Productivity improvement of a small to medium, custom-manufacturing factory

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Executive summary

This report addresses productivity shortcomings at PG Aluminium (PGA) and how to address those challenges in order to improve productivity. The main problem identified through a business process analysis (BPA), value analysis, and work sampling study was labour productivity, as the factory's productivity is at a low of 36% when the time spent on value-adding activities are measured against the total time available for production. Productivity shortcomings can be addressed by implementing Lean principles, such as the Just-In-Time (JIT) tool and techniques. JIT, amongst other things focus on the elimination of wastes. Seven wastes are classified by JIT of which three of the seven were identified in PGA's factory. They were "waiting", "unnecessary motion", and "unnecessary inventory". These three wastes are directly hampering the flow of the fabrication process. The three wastes are therefore addressed in this study by improving the current hardware picking process, as well as through the design of a scheduling model to increase the flow of the process in the factory. The hardware picking process was analysed in more depth by doing a Business Process Analysis (BPA) which highlighted areas for improvement in the picking process. A simplified version of the scheduling model was designed using linear modelling principles and Python software. The model aims to produce as many products as possible in the shortest amount of time. Using the time study data collected for the scheduling model, a hypothetical individual performance measurement tool (IPMT) was designed that PGA can use to compare worker performance to expected performance. The aim is to improve the overall flow of the factory by improving labour productivity so that ultimately the business process can be optimised.
The scheduling model, hardware picking process improvement suggestions, and the IPMT were evaluated using the evaluation methods suggested by Manson (2006). Amongst other evaluation methods, a simulation model was designed using simulation software (AnyLogic), which was used to evaluate the effect of the scheduling model and the hardware picking process improvements. From the analysis it was determined that the overall hardware picking time can decrease by up to 33.8% if the suggested improvements are implemented. The results of the scheduling model using the simulation indicates that the overall dead time (which translates into work-in-progress) can be reduced by 46.3%.

From this study it is therefore clear that the overall productivity at PGA can be improved by implementing an improved hardware picking system as well as a scheduling model.

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Abbreviations

BLT	Blue-light time
BPA	Business Process Analysis
BPD	Business Process Diagrams
BPMN	Business Process Model and Notation
CO	Combinatorial Optimisation
IPMT	Individual Performance Measurement Tool
JIT	Just-in-Time
GOT	Google Optimisation Tools
LP	Linear Programming
MILP	Mixed Integer Linear Programming
PGA	PG Aluminium
RLT	Red-light time
SME	Small to Medium Enterprise
SMED	Single Minute Exchange of Dies
TPS	Toyota Production System
WIP	Work-in-Process
WSS	Work Sampling Study

Chapter 1

Introduction

1.1 Background

Werner and Stefan are two industrial engineers and proud owners of the Johannesburg north franchise of PG Aluminium (PGA). The company specialises in the fabrication, installation, trade and export of aluminium doors and windows and prides themselves in producing customised products.

Before addressing the problems PGA is facing, the company environment needs to be understood in order to have a holistic approach to problem solving. Understanding the work environment and culture helps with later implementation of changes as to avoid unnecessary failure (Bhasin 2012). PGA can be classified as a Small to Medium Enterprise (SME). According to Commission (2016) it is important to classify an enterprise as it helps to establish a clearer picture of the enterprise's economic situation. It will also help to apply the correct analysis and implementation techniques later during the project as techniques sometimes differ depending on the type of company and the size of the company. Commission (2016) suggests that a SME is one that has less than 250 employees and an annual turnover of less than 50 million euros, of which PGA adheres to both these distinguishing factors. PGA went through a retrenchment process a few years ago, as the quantity of products and the fact that each product has to be customised, were too much for the capacity of the factory and it was not a financially beneficial option at the time. Since then PGA moved to a smaller factory and currently has approximately 50 full time employees spread across the office area, the factory, and the installation team. Recently PGA has started expanding again and the company is currently getting an influx of orders. This increase results in strained resources. However, before PGA spends money on buying new equipment or employing more employees, the owners would like to know whether there is a way to utilise their current workforce and equipment more efficiently to accommodate this growth.

PGA's factory consists of an office area and a factory. For the purpose of this project the focus will be on the factory area as analysis indicated more improvement opportunities in the factory than in the office. The main processes to produce windows and doors are similar and consists of six steps. When the raw materials arrive at the factory, it is quality checked and sorted before the fabrication process starts. Cutting is the first step in the process, followed by machining, assembling, beading, glass cutting and finally glazing (which includes wedging). To ensure the products are completed on time, the different steps in the process need to compliment each other by being completed on time and according to the specifications. Once these requirements are met, there will be a good flow in the factory, allowing for new products to enter the system as the older orders are completed and leave the system. The focus areas in the PGA factory are assembly, beading, glazing, and glass cutting, as these are more time consuming activities. Cutting and machining the aluminium seems to be quite quick and efficient and is therefore not a primary concern for PGA.

Productivity is always a goal for any manufacturing company, but unfortunately PGA's produc-

tivity is not currently at its optimum. In order to increase labour productivity, PGA strives to train their employees through a number of initiatives. One of these initiatives include the concept of blue-light time (BLT) and red-light time (RLT), where BLT refers to value-adding activities which the customer would be willing to pay for, and RLT refers to non-value-adding activities that the customer would not be willing to pay for. PGA would like to increase the percentage of value adding activities (BLT) in the factory as much as possible and as a result decrease non-value adding activities (RLT), as a reduction in RLT will result in increased productivity. The classification of activities is, however, sometimes more complicated than that. Some activities can either be BLT or RLT, depending on the workers' motivation and their productivity. For example, using a pop rivet to attach a friction stay to a frame is clearly value adding and thus BLT, whereas walking around or texting is non-value adding, thus RLT. According to the factory workers an activity such as talking can either be BLT or RLT, as it depends on the reason why they are talking. Sometimes workers talk about things unrelated to the work, but they often talk to each other to clarify the job that needs to be done. Such activities are therefore classified as grey time. Besides these three classifications, there is a fourth, namely green time. This refers to time not spent on manufacturing but is part of company policy and regulations. Green time includes tea breaks, morning meetings, cleaning, and lunch time. Green time activities take place at a fixed time every day and it is not likely to change unless the company's policy regarding these activities change. It is crucial for all PGA's employees to understand this classification and to work towards a common goal, namely to increase BLT and to decrease RLT. This classification system can be used to investigate productivity and to address problem areas at PGA. An alternative way of classifying activities will be discussed in the literature review. It would, however, be important for PGA to also consider other techniques to identify productivity shortcomings, such as doing Business Process Analysis (BPA) and value-analysis.
From this brief introduction to PGA and its functioning it is clear that there are many aspects within the factory that can have an effect on the flow of the fabrication process and overall productivity, and all of these factors need to be considered.

1.2 Research problem

Through an in depth analysis of the current processes at PGA it was concluded that the flow of production in the factory is hampered by workers spending a lot of time on non-value added activities, resulting in unproductive labour time. Average labour productivity is currently at a low of 36% average. The three main reasons for a lack of labour productivity identified were unnecessary motion to and from the hardware store, unnecessary waiting at the hardware store due to various reasons (such as the hardware manager being occupied or not present at all), and unnecessary inventory. Between each step in the production process there is an area allocated to Work-in-Process where semi-finished goods are stored resulting in unnecessary inventory taking up the space. The main reason for this phenomenon seems to be due to lack of a proper schedule resulting in semi-finished goods waiting for further processing. This ultimately hampers the flow in the production. The unnecessary motion and waiting was mainly identified at the hardware store; improving the hardware picking process should therefore reduce these two wastes. Once the wastes are reduced the labour in the factory should be more productive, as BLT should increase as a result of a decrease in RLT. Therefore, the research question that this project will address is the following:
How can PGA's labour productivity be improved by using existing resources and without additional financial expenses, whilst accommodating the variability that a custom-manufacturing environment entails?

1.3 Research design

Javadian Kootanaee, Babu & Talari (2013) suggest that reducing wastes, as identified by JIT, will result in the improvement of productivity. The three main identified wastes relate to the labourers' productivity, therefore, labour productivity should increase as wastes are addressed and reduced using appropriate techniques. To be able to do so different techniques had to be investigated and researched to determine which techniques will be most suitable to PGA's work environment as well as applicable to the type of waste being addressed. This report concludes with suggestions to PGA on how to improve the productivity of the factory and the changes that can be made to their current processes. The following tools and models were generated as artefacts of this project and could possibly be implemented at PGA:

- Hardware process improvement analysis: The aim is to reduce the amount of time workers have to wait for the hardware components **(waiting)**, as well as to reduce the number of times the workers have to walk to the hardware store **(unnecessary motion)**. To do this a BPA (Business Process Analysis) was administered to identify improvement opportunities, which is illustrated using BPMN (Business Process Model and Notation).

- Scheduling model: The model can be used to schedule projects more accurately as to reduce the amount of WIP (Work-in-Process) **(unnecessary inventory)**, avoid stock-outs and increase the overall flow of the factory, as the workers will have clarity on their roles and responsibilities. This was done by designing a production scheduling mathematical model using applicable software. The model generates a schedule that PGA can use in the factory to ensure that demand is met on time.

- Individual performance measurement tool (IPMT): The aim of the IPMT is to compliment the scheduling tool, as PGA would like a way of using the scheduling data to measure and reward individual performance. The IPMT tool can be used to measure individual performance by comparing actual production time to calculated average production time, which is then compared to the scheduled times. The data from a time study was used to calculate realistic and achievable goals for the workers. Measuring performance this way will also help to increase labour productivity as workers will be more encouraged to use their time wisely and spend less time on non-value added activities.

1.4 Research methodology

Deciding on a research methodology forms an important part of a project as the methodology directs the project and highlights important steps that should be followed to ensure the project meets the intended outcomes. This project can be classified as an operations research project as the intended outcome includes developing a new model and algorithms for PGA's scheduling system, and designing tools such as the individual performance measurement tool, which are all characteristics of operations research (Manson 2006). Outcomes of a project such as the designed tools and models can be referred to as artefacts of which the design of these artefacts should follow a specific procedure (such as Manson's methodology) as to ensure the artefacts fulfils its intended purposes. This methodology for a design research process will be followed for this project to ensure the successful design and completion of the required artefacts. The following five steps are used.

1. Awareness of the problem
   Sections 1.2 and 3 highlights the problems PGA is currently facing and is thus the output of step 1 in the methodology. The problem being addressed is the lack of labour productivity which originates from a lack of flow in the factory. Part of step 1, "Awareness of the problem", is outlined in the Literature study (chapter 2), where the identified problems

are researched as to find the best possible solution to address these problems in the most efficient way possible. Therefore, productivity and more specifically labour productivity was researched to find ways to increase productivity in the factory. From research it is proposed that JIT, specifically waste elimination techniques, be implemented to reduce the waste and non-value adding activities that are currently part of the system. A part of the problem at PGA is that there seems to be a lack of worker motivation and clarity of duties, products are often not completed on time, and changes in the schedule are difficult to record. This could be due to the lack of a proper schedule or the lack of consequences when products are not completed on time. Products not completed by the specified due dates result in poor customer relations and a build up of WIP in the factory.

2. Suggestion
It is suggested that the flow of products through the factory be revised. Initial analysis of the process, through Business Process Analysis (BPA), suggests that the biggest flow dampers are at the hardware store and the lack of proper scheduling. To address the hardware store flow, the current process has been analysed to identify inefficiencies such as unnecessary motion and wasted time due to inefficient picking. Suggestions are made to address these inefficiencies so that an improved picking process can be established. The improved process will help to eliminate the need for workers to walk to and from the hardware store multiple times a day, as well as the waiting period, as the hardware manager first have to locate and distribute hardware components. It also sometimes happens that some hardware components are out of stock, but this is only realised once the hardware components are needed. The improved picking process allows the hardware manager to order new stock in advance if needed, or a change can be made to the schedule as to accommodate the stock-out but without hampering the flow of the process. To be able to do that, proper scheduling will also have to be done. This can be achieved by designing a scheduling model that will assist the factory manager to determine the factory's capacity, set stricter deadlines, and allow transparency of the flow of products through the process. This will ultimately improve customer relations as products will be completed on time more frequently. Therefore, a mathematical model has been designed as to optimise production scheduling in the factory. The model accommodates capacity constraints of workstations as well as the ability to prioritise.

3. Development
The suggested picking process was designed to accommodate both the hardware manager as well as the workers. A more in depth analysis of the current hardware process was required which is discussed in section 3. The improvement suggestions reduce the amount of time factory workers spend at the hardware store, as well as the amount of times that the workers have to walk to and from the store.
There are two solutions to the scheduling problem. Online scheduling software such as Open Source Software (OSS) is available which has many extra features such as bottleneck identification, 'what-if' scenarios, material planning, etc. The software, however, often have initial costs as well as additional costs. Seeing that PGA specified that they do not want to spend unnecessary money on software and that they only require a basic scheduling tool, a scheduling model using mathematical programming was designed. The model is approached by using the modelling principles outlined by Venkataramanan (2016). Venkataramanan (2016) suggests a seven-step model building process to be able to solve problems within organizations, such as a scheduling problem. These seven steps are followed for the purpose of this project to ensure that a successful model is built that will adhere to PGA's constraints and generate the optimal schedule.

4. Evaluation
This step involves performance measures as an output to ensure that the artefact is func-

tioning in its intended environment and community. A summary of the suggested evaluation methods, according to Manson (2006), are outlined in section 4.1. Different evaluation methods can be used depending on the type of artefact and its intended purpose. These evaluation methods are used to validate and evaluate the scheduling model, as well as the simulation model. More specifically, 'testing', 'observational case study', and 'experimental simulation' were used for the evaluation of the scheduling model. Furthermore, sensitivity and scenario analysis was done for the scheduling model by testing the model's reactivess, stability, and quality when certain parameters are changed. A simulation model was also used to validate the suggested hardware picking process improvements. If suggested changes in the hardware picking process and the scheduling model are implemented in the factory, the change in productivity should be measured by conducting an identical activity sample. The results from the activity sample will determine whether the RLT activities have been reduced and the BLT activities have increased.

5. Conclusion
   A conclusion was drawn on the success of the designed models. A scheduling model that generates the desired results and can be used in an easy and efficient way, can be classified as a success. If not, the model will be re-evaluated to determine the cause for the model not generating the desired results. The IPMT and hardware process improvements will be suggested to PGA. If the hardware process is at all improved with the potential to reduce the waiting and motion waste, it can be classified as being a success. Both the hardware picking process improvements and the scheduling model are deemed a success. All steps, changes, and suggestions are recorded as part of the project close-out to ensure that all tools, techniques, and analysis can be replicated in the future if needed.

1.5 Document structure

This report further investigates literature on productivity improvement techniques and scheduling in chapter 2. Furthermore, the current situation at PGA is analysed in chapter 3. The scheduling model that has been designed will be discussed in section 4.1, followed by a discussion of the suggested hardware process improvements in section 4.2 and IPMT suggestions in section 4.3. Chapter 5 includes the validation of all three artefacts of this project, as well as an evaluation and analysis of the suggested solutions. Chapter 6 highlights some suggestions to PGA if they would choose to implement the suggested solutions. Chapter 7 briefly concludes with a summary of the findings and the way forward.

Chapter 2

Literature review

Literature relating to PGA's job-shop environment and productivity improvements were reviewed to ensure that a holistic view of PGA's current situation is achieved and that the most applicable tools and techniques are used to improve the factory's productivity.

2.1 Productivity improvement and measurements

2.1.1 Productivity improvement overview

According to Attar, Gupta & Desai (2012) there are various factors that affect companies in a negative way. Amongst the list of factors, 'no definite schedule', 'poor management', 'unproductive time', 'poor instructions', and the 'execution factors' were mentioned; all of these factors can have an effect on the productivity of a factory. In order to increase the productivity of a company, one must have a clear understanding of what productivity improvement entails and about the different methods, tools and techniques that can be used to improve the productivity. This literature review investigates productivity measurements and improvement techniques.

2.1.2 Productivity improvement techniques

There are various ways in which the productivity of a company can be measured. Some of these productivity measurements are investigated to determine an appropriate method to measure PGA's productivity. The most well-known measurement technique is based on the number of products produced per day (Weheba 2015). This productivity measure usually works well with production of large batches of products with little variability and where the production schedules and outputs remain constant. An example would be the production of coke cans or aluminium sheets, as there is a standard time per product and the production of one day can directly be compared to the next. However, the type of products PGA produces all vary in size, shape, and extra features are often added due to the customisation of each product. Thus, the basic productivity formula will not be a fair and accurate representation of PGA's productivity. It may happen that two products that are the same size and has the same purpose, may take different times to complete due to the workers' respective skill levels, the type of materials used and added functionality. Alternatively, PGA could quantify each step in the process and determine productivity based on where the product is at in the process. However, to be able to do that the products need to be traceable throughout the factory, which is currently not possible due to a lack of a tracking system.

Work sampling is another way in which productivity can be measured. A study was done by Orth, Welty & Jenkins (2006) to investigate the feasibility of work sampling as a productivity measurement tool. Work sampling (also known as an activity sample) is a technique used to determine the amount of time workers spend on certain activities. This is done by making several observations at random times during the day over a period of time. From the observations the percentage of time spent on each activity should be fairly accurate and can be used as a representation of reality. The more observations recorded the more accurate the results will be. Many companies prefer to use work sampling to measure productivity, as it is easy to use, it does not interfere with the workers, and it can be done for an entire factory; it is not limited to a small group of workers. It furthermore accommodates the custom-manufacturing, job-shop working environment, just like PGA's work environment. The most important factor of a work sampling study is, however, that it should not only be done once, but rather periodically, in order to evaluate and validate productivity improvement. This also ensures that continuous improvement forms part of the nature of the factory as productivity can be measured on a periodic basis. Thus, if PGA uses work sampling as a productivity measure, the productivity can be measured annually or semi-annually to determine whether productivity improvements are in fact improving the factory productivity and percentage of value-adding activities. From the different productivity measurement tools it seems as if work sampling suits PGA's needs and work environment best due to the variability in the product types, as well as the lack of a proper product tracking system during the data-collection phase. Work sampling as a productivity improvement technique is therefore further investigated.

2.1.3 Work sampling

Orth et al. (2006) conducted a study at a pharmaceutical company, Eli Lilly Tippecanoe Laboratories, in Indiana in 2004. The authors concluded that work sampling is an effective tool that can be used to evaluate the amount of productive or non-productive time of employees engaging in the work activities and identify trends that affect production. The initial work sampling study can serve as a baseline for future studies to be compared against to evaluate productivity improvements. Orth et al. (2006) further explain how to conduct a work sampling study on a job site as to reap all the possible benefits. If productivity improvement suggestions are accepted and implemented by PGA at the end of this project, another work sampling study can be conducted as to measure the percentage increase in productivity by comparing the percentage of initial BLT to the new BLT and similarly the RLT can also be compared. When conducting the work sampling study again it can be done in the way that Orth et al. (2006) suggest as to ensure the study is a success. Orth et al. (2006) divide activities into the following three groups: productive, supportive, and recoverable. Productive activities are seen as "direct hands-on action", such as installation and fabrication of materials. Supportive activities are not seen as productive work but are necessary to maintain productive work; typically this would be material handling and equipment mobilisation. Recoverable activities refers to wasted time. This category includes all activities that are non-productive and non-supportive, such as waiting, standing, and starting late or finishing early to go on a break or to go home.

These categories relate very closely to PGA's RLT, BLT and grey time, where BLT can be classified as 'productive', RLT is 'recoverable', and grey time can be seen as supportive. Green time is not represented in the reviewed model. Either way of classifying activities can be used as long as a consistent classification method is chosen; in other words, by either classifying activities according to BLT and RLT (PGA model), or by dividing it into productive, supportive and recoverable activities (Orth et al. 2006). At the end of the day the value of a work sampling study lies in the repetition thereof and the comparison of the results. The focus should therefore be on productivity improvement as a percentage and not on the method being used, provided that the same method is used consistently.

Schmenner (1986) confirms this notion, by stating that although different measurements of productivity could cause variation in the results, this variation will be small enough not to be a primary concern. According to Schmenner (1986), the focus should rather be on the change in productivity over time using a consistent method, as well as the effect the implemented changes had on the productivity level in the factory. The consistent use of a specific method will ensure that the results are more accurate and reliable. Productivity can, however, be increased using many different techniques and can focus on various departments in a factory. One of the areas of productivity that are addressed in this project is labour productivity, as shortcomings and opportunities for improvement within this area were identified during the initial analysis.

2.2 Labour productivity

Various factors affecting labour productivity have been investigated by Attar et al. (2012). From their study the most evident barriers in improving labour productivity were a lack of goal alignment, contractual conflict, difficulties in measuring productivity, weak commitment to continuous improvement, and lack of labour force focus. Therefore, when PGA's work environment was analysed specific attention was given to the factors identified by Attar et al. (2012). From an initial analysis of PGA's factory, it was clear that productivity was indeed difficult to measure as previously mentioned, which could contribute to the lack thereof, as suggested by Attar et al. (2012). The labour force often got distracted by various factors, and even though some workers are completely committed to the goal and have aligned their personal goals with the company's goals, that was not true for everyone, relating to Attar et al. (2012)'s lack of goal alignment barrier. Attar et al. (2012) furthermore outlined 14 guidelines on how to improve labour productivity. Even though all 14 guidelines are worth considering, analysis of the PGA factory environment highlighted a few that seem to be more applicable to PGA, as the other guidelines refer to factors that are not currently something that PGA struggles with. The applicable factors are the following:

- Motivating workers to keep to project deadlines: A factory analysis of PGA highlighted that products are often not completed on the due date communicated to the client. This problem could be linked to a lack of proper scheduling and not knowing the standard times that products should take to produce.
- Proper procurement of materials in advance: Stock-outs did at times occur at PGA as the procurement manager or hardware manager was unaware that those specific stock levels were too low for the current demand. One should, however, keep in mind that due to the vast customisation of PGA products, less common materials are sometimes used and the products are not always monitored as closely as the more commonly used materials.
- Proper training of the workers: PGA aims to cross-train employees as much as possible but there is still an evident lack of cross-training in some areas of the factory. There is also a lack of measurement of individual performance in the factory. If individual performance can be measured it will be more evident who needs training and which skills are lacking.
- Systematic flow in the workplace: Even though the factory layout accommodates the actual flow of materials in the factory, the flow of production seems to be a big problem as production is hampered by factors such as changes in the schedule, stock-outs, waiting for parts, etc.

Keeping these guidelines in mind when designing possible solutions to address the identified problems will help to ensure that the problems are addressed effectively. To be able to follow the guidelines set out by Attar et al. (2012), the factory environment should further be investigated to determine how the guidelines can best be implemented and which guidelines to focus on first. This was done by looking at similar studies and the productivity improvement techniques and guidelines that they deemed most important.
A study done by Schmenner (1986) in the Unites States of America (USA) compared the productivity of a number of factories in order to determine which factors contribute the most to factory productivity. This study had two parts of which the first part included 265 plants in diverse industries nationwide and the second part included visits to 26 plants of which 12 of

them can be classified in the 'fabrication and assembly' category in industry. The results of both parts of the study correlated regarding the factors that affected factory productivity the most. The definition of productivity was quite wide, especially involving such a large number of plants, thus the difference in productivity was rather measured instead of productivity as a ratio. Labour productivity was one of the hardest factors to quantify but it was the most desired productivity measurement. From the study three main factors were highlighted that had the biggest impact on productivity in both parts of the study. These three factors were faster throughput, lower inventories, and better quality. All three aspects directly relate to Just-in-Time (JIT), a subsection of lean manufacturing. The study also determined that factors such as machinery running well, worker cross-training, workforce morale and involvement could also increase productivity. Once the main inefficiencies are addressed, Attar et al. (2012)'s guidelines can be used to further improve productivity as the outlined guidelines seem to focus more on secondary reasons for lack of labour productivity, whereas Schmenner (1986) focus more on the core reasons. From the literature review it seems as if lean manufacturing is a good place to start to improve factory productivity, as there are many different tools and techniques that lean incorporates to address productivity inefficiencies.

2.3 Lean manufacturing

Lean initiatives have been successfully implemented in many companies in order to increase productivity. Lean originated with the Japanese after World War 2 (more specifically the Just-in-Time or JIT approach which will be discussed in 2.3.1) and was first successfully implemented by the Toyota Production System (TPS) (Welo & Ringen 2015). In the earlier days, being lean was seen as a competitive advantage; nowadays it has become an inherent part of factory improvement initiatives. However, according to Bhasin (2012), many companies fail to successfully implement lean principles when there isn't a systematic and controlled change strategy. The main reason for Toyota's success mentioned earlier on, was that a culture of learning and education was created (Welo & Ringen 2015). Implementing lean principles therefore requires a company culture of learning, where management does not enforce routines but rather encourages new habits (Bhasin 2012). In particular, when the company only has a top-down management hierarchy, attention should be given to management objectives to ensure that employees are inspired to adapt to new habits. A controlled implementation plan and systematic change will help ensure the successful implementation of lean. Every company, however, needs to find a way most suitable to them to implement lean principles as each company has a unique culture (Welo & Ringen 2015). Lean manufacturing consists of many different tools and principles, as can be seen in Figure 2.1. From this figure it is clear that the main objectives of lean manufacturing are product quality, reducing costs, quicker delivery times, stability, implementing 5S and Kaizen (continuous improvement principles). To achieve these objectives certain tools can be used, including, JIT, Single Minute Exchange of Dies (SMED), Pull system, Heijunka, Standardisation, Jidoka, and many more. When implementing any of these 'lean' tools, a factory's productivity should improve. However, for the best results, the tool most applicable to the type of factory and type of production (customised vs. mass production) should be used.

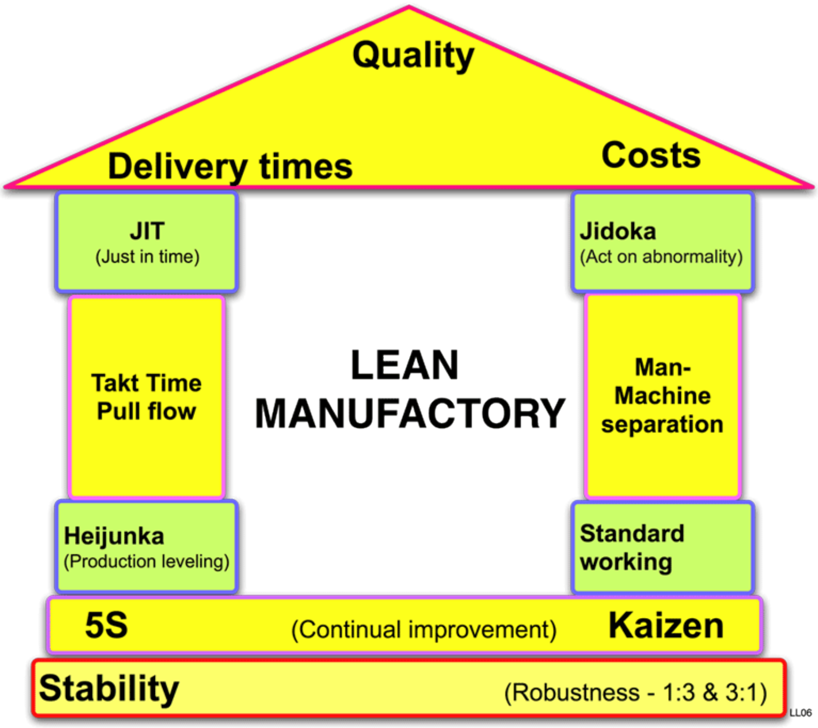


Figure 2.1: Lean Manufacturing Overview. Source: Huynh (2016)

2.3.1 Just-in-Time (JIT)

Labour productivity can be increased by applying Just-in Time (JIT) principles to the system. JIT is a Japanese management philosophy which has been used in practice since the 1970s. The Toyota production plants were the first to start implementing JIT techniques. Toyota quickly realised that the success of implementing JIT relies on the involvement of all the individuals in the company and especially the committed involvement of senior management (Javadian Kootanaee, Babu & Talari 2013). JIT focuses on the timeline from when an order is placed by a customer to the time it has been delivered to that customer, thus reducing non-value adding wastes during that timeline and increasing throughput (Javadian Kootanaee et al. 2013). JIT therefore focuses on producing products just in time; not too early and not too late.

One of the five main objectives of JIT is the elimination of non-value-added activities (such as PGA's RLT time) and the elimination of wastes. To be able to eliminate the wastes one should first understand what the wastes are, therefore, the seven wastes are briefly outlined (Earley 2018).

Over production: To produce more products than required or producing products faster than required.

Inventory: Any raw materials, work in progress, or finished goods that are just standing around in the factory (no value is being added to it).

Waiting: People waiting for parts to be completed from previous steps in the production process, or parts that are waiting to be completed (such as work in progress).

Motion: Unnecessary movement during the production of parts, either the unnecessary movement of people or products.

Transportation: Unnecessary movement of people or parts between different processes.

Rework: When products aren't produced right the first time resulting in unnecessary repetition of certain steps in the process.

Over processing: Unnecessary, extensive processing of products that is not required by the customer, in other words spending more time or money on features not required by the customer.

Recently more types of wastes have been identified. The most commonly identified waste, beyond the seven already mentioned, is wasted potential of people.
From the factory analysis the three wastes identified at PGA were 'motion', 'waiting', and 'inventory'. In order to implement JIT in a company and to reduce the identified wastes, a lot of coordination of tasks and proper scheduling is required. Scheduling should be done to avoid delays in the system, resulting in products not being delivered just in time. Javadian Kootanaee et al. (2013), however, highlight the importance of having a company culture that supports JIT, as discussed in section 2.3 by (Welo & Ringen 2015). Important company cultural aspects include having a "pull system" (products are produced as customers request it), reduced lead times (the time lapse between the material arrivals and the finished product), reduced inventories (raw materials, WIP, and finished goods), using containers to hold inventory (for quick identification and picking), having a clean plant (no wastes hindering production), and visual management. From the literature it is clear that JIT principles are important to consider in an investigation of labour productivity as to improve the overall productivity of the factory.

2.3.2 Single Minute Exchange of Dies (SMED)

To address the non-value added activities such as unnecessary motion and waiting, currently experienced in the hardware picking process, SMED (Single Minute Exchange of Dies), can be considered to identify improvement opportunities. SMED is a lean manufacturing approach that is based on the concept of reducing the number of tasks that are done once the process has started. This can be achieved by performing external tasks before the process starts, therefore reducing the changeover time between products. Cakmakci (2009) classifies internal tasks as tasks that have to be done while the machine is switched off, and external tasks are those that can be done while the machine is running. To apply SMED to PGA, the assemblers (factory workers) can be seen as the machine and the picking process is the process of which the changeover time should be reduced. Tasks that can be done prior to the arrival of the assembler at the hardware store is seen as external tasks and tasks that can only be completed while the assembler is at the hardware store is seen as internal tasks. SMED also aims at reducing the time each task takes by eliminating unnecessary motion or waiting. Therefore, applying SMED to the hardware process will directly address these two wastes (motion and waiting) identified. Figure 2.2 represents a generic and visual way that SMED is applied (Kekeolu 2013).

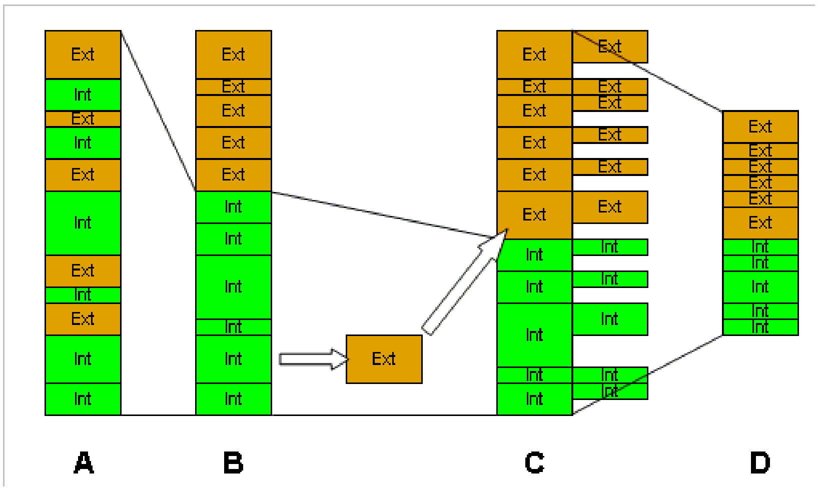


Figure 2.2: Visual summary of how to apply SMED. Source: Kekeolu (2013)

Implementing SMED into the hardware picking process will already improve the flow of production in the factory. To further improve the flow and address the identified wastes, scheduling is considered as a proper schedule will increase the flow of production throughout the entire factory and not only in the assembly area and hardware picking process.

2.4 Scheduling

According to Project Management (2017) scheduling is like a road map to ensure the successful execution of a project, by combining knowledge, experience and intuition of workers. Ideally scheduling should be a tool to address 'what-if' scenarios and consider capacity constraints. Proper scheduling will take project information and combine it with a scheduling tool to generate a scheduling model that will generate valuable information to a company on scheduling times and capacities as an output (Project Management 2017).

According to Harjunkoski et al. (2014), designing a schedule effectively, requires certain questions to be answered, such as: What tasks to execute? Where to process the production tasks? In which sequence to produce? When to execute the production tasks? Answering these questions and designing a good optimisation solution can result in savings because of better capacity utilisation. For PGA capacity utilisation is necessary for the different workstations in the factory, in order to avoid unnecessary build-up of WIP between the workstations. Having a proper schedule could also result in other benefits such as a reduction in environmental load, better coping with uncertainties in production, and a reduction in energy demands.

Some lessons learnt by Harjunkoski et al. (2014) from successful applications included the alignment of stakeholders, as management and the aligned groups all need to agree on the suggested scheduling solution and its value. Furthermore, it was learnt that a generic modelling approach is preferred, as it accelerates project timelines. The model should be adjustable by the scheduler and therefore the model only has to be feasible with respect to the most important constraints, and at the end of the day the scheduler should feel like the scheduling model simplified his work, not complicated it even further. Harjunkoski et al. (2014) continues to discuss an approach to model designing with regards to the technical and mathematical programming aspects thereof. Extensive research has been done on scheduling and the various approaches that can be followed (Castro & Grossmann 2012, Harjunkoski et al. 2014, Merkert et al. 2015). From the literature it is clear that in the design of a schedule, the main goal should be to adhere to all resource constraints while minimising the costs. In order to obtain this goal, it would be important to formulate a scheduling problem and to explore whether appropriate software exists to address the problem.

2.4.1 Scheduling problem formulation

Once the need for a schedule has been identified and the scheduling environment has been analysed, certain factors need to be considered in order to decide on the appropriate software platforms to address the scheduling problem. The main factors that need to be considered and decisions that need to be made are as follows:

- The scheduling problem should be clearly defined and a decision must be made regarding the objective of the model. The objective function, which will either be to minimise or maximise a function for the decision variables, has to be determined.

- The modelling and solution paradigms should be investigated. The different paradigms for optimisation modelling include manual scheduling, expert systems, mathematical programming, evolutionary algorithms, heuristic and meta-heuristic methods and artificial intelligence. Model-based methods seem to be more effective with complex problems (Harjunkoski et al. 2014).

- The model environment and timing of the operations should also be clearly defined. Castro & Grossmann (2012), Harjunkoski et al. (2014), Merkert et al. (2015) suggest two possible scheduling environments, namely, continuous-time precedence based and discrete models (time-grid-based models).

- The production environment should also be defined. The production environment most suited to PGA's fabrication process is a "multi-purpose" environment where there are multiple stages and different products have different sub-processes within the main process, also known as a multi-period scheduling of a multi-stage multi-product process (Kabra, Shaik & Rathore 2013). This is due to flexible job-shop environment of PGA's factory. This means that there are multiple orders that need to be scheduled, each order consisting of various products which will all ultimately be at different stages once production commences and different workstations are able to perform different operations.

- The sequencing of the operations and equipment variables: Binary variables should be used for continuous-time, and constraints should be used for discrete-time formulations.

- Constraints should be formulated that need to define assignments, sequencing, capacity, to name a few. Address questions such as batching policies and applicable constraints to ensure the model is designed as simple as possible while adhering to all the requirements.

- Interaction of the scheduling problem with other planning functions. Other functions that the model should compliment or be compatible with, should be considered.

Discrete-time models have a fixed number of time slots, each having a predetermined duration and a constraint can be defined as to avoid two tasks overlapping. This characteristic of discrete-time models makes it more effective when working with higher level planning models and intermediate events.

Continuous-time models are, however, more sensitive to changes during the process and also more accurate as the exact time can be represented and not a rounded value as with discrete-time models, according to Castro & Grossmann (2012), Merkert et al. (2015). Continuous-time precedence-based models seem to be more effective with multi-stage plants.

However, when there are constraints other than equipment and unit availability, time-based models should rather be used as continuous models would not be able to accommodate the complexity of the model. Therefore, as suggested by Harjunkoski et al. (2014), a discrete time-based model should rather be used for this project as there are constraints for several variables and not only equipment and unit availability.
To generate the model the applicable optimisation modelling method should be selected. Based

on the above mentioned characteristics of PGA's working and scheduling environment, Mixed Integer Linear Programming (MILP) is suggested.

2.4.2 Mixed Integer Linear Programming (MILP)

For this project it was decided to use Linear Programming for the optimisation model as the scheduling problem has the same environment and variables as typical Linear Programming problems (Vanderbei et al. 2015). Linear Programming is used when there is an objective function that should either be maximised or minimised that will allow for an optimal solution (Vanderbei et al. 2015). Furthermore, there are decision variables of which values should be decided on to obtain the optimal solution. There are also constraints limiting the optimal solution which are usually determined by real-life limitations such as resource availability, or the number of hours in a day. In Linear Programming these constraints will be associated with a linear combination of the decision variables based on an equality or inequality. Mixed Integer Linear Programming (MILP) refers to Linear Programming where some variables have to be integer values and other variables can be real values. Vanderbei et al. (2015) researched multiple existing MILP models for job-shop scheduling specifically and combined it to create a simple yet effective mathematical model. Vanderbei et al. (2015) found that the main components of the different models remained relatively constant. The model they suggest includes predefined sets and indices that addresses the machines, operations, and jobs. There is a parameter that addresses the processing time of each operation on machine. Furthermore, there are six decision variables that are explicitly defined. The first two are binary variables that determine whether the machine is used for a specific operation, and the other is precedence constraints for the various operations. The other four decision variables all address some form of time, such as the starting time of an operation, the completion time of the operation, the completion time of the job, and then the maximum completion time over all the jobs (the makespan). PGA's production process can be divided into machines (referred to as workstations), as well as operations. For the purpose of this project the model will, however, only focus on the machines (workstations), as there are too many small operations in between and the standard times for production has been calculated on a workstation level. Furthermore, the six types of standard products can be divided into three categories which will later be explained when looking at the mathematical model in section 4.1.1.

Kabra et al. (2013) did various research projects on different scheduling environments and the best way to schedule in order to accommodate environment needs and constraints. They designed a mathematical model to use for scheduling specifically for multi-period scheduling of a multi-stage multi-product bio-pharmaceutical process, which could be a suitable solution to address PGA's scheduling problem. Scheduling in an industrial area, which is a factory in this project, deals with the optimal allocation of limited resources in the factory (Kabra et al. 2013). The schedule often consists of multiple stages in order to maximise the performance of the factory as to efficiently meet the demand of several different products with different due dates. Typically, short- to medium-term scheduling will be applicable to PGA as production of a product often does not take longer than a few days. Kabra et al. (2013) and Harjunkoski et al. (2014)'s methods and models are both based on Linear Programming and are considered for this project, as the work environment and model requirements are similar to that of PGA. Venkataramanan (2016) provides further insight on how mathematical programming models should be approached, as well as example solutions that prove beneficial to this project. The scheduling and production examples in Venkataramanan (2016) were therefore, investigated for this project.

The model will, however, be discussed in more detail in section 4.1.

An important part of mathematical programming is to determine the type of modelling software to use that will be able to accommodate all the requirements of the model. Therefore, knowing the above-mentioned classifications and characteristics will help in the decision making process of what type of modelling approach to use, and more specifically what type of software.

2.4.3 Software platform

Various software programmes and their characteristics were investigated for the purpose of this study. Although numerous programmes are available on the market, the software investigated for this project were influenced by a number of factors. Firstly, the designer's knowledge and familiarity with the software, and secondly, the costs involved. As PGA does not want to spend unnecessary money on a scheduling model at this stage, only free versions could be considered. A third requirement of a scheduling model that could be implemented at PGA was that the model had to be compatible with Microsoft Excel, as PGA currently uses Microsoft Excel for their planning and production logs as an input and output platform. An outline of the characteristics of the various software platforms investigated, is provided in Table 2.1.

Table 2.1: Characteristics of the different software platforms

Software	Open source	Optimisation modelling category	Compatible with Microsoft Excel	Designer capability level (1-5)
RStudio	Limited	Mathematical Programming	Yes	3
Lingo	Limited	Mathematical Programming	Yes	2
Python	Yes	Mathematical Programming	Yes	3
AnyLogic	Limited	Simulation Modelling	Yes	4
Zimpl	Limited	Mathematical Programming	Unknown	1

Note that in the Open source column of Table 2.1 most software platforms are limited as the full version has to be paid for. The "free" versions have different limitations. The limitations on Lindo is that the free version is only temporary and the number of variables are limited. RStudio's free version can only accommodate certain packages. RStudio has a "Scheduling" product, but it is also one of their most expensive products. AnyLogic can accommodate a maximum of ten agents in the free version, and the 'database' function cannot be used which simply means that the model cannot be linked to a specific database. Based on the specific characteristics of the various software platforms as well the needs and requirements of PGA, the designer / researcher decided to use Python software for the design of the scheduling model. Python has the following advantages:

- Python is free and therefore doesn't hinder the design process at all.
- It has the capability to import and export data from and to Microsoft Excel.
- Python also has the ability to create visual diagrams of the schedule which makes it user-friendly for the factory manager to use.
- There are multiple help functions and platforms to educate users on the more complex parts of a model.

- Python is compatible with various different platforms by means of imported packages that allows for extra functionalities.

There are various example models available that explore different types of scheduling using different types of software. Software platforms, such as Java, (that the schedule designer is unfamiliar with) was analysed as part of the literature review, but was not directly used in the design of the scheduling model. Models designed in Python were analysed in more depth. Bader (2016) designed a small scale job-shop solution. As this model does not directly relate to the job-shop environment at PGA, it was only analysed to understand the scheduling concepts used in the model. Various other models were analysed in the same way.

Google Developers offer an overview on Combinatorial Optimisation (CO) within the Google Optimisation Tools platform. CO is an approach that is used to find the best solution from many different possibilities by using various techniques to narrow down the options (Developers 2018).

Google Optimisation Tools (GOT) offer a software package known as OR-tools for Combinatorial Optimisation. OR-tools was investigated as a way of incorporating optimisation into a Python model. This software package is compatible with Python as the package can simply be downloaded and imported into the Python model. The OR-tools package allows for more specific optimisation problems to be solved. The four main categories of OR-tools are the following.

- **Constraint programming**: When a feasible solution is found based on constraints.
- **Linear programming**: Finding an optimal solution based on a linear objective function, given a set of constraints.
- **Vehicle routing**: Identifying the best vehicle route based on constraints.
- **Graph algorithms**: To find the shortest path, minimise and maxximise cost flows.

Furthermore, GOT provides an example of a scheduling model that use the OR-tools package as an input. The scheduling model is specifically for a job-shop environment where various products are manufactured differently. Even though this example model is very basic, it was considered as a starting point for the scheduling model for PGA. The example model is based on a job-shop environment that consist of three machines and three jobs that need to be completed. Using the Python code and OR-tools package, the optimal schedule was generated.
The model, however, has the following three constraints:

- There is a specific sequence of events. No task can be done without the preceding task being completed first.
- A machine can only do one task at a time, meaning only one job can be at a machine at a time.
- Once a task has been started, it has to be completed. This means that a machine cannot start working on a job, pause that task, work on a different job, and then continue with the first job.

Furthermore, this model has limited functionalities as it only generates a numerical answer and not a visual answer in the form of a type of Gantt chart, which is a desired output for PGA. The model also lacks certain constraints that will make the schedule useful for PGA, such as products being semi-finished by the end of a day and thus needs to be completed the next day, as well as importing product data from Microsoft Excel. Therefore, this example model will simply be used as a building block in the bigger schedule.

From the brief discussion on scheduling and the impact it has on productivity, it is clear that there are many factors that need to be considered in the measurement and improvement of the productivity of a factory. It is, however, also important to consider the working environment and processes within a company. Understanding the processes followed will allow for better scheduling as the schedule designer will have a holistic, yet detailed view of the processes followed to be able to encompass everything needed to ensure the scheduling model is as accurate as possible.

2.5 Business Process Analysis (BPA)

Business Process Analysis (BPA), also known as Business Process Management, is done to better understand working environments and processes, and to identify potential improvement opportunities (van der Aalst, La Rosa & Santoro 2016). To analyse business processes a systematic approach should be followed to ensure a holistic view of the process is achieved. van der Aalst, La Rosa & Santoro (2016) suggest that business processes can be modelled using modelling language Business Process Model and Notation (BPMN). It is important to maintain the focus of a BPA, which should be on the improvement of the process instead of on the models (van der Aalst et al. 2016), as better models do not automatically generate better processes. The improvement opportunities identified through proper BPA will then be the main focus when designing possible solutions to ensure the process is in fact improved.

BPA has various benefits (Havey 2005) such as formalizing the current process, identifying improvement opportunities, facilitating efficient flow of processes, increasing productivity by getting work done faster with fewer people, allowing people to solve more complicated problems, and also simplifying some complex problems if possible. These benefits are only reaped if the BPA is done correctly and the processes are fully understood.

Using BPM has shown progress in areas such as the verification of complex business process models before implementation to avoid mistakes that will cost companies money, identifying process behaviours by looking at workflow patterns, and in the design of configurable process models that analysts can use as guidance when selecting the right configuration (van der Aalst et al. 2016). Havey (2005) suggests that BPMN is like a graphical flowchart to assist business analysts and developers to build business process diagrams such as the figures in this section. A BPMN consists of different graphical constructs such as activities, gateways, events, flows, text annotations, group, pools and lanes, and data objects, data stores and association.

To implement all the techniques and solutions investigated in the literature review, a situational analysis of the factory environment of PGA was done, which is addressed in Chapter 3.

2.6 Model evaluation methods

Model verification and validation is especially important when the model generated is to be used for decision-making purposes (Macal 2005). Model verification determines whether the model performs as it was intended to. A verified model implies that the model was programmed correctly, the algorithms have been implemented the way it was intended, and that the model does not contain any errors or bugs (Macal 2005). Model verification does not, however, ensure that the objective function is correctly addressed or that the model is in fact a representation of the real-world problem. That leads to the need for model validation. Model validation addresses questions such as whether the real-world scenario is being represented by the model and whether the model solves the problem in the intended way (Macal 2005). The main goal of model validation is therefore to ensure that the model is useful to the user as it addresses the correct problem in the correct manner while accurate information is used and generated by the model. Furthermore, model validation establishes credibility of the model.

Model validation can be done in various ways depending on the type of model and the objective of the model.

Amongst other methods, simulation modelling is suggested (Manson 2006) and will thus be further investigated.

2.6.1 Simulation

Companies often have to bring about changes to current processes, systems, or resources as part of improvement or expansion initiatives. These initiatives are often costly and have the risk of not succeeding once implemented. This scenario gave rise to the need for simulation-based optimisation methods. Due to technological and computer science advancements it has been made possible for companies to simulate different alternatives in a cost effective way, which enables them to see the potential outcomes of the identified alternatives and choose the best alternative that produced the optimal solution (Nguyen et al. 2014). The construction of an interactive simulation model can only be done through careful analysis of the real-life system and with constant communication with the process owners to ensure that the model is in fact a realistic representation of reality or a potential improved future reality.

Robinson (2004) suggests different types of model validation that can be done by using simulation, each with a different purpose which will briefly be outlined:

- Conceptual model validation: To determine whether the content is sufficient to meet the objectives of the study at hand.
- Data validation: To ensure that the data is accurate enough for the purpose at hand.
- White-box validation: A detailed view of constituent parts of the model to ensure that it is an accurate representation of the real-world scenario.
- Black-box validation: Used to determine whether the model is an accurate representation of the real-world scenario.
- Experimentation validation: To determine whether the experimental procedures used are a fair representation of the real-world scenario.
- Solution validation: Used to determine whether the results obtained from the solution is accurate.

All of the above mentioned uses of simulation for model validation can be used, but for the purpose of this project 'solution validation', seems to be the most applicable as it only looks at the final suggested model. As the simulation model is not the main focus of this project, and only acts as a supporting model in validating the results, it is sufficient to look at the model output as a whole instead of in detail.
The simulation model designed and the results generated are discussed in Sections 4 and 5.

2.7 Concluding remarks

From the literature review, it is clear that various methods, techniques and tools can be implemented to increase the overall productivity in a company. Work sampling is an effective tool that can be used to evaluate the amount of productive and non-productive time spent on various activities within the factory and identify trends that affect production. Based on a work sampling study performed at PGA it became clear that labour productivity was one of the areas that needed to be addressed. Various factors that affect labour productivity were therefore investigated. According to the literature, lean manufacturing initiatives such as Just in Time (JIT) and Single Minute Exchange of Dies (SMED) could be administered in order to improve labour productivity. To further improve the overall flow in a factory, it was evident from the literature review that a proper schedule is needed. Proper scheduling will use project information and combine it with a scheduling tool to create a scheduling model that will generate valuable information to a company on scheduling times and capacities as an output. Various software platforms and their distinctive characteristics, that would meet the demands and needs of PGA, were therefore investigated. The literature review concluded with an investigation into business process analysis (BPA), as it became clear that the working environment and processes within a company needs to be considered, in order to allow for better scheduling and identification of improvement opportunities.

Chapter 3

Situational analysis

To find the best solutions for PGA's labour productivity shortcomings, it was necessary to do a situational analysis of the factory environment at PGA. In order to analyse PGA's productivity and the current processes, three main analysis techniques were implemented, namely a business process analysis, value analysis and an activity sample. It was followed by a time study that was performed in order to get standard times for custom products.

3.1 Business Process Analysis (BPA)

A Business Process Analysis (BPA) was done to better understand the processes followed by PGA in the office as well as the factory area, in order to be able to identify the reasons for lack of productivity. The Business Process Model and Notation (BPMN) was generated using Bizagi, which is a free Business Process Management (BPM) software that can be used to design process maps (Bizagi 2018).
To understand the BPMN figures that follows, one has to understand the basic components of BPMN which are outlined in Table 3.1. These are only the basic entities used in the BPMN analysis done for PGA (de Vries 2017, Havey 2005).

Table 3.1: BPMN entity descriptions

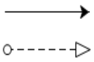
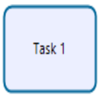
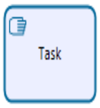
Symbol	Name	Description
	Pool	A process or participant
	Lanes	Different entities inside a pool
	Lines	Solid line: Flow from a source to a target Dotted line: Information flow from a source to a target
	Start event	Start of a process or sub-process
	Message event	Event is started by the receipt of a message
	Signal event	A broadcast to indicate the start of an event or to act as a trigger for an event
	End event	End of a process or sub-process
	Gateway	Used to split or join elements
	Sub-process	Child-level of the parent process, containing more detail
	Task	Task without other specifications
	Manual task	Task performed without the help of a business process execution engine or application
	Receive task	Wait for a message from an external recipient
	Send task	Send a message to an external recipient
	Service task	Call a web service or automated service
	User task	Task performed by a human with the assistance of a software application
	Loop task	Task that can be repeated

Figure 3.1 provides an overview of the processes and users involved in the ordering and fabrication of a product. It consists of the following entities: customer (1), office (2) of which there is a sub-entity quote generator (2A) and procurement manager (2B), directors (3) which refers to Werner and Stefan, the two directors at PGA, and then the factory (4) which consists of the factory manager (4A), the factory workers (4B), and the hardware manager (4C).

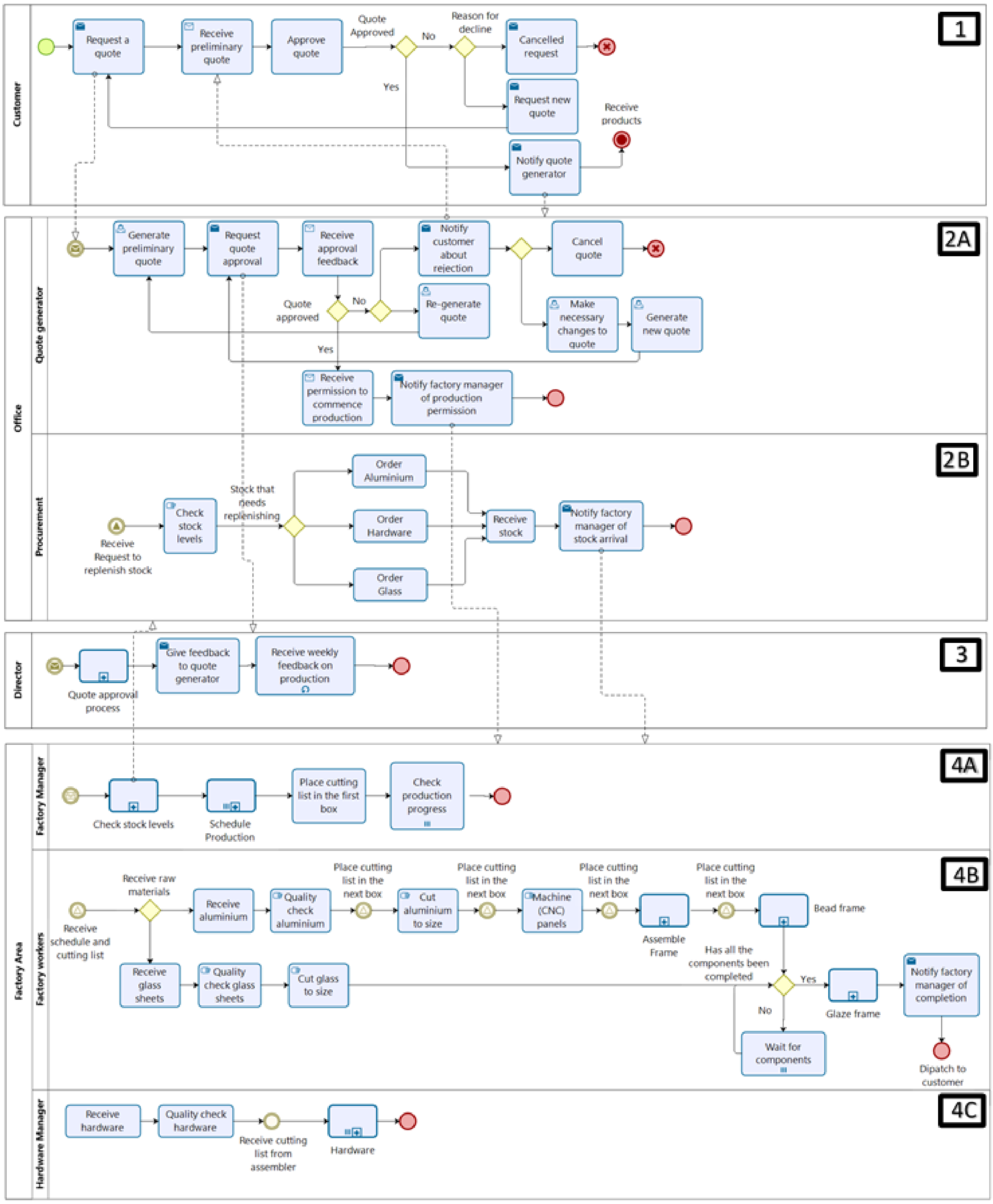


Figure 3.1: BPMN overview

Figure 3.2 represents the start and the finish of the process. The process starts with the customer requesting a quote from one of PGA's quote generator and ends either with the customer declining the quote or receiving the finished products.

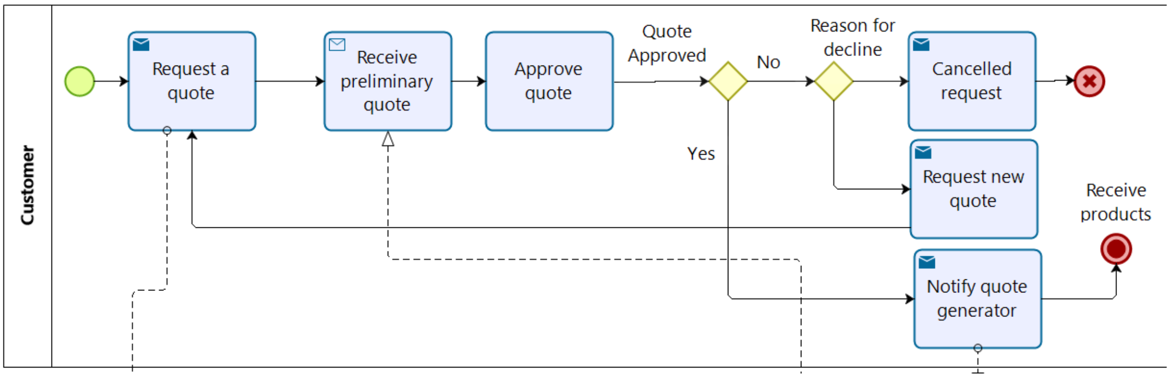


Figure 3.2: BPMN focus on customer-involved processes

Figure 3.3 represents the office area in PGA which consists of two lanes namely, procurement manager and quote generator. The quote generator is responsible for generating the quote, which includes the designs of the products, a job card (also known as a cutting list) and the cost in Rands. Typically a job card is generated per product as a job card specifies the specifications for the product which is used by the factory workers to produce the product. An example of a job card can be seen in Figure 3.4.

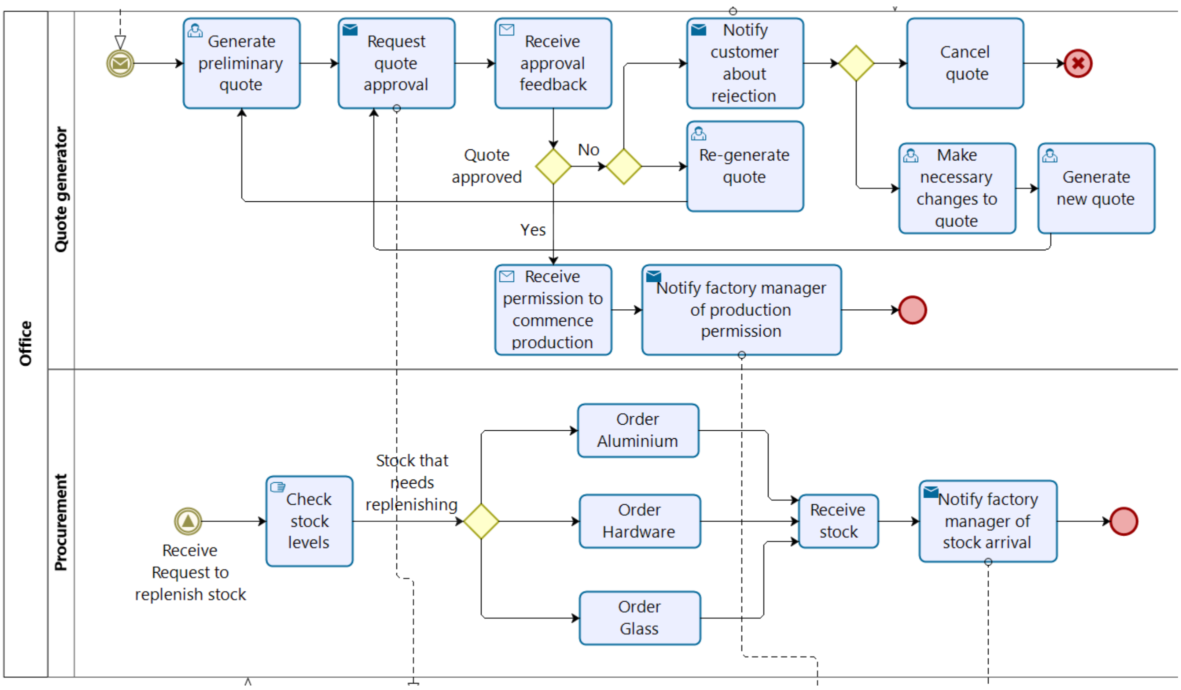
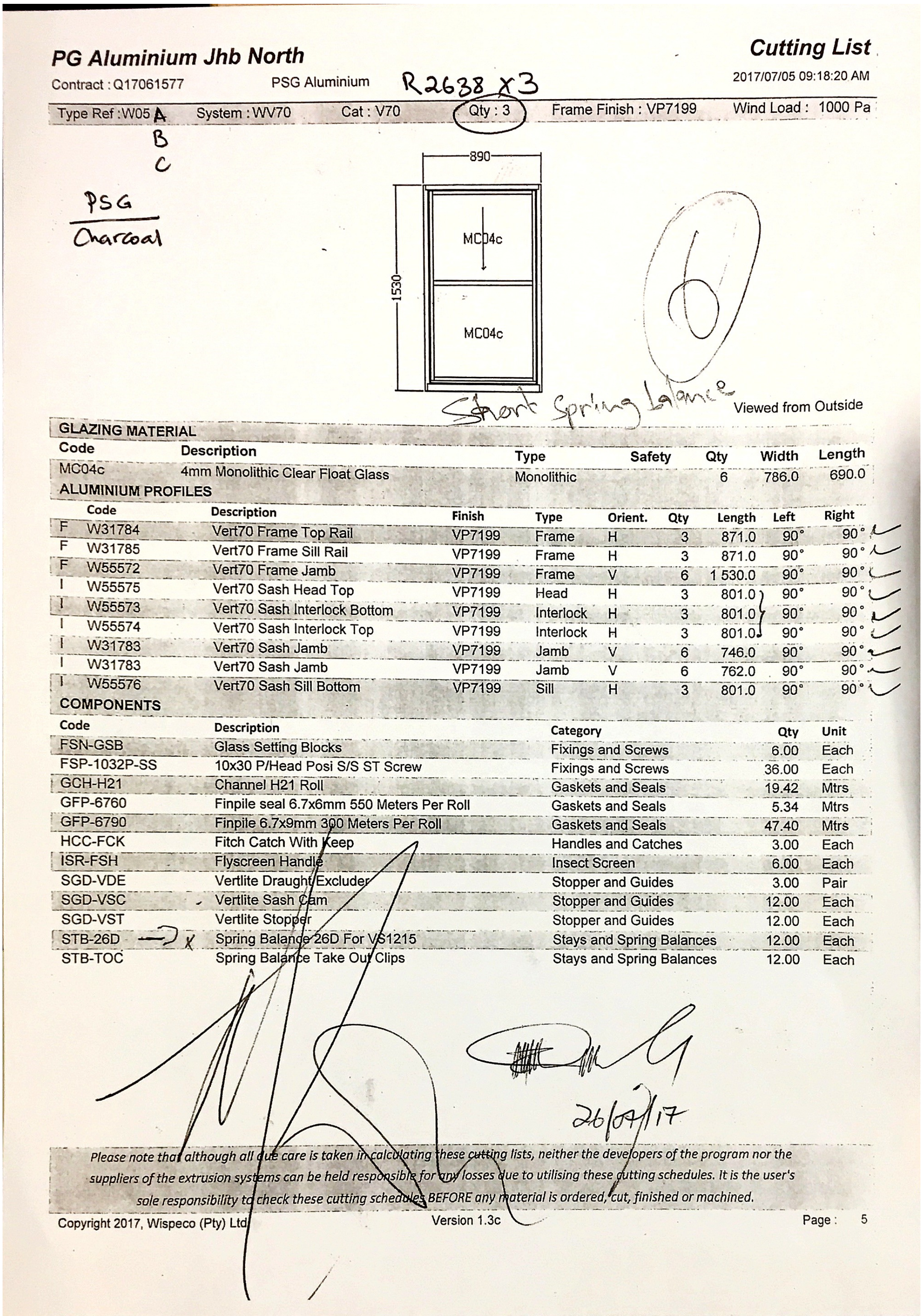


Figure 3.3: BPMN focus on office-involved processes



PG Aluminium Jhb North

Cutting List

Contract : Q17061577 PSG Aluminium R2638 x3

2017/07/05 09:18:20 AM

Type Ref :W05 A B C | System :WV70 | Cat : V70 | Qty : 3 | Frame Finish : VP7199 | Wind Load : 1000 Pa

PSG Charcoal

890

1530

MC04c

MC04c

6

Short Spring Balance

Viewed from Outside

GLAZING MATERIAL

Code	Description	Type	Safety	Qty	Width	Length
MC04c	4mm Monolithic Clear Float Glass	Monolithic		6	786.0	690.0

ALUMINIUM PROFILES

	Code	Description	Finish	Type	Orient.	Qty	Length	Left	Right
F	W31784	Vert70 Frame Top Rail	VP7199	Frame	H	3	871.0	90°	90°
F	W31785	Vert70 Frame Sill Rail	VP7199	Frame	H	3	871.0	90°	90°
F	W55572	Vert70 Frame Jamb	VP7199	Frame	V	6	1 530.0	90°	90°
I	W55575	Vert70 Sash Head Top	VP7199	Head	H	3	801.0	90°	90°
I	W55573	Vert70 Sash Interlock Bottom	VP7199	Interlock	H	3	801.0	90°	90°
I	W55574	Vert70 Sash Interlock Top	VP7199	Interlock	H	3	801.0	90°	90°
I	W31783	Vert70 Sash Jamb	VP7199	Jamb	V	6	746.0	90°	90°
I	W31783	Vert70 Sash Jamb	VP7199	Jamb	V	6	762.0	90°	90°
I	W55576	Vert70 Sash Sill Bottom	VP7199	Sill	H	3	801.0	90°	90°

COMPONENTS

Code	Description	Category	Qty	Unit
FSN-GSB	Glass Setting Blocks	Fixings and Screws	6.00	Each
FSP-1032P-SS	10x30 P/Head Posi S/S ST Screw	Fixings and Screws	36.00	Each
GCH-H21	Channel H21 Roll	Gaskets and Seals	19.42	Mtrs
GFP-6760	Finpile seal 6.7x6mm 550 Meters Per Roll	Gaskets and Seals	5.34	Mtrs
GFP-6790	Finpile 6.7x9mm 300 Meters Per Roll	Gaskets and Seals	47.40	Mtrs
HCC-FCK	Fitch Catch With Keep	Handles and Catches	3.00	Each
ISR-FSH	Flyscreen Handle	Insect Screen	6.00	Each
SGD-VDE	Vertlite Draught Excluder	Stopper and Guides	3.00	Pair
SGD-VSC	Vertlite Sash Cam	Stopper and Guides	12.00	Each
SGD-VST	Vertlite Stopper	Stopper and Guides	12.00	Each
STB-26D	Spring Balance 26D For VS1215	Stays and Spring Balances	12.00	Each
STB-TOC	Spring Balance Take Out Clips	Stays and Spring Balances	12.00	Each

26/07/17

Please note that although all due care is taken in calculating these cutting lists, neither the developers of the program nor the suppliers of the extrusion systems can be held responsible for any losses due to utilising these cutting schedules. It is the user's sole responsibility to check these cutting schedules BEFORE any material is ordered, cut, finished or machined.

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Figure 3.4: Example of a job card (cutting list) used for production

The procurement manager is responsible for ordering the stock. Figure 3.5 represents the simplified process that occurs when stock levels need to be checked for a job. In some areas PGA already makes use of a Kanban system, also known as a ticket system, to initiate stock replenishment. Kanban systems form part of lean manufacturing, specifically a 'pull' system, and aims at reducing inventory and costs (Rahman, Sharif & Esa 2013). Kanban can be classified as a pull system, as a Kanban card (also known as a ticket) is used to indicate the need for stock replenishment. The ticket is then given to the procurement manager who orders new stock. The ticket is placed on a strategic point in stock levels as to provide enough time for stock to be received before a stock-out occurs, but not too soon resulting in unnecessary stock. The ticket is then replaced again at the same stock level as previously. PGA uses this approach with most of the materials such as glass sheets, aluminium, beading, and some hardware components that are most often used. Even though this system is in place, stock-outs still sometimes occur, either because the ticket was not used correctly or because there was a delay from the supplier's side.

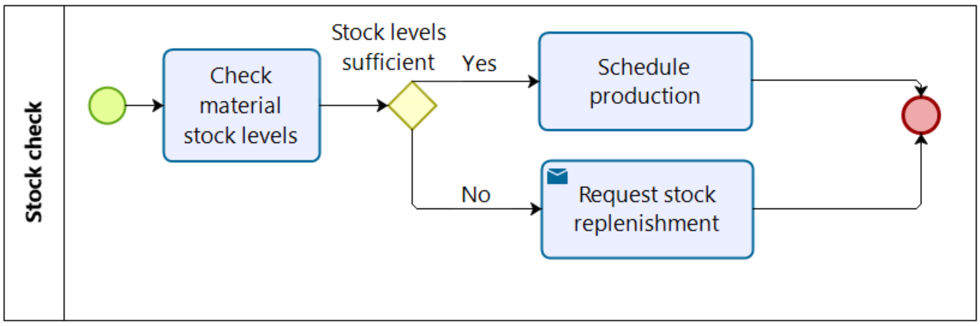


Figure 3.5: BPMN stock replenishment sub-process

PGA's management is involved at the beginning of the production process where the quotes need to be approved (Figure 3.6). PGA uses a quote generating system known as 'Starfront'. Starfront provides the quote generator with an order quote as well as the job cards for each individual product. It also has the ability to show estimated production times, but these times do not seem to be accurate, which creates the need for accurate data which will further be discussed in section 3.4. There are certain percentages and figures that must be entered manually into the system by the quote generator. This could result in variations in quotes, which creates the need for the quote to be approved by management. It also happens that PGA would give discount to certain customers for various reasons. Once management has approved the quote and the stock levels are sufficient, the factory floor manager is notified that production can start. This is also where the gap in scheduling occurs. PGA has a white board in the office area on which orders are recorded based on their Rand value. The board is updated as new orders are placed. There is another white board in the factory (Figure 3.7) on which jobs are allocated to specific factory workers. This is the sum of the scheduling that takes place. The estimated timeline is based on the Rand values of the orders even though the Rand value isn't a fair representation of the time needed for production. The reason for the scheduling being done this way, is because PGA has no idea what the standard time should be to produce products as every product is different due to customisation. It also happens that new orders come in with higher priorities which affects the whole schedule, but the schedule isn't updated as it requires the current white board to be erased, which would mean loosing the information that was previously on it.

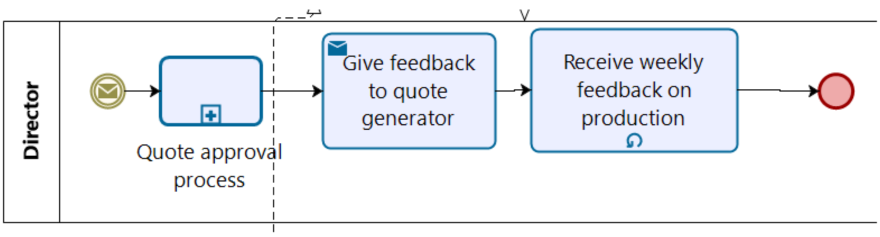


Figure 3.6: BPMN focus on management-involved processes

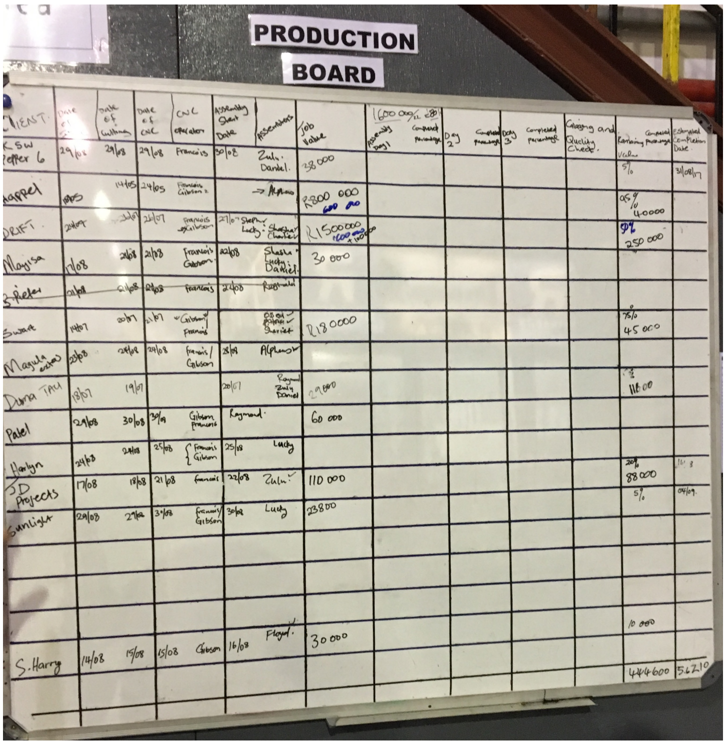


Figure 3.7: White board in the factory used for scheduling

Figure 3.8 represents the quote evaluation process, which shows the determining factors on which management base the approval of the quote. Once the quote has been approved, the factory can start with production.

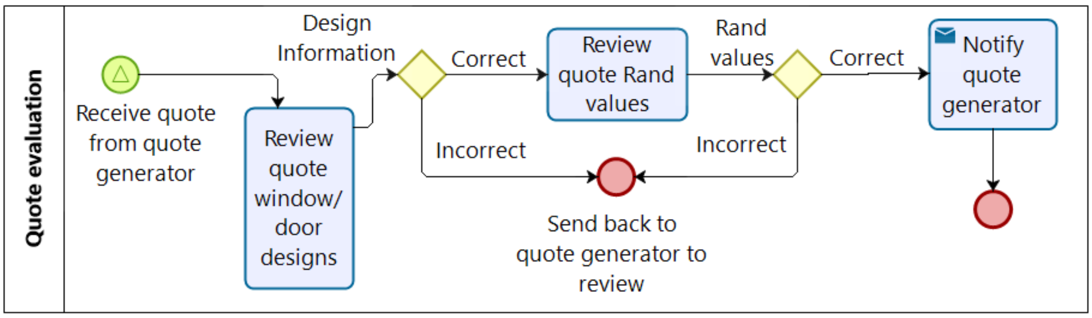


Figure 3.8: BPMN quote evaluation sub-process

The factory consists of three main entities namely the floor manager, the factory workers, and the hardware manager (Figure 3.10). Production in the factory, specifically the assembly area, was analysed in more depth by doing a work sampling study which will be discussed in section 3.3. The job card is used between the factory workers as a signal to indicate that the next step in production can take place. These job cards are placed in labelled boxes as can be seen in Figure 3.9.

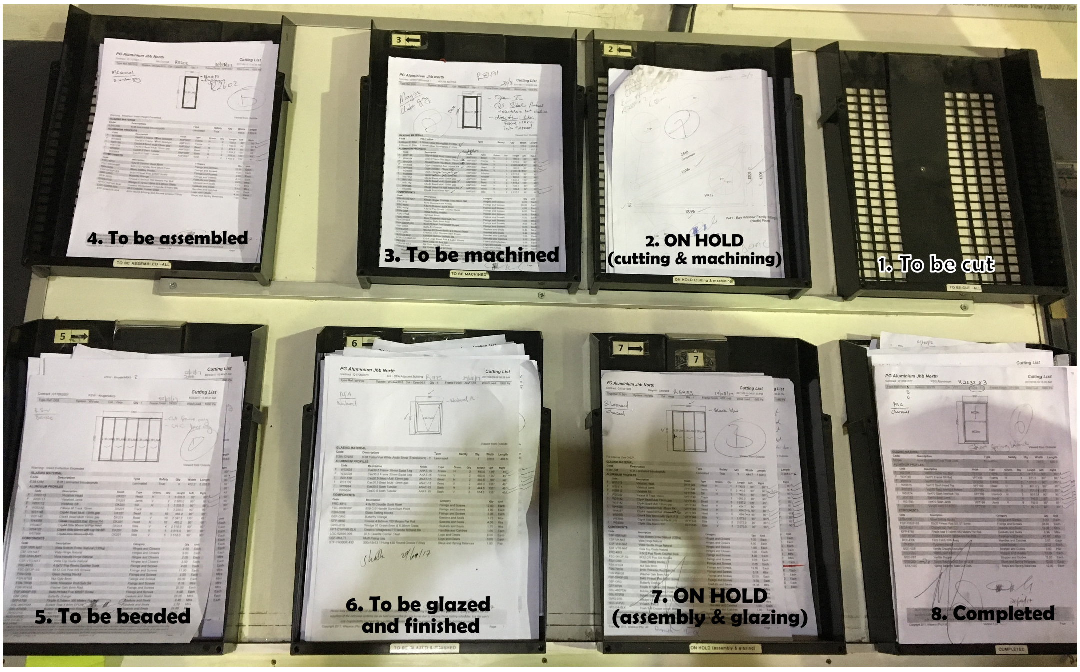


Figure 3.9: Area used to place signals (job cards)

The floor manager is responsible for scheduling the entire production of the factory. The activity "Schedule production according to future orders" is an action that is repeated every time a new order is issued to the factory and on a weekly basis. Every Friday the floor manager updates the production white board in the factory (Figure 3.7) with the latest progress status of the products currently in the factory. Furthermore, the floor manager must through the same scheduling process on a daily basis as to be able to assign specific products to specific assemblers. The schedule could be done in a third instance where a product is issued to the factory with great urgency after daily production has already started and thus might need to be prioritised above one of the previously scheduled products. Figure 3.11 represents the decision variable matrix that the floor manager takes into consideration when making scheduling decisions. Currently the four main aspects involved in the decision making process are the following:

- The priority of the product based on the due date of the product
- Whether the necessary materials are available to start production
- Whether the necessary workforce skill level and capabilities are available
- Lastly, whether there is an available opening for the product to be produced which refers to the workstation/ worker capacity.

In Figure 3.11, a cross indicates that the requirement has not been met whereas a tick indicates that the requirement has been met. If more than two requirements of a low- or medium-priority product are not met, it will not be scheduled until those requirements are met.

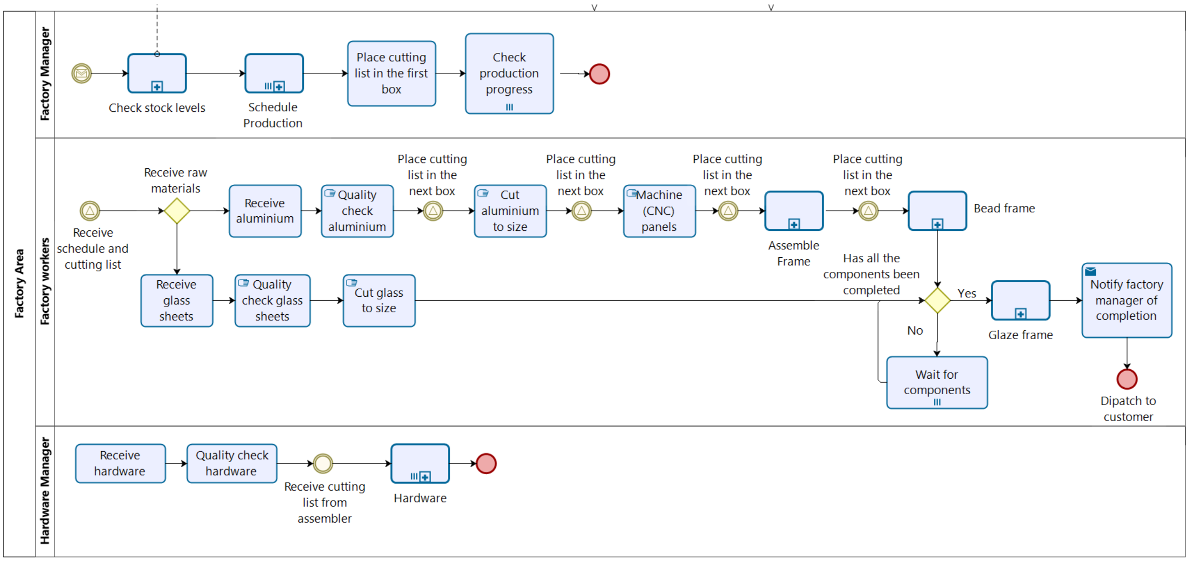


Figure 3.10: BPMN focus on factory-involved processes

Scheduling at the beginning of the day/ end of the week

	Priority	Materials	Workforce Capability	Workstation Availability	Schedule
New Product	Low	✓	✓	✓	Schedule if no Medium or High product is ready to be scheduled
New Product	Low	×	✓	✓	Do not schedule
New Product	Low	✓	×	✓	Schedule for next available time slot. Prioritise Medium/ High priority products.
New Product	Low	✓	✓	×	Schedule for next available time slot. Prioritise Medium/ High priority products.
New Product	Medium	✓	✓	✓	Schedule if no High product is ready to be scheduled
New Product	Medium	×	✓	✓	Do not schedule
New Product	Medium	✓	×	✓	Schedule for next available time slot. Prioritise High priority products.
New Product	Medium	✓	✓	×	Schedule for next available time slot. Prioritise High priority products.
New Product	High	✓	✓	✓	Schedule if no High priority product with a greater urgency is ready to be scheduled
New Product	High	×	✓	✓	Do not schedule
New Product	High	✓	Make workforce available	✓	Schedule if no High priority product with a greater urgency is ready to be scheduled
New Product	High	✓	✓	Make workstation available	Schedule if no High priority product with a greater urgency is ready to be scheduled

Figure 3.11: Scheduling decisions based on the four main criteria

The 'rules' currently used by PGA's factory floor manager to schedule production are sensible, and do not necessarily need to be changed. There are, however, sometimes inconsistency in the application of these rules as it is difficult to keep track of all the orders, their priority, and factory capacity based on the information on the white boards. Therefore, the floor manager might benefit from a more autonomous method of scheduling which includes the 'rules' that he is currently using as a starting point.

Figures 3.12, 3.13, and 3.14 are all sub-processes that take place in the factory. Again, the sub-processes were analysed more in depth by the work sampling study (refer to section 3.3).

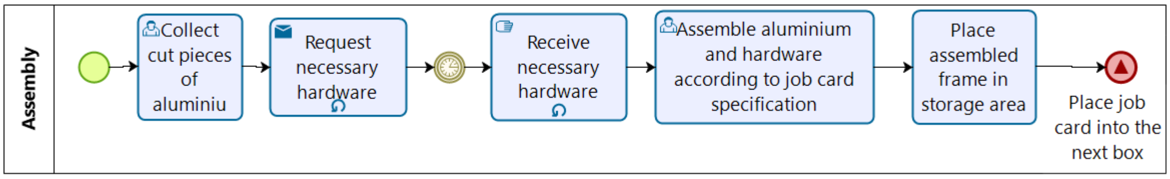


Figure 3.12: BPMN assembly sub-process

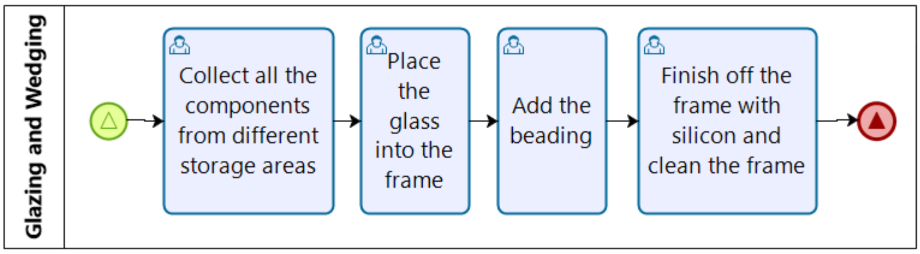


Figure 3.13: BPMN wedging and glazing sub-process

The hardware picking process (outlined in Figure 3.14) seems to be a main contributor to waste in the factory process, as factory workers often have to walk to the hardware store where the hardware manager has to get the necessary components for them. The delay comes in when the hardware manager is already busy assisting another worker, or when the hardware manager is not in his office due to procurement reasons such as receiving hardware, or visiting suppliers to negotiate prices or to discuss the quality of products. As mentioned previously, even though the hardware store makes use of the Kanban system, stock-outs still occur which means that production has to come to a stand still until the required components are received. PGA has been wanting to improve the hardware picking process for quite some time now and has recently shifted the responsibility of hardware procurement from the hardware manager to the procurement officer. This already starts to eliminate some of the reasons for wastes in this area. Typically a factory worker will bring a job card to the hardware manager. The hardware manager will then pick the necessary components, stamp the job card to indicate that the components have been received (recently added as a control measure), and then gives it to the worker. The workers will continue to do that with every product they produce which results in multiple trips to the hardware store per day, depending on the type of product being produced. Furthermore, there are some hardware components such as spigots, pop-rivets, and screws that the hardware manager does not pick for the assemblers but the hardware is located in the hardware store. This results in the assemblers making more trips to the hardware store. Depending on the assembler and where they are located in the assembly area, they sometimes make up to seven additional trips to the hardware store which is an unnecessary waste. It sometimes happens that there aren't any spigots available which result in the assembler having to cut more spigots on the beading machine. Not only does this waste the assembler's time, but the beading process cannot continue during that time; it therefore is an inefficient process and needs to be reconsidered.

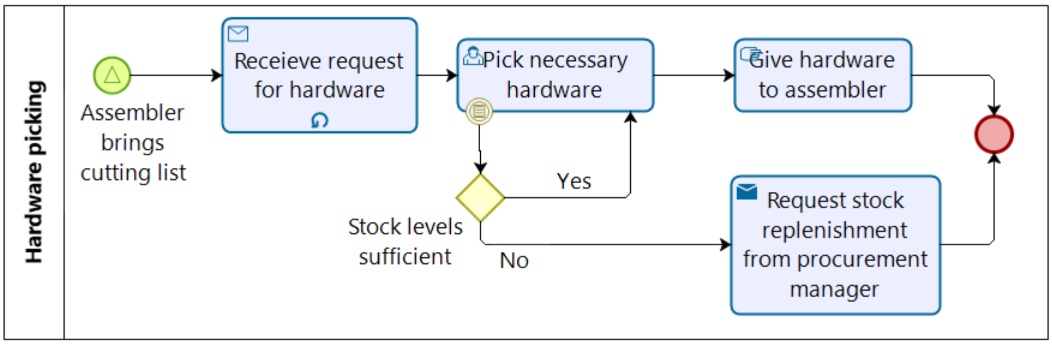


Figure 3.14: BPMN hardware picking sub-process

From the analysis it was evident that the time wasted on collecting hardware was not only due to time spent in the hardware store, but also on time spent collecting hardware that is not stored in the hardware store. The hardware used during assembly can be categorised according to three distinct categories:

- Hardware that is stored in the hardware store which has to be picked by the hardware manager as a security and control measure.
- Hardware that is stored in the hardware store which the assemblers have to pick themselves. This is typically hardware that needs semi-control as it is of medium value.
- Hardware that is stored outside the hardware store so that it is easily accessible to the assemblers. This would typically be hardware such as pop rivets and screws which are low value components that are needed in a high volume.

It was observed that assemblers sometimes walked up to six times in the assembly stage of one product to collect hardware from these three categories of hardware. There was, however, variability in this as some assemblers tried to reduce the amount of times they collect hardware by taking a basket with them to collect as many hardware components as possible at a time. It was observed that the assemblers that are located closer to the hardware store were more likely to collect hardware multiple times as needed, instead of only making one or two trips as done by the assemblers located a bit further away from the hardware store.

The BPMN as discussed, helped to understand the processes followed and to identify areas for improvement. There are, however, various different areas that can be improved and it cannot all be done at once. Therefore, further analysis was required to determine which improvement opportunities to focus on first in order to produce the best results. To do that a value analysis of PGA was performed.

3.2 Value analysis

As part of the initial analysis, a value analysis was performed using raw data gathered to generate Pareto graphs. Pareto graphs (Haughey 2018) focus on the 80:20 principle which states that 20% of the work, hardware or customers contribute to 80% of the value. The Pareto graphs are used to identify key components or areas to focus on for improvement as it is more valuable to focus on the 20% of activities or components that contribute to 80% of the value than focusing on the other activities and components. The value analysis was divided into hardware, aluminium, glass, wages, salaries, and other smaller parts of the income statement. The respective weights can be seen in Figure 3.15.

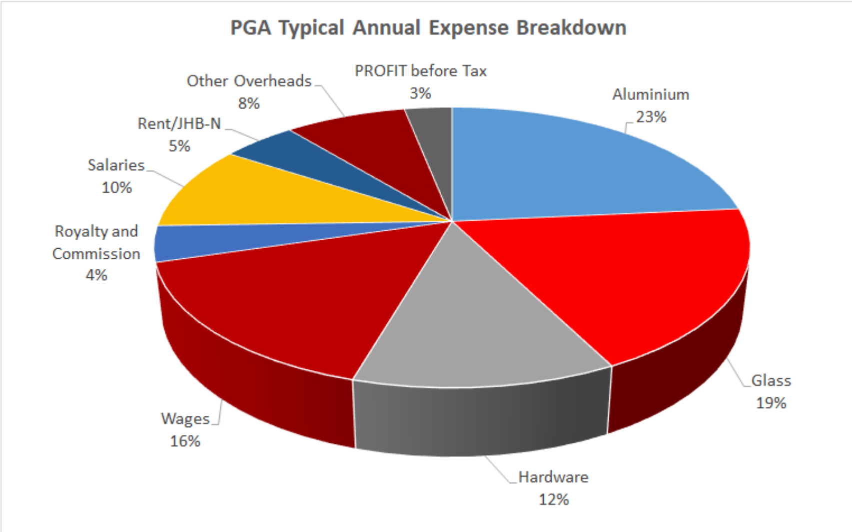


Figure 3.15: Value analysis breakdown of PGA's typical annual expenses

From the graph it can be seen that materials (hardware, aluminium, and glass) account for 54% of PGA's costs. After the value analysis was conducted, action plans were identified for each of the material categories as to reduce costs. The action plans included ideas such as bulk buying of the 20% of the materials responsible for 80% of the volume. Labour, however, accounts for 26% of the costs (10% salaries and 16% wages). Labour costs are more difficult to reduce as PGA cannot simply reduce the number of workers. PGA can however, focus on the productivity of the workers as to increase their capacity.

3.3 Work sampling study (WSS)

Due to the complexity of the process and customisation of each product at PGA, it would be more fitting to measure the current productivity based on the work sampling study (WSS) method as discussed in the literature review. A work sampling study will highlight non-value adding activities which should be reduced or eliminated if possible. Such a work sampling study was conducted at PGA during June 2017. Four main areas in the factory, as well as activities relating to each area were identified. The four identified areas includes assembly, beading, glass cutting, and glazing. In total 20 workstations were observed of which six belonged to assembly, one to beading, one to glass cutting and two to glazing and wedging. The WSS study was conducted over a period of three weeks at random time intervals every day. A different workstation was observed every 15 seconds in a systematic way for a duration of an hour at a time. Note that the classification method as discussed by Orth et al. (2006) is used for the purpose of this study as it is a more established method of classifying the activities in comparison to the Red-light-Blue-light time used at PGA. The results of both methods come to the same conclusion on wasted time (RLT). Also note that green time is not included in the results as the work sampling study only looks at time allocated to manufacturing. Green time is a fixed time during each day and it will not be influenced by productivity improvements. More in-depth results from the WSS can be seen in Appendix A. The final results according to the classifications were as follows are briefly discussed.

The factory's productivity is currently at an average of 36% if the value-adding activities are considered using the formula where productivity is represented by P, time spent on value-added activities (as an output) by T_0, and total time available for production (as an input) by T_i:

$$P = \frac{To}{Ti}$$

Table 3.2: Initial work sampling study results

Area	Blue-light time (Productive)	Red-light time (Recoverable)	Grey time (Supportive)
Assembly	35.7%	44.0%	20.3%
Beading	20.7%	40.7%	38.7%
Glass cutting	20.6%	38.9%	40.5%
Glazing and wedging	67.3%	24.4%	8.3%

where:
$T_o \triangleq$ Time spent on value adding activities where i represents the input value
$T_i \triangleq$ Total time spent on production where o represents the output value

The main culprits for the RLT is 'walking', 'talking', 'standing around', and 'not at workstation'. These four aspects can be due to many different reasons, but the main reasons identified are lack of clarity in duties, not having a definite schedule or deadline for a product, informally helping out in other areas of the factory, having to walk to different areas of the factory to retrieve components and sometimes having to wait there for the components to be completed or to be collected from storage. Currently PGA is scheduling based on the value of the order placed. This is not an accurate way to do it, as the value of the product is not necessarily directly proportional to the amount of time required to produce the product. The floor manager then estimates how long it will take until the order is completed, based on the factory's current load. However, PGA actually has no idea what the standard time for a product is. Therefore, the estimated time is often not reliable. It also happens that new orders come in with a higher priority, but the older orders' timelines are not adjusted accordingly which results in the late delivery of products and dissatisfied customers. PGA is only able to know when the product approximately entered the process and when it was delivered, but the progress of each individual step is not recorded. As BLT is at a low of 36% and labour costs accounts for 26% of the company costs, this is a good area to focus on for productivity improvement. Labour productivity can be increased, as seen in the literature review, by applying JIT principles to the system. The most suitable solution for this problem is to eliminate some of the evident wastes in the system. Looking at the main contributors to RLT, the evident wastes are identified as 'unnecessary motion', 'waiting', and 'unnecessary inventory'. These wastes are directly hampering the flow of production in the factory and should therefore be addressed. Based on the results from the different analysis techniques, it is clear that labour productivity seems to be the biggest area of concern at PGA.

Once the areas for improvement and improvement techniques have been identified, data is required to build the scheduling model and IPMT. One of the data inputs required is the time taken to produce different products so that 'expected' times can be calculated for the IPMT and the schedule can be generated accordingly. To gather the necessary data a time study was done at PGA.

3.4 Time studies

Standard times (expected times) are needed to be able to do scheduling. Seeing that PGA has a custom-manufacturing environment where products all differ slightly, it is difficult to allocate a standard time to products. According to Key 17 of the 20 Keys Bench-marking tool (Kobayashi n.d.), ABC analysis could perhaps be used to divide products into categories based on their average calculated time, and then allocate an average time to each category. The category time could then be used as an input for scheduling. This method is, however, not very accurate and the types of products and differences in size is so great that three categories would not be sufficient. ABC analysis will, therefore, not be used for this project and as a result it will not be discussed in more depth. To get more accurate results a time study can be done and a tool can be designed to make it easy for the floor manager to calculate expected times. A time study is a method used to determine the average time a task takes by measuring the time using a stopwatch (Chandra 2013). To have accurate measurements, specific starting and ending points are identified for each task to ensure that the measurements are taken in a consistent manner. Time studies can help identify areas for improvement in actual processes by identifying 'wasted' time. A time study was done at PGA to determine the average time that different tasks take to perform. The time study was done for all PGA's standard products which consisted out of casements, patio doors, palace sliding doors, vista folding doors, hinge doors and horizontal- or vertical-sliding doors. Detailed tasks were identified and described using starting and ending points for each task. The data was analysed and put into a Microsoft Excel tool that can be used to determine the expected time a product should take to produce. The defining factors for windows were identified as the number of fixed panels, number of saches and number of mullions needed in the product. The different types of doors have different defining components, but the most common defining components were a fixed panel, a lock panel, and a sliding panel. These defining factors are manually inserted by the user and then the expected time and costs are generated by the tool. The estimated time will be used as an input for both the scheduling tool as well as the IPMT. For quick and efficient estimations, standard times were calculated for each standard product. Figure 3.16 shows a screenshot of the Microsoft Excel tool for casements specifically for all the steps in the manufacturing process. Please note that 'MN102' in the second block refers to the order number.

Casement	MN102
Number of openers (sashes)	1
Number of fixed panels	1
Number of mullions	1
Quantity needed	1

Labour Rand/hour	42

Total time (minutes)		135.68
Total time (hours)		2.26
Total cost (Rand)	R	94.97

	Cutting
Total time (min)	25.38
Total time (hours)	0.42
Total labour cost	17.76

	Assembly
Total time (min)	42.39
Total time (hours)	0.71
Total labour cost	29.67

	Beading
Total time (min)	15.56
Total time (hours)	0.26
Total labour cost	10.89

	Glass
Total time (min)	20.35
Total time (hours)	0.34
Total labour cost	14.25

	Glazing
Total time (min)	32.01
Total time (hours)	0.53
Total labour cost	22.40

Figure 3.16: Screenshot of the Microsoft Excel tool for casements

Figure 3.17 shows the final 'Automatic Calculation' tool, also designed in Excel. This tool is used to calculate the assembly time of each standard product based on the number of components needed. Within the tool there is a drop down list of all the possible types of products that could be produced, and based on that selection, the correct time per product is calculated.

Type	Patio / 8	
Vistas, Palace, and Hinge		
Number of Fixed Panels/ Sashes	1	
Number of Lock Panels/ Sashes	1	
Number of Sliding Panels without a lock	1	(Not necessary for hinge doors)
Patio and Horizontal Sliding Window		
Number of Panels/ Sashes	1	
Casements		
Number of Openers per casement	1	
Number of Fixed panels per casement	1	
Number of Mullions	1	
Total number of products		
Quantity	1	(E.g. 2 Vistas)
Labour (min)	59	Labour time in minutes / 60 minutes per hour
Labour (hour)	0.98	Labour hours per product x Quantity required
Total Labour (hr)	1	Labour of 1 product x Quantity
Cost per labour hr	R 42.00	
Total cost	R 41.28	

Figure 3.17: Screenshot of the Microsoft Excel tool for PGA's standard products

This tool in itself is useful but is not likely to be utilised if it is not linked to a schedule that is easy to use and understand. Therefore, a scheduling model is needed that will use the information of the Microsoft Excel tool as an input. Furthermore, it was noticed that not all the workers cooperated with the time study as expected. Some workers worked faster than normal where others worked slower than normal. It was evident that there is a lot of variability in the times, not only between the different workers, but even in the processing times of an individual worker for the same tasks. Due to the great variability, which could either be intentional or not, PGA should decide how much value they want to allocate to the time studies.

3.5 Concluding remarks

Three main analysis techniques were implemented in order to analyse PGA's productivity and the current processes. These are a Business Process Analysis (BPA) by means of a BPMN, value analysis, and a work sampling study.

From the BMPN, the current situation and flow of activities in PGA's factory can be visualised and understood. The BPMN also helped to identify key areas for improvement as deficiencies and unnecessary tasks were identified. The most evident area for improvement from the BPMN, is the hardware picking process, where all the activities are currently being done once production has already started.

The value analysis directed the project to an area in PGA's factory where improvements will have the biggest impact. Labour currently accounts for 26% of PGA's annual costs and are therefore likely to yield a bigger return due to improvements. The hardware picking process, scheduling, and individual performance of workers were identified as probable areas for big improvements as all three these areas have an impact on the labour force.

A work sampling study was conducted at PGA which indicated a 36% productivity level currently being achieved in the factory. The main reason for the lack of productivity was traced back to non-value adding activities namely, "walking", "talking", "standing around", and "workers not at workstation". These four non-value adding activities could also be related to the lack of a proper schedule, lack of individual performance measurements, and the hardware picking process that is inefficient.

Furthermore, time studies were done for all the standard products currently produced at PGA so that it can be used as an input for the scheduling model and also set a standard time for products to be produced. These standard times can then be used to compare individual performance to expected performance.
To address these three inefficiencies identified in the factory (motion, waiting, and inventory), suggested solutions have been designed to directly address these inefficiencies in order to increase labour productivity in the factory.

Chapter 4

Suggested solutions

A number of solutions to address productivity shortcomings at PGA are discussed in this chapter. This includes a Linear Programming scheduling model based on operations research, hardware picking process improvements, as well as an Individual Performance Measurement Tool (IPMT). Finally, to validate whether the suggested hardware picking process improvements and the scheduling model does in fact prove beneficial beneficial and increases labour productivity, a simulation model was generated for both artefacts. The simulation models' logic will also be discussed in this chapter.

4.1 Scheduling model

A discussion of the scheduling model comprises of two parts. The first part covers the mathematical model where the necessary optimisation equations and Linear Programming model will be discussed. The second part addresses the actual model which is designed in Python.
The following seven steps defined by Venkataramanan (2016) were used for the design of a scheduling model.

Step 1 - Formulate the problem: As a starting point, it is important to understand what the problem is and to put it into words that can be translated into a model. For this project formulating the problem requires an understanding of the work environment and the problem at hand. One of the problems that is currently hampering productivity at PGA, is the absence of an adequate scheduling system (discussed in chapter 3). New orders, each with its own priorities and requirements, come in on a daily basis, requiring the schedule to be adjusted accordingly. The objective is to find the optimal schedule which accounts for capacity constraints at different workstations. Ideally, the model should also be able to identify workstations that require extra capacity temporarily to accommodate the demand. The model should maximise the efficiency and work distribution in the factory, as to use the current workforce more efficiently. To be able to attempt such a model the factory environment and the processes followed has to be understood.

Step 2 - Observe the system: This forms part of understanding the environment to be able to understand the processes followed. Observing the system, as well as key relationships, enables the model designer to identify data points that will be referred to in the model. The functioning within the factory at PGA was observed (also during the analysis phase as discussed in chapter 3) to identify key relationships in the process. Some of these processes are the following:

- The process of producing windows, as well as doors;
- The capacity of every step in the process, as well as the capacity of the workstations in every step;

- The process of prioritising certain orders.

Step 3 - Formulate a mathematical model of the problem: A mathematical model is formulated to address the formulated problem. The model adheres to the processes that were observed and their inherent constraints. There are many different types of mathematical models that can be formulated depending on the type of problem at hand. PGA is in need of a scheduling model which can be formulated by using Linear Programming (LP) as the model's needs, requirements, and desired output are in line with that of a MILP (Vanderbei et al. 2015). The mathematical model is further discussed in section section 4.1.1.

Step 4 - Verify the model and use the model for prediction: To gain the benefits of the model, the model should be used to generate valuable information that the factory can practically implement. Using Linear Programming (LP), a mathematical model was developed to optimise the scheduling of operations in the factory. The model determines the optimal combination that orders should be produced in, in order to optimise the capacity load at every workstation. The model contains constraints that ensure that a workstation is not over-loaded and that the estimated schedule time is as accurate as possible. The model also includes constraints to accommodate stock-outs that would result in a delay in production. The model is discussed further in section 4.1.1 and validated in section 5.

Step 5 - Select a suitable alternative: Decide whether the model meets its intended purpose based on the identified need and PGA's stated requirements.

Step 6 - Present the results and conclusion of the study to the organisation: Once the model is functioning the way it should it can be given over to the company to use in the factory to fulfil its intended purpose.

Step 7 - Implement and evaluate recommendations: To ensure that the model is working in real-life situations, the model should be evaluated in such scenarios, which relates to Manson's 'Evaluation' step which is discussed in section 5. It is important that the model be implemented the way it was intended to, to ensure that the maximum benefits are reaped.

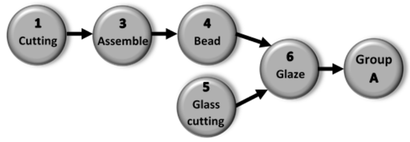
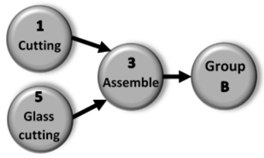
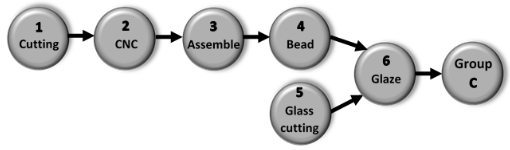
All the necessary findings of this project, suggestions made, and models investigated will be presented to PGA as soon as the project has been completed (Steps 6 and 7).

4.1.1 Mathematical model

In completion of **step 3** of the seven design steps for a scheduling model, the mathematical model has to be formulated and discussed. A linear mathematical model usually compromises of sets and indices where sets refer to a group of indices instead of referring to each index individually. Each mathematical model has an objective function which either describes a maximising or minimising equation which will be the aim of the entire model. The objective function for this model is to fabricate as many products as possible in the shortest amount of time. This can be done by reducing the amount of time a product spends in the factory while not being processed. This objective function is represented by equation 4.1. Furthermore, each model has constraints that it has to adhere to. The constraints ensures that the model is realistic and representative of the factory's reality.
For this mathematical model all the products can be divided into three categories based on its production flow in the factory. The production flow is also known as precedence constraints which will further be discussed in the mathematical model. The three types of products with their production flow sequence can be seen in Table 4.1, where there is a maximum of six

workstations in the process based on the six main steps a product could go through in the factory.

Table 4.1: Product categories based on precedence constraints

Category	Standard products	Precedence Diagram
A	Casement Top Hung Casement Side Hung	
B	Patio Sliding doors Horizontal Sliding Windows Vertical Sliding Windows	
C	Palace Sliding Doors Hinge Doors Vistas	

The mathematical model comprising of sets, indices, and an objective function, that was used for this project is outlined below. Note that the specified jobs in set **J** are just examples of possible products. The mathematical model is not limited to set **J**.

Sets:
Let **W** be the set of workstations such that

$$\boldsymbol{W} = \begin{cases} 1 & \text{Cutting} \\ 2 & \text{Machining} \\ 3 & \text{Assembling} \\ 4 & \text{Beading} \\ 5 & \text{Glass cutting} \\ 6 & \text{Glazing} \end{cases}$$

Let **J** be the set of products such that

$$\boldsymbol{J} = \begin{cases} 1 & \text{D06-SU 02} \\ 2 & \text{D07-SUM 11} \\ 3 & \text{W03B} \end{cases}$$

Let **G** be the set of groups such that

$$\boldsymbol{G} = \begin{cases} 1 & \text{Casements} \\ 2 & \text{Patio's, Horizontal, and Vertical sliding windows} \\ 3 & \text{Palace sliding doors, Hinge doors, and Vista's} \end{cases}$$

Indices:

$$
\begin{aligned}
K_j &\triangleq \text{Total time product j spends in the factory without being processed, where} j \in J \\
C_w &\triangleq \text{Capacity of workstation w on a given day, where } w \in W \\
X_{j,g,w} &\triangleq \text{Total time product j, from group g spent at workstation w, where } j \in J\, and\, w \in W, g \in G \\
E_{j,g,w} &\triangleq \text{Time point that product j, from group g starts production at workstation w,} \\
&\quad \text{where } j \in J,\ g \in G,\ w \in W \\
F_{j,g,w} &\triangleq \text{Time point that product j finishes production at workstation w, where} j \in J, w \in W \\
B_j &\triangleq \text{Given date that product j is issued into the factory, where } j \in J \\
D_j &\triangleq \text{Given due date of product j, where } j \in J
\end{aligned}
$$

Objective function:

$$min\, z = K_j \qquad \forall\, j \in J \tag{4.1}$$

S.t.

$$
\begin{aligned}
\sum_{g\in G} F_{j,g,w} &= \sum_{g\in G} E_{j,g,w} + \sum_{g\in G} X_{j,g,w} && \forall\, j \in J,\ w \in W && (4.2) \\
K_j &= F_{j,g,6} - \sum_{w\in W} X_{j,g,w} - E_{j,g,1} && \forall\, j \in J,\ g \in 1,3 && (4.3) \\
K_j &= F_{j,2,3} - \sum_{w\in W} X_{j,2,w} - E_{j,g,1} && \forall\, j \in J && (4.4) \\
24 * 60 * (D_j - B_j) &\geq \sum_{w\in W} X_{j,g,w} + \sum_{w\in W} K_{j,g,w} && \forall\, j \in J && (4.5) \\
E_{j,1,1} + X_{j,1,1} &\leq E_{j,1,3} && \forall\, j \in J && (4.6) \\
E_{j,1,2} + X_{j,1,2} &= 0 && \forall\, j \in J && (4.7) \\
E_{j,1,3} + X_{j,1,3} &\leq E_{j,1,4} && \forall\, j \in J && (4.8) \\
E_{j,1,4} + X_{j,1,4} &\leq E_{j,1,6} && \forall\, j \in J && (4.9) \\
E_{j,1,5} + X_{j,1,5} &\leq E_{j,1,6} && \forall\, j \in J && (4.10) \\
E_{j,2,1} + X_{j,2,1} &\leq E_{j,2,3} && \forall\, j \in J && (4.11) \\
E_{j,2,2} + X_{j,2,2} &= 0 && \forall\, j \in J && (4.12) \\
E_{j,2,4} + X_{j,2,4} &= 0 && \forall\, j \in J && (4.13) \\
E_{j,2,5} + X_{j,2,5} &\leq E_{j,2,3} && \forall\, j \in J && (4.14) \\
E_{j,2,6} + X_{j,2,6} &= 0 && \forall\, j \in J && (4.15) \\
E_{j,3,1} + X_{j,3,1} &\leq E_{j,3,2} && \forall\, j \in J && (4.16) \\
E_{j,3,2} + X_{j,3,2} &\leq E_{j,3,3} && \forall\, j \in J && (4.17) \\
E_{j,3,3} + X_{j,3,3} &\leq E_{j,3,4} && \forall\, j \in J && (4.18) \\
E_{j,3,4} + X_{j,3,4} &\leq E_{j,3,6} && \forall\, j \in J && (4.19) \\
E_{j,3,5} + X_{j,3,5} &\leq E_{j,3,6} && \forall\, j \in J && (4.20) \\
C_w \geq \sum_{j\in J}\sum_{g\in G} E_{j,g,w} &+ \sum_{j\in J}\sum_{g\in G} X_{j,g,w} && \forall\, w \in W && (4.21) \\
F_{j,g,w},\ E_{j,g,w},\ X_{j,g,w} &\geq 0 && \forall\, j \in J,\ g \in G,\ w \in W && (4.22) \\
C_w &\geq 0 && \forall\, w \in W && (4.23) \\
& && && (4.24)
\end{aligned}
$$

Equation (4.1) describes the objective function for this mathematical model which is to minimise the time a product spends in the factory while waiting to be processed. Equations (4.3) and (4.4) are used to calculate the total amount of time a product spends in the factory while not being processed. Equation (4.26) ensures that the time the product spends in the factory does not exceed the amount of time available until the product is due (in minutes). Equations (4.6) to (4.20) represents the precedence constraints, where equations (4.6) to (4.10) are for category A products, equations (4.11) - (4.15) for category B products, and equations (4.16) - (4.20) for category C products. Equations (4.22) and (4.23) are non-negativity constraints.

This model adheres to workstation capacity constraints and precedence constraints. Other variables and parameters not explicitly defined is imported from Excel spreadsheets as the values differ for each product because of the job-shop environment of the factory. Precedence constraints, interference constraints, processing times at each workstation, priority of each product, and the issue- and due-dates of each product is imported from Microsoft Excel into the mathematical model in Python.

4.1.2 Software model

As discussed in section 2.4.3, the model is designed using Python software. Various other packages, such as OR-tools, also form part of the model. The model adheres to the constraints as set out by the mathematical model in section 4.1.1. Upon start-up the model imports data from the designated Microsoft Excel workbook containing production information. Using information such as the product due date, date issued to the factory, and current status, the schedule is generated. The model aims to find the optimal schedule by reducing the amount of time that each product spends in the factory. The model also ensures that all products are completed before their allocated due date. Figure 4.1 displays typical information that will be imported from Microsoft Excel into the model. An output generated from more data is provided in Appendix C.

Contract Name	Ref #	Product Code	Description	Date Issued to Factory	Due date	Status	State
SERENGETI	D06-SU 02	SDOXX2721	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	22-Sep-18	14-Oct-18	Complete	Glazing
SERENGETI	D06-SU 03	SDOXX2721	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	22-Sep-18	08-Oct-18	Complete	Glazing
SERENGETI	D06-SU 04	SDOXX2721	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	22-Sep-18	11-Oct-18	Complete	Glazing
SERENGETI	D06-SU 05	SDOXX2721	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	22-Sep-18	08-Oct-18	Complete	Glazing
SERENGETI	D06-SU 06	SDOXX2721	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	22-Sep-18	06-Oct-18	Complete	Glazing
SERENGETI	D06-SU 07	SDOXX2721	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	22-Sep-18	17-Oct-18	Complete	Glazing
SERENGETI	D06-SU 01	SDOXX2721	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	14-Sep-18	22-Sep-18	Complete	Glazing
SERENGETI	D06-SUM 08	PALOX2424	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	23-Sep-18	03-Oct-18	Running	Cutting
SERENGETI	D06-SUM 09	PALOX2424	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	23-Sep-18	13-Oct-18	Running	Beading
SERENGETI	D06-SUM 10	PALOX2424	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	23-Sep-18	07-Oct-18	Running	Beading
SERENGETI	D06-SUM 11	PALOX2424	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	23-Sep-18	01-Oct-18	Complete	Glazing
SERENGETI	D06-SUM 12	PALOX2424	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	23-Sep-18	28-Sep-18	Complete	Glazing
SERENGETI	D06-SUM 13	PALOX2424	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	23-Sep-18	11-Oct-18	Running	Cutting
SERENGETI	D06-SUM 14	PALOX2424	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	23-Sep-18	03-Oct-18	Running	Beading
SERENGETI	D06-SUM 15	PALOX2424	VERTICAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	23-Sep-18	13-Oct-18	Complete	Beading
SERENGETI	D07-SU 01	SHDM0921	VERTICAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	24-Sep-18	09-Oct-18	Running	Beading
SERENGETI	D07-SU 02	SHDM0921	VERTICAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	24-Sep-18	29-Sep-18	Running	Beading
SERENGETI	D07-SU 03	SHDM0921	VERTICAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	24-Sep-18	06-Oct-18	Running	Cutting
SERENGETI	D07-SU 04	SHDM0921	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	24-Sep-18	19-Oct-18	Complete	Beading
SERENGETI	D07-SU 05	SHDM0921	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	24-Sep-18	14-Oct-18	Running	Beading
SERENGETI	D07-SU 06	SHDM0921	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	24-Sep-18	10-Oct-18	Running	Cutting
SERENGETI	D07-SU 07	SHDM0921	PALACE SLIDING GLASS DOOR WITH MESH PANEL SLIDERS	24-Sep-18	11-Oct-18	Running	Beading
SERENGETI	D07-SUM 08	SHDM0921	HORIZONTAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	24-Sep-18	07-Oct-18	Running	Cutting
SERENGETI	D07-SUM 09	SHDM0921	HORIZONTAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	24-Sep-18	11-Oct-18	Complete	Beading
SERENGETI	D07-SUM 10	SHDM0921	HORIZONTAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	24-Sep-18	16-Oct-18	Running	Cutting
SERENGETI	D07-SUM 11	SHDM0921	HORIZONTAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	24-Sep-18	10-Oct-18	Running	Beading
SERENGETI	D07-SUM 12	SHDM0921	HORIZONTAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	24-Sep-18	11-Oct-18	Running	Cutting
SERENGETI	D07-SUM 13	SHDM0921	HORIZONTAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	24-Sep-18	15-Oct-18	Running	Cutting
SERENGETI	D07-SUM 14	SHDM0921	HORIZONTAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	24-Sep-18	30-Sep-18	Running	Cutting
SERENGETI	D07-SUM 15	SHDM0921	HORIZONTAL SLIDING WINDOWS WITH MESH PANEL SLIDERS	24-Sep-18	01-Oct-18	Running	Beading

Figure 4.1: Example of input data to the model

Furthermore, Figure 4.2 displays a different sheet of information also imported into the model, which is used to determine the processing time for each product at every workstation based on the times calculated using the time study data.

Product Code	Cutting (hrs)	CNC (hrs)	Assembly (hrs)	Beading (hrs)	Glass Cutting (hrs)	Glazing (hrs	Total time
Casement 30.5 Top Hung Windows							
PT0606	0.29	0	0.21	0.60	0.75	0.67	2.52
PT0906	0.14	0	0.21	0.60	0.40	0.71	2.07
PT1206	0.33	0	0.36	0.67	0.60	0.83	2.80
PT1506	0.17	0	0.36	0.40	0.50	1.00	2.43
PTT1806	0.40	0	0.58	0.50	0.75	0.71	2.95
PTT2106	0.33	0	0.58	0.75	0.40	0.57	2.64
PTT2406	0.67	0	0.58	0.75	0.75	0.71	3.46
PT0609	0.17	0	0.36	0.67	0.50	0.57	2.27
PT0909	0.17	0	0.36	1.00	0.40	0.71	2.65
PT1209	0.29	0	0.52	0.40	0.60	1.00	2.80
PT1509	0.67	0	0.52	0.60	1.00	0.83	3.62
PTT1809	0.40	0	0.88	0.40	0.50	0.83	3.02
PTT2109	0.17	0	0.88	0.75	0.40	0.71	2.92
PTT2409	0.20	0	0.88	0.50	0.50	0.83	2.92
PT0612	0.67	0	0.36	0.75	0.67	0.57	3.02
PT0912	0.40	0	0.36	0.67	1.00	0.80	3.23
PTT1212	0.20	0	0.58	0.40	0.60	0.57	2.35
PTT1512	0.67	0	0.58	0.60	0.67	0.80	3.31
PTT1812	0.20	0	0.58	0.60	0.60	0.57	2.55
PTT2112	0.20	0	0.58	0.40	0.40	1.00	2.58
PTT2412	0.40	0	0.58	0.40	0.75	0.57	2.70

Figure 4.2: Example of standard product processing times at each workstation

Figures 4.3 and 4.4 is a visual depiction of the output currently generated for the software model. The model can either be run through Python or by simply using “PowerShell”, which is an automation engine and scripting language. Using PowerShell is much quicker as there is no need to open Python. Figure 4.3 is an indication of the products that have to be processed on that day at that specific workstation. Figure 4.4 serves as a timeline as it indicates the time each product is going to take to be processed at each workstation based on the standard times for that type of product.

```
Current orders, due dates and states for each:
        #D06-SUM 12 | Due: 2018-09-28 00:00:00 | State: Glazing
        #D07-SU 02 | Due: 2018-09-29 00:00:00 | State: Beading
        #D06-SUM 11 | Due: 2018-10-01 00:00:00 | State: Glazing
        #D07-SUM 15 | Due: 2018-10-01 00:00:00 | State: Beading
        #D06-SUM 08 | Due: 2018-10-03 00:00:00 | State: Cutting
        #D06-SUM 14 | Due: 2018-10-03 00:00:00 | State: Beading
        #D05-15 | Due: 2018-10-04 00:00:00 | State: Beading
        #D07-SUM 14 | Due: 2018-09-30 00:00:00 | State: Cutting
        #D05-10 | Due: 2018-10-02 00:00:00 | State: Cutting
        #D05-12 | Due: 2018-10-03 00:00:00 | State: Cutting
```

Figure 4.3: Output of the scheduling model

```
-Cutting-
        Intervals :  [D06-SUM 12] (0:0)        [D07-SU 02] (0:0)        [D06-SUM 11] (0:0)        [D07-SUM 15] (0:0)        [D06-SUM 08] (0:15)
UM 14] (15:35)      [D05-10] (35:53)        [D05-12] (53:71)
-CNC-
        Intervals :  [D06-SUM 12] (0:0)        [D07-SU 02] (0:0)        [D06-SUM 11] (0:0)        [D07-SUM 15] (0:0)        [D06-SUM 14] (15:15)
UM 14] (88:137)     [D05-10] (137:211)      [D05-12] (211:285)
-Assembly-
        Intervals :  [D06-SUM 12] (0:0)        [D07-SU 02] (0:0)        [D06-SUM 11] (0:0)        [D07-SUM 15] (0:0)        [D06-SUM 14] (15:15)
UM 14] (175:226)    [D05-10] (226:383)
-Beading-
        Intervals :  [D06-SUM 12] (0:0)        [D07-SU 02] (0:33)       [D06-SUM 11] (33:33)      [D07-SUM 15] (33:66)      [D06-SUM 14] (66:106)
UM 14] (226:259)
-Glass Cutting-
        Intervals :  [D06-SUM 12] (0:0)        [D07-SU 02] (0:20)       [D06-SUM 11] (33:33)      [D07-SUM 15] (33:53)      [D06-SUM 14] (66:106)
UM 14] (226:246)
-Glazing-
        Intervals :  [D06-SUM 12] (0:34)       [D07-SU 02] (34:71)      [D06-SUM 11] (71:105)     [D07-SUM 15] (105:142)    [D06-SUM 14] (142:176)
UM 14] (249:286)
```

Figure 4.4: Timeline view of the scheduling model output

4.1.3 Simulation model

A simulation model was generated for the scheduling process. The simulation model act as a dashboard which provides an overview of the processes followed in the factory. The simulation model is simply used to compare the current situation (base-case) with the situation where the suggestions are hypothetically implemented (improved-case).

The base-case refers to scheduling as it is currently being done at PGA. Other, than the previously discussed priority rules applied to do the scheduling currently, the floor manager also distributed the process so that at minimum cutting and machining (CNC) is done on the same day, assembly on a next day, and then beading and glazing on the last day. These decisions contribute to the high volume of Work-in-Process (WIP) and dead time between different workstations. Dead time refers to the time a product lies between workstations without being processed and thus value is not being added.

To better understand the logic behind the simulation models, a process map of each was designed. Process mapping, amongst other benefits, increases ones understanding of the process, it also allows the user to analyse the process and identify how the process can be improved, and it also acts as a communication medium between individuals that engage in the same process or project (LucidChart 2018).

Table 4.2 outlines the main process mapping symbols used for this project.

Table 4.2: Process mapping symbols

Symbol	Description
Terminator	Used to indicate the start (green) or end (red) of a process
Process	Represents a process that takes place
Data	Used to depict data handling (when data is recorded or updated)
Decision	When a decision is made based on a Yes or No answer
Multiple Documents	Used to represent multiple documents (data capturing files) being used

Figure 4.5 is the process map of the schedules simulation model as designed using Lucid Chart online software (LucidChart 2018).

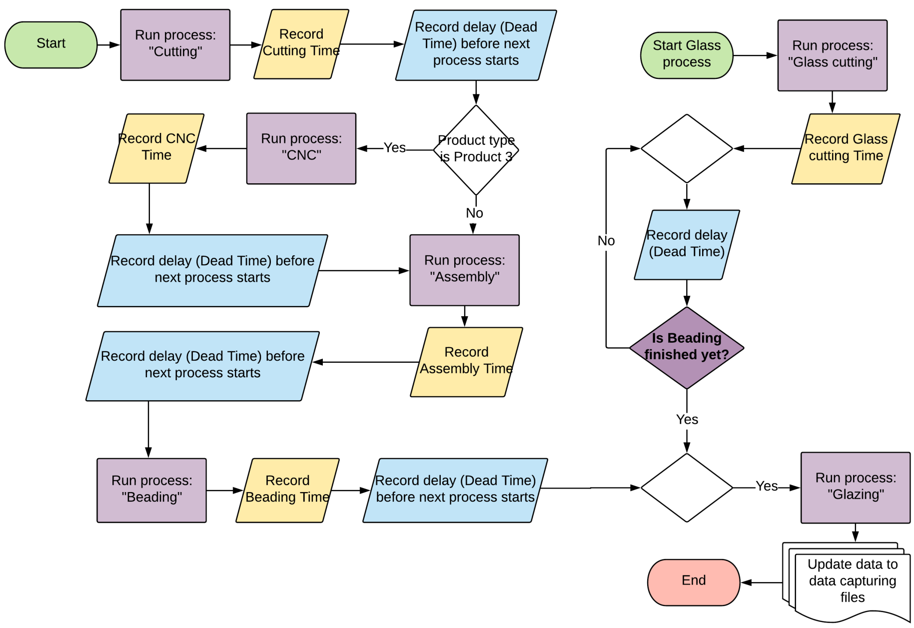


Figure 4.5: Process map of the schedules simulation model logic

The purple 'processes' represent the workstations in the factory that the products have to go through. The processing times (yellow), as well as the delay times (blue) also known as "Dead Time" is recorded for each product. The glass cutting process is independent from the rest of the scheduling model and can thus be used as an indicator of the overall change between the base-case and the improved-case. As the delay time after glass cutting decreases the overall Work-in-Process (WIP) of the factory decreases as the "Dead Time" between the different workstations are reduced. Finally all the data is recorded to text files which is used to analyse the results.

For the simulation model there are a few mathematical equations that are used to calculate the dead time between the different workstations. Note that none of the sets, indices, and constraints hold any connection to the mathematical model previously discussed.

Sets:
Let **W** be the set of workstations such that

$$\boldsymbol{W} = \begin{cases} 1 & \text{Cutting} \\ 2 & \text{Machining} \\ 3 & \text{Assembling} \\ 4 & \text{Beading} \\ 5 & \text{Glass cutting} \\ 6 & \text{Glazing} \end{cases}$$

Let **J** be the set of products such that

$$\boldsymbol{J} = \{1, 2, ...10\}$$

Let **P** be the set of product types such that

$$\boldsymbol{P} = \{1, 2, 3\}$$

Indices:

$E_{j,w,p} \triangleq$ Time point at which product j finishes at workstation w, where $j \in J,\ w \in W and\, p \in P$

$S_{j,w,p} \triangleq$ Time point at which product j starts at workstation w, where $j \in J,\ w \in W and\, p \in P$

$D_{j,w,p} \triangleq$ Dead time after workstation w for product j of product type p, where $j \in J,\ w \in W and\, p \in P$

$T_w \triangleq$ Total dead time after workstation w per simulation run, where $w \in W$

$R_p \triangleq$ Total dead time for product type p per simulation run, where $p \in P$

S.t.

$$R_p = \sum_{j \in J} \sum_{w \in W} D_{j,w,p} \qquad \forall p \in P \tag{4.25}$$

$$T_w = \sum_{j \in J} \sum_{p \in P} D_{j,w,p} \qquad \forall w \in W \tag{4.26}$$

$$D_{j,w,p} = E_{j,w,p} - S_{j,w+1,p} \qquad \forall j \in J,\ w \in \{1, 2, 3\}\, and\, p \in P \tag{4.27}$$

$$D_{j,5,p} = E_{j,4,p} - E_{j,5,p} \qquad \forall j \in J\, and\, p \in P \tag{4.28}$$

Equations (4.25) and (4.26) are used to calculate dead time in different forms so that the dead time of the base-case can be compared to that of the improved-case. Equations (4.27) and (4.28) are used to calculate the individual dead time per product and workstation.

4.2 Hardware process improvements

As discussed in section 3.1, the hardware picking process is currently responsible for a big portion of 'wasted' time in the factory. The current hardware picking process was outlined in section 3.1, Figure 3.14. Hardware picking is done per job card. Sometimes a factory worker only works on one product during the day and other days they might work on five or more job cards, depending on the type and size of the product being produced. To be able to reduce the time spent at the hardware store, Single Minute Exchange of Dies (SMED) technique was used as discussed in section 2.3.2.

4.2.1 Single Minute Exchange of Dies (SMED)

To apply SMED, three basic steps should be followed, as suggested by Cakmakci (2009):

- Separate internal and external tasks
- Convert internal tasks to external tasks
- Streamline all aspects of the process

The three steps were done for the hardware picking process at PGA of which the results can be seen in Figure 4.6. Two delays were identified, namely when the hardware manager is not available or busy with another worker, and when there is a stock-out. The two delays identified do not occur that often but when it occurs it has a very big impact on production. Delay 1 used to occur more frequently, but seeing that the procurement of hardware was reallocated to the procurement manager instead of the hardware manager, the delay occurrence has already decreased. It still, however, happens that more than one worker requires hardware at the same time but the hardware manager is only able to assist one worker at a time.

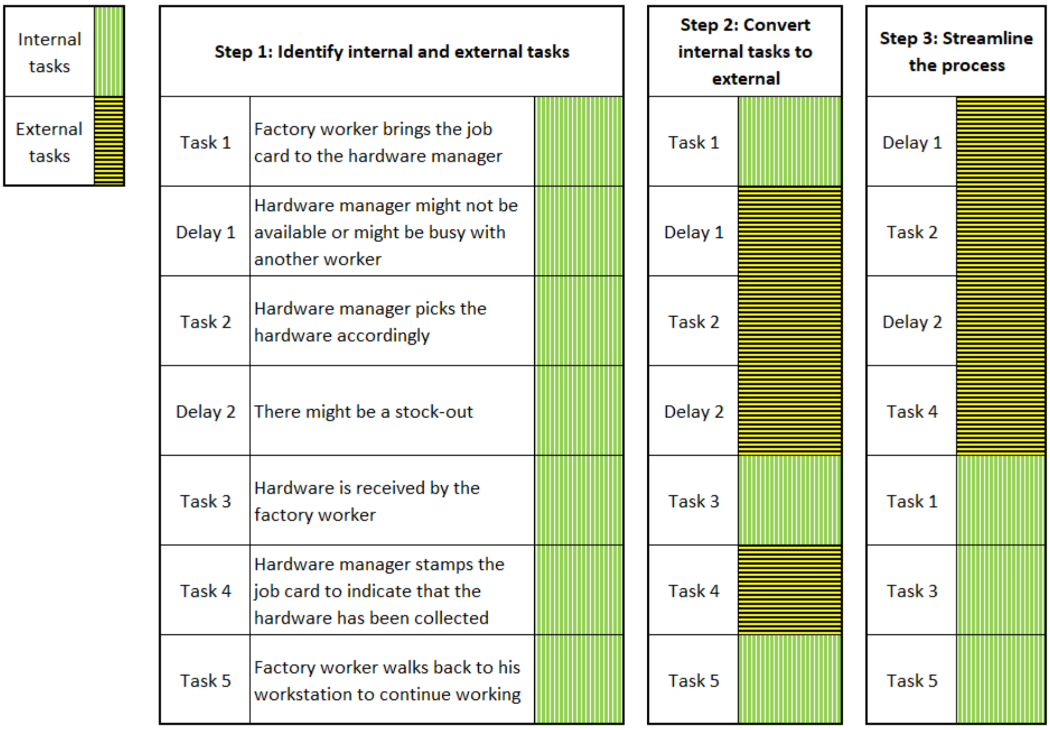


Figure 4.6: Implementation of SMED technique on the hardware picking process

Figure 4.6 shows the tasks that can be done by the hardware manager before the arrival of the workers. The external tasks identified are the actual picking of hardware and the administration involved with the picking process. Both these tasks can be done prior to the start of production. Furthermore, two delays (delay 1 and delay 2) can also be eliminated as there is no need for the hardware manager to be present when the assemblers collect the picked hardware, and stock-outs can be reduced as the hardware manager will be made aware sooner of the stock-out and can act accordingly. The suggested improved process is that the hardware manager receives a copy of the job cards of every order once the order has been received. The hardware manager can then already check stock levels and replenish the stock if needed. Therefore, should a stock-out occur, the waiting time for the stock to be replenished will be reduced. He can then start picking the hardware and placing each order's hardware in a specific box that should be easily accessible to the factory workers. As a control measurement to avoid theft, the hardware manager will still have to stamp the job card once the hardware has been collected. Furthermore, it is suggested that each box is allocated to a specific worker to ensure that worker A does not take worker B's box. The boxes will still have to be in the hardware store to ensure control over the process. The workers will then be able to collect all the hardware necessary for production on that day, first thing in the morning. Even though the walking distance has not been reduced, the number of times the workers have to walk to the hardware store will be reduced to one. Seeing that the boxes will already be picked, the workers will not have to wait for the hardware manager to pick the hardware. The only requirement of the hardware manager during that time is to ensure that the right box goes to the applicable worker and to stamp the job card. The schedule, however, needs to identify how many products workers will be producing during a day. Using the schedule properly will enable the workers to take the hardware necessary for the estimated number of job cards' for the day.

4.2.2 Suggested improvements

The changes that were made to the hardware picking process as a result of the SMED results are briefly outlined and are represented using BPMN in Figure 4.7.

- The floor manager aims to do his planning for the next day by 15:00 every afternoon to be able to allocate certain products to the respective assemblers. Therefore, the floor manager will run the optimised scheduling model everyday at 15:00 based on the progress data that he has at that point in time. The model can always be rerun if needed due to unforeseen circumstances.
- Hardware for the majority of the products expected to be produced the next day must be picked at 15:30 every day.
- The hardware is picked per product per assembler as assigned by the floor manager.
- Each assembler has a picking bin in which the hardware manager picks the hardware he will need the next day. The assembler will then collect his hardware the next morning and put it in a basket that he can take with him to his workstation. At the end of the day the empty basket will be placed in an allocated area. If the basket is not yet empty it is handed to the hardware manager, so that it can be stored inside the hardware store until the next day for control purposes and to avoid hardware being taken by other workers.
- More hardware must be picked than before, to reduce the amount of hardware that the assembler has to pick himself.
- Certain hardware components such as the most used pop rivets and screws must be kept in a small bin at the workstation. The bin can then be replenished as needed.

- The hardware that the assemblers have to pick themselves must be stored outside the hardware picking store. This includes even the components that used to be kept inside the store, to allow for quick and easy access to all the hardware.

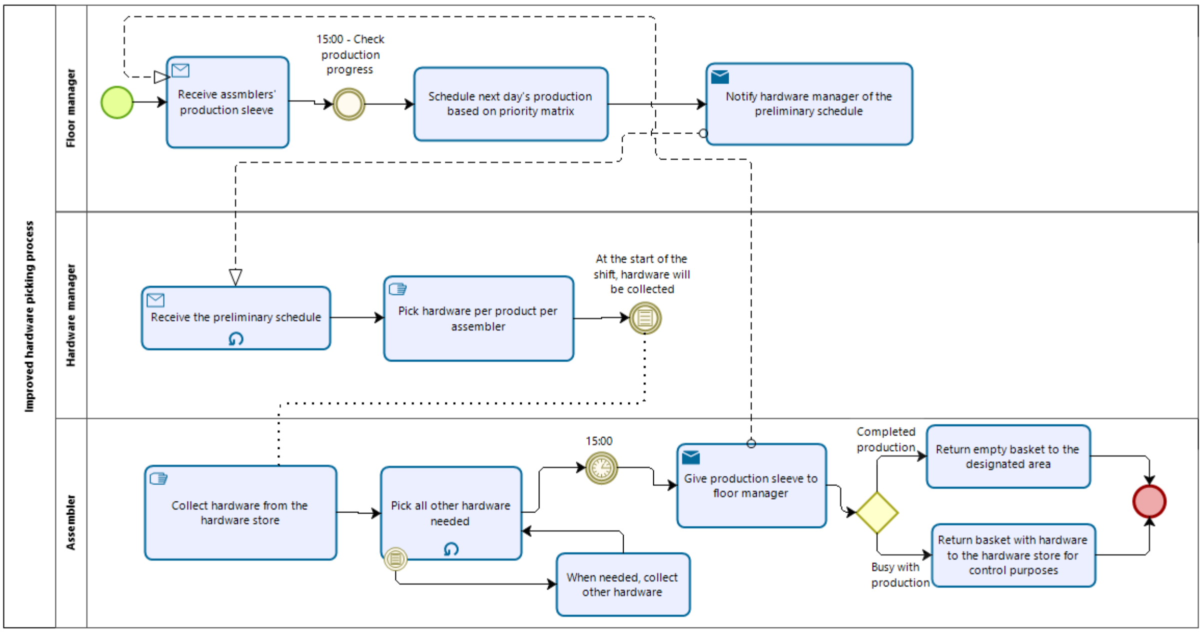


Figure 4.7: Hardware picking process based on improvement suggestions

4.2.3 Simulation model

A simulation model was generated to test the outcome of the suggested improvements. To better understand the logic of the simulation model a process map was generated. The same symbols that were used for the schedule's process map was used for this process map as well.
Figure 4.8 is the process map for the overview of the simulation model for the hardware picking process where the process is terminated once the expected standard time is reached. Once the 'Assembly' process is exited, the disparity of the simulation run is calculated.

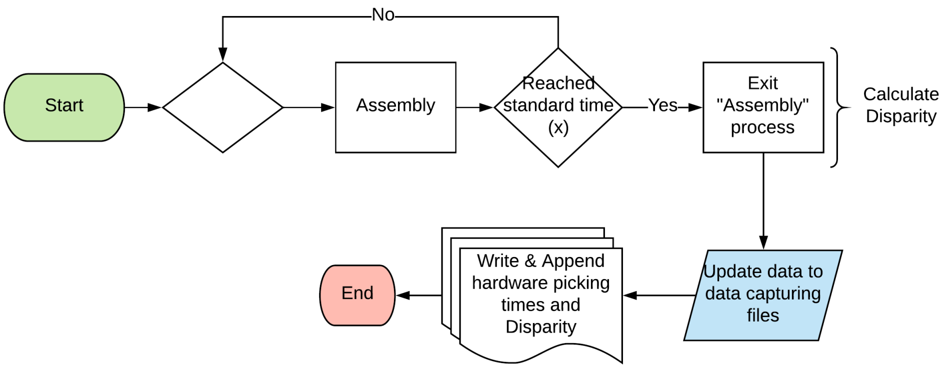


Figure 4.8: Overview process map of the hardware picking process simulation model logic

Figure 4.9 outlines the sub-process within the 'Assembly' process displayed in Figure 4.8. The sub-process contains the three types of hardware picking. This process map only focuses on the "Assembly" process as that is the only workstation that consistently requires hardware.

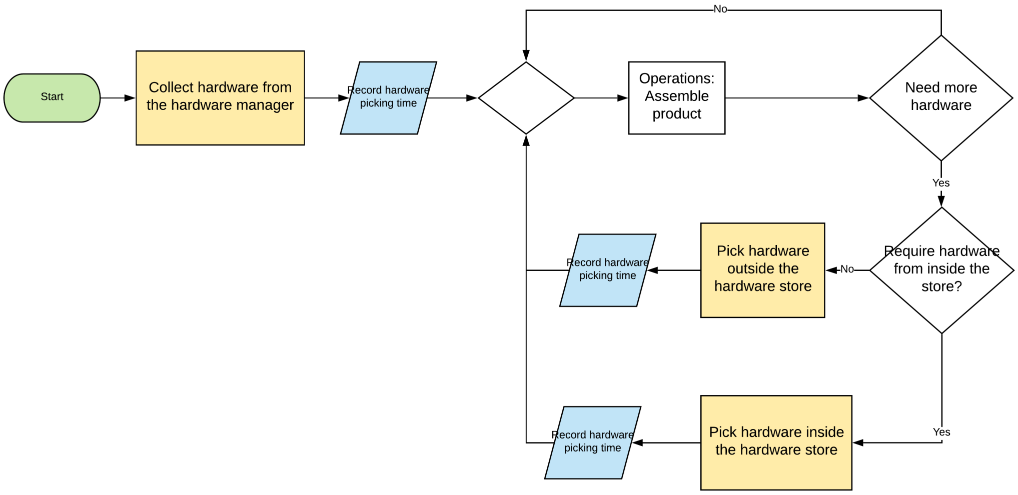


Figure 4.9: Process map of the sub-process within the hardware picking process simulation model

The standard times for each product type is recorded before start-up which is used to indicate that the product has been completed. Initially all the products receive hardware from the hardware manager. The actual assembling of the product, also known as "Operations", then commences where the assembler would go pick hardware (either inside or outside the hardware store) at a predefined rate. Once completed the "Assembly" process is completed and the picking times and disparity is recorded.

The simulation model includes some mathematical calculations required to measure the difference between the base-case and improved-case. The mathematical model is briefly outlined. Note that none of the sets, indices, and constraints hold any connection to the mathematical model previously discussed for the scheduling model and scheduling simulation model.

Sets:
Let **H** be the set of workstations such that

$$\boldsymbol{H} = \begin{cases} 1 & \text{Hardware manager} \\ 2 & \text{Hardware inside the hardware store} \\ 3 & \text{Hardware outside the hardware store} \end{cases}$$

Let **J** be the set of products such that

$$\boldsymbol{J} = \{1, 2, ...10\}$$

Let **P** be the set of product types such that

$$\boldsymbol{P} = \{1, 2, 3\}$$

Let **X** be the set of product types such that

$$\boldsymbol{X} = \{1, 2, ...25\}$$

Indices:

$$\begin{aligned}
Y_h &\triangleq \text{Total time spent on picking hardware per hardware type h, where } h \in H \\
X_p &\triangleq \text{Total time spent on picking hardware per product type p, where } p \in P \\
T &\triangleq \text{Total time spent on picking hardware per simulation run} \\
S_{j,p,h} &\triangleq \text{Time spent on picking hardware from hardware type h, per product j of product type p,} \\
&\quad\ \text{where } j \in J, p \in Pandh \in H \\
D_x &\triangleq \text{Disparity per simulation run x, where } x \in X \\
O_x &\triangleq \text{Time spent on operation (actual assembling) per simulation run x, where } x \in X \\
L_{j,p} &\triangleq \text{Standard time per product j of product type p, where } j \in Jandp \in P \\
E_{j,p,h} &\triangleq \text{Time point at which hardware picking type h finishes for product j of product type p,} \\
&\quad\ \text{where } j \in J,\ p \in Pand\, h \in H \\
U_{j,p,h} &\triangleq \text{Time point at which hardware picking type h starts for product j of product type p,} \\
&\quad\ \text{where } j \in J,\ p \in P\, and\, h \in H
\end{aligned} \tag{4.29}$$

S.t.

$$Y_h = \sum_{j \in J} \sum_{p \in P} S_{j,p,h} \qquad \forall\, h \in H \tag{4.30}$$

$$X_p = \sum_{j \in J} \sum_{h \in H} S_{j,p,h} \qquad \forall\, p \in P \tag{4.31}$$

$$T = \sum_{j \in J} \sum_{p \in P} \sum_{h \in H} S_{j,p,h} \qquad \forall\, j \in J,\ w \in W\ and\, p \in P \tag{4.32}$$

$$O_x = \sum_{j \in J} \sum_{p \in P} \sum_{h \in H} (E_{j,p,h}) - U_{j,p,h}) \qquad \forall x \in X \tag{4.33}$$

$$D_x = \sum_{j \in J} \sum_{p \in P} L_{j,p} - O_x \qquad \forall\, x \in X \tag{4.34}$$

$$\tag{4.35}$$

Equation (4.30) calculates the total time spent on hardware picking for each hardware type. Equation (4.31) calculates the total time spent on picking hardware per product type. Equation (4.32) calculates the total time spent on picking hardware per simulation run. Equation (4.34) is used to calculate the disparity per simulation run where disparity refers to the amount of time the product is not actually being assembler. All these constraints are used to calculate some variable of the base-case which is also calculated for the improved-case and then compared.

4.3 Individual Performance Measurement Tool

A schedule can only be effective if it is followed by all the workers. Although PGA currently attempts to look at individual performance, this process has not been implemented effectively and is not being maintained. PGA expressed the need to have an individual performance measurement tool (IPMT) that calculates the time a worker takes to produce a product and to compare it to a standard time. The Microsoft Excel tool that calculates the standard time of each workstation for each type of standard product is able to supply the information needed for the IPMT. The IPMT was designed using Microsoft Excel as this is the platform that PGA is most comfortable with. Consideration should be given to the value linked to standard times, as a worker might be able to produce a product quickly but the quality might not be up to standard. Another factor to think about is the applicability to all staff. This tool will work well with the assembly, beading, glass cutting, and glazing areas (which are the four main areas identified), but it does not include other individuals such as the floor manager, hardware manager, workers responsible for receiving, etc. If PGA wants a culture of rewarding staff for performance, it should be spread across the entire factory and not just a select few.

The Excel spreadsheet consists of four columns for every area in the factory. The columns indicate the worker responsible, the calculated standard time, the actual time the product took to complete, and whether the actual time was more (scored as over) or less (scored as under) than the calculated standard time. The calculated standard time is imported from a different sheet in the same Excel spreadsheet by means of the VLOOKUP function. Figure 4.10 is a zoomed in version of the IPMT input data.

Production Log	Cutter	Standard Time	Actual Time	Report
SF3924-6	Raymond	0.67	0.22	Under
SF5124-7	Raymond	0.44	0.38	Under
SF2127-3	Raymond	0.51	0.76	Over
SF2121-3	Raymond	0.51	0.51	Under
VS0615	Raymond	0.67	0.72	Over
VS0912	Raymond	0.56	0.90	Over
VS0912	Raymond	0.56	0.90	Over
HS1506	Raymond	0.51	0.81	Over
DHDM1521	Raymond	0.40	0.12	Under

Figure 4.10: Enlarged section of the input data to the IPMT

This data is then converted into summarised tables by means of the PivotTable function in Excel. An individual PivotTable is created for each factory area. The factory area data can either be viewed in totality or be filtered on each individual worker. Figure 4.11 is a representation of such a summarised table where the number of times production took longer than the calculated time is clearly displayed. Furthermore, other visual graphics can be used to represent the data.

Assembler	Lucky
Row Labels	**Count of Actual Time**
Over	6
Under	8
Grand Total	**14**

Figure 4.11: Example of the PivotTable for assembly, specifically assembler 'Lucky'

Figure 4.12 is an example of such visual representations. Once again the pie graph can be filtered to either show the performance of the entire area or an individual worker.

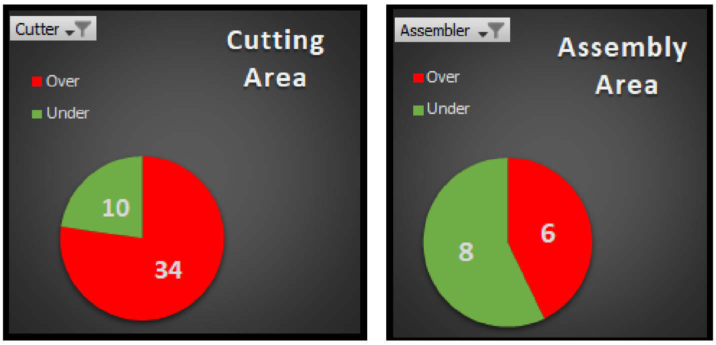


Figure 4.12: Pie chart of the performance of the cutting area and an individual assembler

To be able to effectively use the IPMT, PGA will have to track the time each product spends at each workstation, as well as the employee responsible for that workstation. PGA is currently in the process of designing a tracking system which will make use of a barcode scanning system. The ideal is that this system will be able to give reports on the time it took each worker to complete the products allocated to them. However, the tracking system will not be using the calculated standard times to compare the actual to the expected times. Therefore, the IPMT can be used as a supporting tool to help analyse the information gathered by the tracking tool for management to be able to make decisions effectively and reward hard work.

Furthermore, to ensure the quality is not reduced due to the time goals, it is suggested that PGA include another performance measurement which looks at the quality of the product. This can either be done by rating the actual quality of the product or by counting the number of times a worker produces a defective product that needs to be reworked. This raises other questions such as who is responsible for the lack of quality or number of errors, how many times did the product have to be reworked before being of an acceptable quality, when is the quality measured, who decides the quality of a product and based on what is the quality determined. These are questions that have to be investigated further along with input from PGA in terms of their expectations and standards.

If individual performance is measured based on time as well as quality, PGA can further incorporate an analysis tool in the form of a Microsoft Excel spreadsheet that considers both these performance outcomes in the calculation of the final performance.

4.4 Concluding remarks

Chapter 4 focused on the suggested solution for the scheduling model, hardware picking process improvements, as well as the IPMT. The scheduling model consists of a mathematical formulation, which was done using Mixed Integer Linear Programming (MILP), as well as a software model which was generated using Python software. A simulation model was generated that was used to validate whether the scheduling model is in fact an improvement on the current scheduling method. The hardware picking process suggestions were outlined and a BPMN was included to show how the suggested picking process should be done as to obtain maximum benefits. A simulation model was also generated for the hardware picking process that was used (in section 5) to compare the base-case with the improved-case. Both the simulation models' logic were described by means of process mapping. Furthermore, the IPMT was designed using Microsoft Excel, which serves as a tool which compares the actual performance of workers with the expected performance based on the standard times calculated with the Time studies.

Chapter 5

Evaluation and analysis of solutions

It is important to evaluate a model to ensure the results generated by the model is in actual fact a realistic solution and that it does what it is intended to do. The value of the model lies in its ability to generate the desired output in the desired format (Macal 2005).

5.1 Model verification and validation

As discussed in the literature review, there are various methods that can be used for model validation and verification. Macal (2005) and Manson (2006) suggest methods on how to do model validation. These methods are very similar. As the model for this study falls into the category of operations research, Manson (2006)'s suggestions on model evaluation and validation was considered. The main evaluation methods that are used includes functional and structural testing, observational case studies, and experimental simulation.

5.1.1 Scheduling model

Various methods of validation can be used to validate the scheduling model. Different methods of validation will validate different aspects of the model.

To test the model's functionality and structure (*Testing*) the robustness of the model can be evaluated (Rasconi et al. 2010). According to Rasconi et al. (2010) there are three main aspects that can define the robustness of a model, which will briefly be discussed.

Solution reactiveness: This refers mainly to the speed at which the model can react to changes. The faster a solution is generated, the higher the probability that a quality solution be given; whereas the longer the solution takes to generate, the higher the probability that an execution failure will occur. Measuring reactiveness could be done by looking at the flexibility, or 'slack', allowed in the model.

Solution stability: This refers to the way in which the given solution changes based on unexpected events. If the scheduling model is stable, the initial solution's structure should remain relatively constant. Stability could be measured using a disruptibility metric based on the amount of slack in the model and the number of changes that occur.

Solution quality: The quality of the solution refers to the schedule's ability to keep to a certain makespan. The model's ability to produce a schedule that adheres to all the constraints while optimising the objective function can be seen as a quality schedule.

Having a robust model ensures that the solution can keep up with the execution pace and any possible changes. Unfortunately these three aspects of robustness could sometimes be conflicting and thus one or two of these aspects should rather be pursued instead of all three (Rasconi et al.

2010). Once it has been validated that the model is indeed producing the desired results, the model robustness can be investigated.

Furthermore, the scheduling model was observed (*Observational case study*) based on real data from PGA's production logs but on a smaller scale. The small scale model (which will be referred to as the testing model) was generated using a proportion of the production log's data. Less data was used for the small scale model as to be able to logically determine, by hand, what the optimal solution should be.

The model is validated by comparing the output of the small scale model with a man-made logical solution, based on the priority of the products which is determined by their due dates, as well as where the product currently is within the production process.

The testing model's data consisted of 18 products that were at different stages of production. From the 18 products, 11 have already been completed and should thus not have formed part of the solution. The remaining seven products were allocated to the workstation where their production process has to commence from. The number of days until the product was due, as well as the expected production time for each process were considered. Figure 5.1 is a visual representation of the logic used to determine the order of execution for the seven products as of their starting points in the factory.

	Cutting			CNC			Assembly			Beading			Glazing		
Initial Status	D06-SU 05	29 September, 2018	0.35	D06-SUM 08	28 September, 2018	1.35	D06-SUM 12	26 September, 2018	1.85						
	D06-SUM 10	29 September, 2018	0.35	D07-SU 02	27 September, 2018	0	D07-SU 03	30 September, 2018	1.73						
	D07-SU 01	03 October, 2018	0.25												

	Cutting			CNC			Assembly			Beading			Glazing		
After 1 day status	D06-SU 05	29 September, 2018	0.35	D06-SUM 08	28 September, 2018	1.35	D06-SUM 12	26 September, 2018	1.85	D06-SUM 12	26 September, 2018	0.71	D06-SUM 12	26 September, 2018	0.63
	D06-SUM 10	29 September, 2018	0.35	D07-SU 02	27 September, 2018	0	D07-SU 02	27 September, 2018	1.73	D07-SU 02	27 September, 2018	0	D07-SU 02	27 September, 2018	0
	D07-SU 01	03 October, 2018	0.25	D06-SU 05	29 September, 2018	1.35	D06-SUM 08	28 September, 2018	1.85	D06-SUM 08	28 September, 2018	0.71	D06-SUM 08	28 September, 2018	0.63
				D06-SUM 10	29 September, 2018	1.35	D06-SU 05	29 September, 2018	1.85						
				D07-SU 01	03 October, 2018	0	D06-SUM 10	29 September, 2018	1.85						
							D07-SU 03	30 September, 2018	1.73						
							D07-SU 01	03 October, 2018	1.73						

Figure 5.1: Expected outcome for the first three workstations

Figure 5.1 is a tabular representation of the expected production sequence of the products. The overview of the output of the testing model can be seen in Appendix B. Appendix B also includes a visual representation of the production to ensure that the right sequence of events are followed.

It is expected that the model should adhere to the daily limit of 390 minutes available for production (330 minutes on Friday's). The model should also adhere to the precedence and interference constraints, therefore only one product can be processed per machine at a time, and the sequence of events cannot be changed. The products typed in red indicates that it is expected that the model will not be able to schedule those products for this particular day as the daily limit of 390 minutes would then be exceeded.

A part of the testing model's output can be seen in Figures 5.2 and 5.3. Figure 5.2 produces a closer view of the output of the testing model. The products are listed in the order in which they should be produced. Figure 5.3 is the second part of the generated output which serves as a timeline view of the model which is generated based on the standard times for each step of the production process for each type of standard product.

```
Machine 0 -> Cutting
        Intervals :
        Machines Available: 1 -> #D07-SU 02
        Machines Available: 1 -> #D06-SUM 08
        Machines Available: 1 -> #D06-SU 05
        Machines Available: 1 -> #D06-SUM 10
        Machines Available: 1 -> #D07-SU 03
        Machines Available: 1 -> #D07-SU 01
        Machines Available: 1 -> #D06-SU 07
Machine 1 -> CNC
        Intervals :
        Machines Available: 1 -> #D07-SU 02
        Machines Available: 1 -> #D06-SUM 08
        Machines Available: 1 -> #D06-SU 05
        Machines Available: 1 -> #D06-SUM 10
        Machines Available: 1 -> #D07-SU 03
        Machines Available: 1 -> #D07-SU 01
        Machines Available: 1 -> #D06-SU 07
```

Figure 5.2: A closer view of the testing model's output

```
Time Intervals for Tasks

Machine 0 -> Cutting
        Intervals : [0,15] [15,36] [36,57] [57,78] [78,93]
Machine 1 -> CNC
        Intervals : [15,15] [36,117]
Machine 2 -> Assembly
        Intervals : [15,118]
Machine 3 -> Beading
        Intervals : [118,118]
Machine 4 -> Glass Cutting
        Intervals : [118,163]
Machine 5 -> Glazing
        Intervals : [163,163]
```

Figure 5.3: A closer view of the testing model's one day timeline

By comparing the testing model's output to the expected output it can be seen that the model indeed generates the same results which indicates that the model is adhering to the given constraints and priorities.

Manson (2006) further suggests that experiments can be done to evaluate the model. Therefore, different controlled experiments (*Experimental*) can form part of the scenario evaluation of the scheduling model. Scenario analysis is done when different scenario's are tested to evaluate the result of each scenario. From the evaluation the best option can be selected. To evaluate the scheduling model artefact, experimental simulation was done. Firstly, the different scenario's was generated using the Python model, based on a predetermined set of data which was consistent for each scenario. Secondly these results were tested using a simulation model designed in simulation software, AnyLogic. Experiments, for a job-shop system where there are precedence constraints, is done to evaluate the performance of the model based on different scheduling rules (Vinod & Sridharan 2008). For this scheduling model only the Earliest Due Date (EDD) rule was used as the other rules are not applicable, simply because set-up times are not considered exclusively as it is included in the processing times, and FIFO (First-in-First-Out) rule results in some products not being completed before their due dates. However, if there are two products with the same due date and same processing times, the product that was issued to the factory first will be scheduled first (FIFO).

Table 5.1 outlines the results of the base-case with the improved-case (using the Python schedule) for the different product types.

Table 5.1: Simulation results for the scheduling model

Measurement	Product 1	Product 2	Product 3
Average time: base-case (min)	2512	2251	3483
Average time: improved-case (min)	1397	1236	1795
Difference per product (min)	1116	1015	1688
Difference per product (%)	44.4%	45.1%	48.5%

Table 5.2 outlines the difference between the base-case and the improved-case (using the Python model) of the total . The glass cutting process runs parallel to the rest of the production process. Therefore, the glass cutting process is independent of the rest of the process, and could therefore be used as an indicator of the overall improvement due to the schedule. The scheduling model's objective is to reduce the amount of time a product spends in the factory, therefore, the model aims to move to a Just-In-Time (JIT) system which reduces Work-in-Process (WIP). Therefore, a lot of the dead-time was eliminated in the improved-case.

Table 5.2: Overview of the simulation results for the scheduling model

Measurement	Total dead time	Glass cut dead time
Average time: base-case (min)	2749	1595
Average time: improved-case (min)	1476	814
Difference per product (min)	1273	781
Difference per product (%)	46.3%	48.9%

Figure 5.4 clearly indicates that there is a reduction in the total amount of dead time if the suggested scheduling solution is implemented.

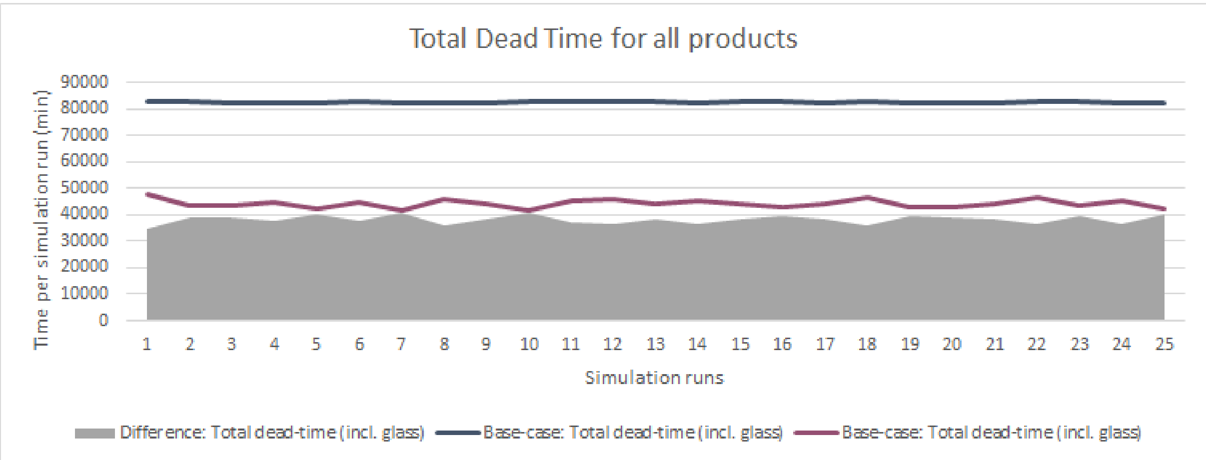


Figure 5.4: The overall dead time per simulation run: Base-case vs. Improved-case

Figure 5.5 acts as a visual depiction of the results for the independent variable (dead time after glass cutting) where it can be seen that there is a definite reduction in dead time.

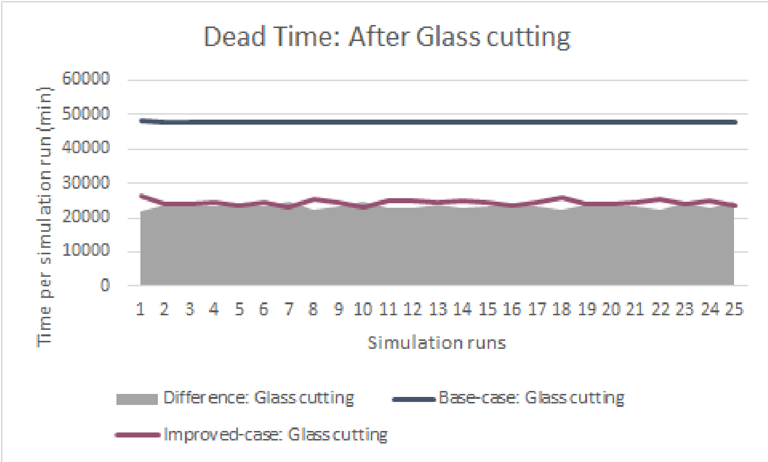


Figure 5.5: Dead time after glass cutting: Base-case vs. Improved case

From the results it is evident that there is a big reduction in dead time (which also translates to Work-in-Progress). Refer to Appedix D for visual representations and expansion on the results of the simulation model.

It is, however, important to also validate the hardware picking process and the suggested improvements.

5.1.2 Hardware picking process

To evaluate the hardware picking process improvements that were suggested, a controlled experiment by means of simulation (*Experimental simulation*) was done in order to show the intended effects of the improvements. Two scenario's were simulated, namely the base-case and the improved-case. The base-case is simulated to represent PGA's current hardware picking process, whereas the improved-case is simulated to represent the hardware picking process if all the suggested improvements are implemented. The simulation acts as a 'dashboard view' as an overview of the scenario was simulated to see the overall change in hardware picking times. Both simulations were run 25 times, where each simulation run generated ten products from each of the three product categories (Product 1, Product 2, and Product 3), therefore, 250 products of each product type was simulated for each scenario. The overall results generated from the simulations are outlined in Table 5.3.

Table 5.3: Simulation results for the hardware picking process

Measurement	**Product 1**	**Product 2**	**Product 3**
Average time: base-case (min)	151.687	153.216	177.350
Average time: improved-case (min)	113.556	115.554	89.273
Difference per product (min)	38.13	37.66	88.08
Difference per product (%)	24.29%	24.24%	49.22%

The average time spent on picking hardware per product (per product type) was calculated based on the simulation results. This included the time spent picking hardware that is stored inside the hardware store, hardware stored outside the hardware store, and the hardware that is picked by the hardware manager.

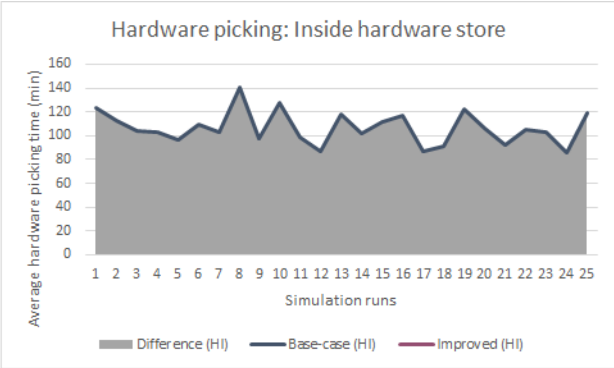


Figure 5.6: Simulation results for the total time spent on picking hardware inside the hardware store per simulation run

Figure 5.6 represents the time 'saved' for picking hardware from inside the hardware store. As the suggested improvement is to remove the hardware station inside the hardware store, the improved-case did not have any time spent picking hardware inside.

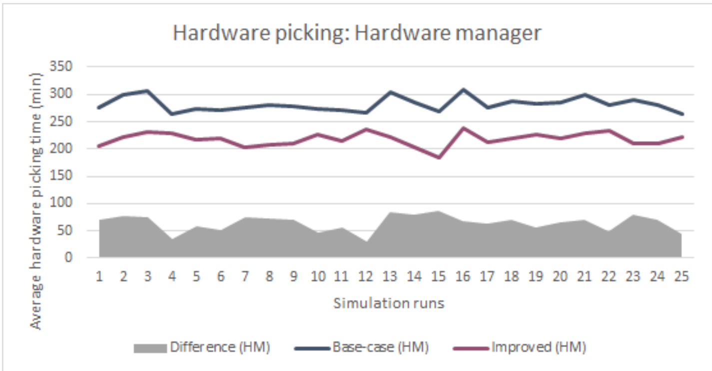


Figure 5.7: Simulation results for the total time spent on picking hardware by the hardware manager per simulation run

Figure 5.7 represents the time spent on picking hardware by the hardware manager. It can be seen that the time for the improved-case is less than the time for the base-case. This is due to the fact that, as suggested, the hardware manager picks the hardware the day before (which does not affect the amount of time the assemblers spend picking hardware) and the assemblers simply come to collect the hardware when needed which takes up a lot less time than having to wait for the hardware to be picked.

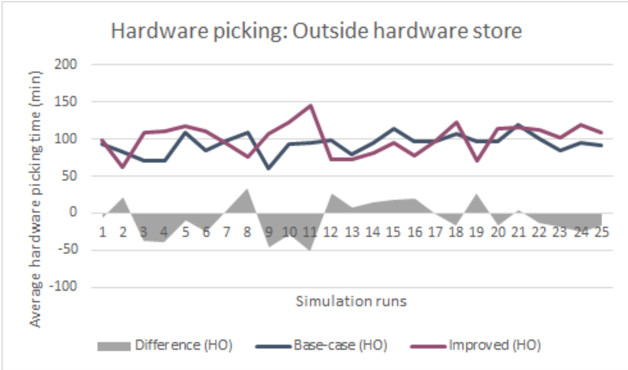


Figure 5.8: Simulation results for the total time spent on picking hardware outside the hardware store per simulation run

Figure 5.8 represents the time spent by the assemblers, picking hardware outside the hardware store. As the hardware station inside the hardware store is being combined with the hardware station outside the hardware store, the time spent picking the hardware might be longer than it used to be. However, as suggested some of the common hardware items such as certain rivets and screws will be kept at the assemblers workstations which could also reduce the amount of time spent picking hardware at the outside station. Due to the variability created by both these factors, the improved-case was only better 40% of the simulation runs.

Furthermore, the disparity of the simulation runs were recorded, where disparity was calculated using the following equation:

$$Disparity = \bar{x} - nTimeOperation \tag{5.1}$$

where

- $\bar{x}$ = the calculated standard time the product is expected to spend in assembly
- nTimeOperation = the time the product actually spent in assembly during that specific simulation run

Therefore, the greater the disparity the more time was spent picking hardware. Ideally the disparity should be less.

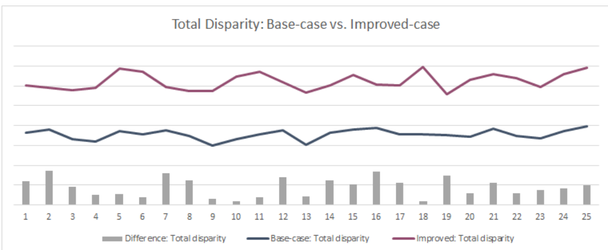


Figure 5.9: Simulation results for the total disparity per simulation run

From the results it is clear that the total disparity per simulation run decreased by 25.19% on average.

For more in depth analysis, the total time spent picking hardware in the three different ways were also analysed, to see which of these are the main contributors to the disparity. These times include the time spent walking to and from the hardware store. Refer to Appendix E for the expanded results of the simulation model for the hardware picking process.

The total time spent on hardware picking, however, was decreased by 33.77%. It can therefore be concluded that the suggested improvements will in fact be beneficial as it will reduce the amount of time spent picking hardware by the assemblers.

If these suggestions are implemented, it is expected that the assemblers' productivity should also increase as less time is spent picking hardware which is classified as Red-light time. It will therefore, be beneficial for the assemblers to have a way of being rewarded for increased productivity as a motivator. This can be done by means of the IPMT. To ensure that the tool is functioning as expected, it needs to be evaluated as well.

5.1.3 Individual Performance Measurement Tool (IPMT)

Finally, the IPMT also needs to be evaluated. As the tool is dependent on the tracking tool (which is still being designed by a third party), the actual functionality of the IPMT tool in the 'field' cannot be tested. Instead, the tool can only be evaluated to see if it functions as one would expect, assuming the tracking tool is functioning as expected.

To validate the IPMT it is necessary to determine whether the tool functions the way one would expect and whether it addresses the need which lead to the actual design of the IPMT. If the tool adheres to the following statements, it can be deemed as valid:

- The tool compares the actual performance of workers with the expected performance.
- The tool clearly shows when performance is less than expected.
- The output of the tool can be seen on an individual level, as well as on a group level (per area in the factory).
- Decision-making regarding factory performance can be done based on the results of the model.

Should the tool adhere to all the above listed requirements, the structure of the tool will be validated. The functional analysis can, however, only be done once the tracking system is complete and functioning.

Besides validating and evaluating the models and tools, a sensitivity analysis is required to determine how the models react to change.

5.2 Sensitivity analysis

Sensitivity analysis can be done in various ways depending on the type of model. Manson's evaluation methods are once again relevant and can therefore still be used. However, the difference between the validation of the model and scenario analysis compared to the sensitivity analysis is that the sensitivity analysis consists of multiple runs with small changes being made between each run.

Petrovic et al. (2008) addresses sensitivity analysis for typical complex job-shop scheduling models. The sensitivity analysis approach suggested by Petrovic et al. (2008) is specifically for scheduling problems where there are a large number of machines and jobs, the processing times vary for different products, and where there are multiple measures of schedule performance. The sensitivity analysis done by Petrovic et al. (2008) started with the base case which is the optimised schedule generated by the model. Changes were then made to the processing times. Parameters affected by these changes were measured and compared.

Scenario analysis is done in this section where the changing variable is the number of products that have to be produced and the time taken to generate the results is measured (the number of high priority products changes).

It is not expected that much time will be saved because of the optimised schedule, instead the value lies in the consistency of the scheduling and improved customer service, as the schedule ensures that products are not 'missed' or 'skipped' during production. The schedule will also allow for production to commence effectively even when the floor manager, who currently does the scheduling, is not in the factory. If the schedule is applied consistently the factory should be able to lean towards a Just-In-Time (JIT) system as that is in line with the objective of the scheduling model which is to reduce the amount of time a product spends in the factory.

For the sensitivity analysis of this project's scheduling model, the following scenario's were evaluated, and the stipulated parameters measured for each change was also recorded. The changes that was made were to the number of products in the production log and the number of high priority products in the system. The priority distribution will vary according to the ratio's stipulated in Table 5.4.

Table 5.4: Priority distribution of the input data for each run

Run #	**Low Priority**	**Medium Priority**	**High Priority**
1	0.33	0.33	0.33
2	0.25	0.25	0.50
3	0.20	0.20	0.60
4	0.15	0.15	0.70
5	0.10	0.10	0.80
6	0.05	0.05	0.90

Note that the priority distribution changes mainly focus on the percentage of high priority products as these are the products that are most likely to influence the schedule.

The following performance measurements were observed:

- Number of products processed
- Model reactiveness (the time taken to generate a solution)

100 products were scheduled with varying processing times based on the factor f. As expected the optimal schedule length increased as the processing times increased. The model was able to generate an optimal schedule within less than 2 seconds every time.

100 products were once again scheduled with varying priorities based on the priority distribution outlined in Table 5.4. All the schedules were generated within less than 2 seconds which is a satisfactory processing time. From run #3 the products were not completed before the specified due date. This was, however, due to the lack of sufficient resource capacity and the model was still able to generate the optimal solution for a specified day.

Changes were made to the number of products in the production log to observe the effect this has on the processing time of the schedule. The scheduling model has a built-in functionality that allows the scheduler to limit the number of products being scheduled (independent on whether the day's capacity has been filled or not). This functionality simply looks at the due dates of the products and then finds the optimal schedule of the last n-number of products where n is the specified limit. The results from these changes are outlined in Table 5.5. The horizontal headings refer to the specified limit value (number od producta), whereas the vertical headings refer to the number of products in the production log.

Table 5.5: Effect of the number of records in the production log on the processing times

No. of products	100	200	400	800
600	3.53	6.94	30.92	-
1200	3.06	7.22	31.31	264
2400	4.66	7.8	31.98	275
4800	4.88	8.15	36.53	267

From the results it can be seen that the number of products in the production log does not have a significant effect on the processing time. There is no pattern that suggests that the number of products in the production log has a significant effect on the processing times as sometimes the processing time decreased when the number of products doubled. Even when there are 11000 products in the production log (which is about the current number of products in PGA's actual production log), the processing time is still less than 10 seconds (approximately 7 seconds) which is a reasonable amount of time. Furthermore, it can be seen that the model was rather influenced by the limit specified as there is exponential growth in the processing times as the limit increases. Figure 5.10 depicts the growth rate of the processing times as the limit value increases. Majority of the time less than 100 products are in the system and therefore the processing time is still acceptable.

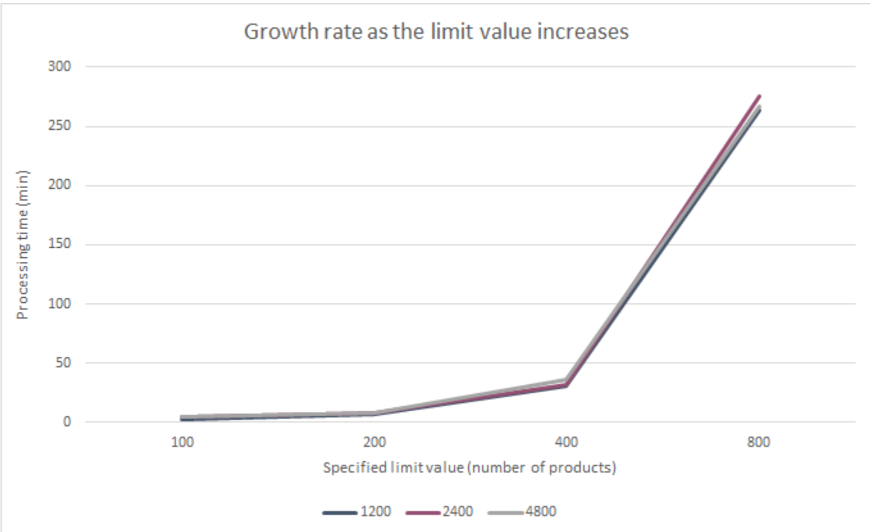


Figure 5.10: Effect on the processing time as the limit value increases

Based on the results from these three sensitivity analysis scenarios it can be concluded that the model is in fact robust, as the reactiveness of the model remained fairly constant within boundaries, the solution output stability based on the outputs given remained constant, and the solution quality remained constant as the schedule maintained its specified makespan. Therefore, it can be concluded that the model is robust and is therefore not sensitive to external factors. During the sensitivity analysis no errors or bugs were detected which confirms that the model is in fact verified (Macal 2005).

5.3 Concluding remarks

Model evaluation includes model verification, validation, and sensitivity analysis. All of these are done to ensure that the model performs the way it was intended to and can be of value for the end-user. Model evaluation was done by using the evaluation methods suggested by Manson (2006). The scheduling model was validated using various methods; and the sensitivity analysis was done by changing the predefined parameters and recording the effect it had on the scheduling model's ability to generate quick (solution reactiveness), consistent (solution stability), and accurate (solution quality) results. From the sensitivity analysis it can be concluded that the scheduling model can in fact be classified as a robust model.

The hardware picking process' suggested improvements were validated by means of experimental simulation, using a simulation model designed in AnyLogic. Convincing results were generated that suggest that the suggested hardware picking improvements will in fact save a lot of time for PGA and thus reduce the amount of Red-light time (RLT)

The IPMT was also validated by comparing the predefined requirements for the tool with the outcome and functionality of the tool.

Chapter 6

Proposed implementation

From the previously discussed results it is evident that these artefacts and suggested solutions will in fact prove beneficial to PGA and may improve overall labour productivity. To ensure the successful implementation of these changes (if PGA chooses to do so) change management should be investigated. According to McKingsley (cited in Bezuidenhout (2018)) there are several elements of successful transformation, such as setting clear targets, having strong leadership from the top supporting the changes, creating a definite structure for the transformation, and ensuring continuous involvement by the organisation.

Keeping these elements in mind, it is also important to have a change model. There are various types of change models such as Kotter's model, Lewin's model, McKingsley's model, ADKAR's model and DICE framework, to mention just a few. For this project the ADKAR model is considered as it focuses on the business as well as the individual. The ADKAR model also provides a clear check-list for management to assist with the transformation process. The acronym for ADKAR is explained below.

- A: As a starting point it is important to explain to the workers exactly why change is needed and what the change entails. At the end of this stage the workers should understand why the change is being implemented.
- D: It is important that it becomes a personal decision for the workers so that they can choose to participate in the change. Therefore, the aim of this stage is to ensure that the workers have decided for themselves that they will participate in the change.
- K: This stage focuses on equipping the workers to know how to change and to ensure they

have the necessary skills and tools. This can be done in various ways, depending on the type of change that is taking place.

- A: Furthermore, the workers should be capable of implementing the change. The aim is to ensure that the workers are able to achieve the desired performance.
- R: Finally, there should be some form of recognition or reward system that will increase the likelihood of the change being continued in the long run. What will motivate the workers to keep the change going, instead of reverting back to the old system or habits?

PGA is already implementing some of these stages of the change model such as having feedback sessions, as well as brainstorming sessions with the workers to involve them and receive their buy-in to the change. A discussion has already been held with the staff regarding the need for improvement, especially regarding the labour productivity, which lead to the time studies and work sampling study being done.

For each artefact of the project, different skill sets or training would be required. PGA should also ensure that the workers are able to achieve the desired change by giving them the necessary tools and equipment. Furthermore, to encourage workers to continue with the change a reward system should be implemented. For the reward system, the Individual Performance Measurement Tool (IPMT) can be used where certain standards are set out, and the actual performance of the workers are compared to that standard. Workers that consistently achieve or exceed the expected performance should then be rewarded accordingly [*R* of ADKAR].

An area that suggested the highest return for improvements is the hardware picking process. Suggestions were made on how to improve the hardware picking process based on the results from the SMED analysis.These suggestions are briefly outlined:

- The floor manager aims to do his planning for the next day by 15:00 every afternoon to be able to allocate certain products to the respective assemblers. Therefore, the floor manager will run the optimised scheduling model everyday at 15:00 based on the progress data that he has at that point in time. The model can always be rerun if needed due to unforeseen circumstances.
- Hardware for the majority of the products expected to be produced the next day must be picked at 15:30 every day.
- The hardware is picked per product per assembler as assigned by the floor manager.
- Each assembler has a picking bin in which the hardware manager picks the hardware he will need the next day. The assembler will then collect his hardware the next morning and put it in a basket that he can take with him to his workstation. At the end of the day the empty basket will be placed in an allocated area. If the basket is not yet empty it is handed to the hardware manager, so that it can be stored inside the hardware store until the next day for control purposes and to avoid hardware being taken by other workers.
- More hardware must be picked than before, to reduce the amount of hardware that the assembler has to pick himself.
- Certain hardware components such as the most used pop rivets and screws must be kept in a small bin at the workstation. The bin can then be replenished as needed.
- The hardware that the assemblers have to pick themselves must be stored outside the hardware picking store. This includes even the components that used to be kept inside the store, to allow for quick and easy access to all the hardware.

To ensure the successful implementation of these suggestions, the hardware manager's and assemblers' buy-in have to be achieved and consensus has to be reached on the products that the hardware manager will pick and the hardware items that will be kept at the assemblers' workstations [D of ADKAR]. An information session should be held where the changes and expected performance outputs are discussed with the involved parties to ensure that everyone has the knowledge of how to implement the change [K of ADKAR]. Furthermore, a picking bin for each assembler will have to be provided, as well as a basket in which he can take the hardware to his workstation [A of ADKAR]. The basket is simply necessary to ensure that the hardware manager always has a dedicated bin per assembler to start picking new hardware even when the assembler is still busy with the hardware in his basket. Another consideration is the control of this system. To reduce theft and to ensure that assemblers do not take one another's hardware, the hardware manager should still sign the job card when the employee comes to collect the hardware. Bins should also be kept in a secure, allocated area especially between shifts. If an assembler does not complete a product within a shift, the remaining hardware should be taken back to the hardware store where it can safely be stored for the next shift. The result of implementing these changes is that the total time spent assembling a product will decrease, hence it will be easier for assemblers to achieve the desired performance levels and thus be rewarded accordingly [R of ADKAR].

To successfully implement the hardware picking changes, a proper schedule is needed so that the hardware manager is able to pick the hardware for the following day. To achieve this, a scheduling model was designed, with the aim of reducing the amount of Work-in-Progress (WIP) in the factory. As a starting point, the buy-in of the floor manager has to be achieved as he will be the driver of this change. To achieve this, a discussion should be held with the floor manager where the need for a schedule, as well as the expected performance improvements are discussed [A and K of ADKAR]. The floor manager should know exactly what is expected of him and how the scheduling model works. The model should make it easier for the floor manager to schedule the products, not harder. It is therefore necessary to train the floor manager how to run the model and how to get the most out of the schedule with the least amount of effort [K of ADKAR]. Perhaps there should be a reward connected to the overall productivity improvement of the factory for the floor manager as motivator [R of ADKAR].

Furthermore, to be able to use the scheduling model in the factory there are a few requirements that have to be adhered to, which now be outlined:

- Python software will have to be installed on the computer which will be used to generate the schedule, as well as other software requirements such as openpyxl and ORtools (Google's optimisation software package) which is used in the scheduling model. There is a 'requirements' text file with the scheduling model, stipulating these requirements.
- The production log must be up to date at all times and there can be no gaps in the data.
- The product's reference code (e.g. D02-SU 05) must be included to be able to keep track of the correct products in the schedule.
- A column, 'Product Code', should be added to the production log as the product code is used to look up the processing times.
- A sheet, 'Processing Times', should be added to the production log so that the processing times can easily be located.

If these requirements are met, PGA should easily be able to schedule their daily production and improve overall productivity.

Chapter 7

Conclusion and the way forward

The overall productivity of PGA, a small-to-medium manufacturing company, was investigated for the purpose of this project as the productivity of the factory is not at an optimal level. An in depth analysis of the factory's production was administered by doing a business process analysis (BPA), value analysis, as well as a work sampling study. These three techniques helped to identify the reasons for the productivity being as low as it is. Based on the BPA, improvement opportunities were identified for the factory process as a whole. Specific improvements for the hardware picking process were also identified through the BPA. Furthermore, the value analysis helped to identify areas to focus on, which should result in the biggest productivity improvement; this area was labour productivity, as it accounts for 26% of PGA's annual costs. A 1% improvement in labour productivity will be more valuable than a 1% improvement in glass costs which accounts for 19% of PGA's annual cost. The improvement opportunities that were identified by the value analysis for other areas such as hardware, aluminium and glass are not addressed in this project, but were discussed with the applicable workers at PGA. The work sampling study focused more in depth on the labour productivity of the factory. From this study it was calculated that factory productivity is at a low of 36% if the value-added activities are measured against the total time available for production.

To increase labour productivity Lean Manufacturing was investigated. Using Lean Principles, and specifically the JIT approach, three main wastes were identified in the factory, namely unnecessary motion, unnecessary waiting, and unnecessary inventory. Unnecessary motion and waiting were tracked back to the hardware picking process. A suggestion was made on how to reduce these two wastes by improving the picking process. The improvement suggestion included identifying tasks that can be done before the worker comes to collect the hardware as to reduce the amount of time the worker spends at the hardware store, as well as the number of times a worker has to walk to the hardware store every day. The third waste, unnecessary inventory, was tracked back to the lack of a proper schedule. Between every step in the production process there is Work-in-Progress (WIP), waiting for the next step. If scheduling could be improved, the flow of production would also improve, as workstation capacity loads will be taken into account. A scheduling model was therefore designed using mathematical programming to design a Linear Programming model that is programmed using Python and the Google Optimisation tools package, OR-tools. The schedule is generated based on the available information of the production status of each individual product at a certain point in time. The schedule produces the optimal order in which products should be produced on a specific day and should be re-run every day based on the new production status of the product. The hardware picking process was analysed and suggestions were made on how to improve the process based on SMED (Single Minute Exchange of Dies) principles. These suggestions have already been implemented in the factory. PGA also expressed a desire to measure the individual performance of workers. As individual performance of workers is directly linked to labour productivity, an Individual Performance Measurement Tool (IPMT) has been designed. The expected result is that measuring and rewarding individual performance will result in increased performance, increasing labour productivity. The IPMT has been designed using Microsoft Excel, but it is dependent on a product tracking system to be used effectively. The IPMT consists of an input data section, as well as an analysis section where the input data is summarised in pivot tables and graphs are generated based on the summarised data.

Furthermore, the scheduling model, hardware picking process improvement suggestions, and the IPMT were evaluated. The scheduling model was validated with the suggested evaluation methods namely, testing the robustness of the model, observing a typical case study, and experimental simulation. The hardware picking process improvement suggestions were validated by means of a simulation experiment using a simulation model designed in Anylogic. From the results it was concluded that hardware picking time can be reduced by up to 33.8% if the suggested improvements are implemented.

The IPMT was also validated by ensuring the tool meets all the predefined requirements.

Therefore, to conclude, the three artefacts of this project will effectively address labour productivity at PGA. The hardware picking process improvements will directly affect the amount of time wasted on walking to and from the hardware store (motion) as well as the time wasted waiting while the hardware is being picked (waiting). The scheduling model aims to move towards a JIT system and is thus decreasing the amount of Work-in-Process in the factory (inventory). To bring it all together the suggested IPMT can be used to reward productiveness in the factory which should contribute to the effectiveness of the change management. Therefore, by using the resources available at PGA, the labour productivity could definitely be increased.

As part of a future project the scheduling model can be expanded on in one or more of the following ways:

- The model can accommodate multiple workers at each workstation, and adjusts accordingly based on the demand.
- Send feedback messages notifying the user that due dates will not be met with the current capacity.
- Use a tracking model (as the one currently being designed by a third party) to automatically update product progress statuses to reduce the amount of manual inputs.
- Provide a weekly or monthly schedule in addition, as required.

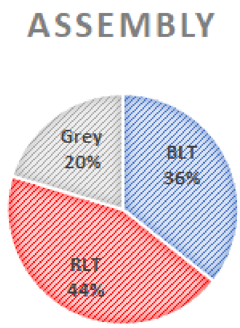
These are all suggestions that could be considered for future expansion on this project. All of these suggestions would add to the usability and attractiveness of the model.

Appendices

Appendix A: Work sampling study results

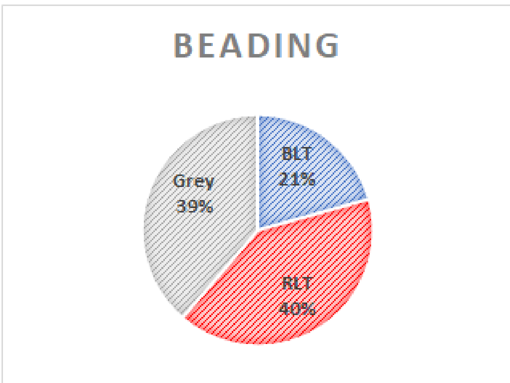
Appendix A.1: Assembly area results

Assembly Area																				
	Productive (BLT)											Supportive (Grey time)					Recovery (RLT)			
	Attach component	Crimp	Drill/ screw driver	Endmil	Filing (smoothe)	Friction Spay	Grinding	Pop riviting	Silicon	Woolpile	Using a tool (not individually identified)	Admin/ measure	Clean / Test	Collect/ Return/ Move frame	Position	Look for a coponent	Not at workstation	Stand	Talk	Walk
Number of observations	206	40	158	52	39	12	22	46	43	35	140	51	63	37	206	95	609	136	88	145
Percentage (%) of time	9.27%	1.80%	7.11%	2.34%	1.75%	0.54%	0.99%	2.07%	1.93%	1.57%	6.30%	2.29%	2.83%	1.66%	9.27%	4.27%	27.40%	6.12%	3.96%	6.52%
Total % of category	35.67%											20.32%					44.00%			
Cost per day (per person)	R 26.27	R 5.10	R 20.15	R 6.63	R 4.97	R 1.53	R 2.81	R 5.87	R 5.48	R 4.46	R 17.85	R 6.50	R 8.03	R 4.72	R 26.27	R 12.12	R 77.67	R 17.34	R 11.22	R 18.49
Cost per day (whole area) 6 workstations	R 157.63	R 30.61	R 120.90	R 39.79	R 29.84	R 9.18	R 16.83	R 35.20	R 32.90	R 26.78	R 107.13	R 39.02	R 48.21	R 28.31	R 157.63	R 72.69	R 466.00	R 104.06	R 67.34	R 110.95
Cost per month (whole area) 22 working days per month	R 3 467.81	R 673.36	R 2 659.77	R 875.37	R 656.53	R 202.01	R 370.35	R 774.36	R 723.86	R 589.19	R 2 356.76	R 858.53	R 1 060.54	R 622.86	R 3 467.81	R 1 599.23	R 10 251.91	R 2 289.43	R 1 481.39	R 2 440.93
Total cost per month	R 13 349.37											R 7 608.97					R 16 463.66			



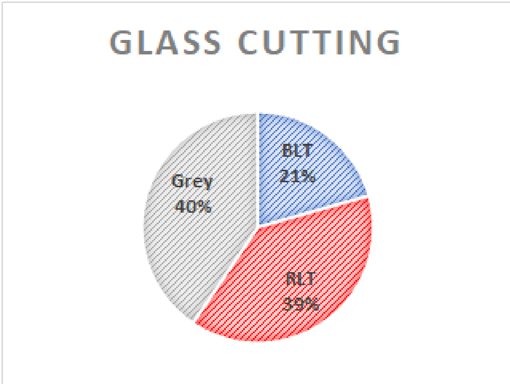
Appendix A.2: Beading area results

Beading Area											
	Productive (BLT)		Supportive (Grey time)					Recovery (RLT)			
	Cut	Place beading	Adjust Machine	Collect Bead	Measure	Move Frame	Position	Talk	Not at workstation	Stand	Walk
Number of observations	8	23	21	7	11	4	15	6	25	15	15
Percentage (%) of time	5.33%	15.33%	14.00%	4.67%	7.33%	2.67%	10.00%	4.00%	16.67%	10.00%	10.00%
Total % of category	20.67%		38.67%					40.67%			
Cost per day (per person)	R 15.12	R 43.47	R 39.69	R 13.23	R 20.79	R 7.56	R 28.35	R 11.34	R 47.25	R 28.35	R 28.35
Cost per day (whole area) 1 workstation (2 workers)	R 30.24	R 86.94	R 79.38	R 26.46	R 41.58	R 15.12	R 56.70	R 22.68	R 94.50	R 56.70	R 56.70
Cost per month (whole area) 22 working days per month	R 665.28	R 1 912.68	R 1 746.36	R 582.12	R 914.76	R 332.64	R 1 247.40	R 498.96	R 2 079.00	R 1 247.40	R 1 247.40
Total cost per month	R 2 577.96		R 4 823.28					R 5 072.76			



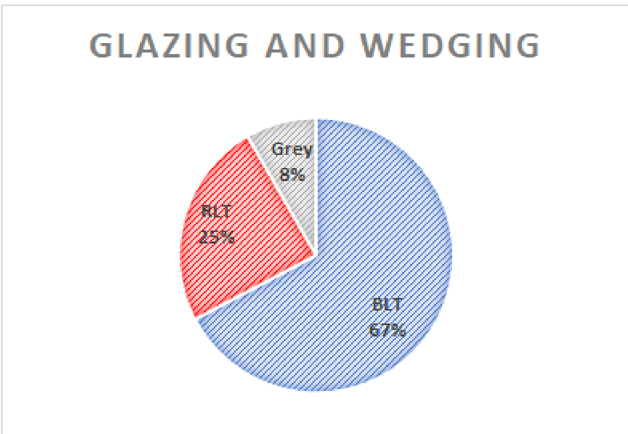
Appendix A.3: Glass cutting area results

Glass cutting Area													
	Productive (BLT)				Supportive (Grey time)					Recovery (RLT)			
	Cut/ Clean	Melt Middle	Polishing/ Edging	Separate	Collect & look for glass sheets	Mark & Measure & plan	Position	Transport	Tool	Talk	Not at workstation	Stand	Walk
Number of observations	29	13	13	7	20	43	35	23	1	15	46	26	30
Percentage (%) of time	9.63%	4.32%	4.32%	2.33%	6.64%	14.29%	11.63%	7.64%	0.33%	4.98%	15.28%	8.64%	9.97%
Total % of category	20.60%				40.53%					38.87%			
Cost per day (per person)	R 27.31	R 12.24	R 12.24	R 6.59	R 18.84	R 40.50	R 32.97	R 21.66	R 0.94	R 14.13	R 43.33	R 24.49	R 28.26
Cost per day (whole area) 1 workstation (3 workers)	R 81.94	R 36.73	R 36.73	R 19.78	R 56.51	R 121.50	R 98.90	R 64.99	R 2.83	R 42.38	R 129.98	R 73.47	R 84.77
Cost per month (whole area) 22 working days per month	R 1 802.72	R 808.12	R 808.12	R 435.14	R 1 243.26	R 2 673.00	R 2 175.70	R 1 429.74	R 62.16	R 932.44	R 2 859.49	R 1 616.23	R 1 864.88
Total cost per month	R 3 854.09				R 7 583.86					R 7 273.05			



Appendix A.4: Glazing and wedging area results

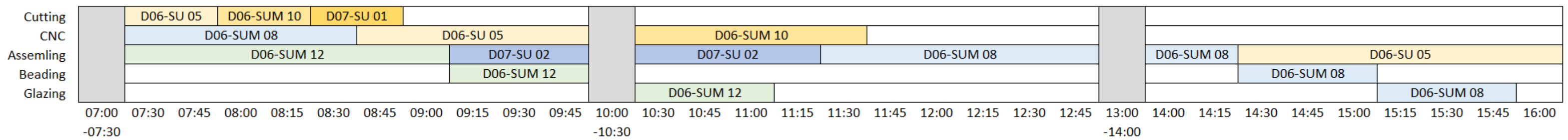
Glazing and wedging Area															
	Productive (BLT)								Supportive (Grey time)			Recovery (RLT)			
	Clean glass and frame	Insert butterfly	Insert beading	Insert glass	Insert wedge	Plastic	Wrap	Quality inspection	Collect glass	Positioning	Transport	Talk	Not at workstation	Stand	Walk
Number of observations	46	30	42	15	102	66	67	4	7	32	7	40	33	37	25
Percentage (%) of time	8.32%	5.42%	7.59%	2.71%	18.44%	11.93%	12.12%	0.72%	1.27%	5.79%	1.27%	7.23%	5.97%	6.69%	4.52%
Total % of category	67.27%								8.32%			24.41%			
Cost per day (per person)	R 23.58	R 15.38	R 21.53	R 7.69	R 52.29	R 33.84	R 34.35	R 2.05	R 3.59	R 16.41	R 3.59	R 20.51	R 16.92	R 18.97	R 12.82
Cost per day (whole area) 2 workstations (but usually 4 workers)	R 94.33	R 61.52	R 86.13	R 30.76	R 209.16	R 135.34	R 137.39	R 8.20	R 14.35	R 65.62	R 14.35	R 82.03	R 67.67	R 75.87	R 51.27
Cost per month (whole area) 22 working days per month	R 2 075.24	R 1 353.42	R 1 894.78	R 676.71	R 4 601.62	R 2 977.52	R 3 022.63	R 180.46	R 315.80	R 1 443.65	R 315.80	R 1 804.56	R 1 488.76	R 1 669.22	R 1 127.85
Total cost per month	R 16 782.38								R 2 075.24			R 6 090.38			



Appendix B: Testing Model's output

	Cutting			CNC			Assembly			Beading			Glazing		
Initial Status	D06-SU 05	29 September, 2018	0.35	D06-SUM 08	28 September, 2018	1.35	D06-SUM 12	26 September, 2018	1.85						
	D06-SUM 10	29 September, 2018	0.35	D07-SU 02	27 September, 2018	0	D07-SU 03	30 September, 2018	1.73						
	D07-SU 01	03 October, 2018	0.25												

	Cutting			CNC			Assembly			Beading			Glazing		
After 1 day status	D06-SU 05	29 September, 2018	0.35	D06-SUM 08	28 September, 2018	1.35	D06-SUM 12	26 September, 2018	1.85	D06-SUM 12	26 September, 2018	0.71	D06-SUM 12	26 September, 2018	0.63
	D06-SUM 10	29 September, 2018	0.35	D07-SU 02	27 September, 2018	0	D07-SU 02	27 September, 2018	1.73	D07-SU 02	27 September, 2018	0	D07-SU 02	27 September, 2018	0
	D07-SU 01	03 October, 2018	0.25	D06-SU 05	29 September, 2018	1.35	D06-SUM 08	28 September, 2018	1.85	D06-SUM 08	28 September, 2018	0.71	D06-SUM 08	28 September, 2018	0.63
				D06-SUM 10	29 September, 2018	1.35	D06-SU 05	29 September, 2018	1.85						
				D07-SU 01	03 October, 2018	0	D06-SUM 10	29 September, 2018	1.85						
							D07-SU 03	30 September, 2018	1.73						
							D07-SU 01	03 October, 2018	1.73						



Appendix C: Python Model's output

```
Optimal Schedule

Machine 0 -> Cutting
        Intervals :
        Machines Available: 1 -> #D07-SU 02
        Machines Available: 1 -> #D06-SUM 08
        Machines Available: 1 -> #D06-SU 05
        Machines Available: 1 -> #D06-SUM 10
        Machines Available: 1 -> #D07-SU 03
        Machines Available: 1 -> #D07-SU 01
        Machines Available: 1 -> #D06-SU 07
Machine 1 -> CNC
        Intervals :
        Machines Available: 1 -> #D07-SU 02
        Machines Available: 1 -> #D06-SUM 08
        Machines Available: 1 -> #D06-SU 05
        Machines Available: 1 -> #D06-SUM 10
        Machines Available: 1 -> #D07-SU 03
        Machines Available: 1 -> #D07-SU 01
        Machines Available: 1 -> #D06-SU 07
Machine 2 -> Assembly
        Intervals :
        Machines Available: 8 -> #D07-SU 02
        Machines Available: 8 -> #D06-SUM 08
        Machines Available: 8 -> #D06-SU 05
        Machines Available: 8 -> #D06-SUM 10
        Machines Available: 8 -> #D07-SU 03
        Machines Available: 8 -> #D06-SU 07
        Machines Available: 8 -> #D07-SU 01
Machine 3 -> Beading
        Intervals :
        Machines Available: 1 -> #D07-SU 02
        Machines Available: 1 -> #D06-SUM 08
        Machines Available: 1 -> #D06-SU 05
        Machines Available: 1 -> #D06-SUM 10
        Machines Available: 1 -> #D07-SU 03
        Machines Available: 1 -> #D06-SU 07
        Machines Available: 1 -> #D07-SU 01
Machine 4 -> Glass Cutting
        Intervals :
        Machines Available: 1 -> #D07-SU 02
        Machines Available: 1 -> #D06-SUM 08
        Machines Available: 1 -> #D06-SU 05
        Machines Available: 1 -> #D06-SUM 10
        Machines Available: 1 -> #D07-SU 03
        Machines Available: 1 -> #D06-SU 07
        Machines Available: 1 -> #D07-SU 01
Machine 5 -> Glazing
        Intervals :
        Machines Available: 3 -> #D07-SU 02
        Machines Available: 3 -> #D06-SUM 08
        Machines Available: 3 -> #D06-SU 05
        Machines Available: 3 -> #D06-SUM 10
        Machines Available: 3 -> #D07-SU 03
        Machines Available: 3 -> #D06-SU 07
        Machines Available: 3 -> #D07-SU 01


Time Intervals for Tasks

Machine 0 -> Cutting
        Intervals : [0,15] [15,36] [36,57] [57,78] [78,93]
Machine 1 -> CNC
        Intervals : [15,15] [36,117]
Machine 2 -> Assembly
        Intervals : [15,118]
Machine 3 -> Beading
        Intervals : [118,118]
Machine 4 -> Glass Cutting
        Intervals : [118,163]
Machine 5 -> Glazing
        Intervals : [163,163]
```

Appendix D: Simulation model for scheduling model (expanded results)

Figure 1 outlines the simulation results for Product 1 where the base-case is compared to the improved-case. It can clearly be seen that there is a definite improvement from the base-case.

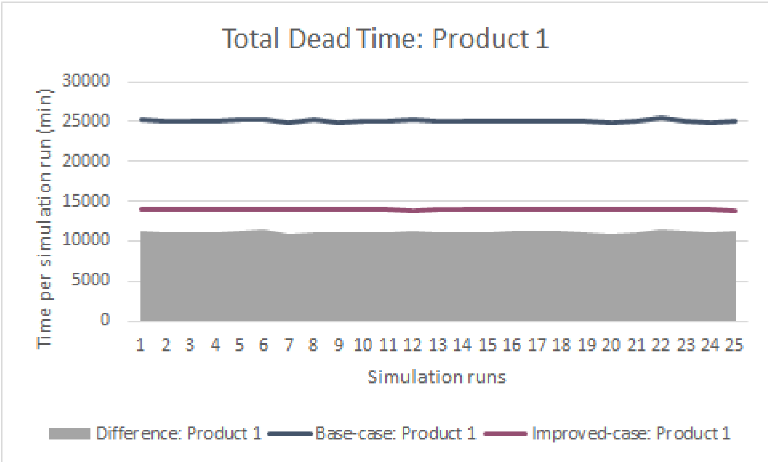


Figure 1: Base-case vs. Improved-case of Product 1

Figure 2 outlines the simulation results for Product 2 where the base-case is compared to the improved-case. It can once again clearly be seen that there is a definite improvement from the base-case.

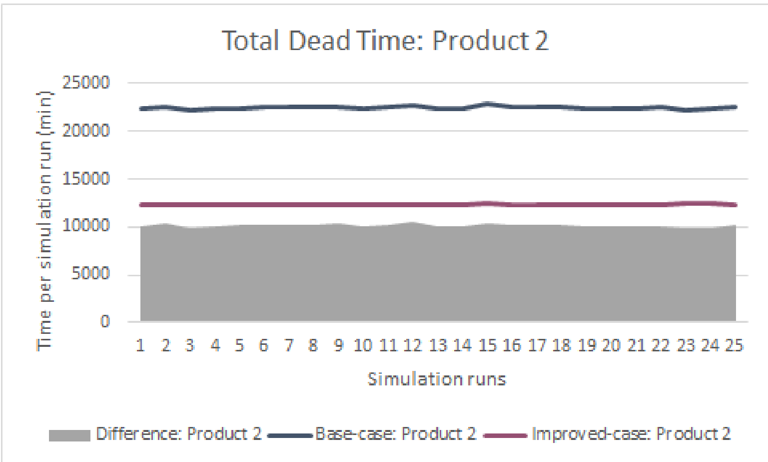


Figure 2: Base-case vs. Improved-case of Product 2

Figure 3 outlines the simulation results for Product 3 where the base-case is compared to the improved-case. It is evident that there is a definite improvement from the base-case.

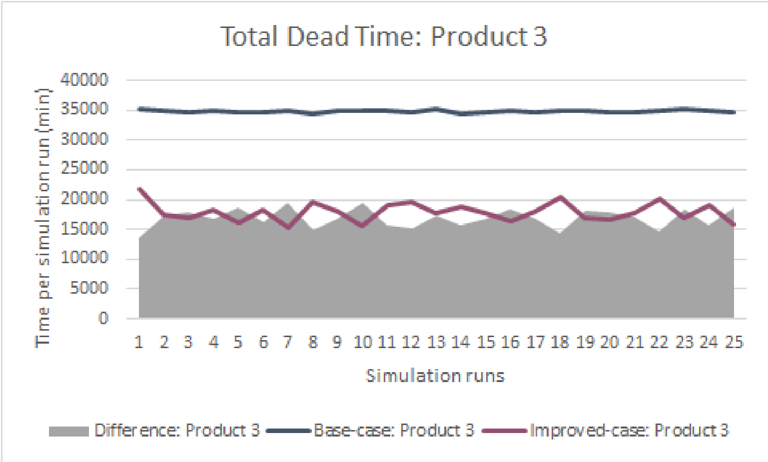


Figure 3: Base-case vs. Improved-case of Product 3

Appendix E: Simulation model for hardware picking (expanded results)

For each product type there was a decrease in the amount of time spent picking hardware. It can be seen that the product type most influenced by these changes is Product 3 which includes Vistas, Palace sliding doors, and Hinge doors.

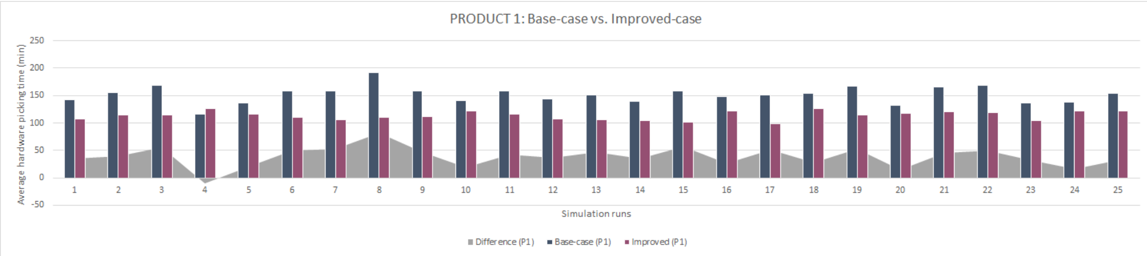


Figure 4: Simulation results for Product 1

Figure 4 is a visual representation of the simulation results for Product 1 for each simulation run. It can be seen that $\frac{1}{25}$ of the time the base-case time was less than the improved-case's time. At simulation run #4 the base-case had a better time than the improved case.

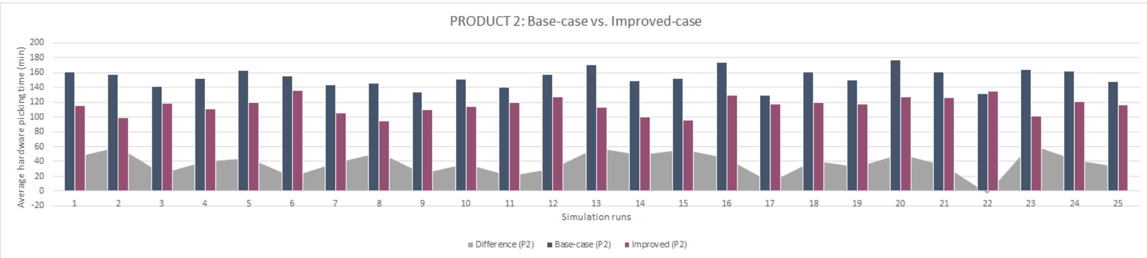


Figure 5: Simulation results for Product 2

Figure 5 is a visual representation of the simulation results for Product 2 for each simulation run. It can be seen that $\frac{1}{25}$ of the time the base-case time was less than the improved-case's time. At simulation run #22 the base-case had a better time than the improved case.

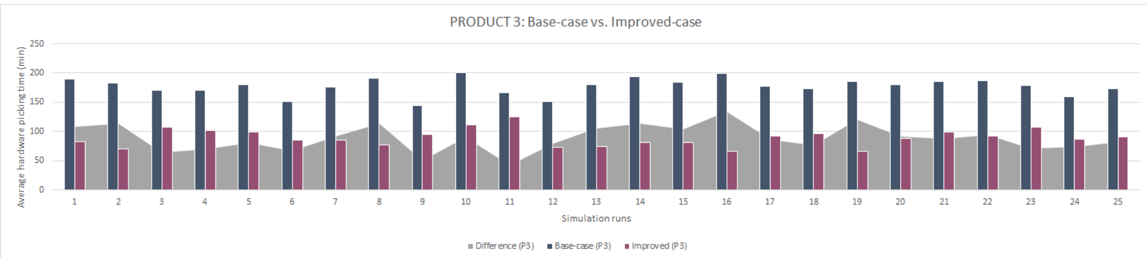


Figure 6: Simulation results for Product 3

Figure 6 is a visual representation of the simulation results for Product 3 for each simulation run. It can be seen that in all 25 simulation runs, the improved-case's time was less than that of the base-case.

Appendix F: Industry sponsorship form

Department of Industrial & Systems Engineering
University of Pretoria

Final Year Project Mentorship Form
2018

Introduction

An industry mentor is the key contact person within a company for a final year project student. The mentor should be the person that could provide the best guidance on the project to the student and is most likely to gain from the success of the project.

The project mentor has the following important responsibilities:

1. To select a suitable student/candidate to conduct the project.
2. To confirm his/her role as project mentor, duly authorised by the company by signing this **Project Mentor Form.** Multiple mentors can be appointed, but is not advised.
3. To ensure that the **Project Definition** adequately describes the project.
4. To review and approve the **Project Proposal**, ensuring that it clearly defines the problem to be investigated by the student and that the project aim, scope, deliverables and approach is acceptable.
5. To review and approve all subsequent project reports, particularly the **Final Project Report** at the end of the second semester, thereby ensuring that information is accurate and the solution addresses the problems and/or design requirements of the defined project.
6. Ensure that sensitive confidential information or intellectual property of the company is not disclosed in the document and/or that the necessary arrangements are made with the Department regarding the handling of the reports.

Project Mentor Details

Company:	**PG Aluminium**
Project Description:	**Overall productivity improvement model for a typical small to medium, custom manufacturing enterprise.**
Student Name:	Tanisha Moolman
Student number:	15010334
Student Signature:	
Mentor Name:	Werner Röhrs
Designation:	Director
E-mail:	Werner.jhbnorth@pgaluminium.co.za
Tel No:	011 027 9000
Cell No:	071 875 2036
Fax No:	-
Mentor Signature:	

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