. The second column is for problems where one or both of the objective and constraint functions are non-smooth (They can be linear or nonlinear). As it is clear from the problem in hand, the second column seems to be the right choice. The rows, at the other hand, give different options regarding the desired solution to the problem. Since it is more interesting to find a global minimum than one or several local minimums, options that offer local solutions should be put aside. The third row provides a single global solution, an answer similar to one with the exact methods and seems a proper choice. The intersection of the third row and second column offers three algorithms to choose: *pattern search, genetic algorithm and simulated annealing.* For the ease of use and familiarity and the sizable literature that exists about genetic algorithm, this algorithm is chosen for solving the problem. One convenient way to use this algorithm is "*Optimization Tool"*, a tool in MATLAB that makes it easy to enter input parameters of the problem or change different settings (Figure 34):

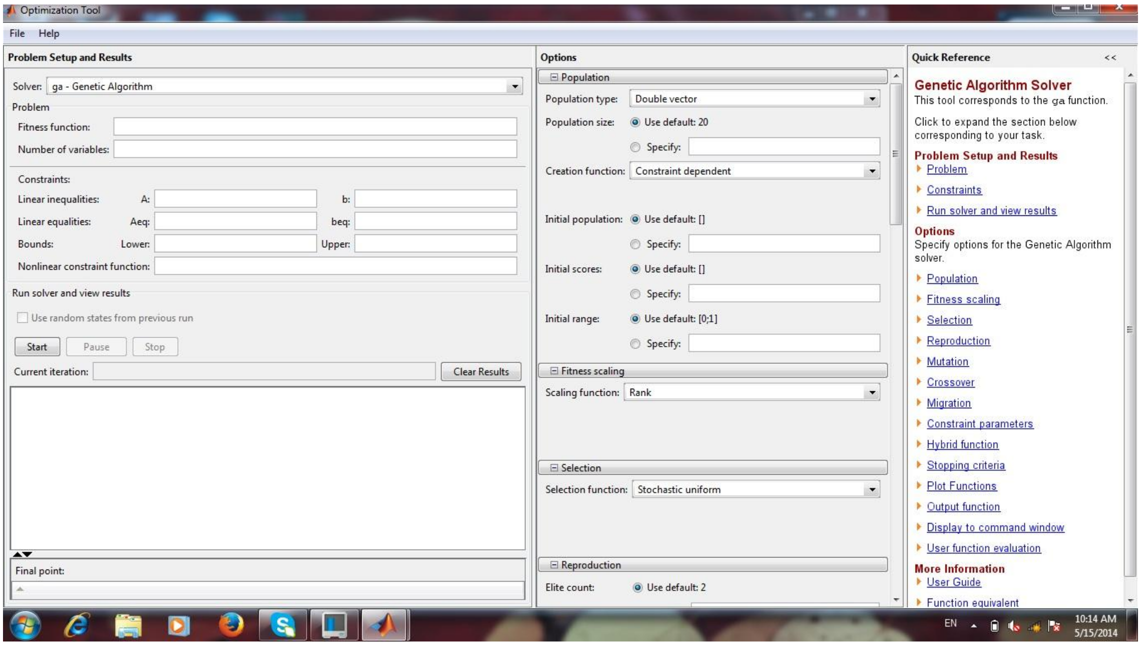

Figure 34: Optimization tool in MATLAB

As it is clear from Figure 34, the Optimization Tool requires many different input data for performing the optimization. In the solver text box, a series of different solvers are available through a pop-up menu (here GA is chosen). Fitness function is the equivalent of the objective function. The objective function should be written and saved separately in an f-file in MATLAB and is recalled with the help of a *function handle*. In the field "Number of variables", the total number of decision variables should be written. The constraint section asks for information such as upper bounds and lower bounds, linear equalities and inequalities, and nonlinear constraint. The nonlinear constraint, similar as objective function, should be written and saved in a MATLAB f-file and is recalled by its name. The *Options* section on the right hand side also has several settings that should be decided according to the problem.

Different settings give different answers when running the optimization. From experience it can be said that higher mutation rates result in faster and more optimum solutions since they increase the diversity of the solution population and help the algorithm search a wider area to find the optimum answer. After running the algorithm for several times, the best answer for batch sizes was chosen and modified to adapt to *multiple lot sizes* (the number of boards in each panel) so that the technical side of the problem is considered too. The final result with the total inventory value of final batch sizes compared to current ones is shown in Table 10 below:

Table 10: Optimum batch sizes

Boards	Multiple Lot Sizes	Fixed Values	Lower Bound	Demand	Price (SEK)	Current Batch Sizes	GA Solution	Final
X1	2		10	52	158,52	10	17,5	18
X2	2		4,8	24	112,88	20	12,0	12
X3	2		10	62	245,93	10	12,6	14
X4	2		4,18	92	168,03	20	18,6	20
X5	2		4,7	170	82,49	20	34,1	36
X6	3		6,33	133	105,02	30	33,4	36
X7	2		7,3	532	62,64	30	76,4	78
X8	3	3	3	24	338,81	3	3,0	3
X9	2		8,6	458	63,45	40	66,1	68
X10	2		9	36	154,16	20	12,2	14
X11	2		12,7	318	182,45	30	35,7	36
X12	2		4	32	147,75	20	10,7	12
X13	2		4,9	49	299,15	20	12,5	14
X14	4		11,8	792	119,02	40	66,3	68
X15	6		12,8	192	70,11	60	38,4	42
X16	6		20,2	808	69,05	60	89,9	90
X17	3		8,6	284	118,63	30	40,7	42
X18	4		7,3	372	408,35	12	26,7	28
X19	4		8	176	350,13	12	22,4	24
X20	4		6,2	240	295,43	60	24,9	28
X21	1		6,2	240	147,69	60	40,0	40
X22	2		10,6	814	227,25	20	47,9	48
X23	4		6,7	300	232,47	20	28,1	32
X24	6		17,8	1226	79,07	60	112,4	114
X25	4		5,5	180	135,8	24	30,4	32
X26	2		6,7	782	214,02	40	49,3	50
X27	2		5,5	472	217,73	40	40,0	40
X28	2		27,4	2460	190,29	100	100,0	100
X29	2		17	1772	168,67	50	93,4	94
X30	2		14,4	864	184,89	30	57,6	58
X31	2		21,4	2095	142,56	100	99,8	100
X32	4	20	20	140	191,06	20	20,0	20
X33	2		9,7	370	465,1	20	26,8	28
X34	2		28,4	4146	375,24	100	98,9	100
X35	2		56,8	6590	261,8	250	149,9	150
X36	2		5,4	232	305,97	20	19,4	20
X37	2		4,4	204	424,09	20	17,2	18
X38	4		16,3	1499	370,84	60	60,0	60
X39	4		40	1480	85,44	80	106,8	108
X40	2		10,8	1412	197,85	60	78,5	80

X41	2		14,4	1326	230,18	50	57,7	58
X42	2		6,3	160	247,47	20	20,0	20
X43	6		23,3	1624	97,1	42	108,5	114
X44	6	12	6	42	195,23	12	12,0	12
X45	4		12,2	1296	91,47	40	108,9	112
X46	4		10,9	1632	96,66	80	109,7	112
X47	4		5,2	320	317,25	20	24,6	28
X48	4		17	2359	92,77	80	131,4	132
X49	2		15,3	1802	393,22	70	62,8	64
X50	6		23	1860	39,31	90	206,8	210
X51	2		13,6	1831	357,56	100	67,9	68
X52	6		27,6	1762	30,78	90	196,7	198
X53	6		22,4	4061	44,41	300	270,8	276
X54	2		5	164	481,59	20	16,6	18
X55	6		5	164	73,03	60	55,4	60
X56	2		4,5	117	439,06	20	14,7	16
X57	2		4	24	300,08	10	6,0	6
X58	2		4	55	569,25	8	7,9	8
X59	2		10	294	668,33	10	19,9	20
X60	2		48	5467	581,26	180	81,6	82
X61	2		16	1706	167,52	60	94,9	96
X62	2		9,24	350	167,89	40	39,7	40
X63	2		12,5	1348	125,22	70	84,3	86
X64	2		11,5	521	144,07	20	52,2	54
X65	4		20	230	847,85	60	20,7	24
X66	4		20	230	464,95	60	20,1	24
X67	4		62	3350	962,17	100	62,8	64
X68	4		66	3660	379,99	100	87,8	88
X69	4		120	4770	335,64	200	122,6	124
X70	4		30	996	1905,95	40	30,5	32
X71	2		190	3220	51,98	200	214,9	216
X72	30		90	3452	202,94	120	111,4	120
X73	60		120	3452	39,46	120	246,9	240
X74	4		65	2233	434,81	80	67,9	68
X75	4		40	951	381,37	40	40,0	40
X76	2	40	40	260	156,06	40	40,0	40
X77	10	20	20	210	305,33	20	20,0	20
X78	6		16,8	252	269,25	30	28,7	30
X79	4	40	40	640	347,37	40	40,0	40
X80	4	40	40	1220	458,89	40	40,0	40
X81	4		33	1074	472,91	40	40,0	40
X82	4		6,4	320	207,92	20	35,8	36
X83	4		16	774	190,92	40	51,8	52

X84	4		6,4	316	672,44	40	19,8	20
X85	4		45	9685	329,99	200	156,3	160
X86	4		30	4944	971,25	160	63,4	64
X87	4		6	240	1451,76	40	10,0	12
X88	4		17	70	974,01	40	17,5	20
X89	4		4	140	1023,75	40	10,2	12
X90	4		20	1693	1084,07	40	34,6	36
X91	4		16	774	1143,52	60	22,8	24
X92	6		16	774	173,75	60	60,0	60
X93	4		18	2139	1168,08	60	37,0	40
X94	2		18	2139	310,5	60	67,1	68
X95	4		21	915	1059,75	40	28,6	32
X96	4		7	604	537,3	60	28,9	32
X97	4		13	2469	472,03	80	70,8	72
X98	2		18	378	271,92	40	34,9	36
X99	4		8	641	891,38	20	21,4	24
X100	4		4	119	811	20	13,2	16
X101	4		7	641	781,26	20	22,9	24
X102	4		25	1608	57,27	60	124,0	124
X103	4		16	352	509,43	40	23,6	24
X104	4		23	1316	477,9	60	48,8	52
X105	4		6	128	864,07	20	11,7	12
X106	4		20	267	711,74	20	20,0	20
X107	4		6	315	1196,4	20	16,8	20
X108	4		10	786	1139,62	40	25,1	28
X109	4		7	548	217,67	60	39,4	40
X110	2		16	676	55,32	40	84,9	86
X111	4		7	347	1087,27	20	17,4	20
$\sum_{i=1}^{111} (\boldsymbol{New\ Batch\ Sizes} \times \boldsymbol{Price})$						2134288,15	1616642	1681570
$\boldsymbol{Total\ Inventory\ Value}\ (\boldsymbol{Ratio}) = \frac{\sum_{i=1}^{111} (\boldsymbol{New\ Batch\ Sizes} \times \boldsymbol{Price})}{\sum_{i=1}^{111} (\boldsymbol{Current\ Batch\ Sizes} \times \boldsymbol{Price})}$						100,00%	75,75%	78,79%

The first column of the table simply indicates different boards. The second column, multiple lot sizes, is the number of boards in each panel. For example, if multiple lot size for a board is 6, there are 6 boards in each panel that goes through the production line. As a result, the batch size for this board can be 6, 12, 18, 24, etc. The third column, fixed values, is those boards that their lot size was predetermined as a fixed value so that they are not a decision variable anymore. The reason for these fixed values was discussed before. Fourth column is the lower bound for variables, meaning that the batch sizes cannot be less than this quantity. Lower bounds are the average demand quantity "$\bar{d}$ " for each board. The fifth column is the modified annual demand for each board. Modified, meaning that the outlier data has been taken away. The sixth column is the price of each board. The seventh column is the current batch sizes for boards. The eighth column, GA Solution, is the answer given by MATLAB. This answer was obtained after running the optimization for several times and changing the settings in order to improve the optimal solution. The reason that problem is not solved with integer values and batch sizes are not complete integers is that it is much easier and faster for MATLAB to solve problems with continuous values than integer ones. These values had to be modified to comply with multiple lot sizes. The results are shown in column ninth, *"Final"*, as final optimum batch sizes.

The last row in the table shows the ratio of total inventory value resulted from new batch sizes over total inventory value resulted from current batch sizes. As it was mentioned before, the average inventory level for a board is considered to be half the batch size. At worst, it can be considered as a fraction of the batch size. However, when the total inventory values of new and current batch sizes are divided over to calculate the ratio, these constants cancel out. The formula used for calculating the ratio of total inventory value for two different batch sizes is shown below:

$$Ratio\ of\ Total\ Inventory\ Value = \frac{Constant \times \sum_{i=1}^{111} (New\ Batch\ Sizes \times Price)}{Constant \times \sum_{i=1}^{111} (Current\ Batch\ Sizes \times Price)}$$

$$= \frac{\sum_{i=1}^{111} (New\ Batch\ Sizes \times Price)}{\sum_{i=1}^{111} (Current\ Batch\ Sizes \times Price)}$$

As a result, the new batch sizes will reduce the total inventory value by 21.21% (100% - 78.79%).

4.5 Setup improvement

Setup times for the pick and place machines are quite long. To reduce the effect of long setups, operators use the *group setup* strategy. In this strategy, boards with similar components are grouped as one family and are produced sequentially. The software equipped with the machines makes it possible to create different setup families from different boards. Operators have access to the production plan for each day through IFS. Doing that, operators know what boards have to be produced each day. They can choose some of the boards that have similar components (based on their experience) and give their article numbers to the software. The software, then, evaluates their compatibility considering their components and the maximum number of positions available for feeders on the machine's feeder bank. If they can fit in to one family, software will produce a list of the required feeders and their exact placement. The process of finding the optimum placement for feeders to increase the production speed is done automatically by software and takes only a few seconds.

Since it is very likely that some of the components required for a new setup family is already in use in the previous family (currently in the machine), one of the operators compares the two different lists of components. Common components are found and their places on the feeder banks are recorded and they will be used in the new setup family, in their new places. The number of components in each list can differ based on the boards in the family but it is very likely that at least one of the two feeder banks of the machine is completely full. Each feeder bank (stage) has the capacity of 70 feeders. The process of finding the common feeders used to be done manually, taking an average of five minutes but now it is an automatic process.

In order to save time, those feeders that are not common between two sequential setups are collected and put on a rack. Feeders are placed on the rack based on their orders in the list. If one of the stages is already empty (it can happen if all the feeders in previous setup could fit into one stage) it is not in operation and operators can put the feeders for the new setup on the stage. This is called offline setup. However they can’t fill the places for common feeders and they have to wait until the current operation is finished.

When the last board from the previous family leaves the machine, the machine can start its setup process. Setup operations on each machine are performed by one, two or three operators. However, there is no significant reduction in setup time when the number of operators increases because the activities are not performed in parallel and there is no clear division of labor or clear setup procedure that can exploit the increase in number of operators.

After the last scheduled panel of boards is produced, the two stages are distracted, meaning that they move away from each other and make it possible for operators to change the feeders or adjust and clean the nozzle. Then, there are a series of activities that are done:

- The width of the conveyor belt that carries the panels is adjusted
- The nozzle head is adjusted and cleaned if needed (this is done automatically)
- An operator brings a wagon and picks up common feeders for the new setup (this is done either by one operator looking at the list and picking up the feeders or by two operators, one reading the list out loud and the other picking up the feeders)
- The rest of the feeders that are not used in the new family setup are picked up and put on the wagon
- After emptying the two stages, common feeders are put on the stages in their specified places; following them the new feeders are taken out from the rack and put on the stages (this process also requires the list of components and their places. If it is done by one person, he looks at the list and puts the feeders on the stage. If it is done by two operators, one reads the list and the other puts the feeders on the stage)
- The setup program is sent
- The reels in the feeders are checked with a barcode scanner to check if they are at their right location

The family setup time for pick and place machine of small components (CP) has an average of 23 minutes with the standard deviation of 7 minutes while the total setup time for both machines has an average of 35 minutes and a standard deviation of 2.

After making a number of observations of the setup process, a list of suggestions was prepared that could help to reduce the setup time. The setup improvement process has four conceptual stages. At stage zero or the preliminary stage, the internal and external setup operations are not distinguished and what is done as internal setup can in fact be done externally. In case of setup operations for pick and place machines, the process of putting the feeders back on the shelves is an external setup while it is done as an internal setup. The process takes 4 to 5 minutes in average. Another example of external setup performed internally can be bringing of the wagon.

At stage 1, there is a clear distinction between internal and external setup operations. Those operations that are external are performed before or after setup. A number of suggestions were given to take away the external activities and reduce the setup time. For example putting the feeders on the shelves can be done after the setup. One thing that was observed during the setup was that when operators take out the feeders from the feeder banks (stages), they tend to sort them in groups. That makes it easier for them to put them back on the shelves. This is obviously an external operation that can be done after the setup. The four operations of taking out the feeders, sorting them, putting them on the wagon and putting them back on the shelves can be reduced to two internal setup operations of taking out the feeders and putting them on the wagon. The other two operations can be done after setup as external operations.

Another suggestion was regarding the setup performed on pick and place machine of big components (QP). Since there is only one wagon in the workstation and it is used for the first machine (CP), the operators have to take out the feeders from second machine (QP) one by one and put them back on the shelves. This also involves a lot of transportation and slows down the process significantly. Both of these activities are external setups and are currently done as internal. Adding one or two wagons can help a lot.

Some of the components that are used on second machine (QP) are special components that are sensitive to humidity and therefore are kept in a special cabinet. The QP has 6 modules and the module 6 is especially for these components. The components are first put on trays and then are put in module 6 in their specified places. In the current state, the processes of taking old components out of the machine and putting them in the cabinet, taking out new components based on the list, putting them on trays and then putting them in the machine is done as internal setup. However one suggestion can be to have those new components arranged on trays before setup starts and keep them in the cabinet. When setup begins, the only thing the operator has to do is to take the old components out from the machine and replace them with new trays. Putting the old components back in the cabinet or putting and sorting new components on the trays are both external setup operations.

One more thing that can be done is to have the wagons ready at the machines. In that way, the external process of bringing the wagon will not be performed during the internal setup even though the whole process does not take so much time most of the time.

In stage two, the focus is on turning internal setup operations into external operations. For example, one internal setup operation is to find those feeders that should be taken out and used again in the new setup family. This is done through looking at a list. However, the required feeders can be marked with a sticker before the setup starts. The new placement for the feeders can also be indicated on the stickers. This can be done on both machines.

The other thing that can be done to remove the need for checking with a list is to put feeders of the next setup on the rack in their actual order in the stages. If some of the feeders are already in use by the current operation they can be represented by some physical objects like magazines as a sign of missing feeders. These common feeders can be taken out from the machines later and put on the lower shelves based on their order in the list. Figure 35 illustrates this (black shapes represent missing feeders while blue ones represent common feeders taken out from the machine):

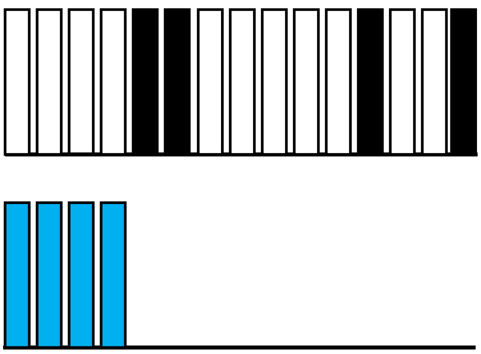

Figure 35: Sorting feeders on the rack

Doing so, the operator can take the first four feeders (according to the picture) and put them on the stages. Then he knows that there are two magazines or plastic parts that represent the missing feeders. Therefore he takes two of the feeders from the lower shelf. Then he takes five feeders from the first shelf and then one feeder from the lower shelf and so on. By this method, the operators do not need to waste time looking at the list. The process has been converted into external setup.

There is a rack close to QP machine that operators use it to keep the feeders for the new setup on it. The rack can be divided into five modules and feeders for every module can be put in their places according to their order. Then, some stickers can be used on the machine on each module that shows the place of the feeders on the stage. This process also eliminates the need for a list and checking through it during the setup because it has been converted into an external operation.

The third stage in SMED system focuses on streamlining the activities in both internal and external setup. For example, using parallel activities during setup on each machine, with two operators doing different things at the same time can reduce the internal setup time. Finding the common feeders between two setup lists used to be done manually but now it is performed automatically. It can also be set as a policy that in each setup occasion, there should be at least three operators ready for performing setup. That way, it can be made sure that operators can perform parallel activities. For example two operators at machine one and one or two operators at machine two, doing the setup at the same time.

5. Analysis

One question that remains is how changes in setup time will affect the batch sizes and total inventory value? The SMED theory suggests that short setups will lead to smaller batch sizes and lower stock values. In order to test that, batch sizes and ratios of stock values are calculated for different setup times to see how they are affected. The calculations are the same as previous calculations for optimum batch sizes. The same model is used for both problems. The only thing that changes in the model is the setup time. The setup time is reduced by steps of one minute and for each new setup time (21, 20, 19, 18, …etc.) the model is solved and the values are recorded. The result, showing reductions in stock value is illustrated in Figure 36:

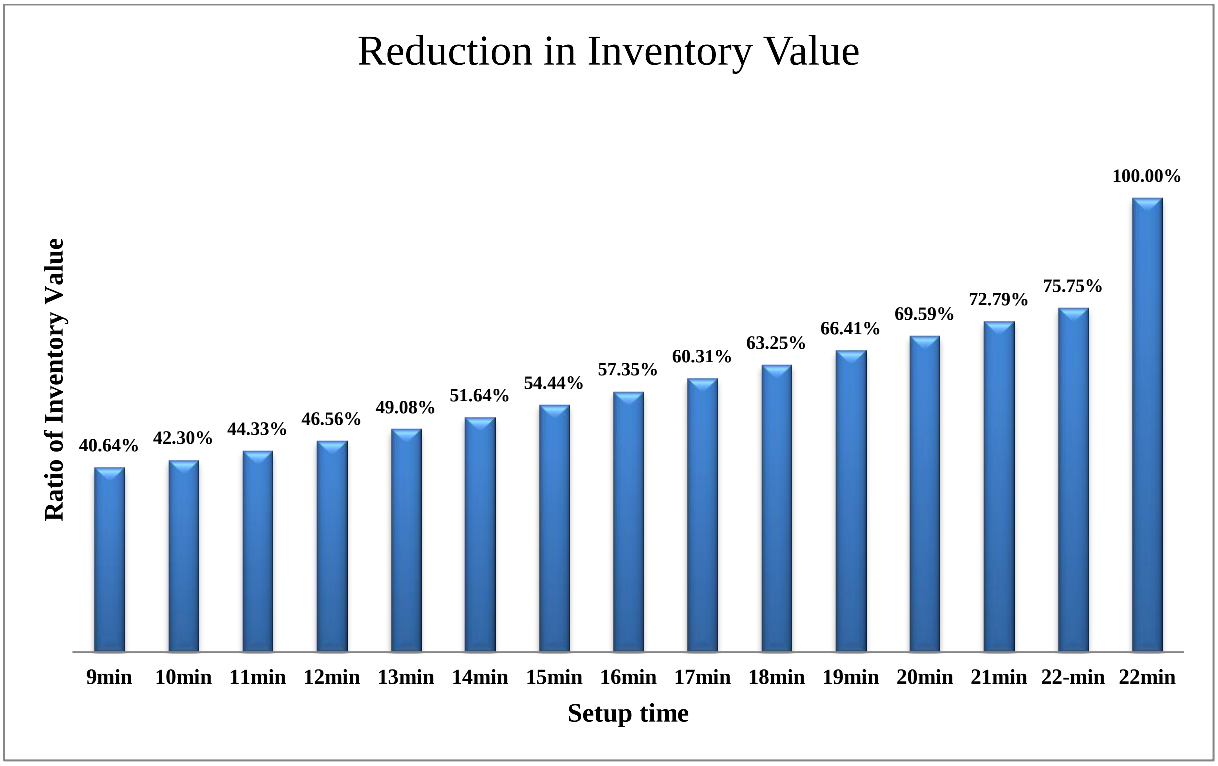

Figure 36: Reduction in Inventory Value

In the Figure 36, the ratio means the inventory value resulted from the new batch sizes divided by the inventory value from current batch sizes. As it is shown, there are two columns labeled 22-min (meaning setup time = 22 minutes). The first one is the current stock value for the current batch sizes. It is assigned the value of 100% since it is the benchmark for our evaluations and every new inventory value is compared to this one. The second 22-min column belongs to new batch sizes or the optimum batch sizes (the setup time is still 22 minutes). The rest of the columns are optimum solutions for new setup times. As it is shown above, every minute reduction in setup time can result in almost 3 percent reduction in inventory value. However, when setup times reach the values around 10 minutes, the rate of stock value reduction starts to decrease.

The new batch sizes resulted from reducing setup times are shown in Table 11. However it is worth mentioning that these values have not been adapted to fit the panel sizes (multiple lot sizes) and therefore they are still raw values.

Table 11: Effect of setup time reduction on batch sizes

Boards	Current Batch Sizes	Opt.22 min	21 min	20 min	19 min	18 min	17 min	16 min	15 min	14 min	13 min	12 min	11 min	10 min	9 min
X1	10	17	14	18	14	13	11	12	11	10	11	11	11	10	10
X2	20	12	13	12	13	8	9	12	8	9	7	5	6	5	6
X3	10	13	13	13	13	10	10	12	11	10	10	10	10	10	10
X4	20	19	19	16	17	13	15	14	16	11	12	9	10	8	6
X5	20	34	34	34	43	31	29	26	30	23	20	20	19	13	16
X6	30	33	27	29	34	23	23	22	15	19	17	18	10	11	12
X7	30	76	71	82	54	53	68	53	44	49	34	30	30	30	30
X8	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
X9	40	66	69	66	62	58	64	52	51	44	40	40	40	18	21
X10	20	12	9	12	10	12	9	10	10	9	12	9	9	9	10
X11	30	36	32	30	30	32	29	27	27	20	19	20	15	18	13
X12	20	11	11	12	11	11	11	8	6	8	6	5	7	5	4
X13	20	12	13	10	8	10	7	9	6	6	6	6	6	5	5
X14	40	66	66	69	67	57	48	42	47	40	40	32	35	24	18
X15	60	38	53	39	39	33	32	29	32	27	25	18	20	14	14
X16	60	90	104	93	82	78	74	62	59	54	49	48	36	32	26
X17	30	41	41	36	30	30	32	27	24	24	19	24	19	15	16
X18	12	27	25	22	21	21	20	20	16	16	12	12	11	11	10
X19	12	22	18	18	15	15	14	12	13	12	10	10	11	12	10
X20	60	25	23	25	17	16	18	20	15	15	13	16	7	7	9
X21	60	40	35	32	32	30	22	28	28	20	16	15	14	10	9
X22	20	48	51	48	47	39	35	36	29	31	29	24	20	18	14
X23	20	28	35	22	23	30	20	20	20	20	20	20	17	9	11
X24	60	112	102	103	97	98	91	69	68	65	59	53	42	44	26
X25	24	30	26	30	26	30	26	24	18	19	16	18	14	12	8
X26	40	49	47	47	49	40	40	38	34	30	32	24	25	17	14
X27	40	40	40	40	40	34	34	27	25	23	25	18	16	15	12
X28	100	100	100	88	82	80	71	76	61	58	56	43	42	29	28
X29	50	93	75	93	77	69	66	52	51	50	51	42	42	35	24
X30	30	58	56	54	51	47	51	40	35	34	30	30	28	30	16
X31	100	100	100	100	95	100	84	73	74	59	56	43	32	39	28
X32	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
X33	20	27	27	20	20	20	20	16	15	14	17	11	10	11	10
X34	100	99	90	81	77	75	65	74	60	53	49	43	36	31	29
X35	250	150	125	120	120	105	100	96	83	74	76	64	58	57	57
X36	20	19	20	23	20	18	18	15	17	14	13	13	10	8	6
X37	20	17	21	17	16	15	16	15	11	10	12	8	8	5	7
X38	60	60	60	52	54	41	41	33	34	31	28	27	23	19	16
X39	80	107	100	115	106	106	80	80	83	75	60	51	50	42	43
X40	60	79	72	64	67	60	53	58	46	48	37	34	29	26	17

X41	50	58	58	58	61	48	49	43	48	41	41	33	26	21	15
X42	20	20	20	20	20	20	18	18	14	13	13	11	8	7	8
X43	42	108	110	98	97	77	82	74	68	71	56	42	42	42	40
X44	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
X45	40	109	94	99	87	88	83	58	64	65	58	40	40	40	27
X46	80	110	97	97	110	87	78	78	68	68	63	53	49	32	28
X47	20	25	27	20	20	20	20	20	20	20	13	13	12	8	8
X48	80	131	139	126	113	108	99	91	91	76	72	74	59	45	35
X49	70	63	63	53	52	52	46	42	39	36	32	29	23	18	16
X50	90	207	186	189	145	170	134	126	111	112	89	90	90	72	57
X51	100	68	62	54	49	51	42	44	39	39	32	31	27	23	16
X52	90	197	203	183	185	177	126	148	136	122	105	90	93	64	52
X53	300	271	255	226	239	239	214	172	165	152	151	120	107	98	63
X54	20	17	15	17	14	15	15	12	10	10	8	10	7	6	5
X55	60	55	42	41	34	42	28	28	28	18	17	19	16	15	10
X56	20	15	13	12	12	10	12	10	11	8	7	6	6	5	6
X57	10	6	6	6	6	6	5	6	5	5	5	4	4	5	4
X58	8	8	8	8	8	8	8	6	6	4	5	4	5	6	5
X59	10	20	19	16	15	15	16	14	13	10	10	10	10	10	10
X60	180	82	83	76	72	64	63	59	53	50	49	48	49	49	50
X61	60	95	82	78	72	66	60	62	58	51	48	39	35	29	27
X62	40	40	40	35	30	30	29	33	26	30	24	14	16	14	11
X63	70	84	89	80	72	69	68	54	59	56	45	36	32	27	20
X64	20	52	48	53	48	53	35	33	26	28	21	29	22	17	15
X65	60	21	21	21	21	20	21	20	21	21	20	20	21	20	21
X66	60	20	21	22	23	22	26	21	21	20	20	23	20	21	20
X67	100	63	62	63	62	62	63	63	63	62	63	62	65	62	62
X68	100	88	88	76	80	68	72	68	67	66	67	68	66	66	67
X69	200	123	121	123	120	121	122	122	122	120	122	120	121	120	122
X70	40	30	30	31	31	31	30	30	30	31	31	30	31	31	30
X71	200	215	215	192	202	191	192	192	191	192	190	192	196	192	197
X72	120	111	120	114	102	99	91	94	95	92	93	92	90	91	91
X73	120	247	248	232	203	204	216	183	158	139	120	124	120	120	120
X74	80	68	68	66	68	68	66	66	65	66	67	65	66	66	66
X75	40	40	42	40	40	40	40	40	40	40	40	40	40	40	40
X76	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
X77	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
X78	30	29	23	23	25	19	20	19	17	21	18	23	18	17	18
X79	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
X80	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
X81	40	40	40	40	40	36	34	35	37	36	34	33	33	34	34
X82	20	36	27	32	36	32	25	20	20	20	20	20	12	14	11
X83	40	52	49	56	43	39	37	42	35	39	36	27	22	20	18

X84	40	20	21	16	15	15	14	11	11	11	10	9	7	9	7
X85	200	156	150	142	123	117	111	109	100	87	75	68	60	49	46
X86	160	63	61	55	54	49	45	42	41	37	33	31	32	30	31
X87	40	10	10	10	10	8	11	9	7	7	6	6	6	6	7
X88	40	18	17	17	17	18	18	18	17	18	18	17	17	17	17
X89	40	10	8	9	9	9	8	8	6	6	8	5	5	4	5
X90	40	35	35	33	28	26	26	24	22	20	22	21	20	20	21
X91	60	23	21	21	19	20	17	16	17	16	16	17	16	17	16
X92	60	60	60	56	52	45	43	37	44	35	25	26	22	20	18
X93	60	37	36	34	31	31	26	24	24	21	19	19	18	19	18
X94	60	67	71	61	60	60	55	55	45	43	36	34	28	24	24
X95	40	29	25	23	22	21	21	21	23	22	21	22	23	22	22
X96	60	29	27	28	23	23	21	21	20	18	15	13	11	10	9
X97	80	71	61	54	53	48	46	44	44	34	29	30	25	23	17
X98	40	35	32	25	22	25	24	20	27	24	19	19	18	19	21
X99	20	21	20	20	22	19	18	15	16	13	12	11	9	8	9
X100	20	13	11	9	9	9	8	7	6	5	6	4	5	4	4
X101	20	23	23	20	23	21	20	19	16	14	13	13	12	12	7
X102	60	124	124	147	137	116	116	95	90	77	78	62	62	60	43
X103	40	24	19	21	18	17	20	16	17	17	16	17	16	18	16
X104	60	49	40	51	38	39	32	32	29	28	25	23	24	26	25
X105	20	12	11	9	9	9	7	8	7	7	7	6	6	7	7
X106	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
X107	20	17	12	12	12	11	11	10	9	8	8	7	6	6	6
X108	40	25	23	22	20	20	17	17	15	12	12	12	11	10	11
X109	60	39	46	40	38	32	32	29	22	30	22	18	17	16	13
X110	40	85	87	86	68	87	76	58	53	62	50	40	40	36	26
X111	20	17	17	15	14	12	13	10	9	10	9	10	8	8	7
Aver. Batch Sizes	55	56	54	52	49	47	44	41	39	37	34	31	29	27	24

The last row in the table shows the average batch sizes for each setup time. As it is shown, by reducing the setup time, batch sizes will decrease too. This coordinates with SMED theory that suggests reducing setup times will result in flexibility and small lot sizes for the system.

In the previous calculations, the production capacity was considered as the sum of production times (cycle time × production quantity) and setup times for producing all the boards. This is a very pure time and is the minimum time that is certainly available in the system. However, the real available time is usually more than this amount. In order to perform the calculations with the actual available capacity, this value should be measured first. Through software designed in the company, historical data for available production times and different losses in production capacity are available since January (Figure 37):

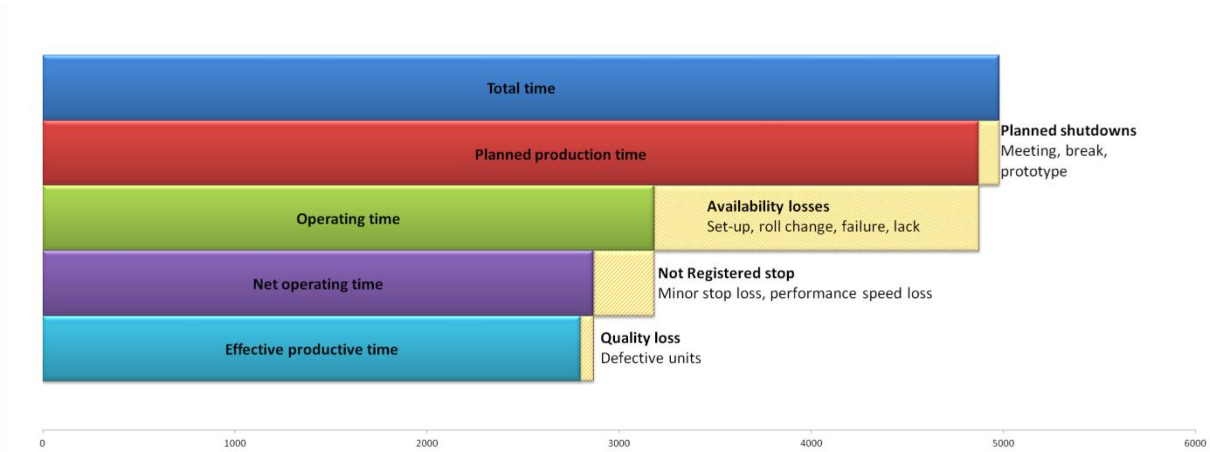

Figure 37: Available time for production in a week

A time period from first of January to first of April was chosen as the total time. After removing the losses from these three months, the total available time for production was calculated as approximately 64667 minutes. The production quantities for boards during these three months were also calculated through extracting historical data from IFS. Cycle times for each board were obtained from IFS too. Fewer boards were excluded this time from the calculations. Except from the prototypes, almost every other board that was produced during that period was included. That led to a list of 143 different boards. By putting the new input values, the new batch sizes were easily calculated (Table 12).

One of the company's policies is to switch from three shifts to two shifts. This means a reduction in work time requirements. However, this is not a 33 percent reduction in work time requirement. When the work shifts are reduced from three to two, the operators from the third shifts will spread over the other two shifts. This increase in the number of operators will reduce the losses in time caused by breaks or lunch hours. This is because operators can take turns when having lunch or breaks and there will always be some operators on the machines. At the other hand, some of the operators will join the shifts later and therefore they leave the shifts later too. Therefore, a shift of 8 hours can turn into 9 or 10. Calculating the total time for these three months based on two shift policy will lead to a total available time of 56514 minutes. This is almost 12.61% reduction in total available time. By having this new information, the model was solved with two different setup times (22 and 15 minutes) to see how work time requirement reduction will affect the total inventory value under different setup times and how setup reduction can help to cushion the effect of work time requirement reduction. The work time requirement was reduced in steps of 3 percent and each time model was solved for the new capacity. The results for work tiem requirement reductions are shown in Figures 38 and 39:

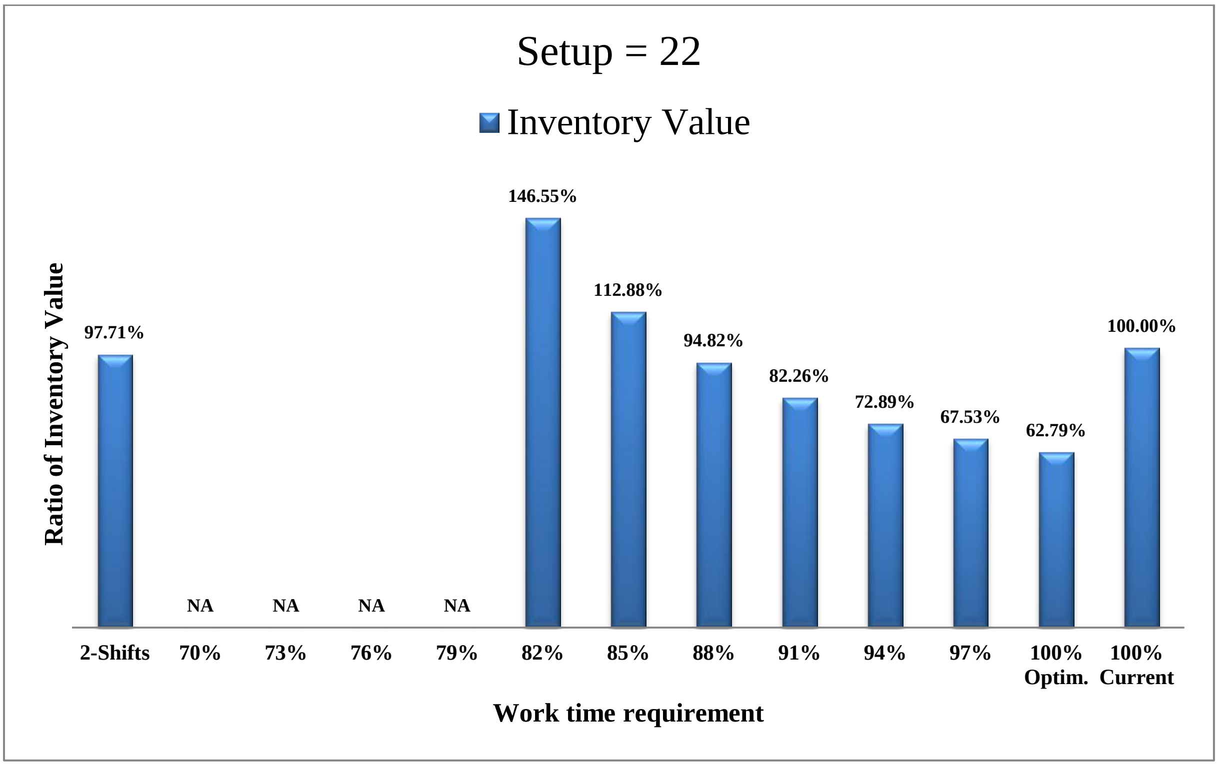

Figure 38: Work time requirement reduction with setup time = 22 minutes

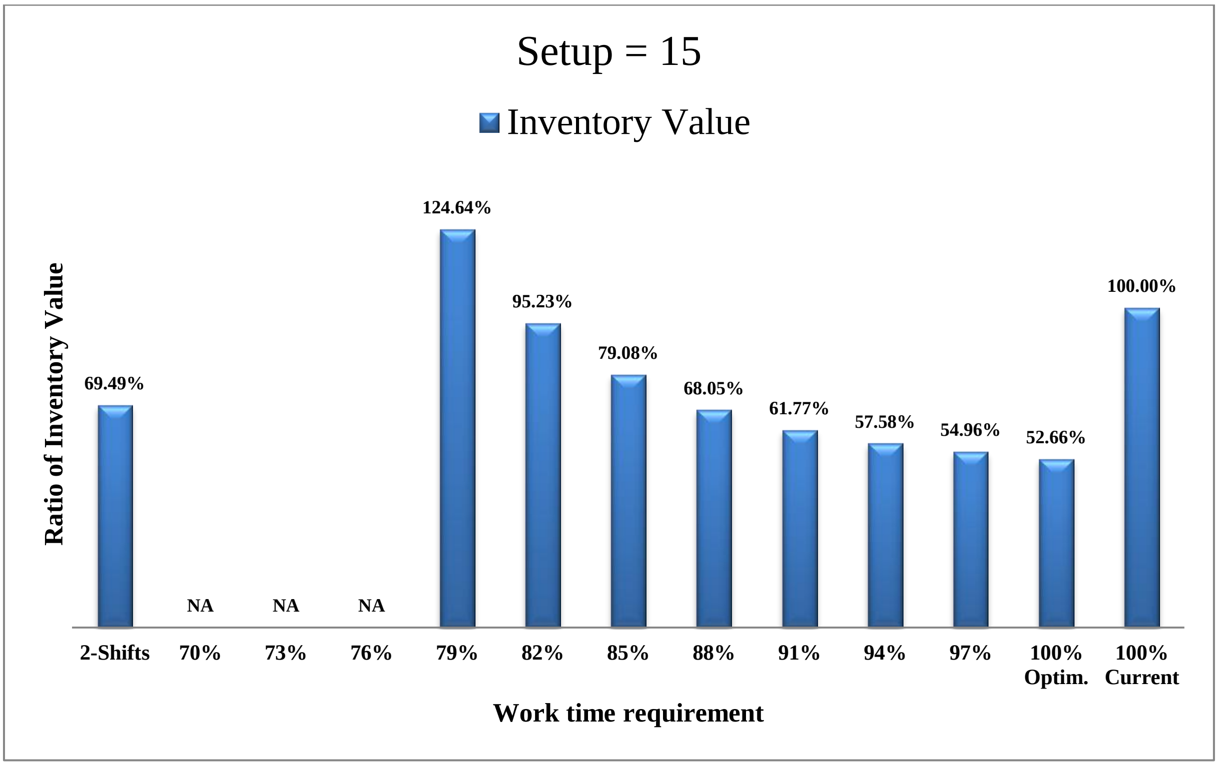

Figure 39: Work time requirement reduction with setup time = 15 minutes

As it is shown in figures above, work time requirement reduction will increase the inventory value (resulted from bigger batch sizes). This is caused because bigger batches will lead to fewer setups which are necessary if time is limited. For setup time of 22 minutes, the work time requirement reduction more than 18 percent is not available. This means that it is impossible to reduce the work time requirement more without violating some of the constraints. However, when setup time is reduced to 15 minutes, this value is 21 percent. The figures show that setup time reduction can help to cushion the effect of reduced capacity. According to the figures, by reducing the setup time to 15 minutes and by optimizing the batch sizes, all the boards from January to April could be produced in two shifts with lower stock value compared to current state. In order to see how setup time reduction will affect the ratio of inventory value (while working in two shifts), new calculations were carried on by reducing the setup time while work time requirement was fixed at 2 shifts. The results are shown at Figure 40 below:

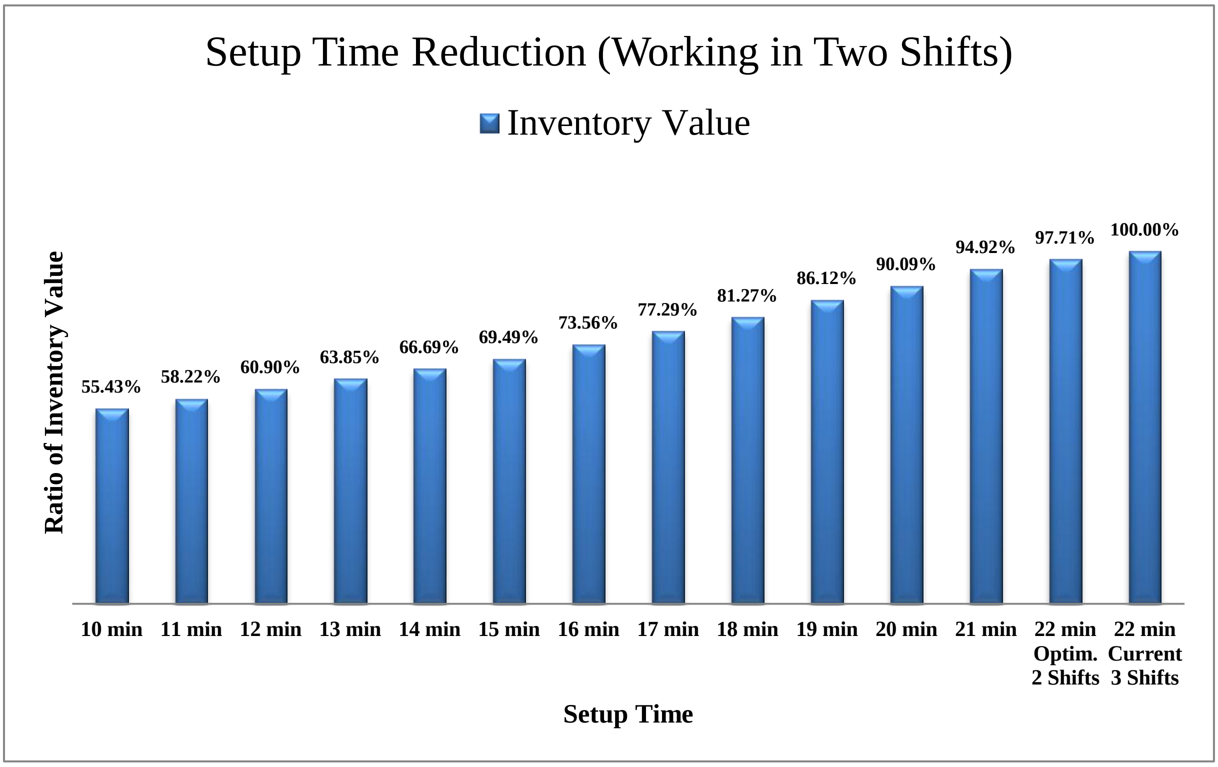

Figure 40: Setup time reduction when work time requirement is fixed at two shifts

One important thing to mention is that these results were obtained by optimizing the batch sizes (changing their quantity to find the best fit). Without optimizing the batch sizes, the result for inventory values would be different. However, it is still expected that setup time reduction will help to reduce the effect of work time reduction. Nonetheless, the inventory value will not change if batch sizes stay the same. The effect of work time reduction on optimum batch sizes and the effect of setup time reduction on optimum batch sizes are shown in Tables 12 to 14 in appendix B. Table 12 shows the effect of work time reduction on optimum batch sizes when setup time is equal to 22 minutes. Table 13 shows the same information but for the setup time equal to 15 minutes. Table 14 shows the effect of setup time reduction on optimum batch sizes when the work time requirement is fixed at two shifts. It is good to mention that these batch sizes are not adapted to panel sizes (multiple lot sizes) and therefore still are raw values.

6. Conclusions and Recommendations

In this thesis project, the problem of finding the optimum batch sizes in a High mix, Low volume production line was investigated. The case was an SMT line producing a high mix of different circuit boards in different volumes. The first problem faced throughout the project was finding an alternative for EOQ method. Economic order quantities, traditionally used in many firms, were mainly developed for the purpose of inventory management and purchasing. Within those borders where there is a clear ordering cost including transportation, insurance and salaries for purchasing staff, the EOQ method makes perfect sense. Implementing the same principles in a different environment like production can mislead us enormously. Although many parameters like total demand and inventory holding costs are the same in both environments, the idea that setup cost is the proper equivalent of ordering cost in a procurement environment can lead us to many troubles. Setup costs are hard to measure in many cases and they are usually not fixed values. However, they are widely used in academic papers as a criterion for calculating the batch sizes. A good alternative for EOQ method was found to be OR models. By replacing setup cost with setup time and linking that time to the total available capacity, an OR model can be built that minimizes the inventory value and finds the optimum batch sizes.

Single Minute Exchange of Die is not a method for calculating batch sizes but it is a powerful tool for making improvements. It claims that by reducing setup times to less than 10 minutes, there is no need for specifying batch sizes and one can produce quantities equal to customer demand. Aside from this claim, the analysis part of this paper shows that reducing setup times does reduce the average batch sizes. The reduction in inventory value and the increase in production capacity are among other benefits. It also shows that it can work as a cushion when work time is reduced. When capacity is limited, it is impossible to perform frequent setups and produce small lots. However, shortening the setup times can unleash an extra capacity that was wasted before. Furthermore, the analysis part shows that SMED is at the heart of a lean production system. Without having short setups, a firm cannot produce in small batches.

However, working with operators during the thesis work showed that implementing SMED requires a tremendous amount of soft skills. It is often rejected by the operators, loses its momentum, management focus turns away and not so before long, it is put aside as one of the fancy tools of lean that did not work and therefore everyone forgot about it. One way to avoid that is to build an SMED team that includes both operators and management. This team can be part of a larger team that is devoted to implement lean company-wide. It is very natural for the operators to want to prolong setup operations and it is up to management to create the motivation and devotion in the team and emphasize the importance of the SMED project. Therefore, management involvement and persistence is critical in the success of any improvement project.

The analysis part regarding capacity shows that it is possible to reduce the production work time requirement and batch sizes at the same time. This is possible provided that setup times are also reduced. Without reducing setup times, reduction in work time requirement will increase the batch sizes and inventory value. However, the time that is saved by reducing setup times can cover the reduced work time. In addition, optimizing the batch sizes at the same time is necessary for reducing the inventory value since inventory value is closely linked with batch sizes. Based on the analysis part, there is a point where extra reduction in work time requirement will prevent the system to produce all the customer demand and will cause serious under production.

Both empirical part and analysis part of this report show that optimization techniques in operations research can lead to significant savings in money. Contrary to that, they are not widely used in most industries. One further improvement for this work is to develop the OR model so that it will include panel sizes for each board too. The other improvement is to try to solve it only with integer values.

The main recommendation for further development of this work is to perform a simulation of the production line. This simulation should include the SMT line but it can involve other workstations too. ExtendSim is the best simulation software that comes to mind since it covers Discrete Event Simulation (DES) topic very well. By having an accurate simulation of the production line, different scenarios can be tested to see the results. For example, the answers for optimum batch sizes from MATLAB can be tested to see if they really affect the inventory value. It is good to see how the system reacts when a large demand arrives or how changes in setup times affect the stock value or system's flexibility. ExtendSim is not a software suitable for optimization specially when there is a wide range of variables or input data but it is a very strong tool of simulation that can help to verify the optimization results. One interesting simulation project is to test Shigeo Shingo's claim that reducing setup times to less than 10 minutes (For example, three minutes in case of Toyota) can enable a production system to produce according to customer order quantities.

Finally, another further work can be to look at the setup process of all machines in the SMT line and try to come up with a procedure that schedules setup tasks in an optimum manner.

7. References

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8. Appendices

A. The GA code for MATLAB

```
function [x,fval,exitflag,output,population,score] =
GACode(nvars,lb,ub,PopInitRange_Data,PopulationSize_Data,Generations_Data,T
olFun_Data,TolCon_Data,InitialPopulation_Data)
% This is an auto generated MATLAB file from Optimization Tool.

% Start with the default options
options = gaoptimset;
% Modify options setting
options = gaoptimset(options,'PopInitRange', PopInitRange_Data);
options = gaoptimset(options,'PopulationSize', PopulationSize_Data);
options = gaoptimset(options,'Generations', Generations_Data);
options = gaoptimset(options,'TolFun', TolFun_Data);
options = gaoptimset(options,'TolCon', TolCon_Data);
options = gaoptimset(options,'InitialPopulation', InitialPopulation_Data);
options = gaoptimset(options,'FitnessScalingFcn', {  @fitscalingtop [] });
options = gaoptimset(options,'CrossoverFcn', @crossoverscattered);
options = gaoptimset(options,'Display', 'off');
options = gaoptimset(options,'PlotFcns', { @gaplotbestf });
[x,fval,exitflag,output,population,score] = ...
ga(@minboards,nvars,[],[],[],[],lb,ub,@capacity,options);
```

B. Tables 12 to 14

Table 12: Reduction in work time requirements by steps of 3% when setup time is 22 minutes

Boards	Current Batches/ Current Capacity	Optim. Batches/ Current Capacity	97 %	94 %	91 %	88 %	85 %	82 %	Two Shifts	Price
X1	10	20	20	20	20	20	20	20	20	158,52
X2	20	20	20	20	20	20	20	20	20	168,03
X3	20	25	25	25	30	30	25	27	27	82,49
X4	30	30	30	30	32	31	32	32	38	105,02
X5	30	54	57	86	84	83	86	81	81	62,64
X6	3	8	8	8	8	8	8	8	8	338,81
X7	40	40	44	42	42	42	43	54	42	63,45
X8	20	31	31	30	36	37	31	31	31	83,44
X9	30	20	20	30	30	32	31	38	32	182,45
X10	20	20	20	20	20	20	20	20	20	147,75
X11	40	37	54	72	83	81	110	112	109	119,02
X12	60	31	31	31	32	31	31	31	33	70,11
X13	60	60	40	60	60	63	61	67	62	69,05
X14	30	30	30	31	32	32	33	33	34	118,63
X15	12	12	15	20	21	31	31	31	30	408,35
X16	12	8	8	8	9	9	8	10	9	350,13
X17	60	15	20	20	31	32	31	32	31	295,43
X18	60	21	30	30	32	31	32	35	31	147,69
X19	20	20	25	25	34	36	55	51	52	227,25
X20	20	20	27	28	28	42	41	43	41	232,47
X21	60	60	61	61	91	90	92	93	101	79,07
X22	24	19	19	28	28	28	29	32	28	135,8
X23	50	116	116	116	116	116	116	116	116	213,88
X24	40	40	32	40	54	54	83	83	54	214,02
X25	40	40	33	40	67	51	100	112	70	217,73
X26	100	82	102	91	92	136	165	207	137	190,29
X27	50	50	74	99	101	100	154	221	118	168,67
X28	30	42	71	70	70	107	140	140	107	184,89
X29	100	100	67	100	125	158	152	201	151	142,56
X30	16	20	20	20	20	20	20	20	20	191,06
X31	20	16	21	27	27	27	36	53	36	465,1
X32	100	73	69	85	104	135	171	293	165	375,24
X33	250	98	117	126	160	177	250	298	196	261,8
X34	20	22	22	22	22	22	22	22	22	305,97
X35	20	8	8	8	8	8	8	8	8	424,09
X36	60	36	40	50	60	71	92	129	59	370,84
X37	80	80	101	100	136	146	201	206	201	85,44
X38	60	58	72	83	101	145	145	201	98	197,85

X39	50	47	53	70	84	109	105	142	88	230,18
X40	20	9	14	14	14	15	16	15	15	247,47
X41	42	81	82	80	101	206	137	208	134	97,1
X42	40	66	61	75	111	159	154	155	156	91,47
X43	80	80	80	80	136	139	209	206	136	96,66
X44	20	19	19	31	35	33	46	48	32	317,25
X45	80	112	131	157	157	200	273	393	210	92,77
X46	70	41	57	62	96	98	125	151	93	393,22
X47	90	196	167	195	200	264	414	406	268	39,31
X48	100	44	45	44	66	56	101	132	83	357,56
X49	90	90	133	183	187	186	229	181	200	30,78
X50	300	149	180	242	242	401	445	600	299	44,41
X51	20	10	12	20	20	20	30	30	30	481,59
X52	60	32	30	31	30	39	33	31	32	73,03
X53	24	24	24	37	36	37	36	39	41	110,19
X54	20	20	16	20	21	30	30	31	30	439,06
X55	10	22	22	22	22	22	22	22	22	1572,85
X56	180	71	69	88	102	132	160	241	141	581,26
X57	60	61	68	97	114	173	227	234	174	167,52
X58	40	13	21	20	20	23	20	22	21	167,89
X59	70	70	42	53	78	111	112	107	108	125,22
X60	20	37	37	55	56	56	55	59	57	144,07
X61	60	3	3	3	3	3	3	3	3	847,85
X62	60	8	8	8	8	8	8	8	8	464,95
X63	100	62	62	62	67	72	85	125	78	962,17
X64	100	70	78	70	79	88	141	180	88	379,99
X65	200	132	132	132	132	124	132	241	136	335,64
X66	40	30	30	30	32	32	36	54	33	1905,95
X67	5	6	6	6	6	6	6	6	6	374,05
X68	200	199	216	204	281	268	400	406	270	51,98
X69	120	93	93	93	93	102	155	240	99	202,94
X70	30	16	15	20	22	33	30	31	31	227,75
X71	60	60	91	90	97	90	95	95	95	43
X72	120	120	120	240	242	248	248	279	252	39,46
X73	20	8	8	8	8	8	8	8	8	498,67
X74	20	16	16	16	16	16	16	16	16	704,04
X75	20	12	12	12	12	12	12	12	12	1083
X76	12	12	12	16	16	16	16	16	16	570,33
X77	20	12	12	12	12	12	12	12	12	410,81
X78	20	8	8	8	8	8	8	8	8	525,68
X79	10	12	12	12	12	12	12	12	12	1969,74
X80	20	8	8	8	8	8	8	8	8	2022,11
X81	20	20	20	20	20	20	20	20	20	514,65

X82	20	20	20	20	20	20	20	20	20	1927,21
X83	20	7	7	7	7	7	7	7	7	296,6
X84	80	80	70	65	72	93	96	142	81	434,81
X85	40	40	60	40	48	63	64	81	62	381,37
X86	40	20	20	20	20	20	20	20	20	156,06
X87	40	40	49	48	48	77	95	98	64	458,89
X88	20	20	25	32	32	37	44	75	45	636,37
X89	20	20	22	22	28	36	55	56	28	480,16
X90	40	40	36	44	57	58	80	100	66	472,91
X91	20	21	27	30	36	53	55	71	44	505,74
X92	20	20	25	24	24	33	48	48	35	494,4
X93	40	33	25	34	54	54	51	50	50	190,92
X94	40	2	2	2	2	2	2	2	2	672,44
X95	20	20	26	34	32	42	52	85	47	1462,96
X96	20	37	45	51	60	64	86	128	70	634,65
X97	20	16	17	17	20	24	29	37	24	2206,97
X98	20	15	15	15	15	17	21	30	20	2025,49
X99	20	20	20	21	26	29	39	59	30	1371,23
X100	20	15	15	15	21	24	24	41	28	1472,85
X101	20	12	13	14	13	13	18	18	13	1937,11
X102	20	20	22	21	28	40	40	51	33	1558,08
X103	20	21	36	36	41	46	64	109	54	571,11
X104	200	107	111	122	154	189	246	353	209	329,99
X105	20	36	36	36	36	36	36	36	36	345,42
X106	160	43	53	60	79	88	107	138	93	971,25
X107	40	8	10	10	13	16	21	28	17	1451,76
X108	40	47	47	47	47	47	47	47	47	974,01
X109	40	9	13	15	15	15	25	37	19	1023,75
X110	40	4	3	3	4	3	3	3	3	1283,37
X111	40	20	21	26	34	37	48	67	42	1084,07
X112	60	16	19	18	20	26	32	53	27	1143,52
X113	60	27	34	44	66	67	69	70	67	173,75
X114	60	22	27	34	34	43	63	75	48	1168,08
X115	60	42	51	57	65	105	102	170	110	310,5
X116	20	49	49	49	49	49	49	49	49	1455,41
X117	20	20	20	20	20	20	20	20	20	1462,16
X118	40	22	23	25	29	29	38	76	32	1059,75
X119	40	11	11	11	11	11	11	11	11	777,51
X120	20	1	1	1	1	1	1	1	1	1283,74
X121	60	16	21	21	22	32	43	64	33	537,3
X122	20	7	7	7	7	7	7	7	7	565,14
X123	80	44	40	52	58	87	105	131	75	472,03
X124	40	30	30	40	41	40	66	61	61	271,92

X125	20	4	4	4	4	4	4	4	4	534,67
X126	20	14	14	14	21	25	34	53	28	891,38
X127	20	8	8	10	10	14	20	21	14	811
X128	20	1	1	1	1	1	1	1	1	891,38
X129	20	13	16	21	21	21	35	53	26	781,26
X130	20	8	8	8	8	8	8	8	8	781,26
X131	60	84	146	105	141	213	217	212	249	57,27
X132	40	16	20	20	21	29	40	41	27	509,43
X133	60	31	37	37	57	49	68	97	68	477,9
X134	20	8	8	10	14	14	13	20	13	864,07
X135	20	20	20	20	20	26	26	27	20	711,74
X136	20	8	9	10	15	20	20	30	21	1196,4
X137	40	16	18	20	21	34	34	59	30	1139,62
X138	60	20	25	31	44	60	64	62	66	217,67
X139	40	40	64	61	62	65	66	67	62	55,32
X140	20	8	8	8	8	8	8	8	8	143,45
X141	20	6	6	6	6	6	6	6	6	272,07
X142	20	7	9	9	11	16	22	22	15	1087,27
X143	20	8	8	8	8	8	8	8	8	1308,66
Average	48	36	39	44	50	59	70	84	60	

Table 13: Reduction in work time requirements by steps of 3% when setup time is 15 minutes

Boards	Current Batches/ Current Capacity	Optim. Batches/ Current Capacity	97 %	94 %	91 %	88 %	85 %	82 %	79 %	Two Shifts	Price
X1	10	20	20	20	20	20	20	20	20	20	158,52
X2	20	20	20	20	20	20	20	20	20	20	168,03
X3	20	13	19	19	29	29	26	27	29	29	82,49
X4	30	12	16	22	31	33	31	34	31	32	105,02
X5	30	40	33	33	55	80	80	80	82	80	62,64
X6	3	8	8	8	8	8	8	8	8	8	338,81
X7	40	16	24	43	42	44	54	42	42	43	63,45
X8	20	21	17	20	31	34	30	42	30	31	83,44
X9	30	13	16	18	23	20	31	35	30	31	182,45
X10	20	20	20	20	20	20	20	20	20	20	147,75
X11	40	25	24	43	51	47	74	111	121	72	119,02
X12	60	17	22	34	31	31	30	33	37	32	70,11
X13	60	25	33	30	43	60	60	75	61	67	69,05
X14	30	16	15	20	30	31	37	31	33	30	118,63
X15	12	9	11	10	15	16	22	32	30	15	408,35
X16	12	8	8	8	9	9	10	8	8	8	350,13
X17	60	13	13	13	15	20	33	35	32	22	295,43
X18	60	12	17	15	22	31	32	30	30	31	147,69
X19	20	14	15	17	26	26	37	35	51	25	227,25

X20	20	9	14	16	22	20	31	43	40	28	232,47
X21	60	26	37	47	48	61	97	95	92	47	79,07
X22	24	12	11	20	28	29	32	37	29	31	135,8
X23	50	116	116	116	116	116	116	116	116	116	213,88
X24	40	19	20	28	27	41	57	81	80	32	214,02
X25	40	14	25	37	33	41	51	68	100	35	217,73
X26	100	35	34	68	63	92	98	147	212	76	190,29
X27	50	30	36	66	63	86	102	127	204	85	168,67
X28	30	35	31	48	71	52	91	118	150	53	184,89
X29	100	44	41	46	68	75	121	103	201	101	142,56
X30	16	20	20	20	20	20	20	20	20	20	191,06
X31	20	10	13	14	15	21	23	36	54	18	465,1
X32	100	31	43	47	70	92	104	145	207	91	375,24
X33	250	57	66	68	98	109	127	196	292	98	261,8
X34	20	22	22	22	22	22	22	22	22	22	305,97
X35	20	8	8	8	8	8	8	8	8	8	424,09
X36	60	20	25	30	29	45	62	60	89	46	370,84
X37	80	45	52	52	72	100	104	135	204	83	85,44
X38	60	29	32	54	58	73	85	116	194	64	197,85
X39	50	22	36	33	43	53	89	87	147	71	230,18
X40	20	8	7	10	14	11	15	15	15	14	247,47
X41	42	52	46	53	81	71	81	147	202	81	97,1
X42	40	32	51	50	61	64	109	104	154	78	91,47
X43	80	42	51	47	60	135	101	200	201	88	96,66
X44	20	10	9	13	17	23	24	32	48	23	317,25
X45	80	44	93	87	98	112	173	215	266	115	92,77
X46	70	25	36	37	39	67	74	94	126	53	393,22
X47	90	89	93	159	167	163	214	261	407	205	39,31
X48	100	17	24	30	34	36	51	81	100	57	357,56
X49	90	51	95	73	120	184	196	200	182	126	30,78
X50	300	93	93	111	176	174	304	422	624	244	44,41
X51	20	8	10	11	11	12	20	20	30	20	481,59
X52	60	15	20	30	32	32	34	35	42	37	73,03
X53	24	13	26	26	38	36	39	37	38	36	110,19
X54	20	8	9	10	12	15	21	30	32	15	439,06
X55	10	22	22	22	22	22	22	22	22	22	1572,85
X56	180	50	52	51	70	74	92	138	161	80	581,26
X57	60	38	46	57	68	77	97	139	183	89	167,52
X58	40	14	10	14	20	20	21	20	23	20	167,89
X59	70	26	35	31	36	44	74	73	119	53	125,22
X60	20	14	22	20	29	31	56	55	58	37	144,07
X61	60	3	3	3	3	3	3	3	3	3	847,85
X62	60	8	8	8	8	8	8	8	8	8	464,95

X63	100	62	62	63	62	62	62	72	93	63	962,17
X64	100	70	67	75	70	73	74	79	120	73	379,99
X65	200	120	134	128	121	122	135	135	198	132	335,64
X66	40	30	30	30	31	30	30	32	40	30	1905,95
X67	5	6	6	6	6	6	6	6	6	6	374,05
X68	200	195	230	196	207	199	200	278	407	210	51,98
X69	120	96	97	91	93	96	95	94	159	94	202,94
X70	30	17	21	15	22	20	31	30	31	22	227,75
X71	60	37	51	45	63	60	98	92	93	95	43
X72	120	122	144	124	122	125	251	277	242	172	39,46
X73	20	8	8	8	8	8	8	8	8	8	498,67
X74	20	16	16	16	16	16	16	16	16	16	704,04
X75	20	12	12	12	12	12	12	12	12	12	1083
X76	12	12	13	12	13	13	12	17	17	17	570,33
X77	20	12	12	12	12	12	12	12	12	12	410,81
X78	20	8	8	8	8	8	8	8	8	8	525,68
X79	10	12	12	12	12	12	12	12	12	12	1969,74
X80	20	8	8	8	8	8	8	8	8	8	2022,11
X81	20	20	20	20	20	20	20	20	20	20	514,65
X82	20	20	20	20	20	20	20	20	20	20	1927,21
X83	20	7	7	7	7	7	7	7	7	7	296,6
X84	80	65	66	66	66	65	72	80	112	66	434,81
X85	40	40	41	40	41	44	40	63	80	40	381,37
X86	40	20	20	20	20	20	20	20	20	20	156,06
X87	40	43	43	41	43	43	54	63	95	43	458,89
X88	20	20	20	20	20	25	32	44	56	28	636,37
X89	20	20	22	21	22	22	30	37	57	22	480,16
X90	40	33	34	33	34	40	57	57	80	37	472,91
X91	20	20	24	21	21	27	31	53	54	30	505,74
X92	20	20	21	21	20	21	26	26	49	20	494,4
X93	40	21	21	27	27	35	33	52	50	33	190,92
X94	40	2	2	2	2	2	2	2	2	2	672,44
X95	20	22	22	20	20	24	30	43	63	27	1462,96
X96	20	25	26	33	39	51	59	86	110	55	634,65
X97	20	16	16	16	16	16	19	22	37	16	2206,97
X98	20	15	15	15	15	15	15	17	24	15	2025,49
X99	20	20	20	20	20	22	24	30	40	22	1371,23
X100	20	15	15	15	17	17	18	21	33	15	1472,85
X101	20	12	13	12	12	13	13	13	18	13	1937,11
X102	20	21	20	20	20	24	28	33	51	22	1558,08
X103	20	20	25	19	21	34	41	54	80	29	571,11
X104	200	48	60	70	88	130	154	189	272	111	329,99
X105	20	36	36	36	36	36	36	36	36	36	345,42

X106	160	35	32	40	42	47	60	93	125	53	971,25
X107	40	6	6	7	8	9	12	17	21	10	1451,76
X108	40	47	47	47	47	47	47	47	47	47	974,01
X109	40	5	7	9	8	11	17	19	25	12	1023,75
X110	40	3	3	3	3	3	3	3	3	3	1283,37
X111	40	20	20	20	21	21	30	34	47	26	1084,07
X112	60	17	16	16	17	18	20	27	40	17	1143,52
X113	60	19	22	23	27	33	66	71	70	34	173,75
X114	60	18	18	24	22	30	32	42	64	32	1168,08
X115	60	21	26	32	46	51	76	89	173	57	310,5
X116	20	49	49	49	49	49	49	49	49	49	1455,41
X117	20	20	20	20	20	20	20	20	20	20	1462,16
X118	40	21	21	21	21	23	28	33	56	22	1059,75
X119	40	11	11	11	11	11	11	11	11	11	777,51
X120	20	1	1	1	1	1	1	1	1	1	1283,74
X121	60	9	11	12	13	18	25	32	43	21	537,3
X122	20	7	7	7	7	7	7	7	7	7	565,14
X123	80	24	20	29	35	45	52	74	87	44	472,03
X124	40	25	21	21	24	30	41	61	64	31	271,92
X125	20	4	4	4	4	4	4	4	4	4	534,67
X126	20	9	9	9	11	15	21	21	33	15	891,38
X127	20	4	6	6	8	10	13	15	20	11	811
X128	20	1	1	1	1	1	1	1	1	1	891,38
X129	20	7	9	11	13	18	18	35	35	15	781,26
X130	20	8	8	8	8	8	8	8	8	8	781,26
X131	60	57	53	74	77	105	222	214	214	108	57,27
X132	40	16	18	16	16	20	20	28	45	17	509,43
X133	60	29	24	26	29	34	48	58	84	31	477,9
X134	20	7	6	7	8	9	15	14	20	8	864,07
X135	20	20	20	20	20	20	21	27	26	20	711,74
X136	20	6	7	7	9	10	12	16	21	10	1196,4
X137	40	10	10	13	13	18	24	34	47	21	1139,62
X138	60	11	21	20	31	30	31	61	61	30	217,67
X139	40	21	42	44	60	62	78	67	71	63	55,32
X140	20	8	8	8	8	8	8	8	8	8	143,45
X141	20	6	6	6	6	6	6	6	6	6	272,07
X142	20	7	8	7	7	8	11	15	22	9	1087,27
X143	20	8	8	8	8	8	8	8	8	8	1308,66
Average	48	26	29	31	35	40	49	59	76	41	

Table 14: Reduction in setup time by steps of 1 minute when working time is fixed at 2 shifts

Boards	Current Batch Sizes	Optim. 22 min	21 min	20 min	19 min	18 min	17 min	16 min	15 min	14 min	13 min	12 min	11 min	10 min
X1	10	20	20	20	20	20	20	20	20	20	20	20	20	20
X2	20	20	20	20	20	20	20	20	20	20	20	20	20	20
X3	20	27	31	27	27	26	26	27	29	28	28	26	28	18
X4	30	38	35	32	31	30	32	32	32	32	30	31	23	15
X5	30	81	94	81	91	87	94	55	80	80	41	59	56	41
X6	3	8	8	8	8	8	8	8	8	8	8	8	8	8
X7	40	42	46	45	45	41	41	41	43	42	42	45	35	21
X8	20	31	33	34	31	33	33	34	31	34	34	24	23	16
X9	30	32	34	37	39	32	30	32	31	20	21	18	15	13
X10	20	20	20	20	20	20	20	20	20	20	20	20	20	20
X11	40	109	117	73	81	73	57	54	72	59	35	39	41	32
X12	60	33	47	39	32	33	34	31	32	38	31	19	22	20
X13	60	62	71	67	68	62	63	62	67	65	42	37	36	30
X14	30	34	30	32	32	31	31	32	30	33	30	22	21	15
X15	12	30	31	31	20	20	21	21	15	15	12	12	10	14
X16	12	9	8	9	8	8	9	8	8	8	8	10	8	8
X17	60	31	35	31	30	30	32	22	22	23	14	17	13	10
X18	60	31	34	33	36	30	36	32	31	22	31	21	15	15
X19	20	52	33	50	51	34	34	36	25	26	26	26	20	18
X20	20	41	42	43	42	42	28	28	28	20	21	19	20	13
X21	60	101	92	93	95	91	94	94	47	68	47	46	45	26
X22	24	28	30	28	31	33	34	29	31	31	28	19	20	14
X23	50	116	116	116	116	116	116	116	116	116	116	116	116	116
X24	40	54	81	59	54	55	42	36	32	54	27	24	27	18
X25	40	70	71	68	56	75	52	40	35	34	36	30	25	23
X26	100	137	138	123	87	104	103	118	76	82	68	76	56	43
X27	50	118	163	119	119	122	85	74	85	66	61	62	54	33
X28	30	107	110	105	108	87	60	71	53	53	67	47	47	33
X29	100	151	141	122	126	124	125	103	101	69	69	67	51	44
X30	16	20	20	20	20	20	20	20	20	20	20	20	20	20
X31	20	36	36	27	37	27	21	27	18	19	15	15	12	12
X32	100	165	162	112	115	113	105	91	91	77	77	49	36	49
X33	250	196	147	150	148	135	163	128	98	97	98	63	74	71
X34	20	22	22	22	22	22	22	22	22	22	22	22	22	22
X35	20	8	8	8	8	8	8	8	8	8	8	8	8	8
X36	60	59	72	72	61	51	59	40	46	45	26	31	25	22
X37	80	201	134	150	108	104	100	104	83	83	72	73	59	51
X38	60	98	123	118	119	98	72	73	64	83	64	64	53	53
X39	50	88	106	107	71	72	62	84	71	62	47	53	43	25
X40	20	15	14	15	15	15	16	15	14	14	14	14	9	10

X41	42	134	135	151	147	102	136	81	81	83	60	86	53	51
X42	40	156	101	109	103	105	109	105	78	80	101	60	52	38
X43	80	136	135	140	137	87	140	83	88	88	81	68	59	45
X44	20	32	34	32	33	31	31	26	23	19	17	19	16	13
X45	80	210	212	209	168	196	162	157	115	99	115	99	98	66
X46	70	93	83	107	93	75	75	69	53	63	50	39	31	30
X47	90	268	274	408	262	275	208	163	205	158	196	176	122	119
X48	100	83	84	68	68	51	51	57	57	51	33	31	28	20
X49	90	200	180	189	186	191	185	183	126	185	109	127	120	72
X50	300	299	402	307	312	305	262	205	244	203	200	172	158	120
X51	20	30	30	21	21	20	21	20	20	16	13	14	9	8
X52	60	32	34	32	30	40	41	34	37	33	31	20	21	15
X53	24	41	37	42	38	38	40	38	36	37	37	36	24	19
X54	20	30	30	30	20	21	20	21	15	13	12	18	7	9
X55	10	22	22	22	22	22	22	22	22	22	22	22	22	22
X56	180	141	120	113	98	97	92	88	80	69	69	61	50	63
X57	60	174	138	137	136	114	86	76	89	87	87	76	50	40
X58	40	21	23	22	22	22	23	20	20	15	14	22	15	10
X59	70	108	112	111	105	110	74	70	53	55	44	36	43	35
X60	20	57	63	56	60	40	39	48	37	37	28	37	23	22
X61	60	3	3	3	3	3	3	3	3	3	3	3	3	3
X62	60	8	8	8	8	8	8	8	8	8	8	8	8	8
X63	100	78	72	62	67	63	62	67	63	62	63	62	66	63
X64	100	88	88	92	72	73	70	71	73	67	67	67	66	66
X65	200	136	122	133	121	152	123	125	132	133	125	121	132	120
X66	40	33	33	32	30	32	33	30	30	31	31	30	31	30
X67	5	6	6	6	6	6	6	6	6	6	6	6	6	6
X68	200	270	282	280	273	201	211	221	210	211	211	206	195	199
X69	120	99	95	121	120	94	93	93	94	94	96	94	94	93
X70	30	31	31	30	32	32	30	31	22	21	20	16	15	15
X71	60	95	91	97	131	109	105	98	95	91	65	64	64	46
X72	120	252	241	248	261	165	242	166	172	131	124	132	121	129
X73	20	8	8	8	8	8	8	8	8	8	8	8	8	8
X74	20	16	16	16	16	16	16	16	16	16	16	16	16	16
X75	20	12	12	12	12	12	12	12	12	12	12	12	12	12
X76	12	16	16	18	17	17	17	12	17	13	13	12	12	12
X77	20	12	12	12	12	12	12	12	12	12	12	12	12	12
X78	20	8	8	8	8	8	8	8	8	8	8	8	8	8
X79	10	12	12	12	12	12	12	12	12	12	12	12	12	12
X80	20	8	8	8	8	8	8	8	8	8	8	8	8	8
X81	20	20	20	20	20	20	20	20	20	20	20	20	20	20
X82	20	20	20	20	20	20	20	20	20	20	20	20	20	20
X83	20	7	7	7	7	7	7	7	7	7	7	7	7	7

X84	80	81	71	81	70	65	66	66	66	66	67	65	66	65
X85	40	62	49	49	48	50	41	60	40	41	42	40	46	40
X86	40	20	20	20	20	20	20	20	20	20	20	20	20	20
X87	40	64	68	56	64	55	48	43	43	43	42	49	44	40
X88	20	45	45	37	38	37	28	32	28	22	23	25	21	21
X89	20	28	37	28	28	28	22	23	22	22	27	22	22	20
X90	40	66	57	66	57	50	44	36	37	34	37	36	44	34
X91	20	44	36	37	43	31	30	30	30	21	23	22	25	25
X92	20	35	24	33	24	24	24	20	20	21	27	22	24	21
X93	40	50	52	51	54	33	33	34	33	26	26	25	25	18
X94	40	2	2	2	2	2	2	2	2	2	2	2	2	2
X95	20	47	40	42	34	30	30	27	27	24	22	21	22	23
X96	20	70	64	77	56	70	48	48	55	40	39	31	35	26
X97	20	24	26	20	22	20	17	19	16	16	16	16	16	16
X98	20	20	20	20	15	15	15	16	15	15	17	15	15	15
X99	20	30	26	24	30	24	22	24	22	22	23	20	20	20
X100	20	28	24	21	20	19	21	17	15	17	15	16	15	15
X101	20	13	14	13	13	14	13	13	13	12	12	13	12	14
X102	20	33	36	27	28	26	27	23	22	20	22	20	21	20
X103	20	54	48	46	54	54	36	33	29	36	32	28	23	21
X104	200	209	189	154	208	165	137	154	111	107	99	94	68	54
X105	20	36	36	36	36	36	36	36	36	36	36	36	36	36
X106	160	93	83	75	75	66	71	60	53	44	40	40	35	43
X107	40	17	18	17	14	12	12	12	10	10	9	7	7	8
X108	40	47	47	47	47	47	47	47	47	47	47	47	47	47
X109	40	19	25	19	15	15	15	12	12	10	10	10	7	7
X110	40	3	3	3	3	3	3	3	3	3	3	3	3	3
X111	40	42	40	41	30	30	33	26	26	22	22	22	26	21
X112	60	27	26	24	23	20	22	18	17	18	16	17	16	16
X113	60	67	66	49	47	48	34	47	34	37	34	35	27	21
X114	60	48	40	46	37	34	31	31	32	24	23	20	20	20
X115	60	110	91	75	86	64	86	57	57	57	47	47	32	26
X116	20	49	49	49	49	49	49	49	49	49	49	49	49	49
X117	20	20	20	20	20	20	20	20	20	20	20	20	20	20
X118	40	32	33	28	32	27	25	22	22	23	23	22	22	22
X119	40	11	11	11	11	11	11	11	11	11	11	11	11	11
X120	20	1	1	1	1	1	1	1	1	1	1	1	1	1
X121	60	33	33	26	33	32	22	26	21	18	18	19	15	11
X122	20	7	7	7	7	7	7	7	7	7	7	7	7	7
X123	80	75	78	67	76	58	59	55	44	44	44	33	33	28
X124	40	61	41	33	40	30	40	31	31	24	21	20	20	18
X125	20	4	4	4	4	4	4	4	4	4	4	4	4	4
X126	20	28	25	26	21	17	16	15	15	16	10	11	9	9

X127	20	14	14	14	11	14	10	10	11	8	7	7	6	6
X128	20	1	1	1	1	1	1	1	1	1	1	1	1	1
X129	20	26	35	26	17	21	21	17	15	18	13	13	11	9
X130	20	8	8	8	8	8	8	8	8	8	8	8	8	8
X131	60	249	213	156	214	153	140	141	108	113	116	87	78	62
X132	40	27	30	20	20	27	20	20	17	16	18	18	16	16
X133	60	68	61	59	56	56	44	38	31	31	31	31	30	25
X134	20	13	13	15	14	14	10	11	8	10	8	7	7	6
X135	20	20	28	21	23	21	20	21	20	20	21	20	21	21
X136	20	21	15	15	15	12	10	10	10	9	9	8	8	7
X137	40	30	34	30	27	24	24	21	21	20	16	12	12	12
X138	60	66	62	65	43	62	42	32	30	32	26	22	21	17
X139	40	62	62	69	63	66	61	62	63	64	45	35	44	40
X140	20	8	8	8	8	8	8	8	8	8	8	8	8	8
X141	20	6	6	6	6	6	6	6	6	6	6	6	6	6
X142	20	15	15	16	11	11	11	11	9	10	8	8	8	7
X143	20	8	8	8	8	8	8	8	8	8	8	8	8	8
Average	48	60	59	56	54	50	47	44	41	40	37	35	32	28